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Cc: 'B. Arrindell'
Subject: docket 2010-0674 submission of Resnikoff comments on RDSGEIS

On behalf of Damascus Citizens for Sustainability and NYH2O, I am submitting the attached paper by Resnikoff on potential health effects of radon in natural gas from Marcellus shale.

Dr. Resnikoff's paper was submitted as comments to the New York State Department of Environmental Conservation on the draft supplemental generic environmental impact statement on unconventional shale gas development. NYSDEC has made his submission available with all the hundreds of thousands of other comments?

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Radon in Natural Gas from Marcellus Shale

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ABSTRACT: A potential public health hazard associated with radon in natural gas from the Marcellus Shale formation should be investigated by regulatory agencies. Unlike present sources for natural gas, located in Texas and Louisiana, the Marcellus Shale formation is considerably closer to New York consumers and the radon concentrations at wellheads in New York and Pennsylvania are higher than the national average for natural gas wells. Using a simple Fortran program that simulates the production of radon in the well bore and transit to the well head, we calculate the wellhead concentrations of radon in natural gas from Marcellus Shale. Then accounting for the transit time to consumers, and the average dilution in homes, including smaller apartment volumes in urban areas, we determine the potential health effects of releasing radon in natural gas from unvented kitchen stoves, using Environmental Protection Agency data. While several uncertainties must be resolved, the potential health effects require investigation by regulatory agencies.

KEYWORDS: Marcellus shale, natural gas, radon, lung cancer

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I. INTRODUCTION

A significant public health hazard associated with drilling for natural gas in the Marcellus Shale formation should be seriously investigated by State regulators and the Environmental Protection Agency (EPA). This hazard is from radioactive radon gas and the potential for large numbers of lung cancer among customers who use natural gas in unvented kitchen stoves and space heaters. Unlike present sources for natural gas, located in Texas and Louisiana, the Marcellus Shale is considerably closer to New York consumers, implying less time for radon to decay. In addition, the radium concentrations in Marcellus shale and the radon concentrations at the wellheads in New York and Pennsylvania are likely higher than the national average for natural gas wells.

There are strong economic interests supporting the development of Marcellus Shale gas. The potential for significant generation of jobs through the development of this resource is a real and important factor. Doubtless these economic factors will weigh on State regulators and potentially influence decisions regarding whether States will move forward to adequately address the concerns raised in this paper. In this regulatory environment where the stakes are so high, it is difficult to do objective science.

In this paper we calculate the wellhead concentrations of radon in natural gas from Marcellus Shale, the time to transit to consumers, particularly New York City residents, and the potential health effects of releasing radon, especially in the smaller living quarters found in urban areas. We also discuss other factors that must be taken into account, such as processing plants and storage facilities.

It has been known since the early 1900's that radon, a radioactive gas, is present in natural gas. Reports by R.H. Johnson[1] and C.V. Gogolak[2] calculate the health effects due to burning natural gas in unvented kitchen stoves and space heaters. In an U.S. Environmental Protection Agency report, Raymond Johnson calculated the number of lung cancer deaths due to inhalation of radon in homes throughout the U.S. as 95 due to radon concentrations of 1,370 Becquerels per cubic meter [Bq/m^3; 37 picoCuries per liter (pCi/L)] in the pipeline. As seen below, we calculate a number of potential lung cancer deaths considerably higher. More recent measurements in British Columbia[3] show lower wellhead radon concentrations, up to 926 Bq/m^3 (25 pCi/L); the Marcellus shale has radium concentrations and therefore radon concentrations, considerably greater.

Radon at the wellhead is transported through natural gas pipelines to distribution centers and to homes for use in cooking and heating. Most of the natural gas currently consumed in New York State arrives from the Gulf Coast, a distance of 1800 miles. The closer to the point of use, the shorter the transport time. And the Marcellus shale is much closer, less than 400 miles to New York City. Radon-222 has a half-life of 3.8 days.

Radon is an inert radioactive gas. This means it does not react chemically with other elements. Whatever radon is in the pipeline and is delivered to homes is released to the home environment from unvented kitchen stoves and space heaters. The radon is not oxidized and is not made benign or non-radioactive in the burning process.

Once radon enters the home through cooking, it is diluted within the home volume and also by air exchanges with the outside air. Most calculations assume this radon gas mixes uniformly within the living space. Thus, once radon enters the home, the average concentrations depend on the home volume, and also on the number of air interchanges. Previous calculations by Johnson and Gogolak make specific assumptions about the average volume of a home and the number of air interchanges per hour. Their assumptions are not necessarily appropriate for apartments in major urban areas, such as New York City.

Since radon is an inert gas, when it is inhaled, the gas is mostly exhaled. However, radon does decay to other radioactive decay products, such as polonium, bismuth and lead. These are solid fine radioactive particles that can reside in the lung. Radioactivity due to these radon decay products may resides in the lung, yielding a radiation dose to the lung. Using an EPA model developed in 2003[4], we can calculate the radiation dose to an individual over a 30-year period and the number of lung cancer deaths to New York State residents. As will be seen, the total number of lung cancers is significant, far more than estimated by Johnson et al. in 1973

To estimate the health effects of radon in natural gas three factors must be addressed: 1) the concentration of radon at the natural gas wellhead, 2) transport from the wellhead to the household, and 3) the dilution of incoming radon in the home.

None of this analysis has been done by State regulatory agencies, such as the New York Department of Environmental Conservation (DEC) in its revised draft Generic Environmental Impact Statement[5]. In the entire 1400 page EIS, one sentence appears. "Radon gas, which under most circumstances is the main human health concern from NORM, is produced by the decay of radium-226, which occurs in the uranium-238 decay chain" (NORM refers to Naturally Occurring Radioactive Material.) This one sentence is the full extent of DEC's analysis of the environmental impact of radon.

II. RADON AT THE WELLHEAD

The first step is to calculate the initial source term, the concentration of radon at the wellhead. The Marcellus shale formation is more radioactive than most other sources of natural gas in the United States. In exploring for gas and oil in shale, the industry identifies natural gas formations by the high radioactivity and high carbon content at the Marcellus Shale horizon. Since radon is a decay product of radium-226, to calculate radon levels it is necessary to know the concentrations of radium-226. Based on a USGS study[6] and gamma ray logs (also known as GAPI logs) that we have examined, the radium concentrations in the Marcellus Shale is 8 to 32 times background. This compares to an average radium-226 in surface soil in New York State of 0.03 Bq/g [0.81 picoCuries per gram (pCi/g)][7]. [a]

[a] Note, DEC claims that "black shale typically contains trace levels of uranium and gamma ray logs indicate that this is true of the Marcellus shale" Based on gamma ray logs, a study by the United States Geological Survey and also statements in the rdGEIS, we differ strongly with the DEC assessment that the concentrations are "trace levels"

As seen in Fig. 1, the Marcellus shale formation is quite large extending from New York State, into Virginia. Another shale formation, below Marcellus shale, the Utica shale, extends further south, into Tennessee.

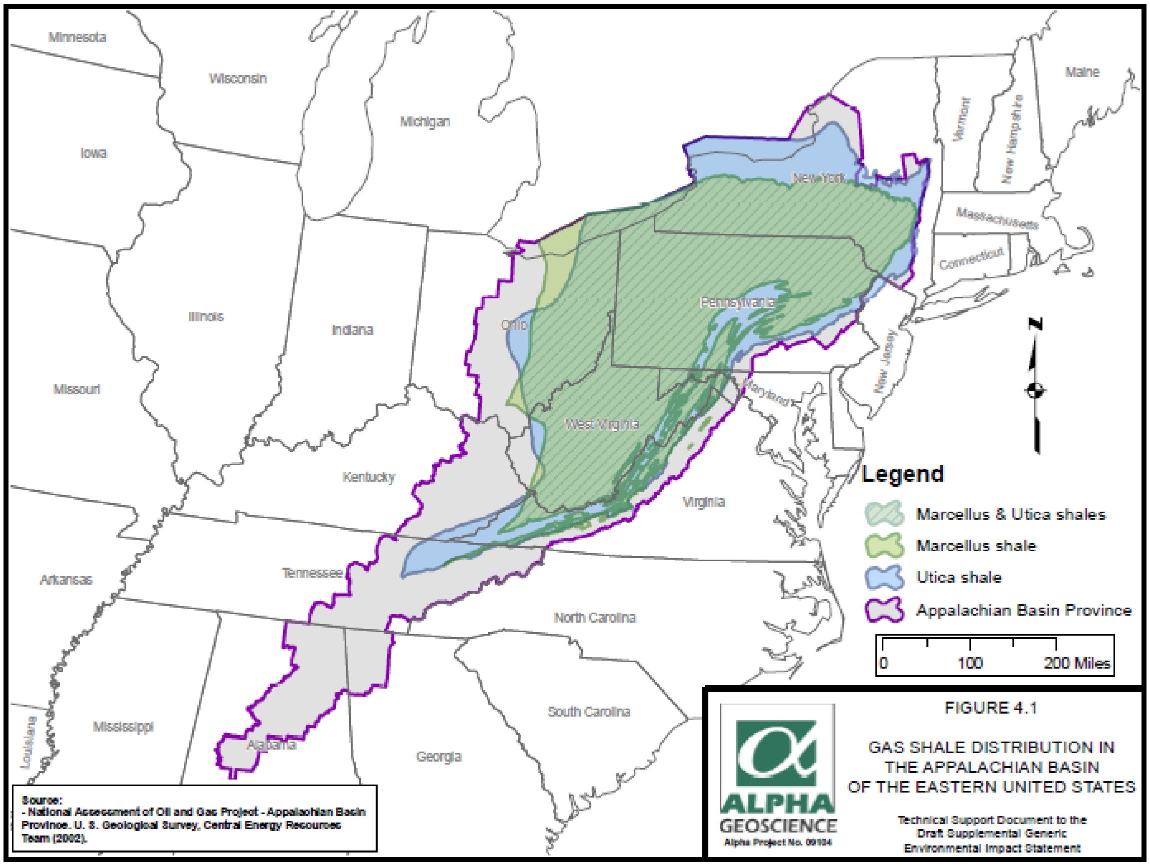

Figure 1. Areal Extent of Marcellus Shale[25]

As one goes further south, the Marcellus shale formation is deeper. Marcellus actually surfaces in the upstate town of Marcellus, but at the border with Pennsylvania, the Marcellus formation is 3000 to 5000 feet below the surface, as seen in Fig. 2. In Pennsylvania, the Marcellus formation is 5000 to 9000 feet below the surface. The thickness of the Marcellus formation ranges from 50 to 300 feet.

At RWMA, we analyzed the gamma-ray well logs from wells in three towns in New York State: Reading, Dix and Pulteney. The Pulteney well (also referred to as the Bergstresser well) would be used as a disposal well for radioactive waste water from other exploratory wells in New York State[8]. Gamma radioactivity within each well was sampled with a sensitive Geiger counter and the measurements were plotted on a graph in what are known as GAPI (Gamma-ray, American Petroleum Industry) units against depth.

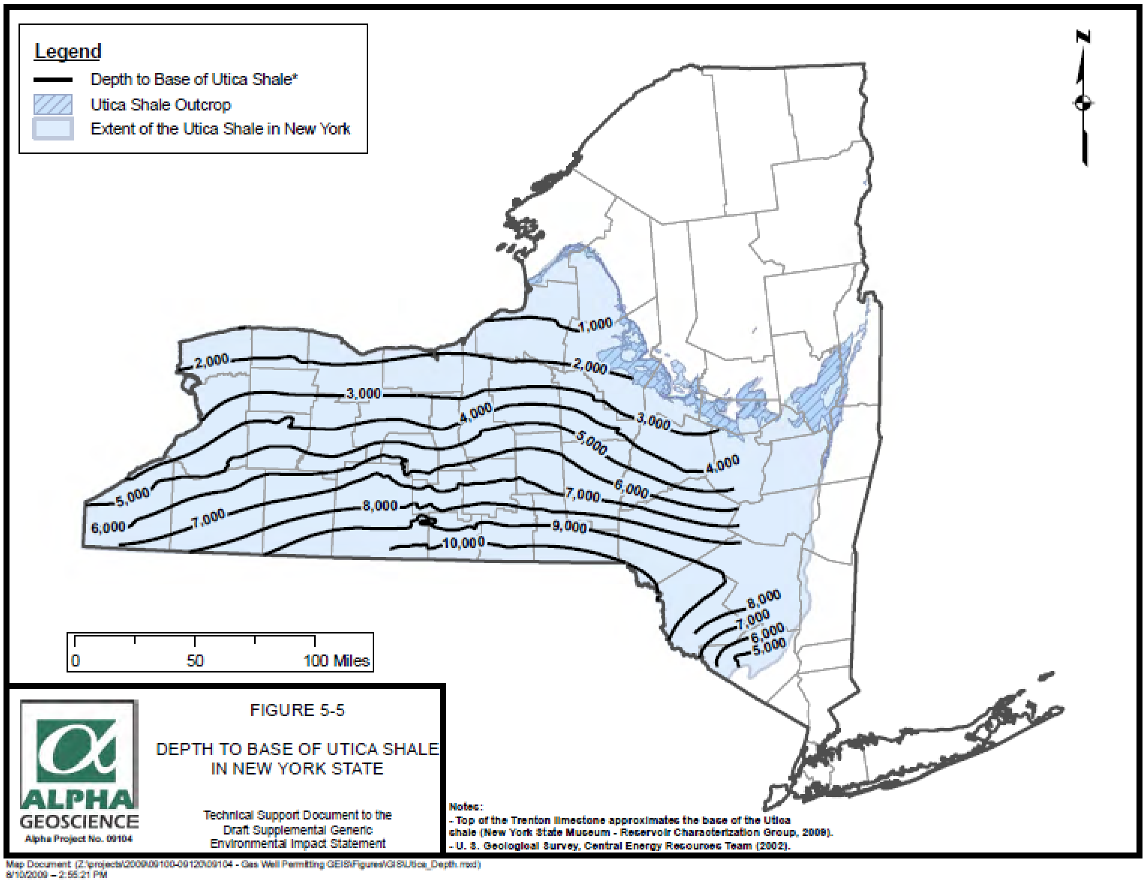

Figure 2. Depth of Marcellus Shale in New York State[25]

The GAPI unit is defined by a calibration facility at the University of Houston, Texas. Located at this facility are three pits, each with a different mixture of thorium, uranium, and potassium. The actual GAPI unit is arbitrary. It is defined as 1/200th of the deflection measured between the high and low activity zones in the pits[9]. In order to convert the GAPI units to curies we used a method cited by several sources, in which 16.5 GAPI units equal 1 microgram of Radium-equivalent per metric ton [or 0.037 Bq/m^3 (or 1 picocurie per gram)][10].

In general, the total radioactivity throughout the depth of the bedrock, including K-40, appears to be equal to or less than 0.37 Bq/m^3 [10 picocuries per gram (pCi/g)]. However, at certain depths in each well the radioactive activity is significantly higher.

All logs have a provision for the shifting of scale from the standard 0-200 GAPI range to greater than 200 GAPI or even greater than 400 GAPI. It is unclear from the logs how the shifting of scale is recorded, but at a certain depth the gamma ray line indicates measurements beyond the 0-200 GAPI range.

A sample log from upstate New York is shown in Fig. 3. As seen, below 1900 feet, in the Union Springs formation of Marcellus shale, the gamma log and total organic content go off scale; this is the depth where natural gas is located. Below the Union Springs formation, in the Onondaga Limestone formation, the gamma ray logs and total organic content drop precipitously. The thickness (less than 100 feet) and the depth of the shale are consistent with the general geological predictions of the Marcellus formation in the region.

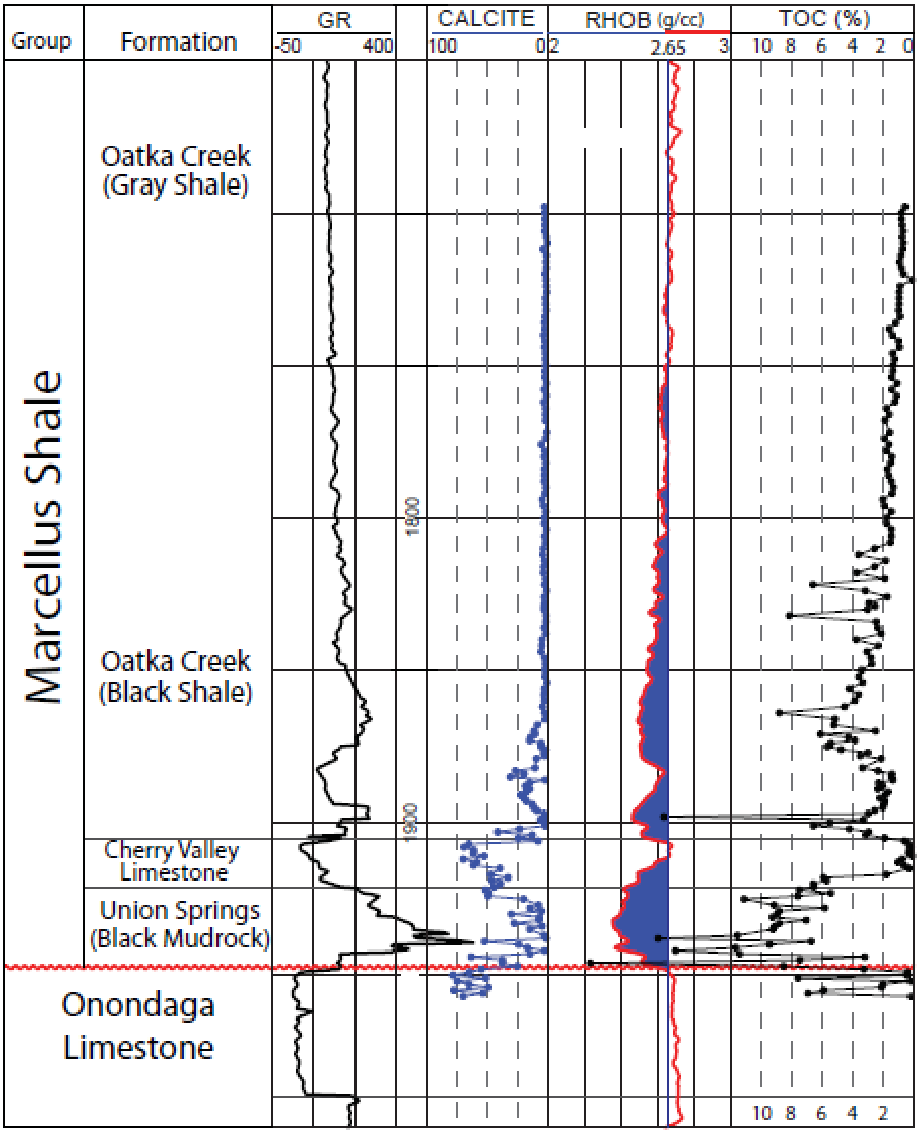

Figure 3. Beaver Meadows Core[26]

- Insert Fig. 3 here -

It is not possible to give the specific radioactivity measurement due to the log quality, but if we consider that these sections indicate the gamma ray range of 200-400 GAPI, it would represent radioactive radium concentrations of about 0.44 to 0.89 Bq/g (12-24 pCi/g) or higher. These radium concentrations are far higher than average background radium concentration in New York State[7], 0.031 Bq/m^3 (0.85 pCi/g).

Another source of information is the United States Geological Survey (USGS). In 1981 the USGS performed a geochemical study of trace elements and uranium in the Devonian shale of the Appalachian Basin[6]. A brief review of this analysis is necessary to evaluate and verify the data provided by the GAPI logs for the three locations in New York State.

The Devonian layer refers to sediment formed 350 million years ago from mud in shallow seas. Since the layers do not form in a line parallel to the ground surface, the depth at which

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Marcellus is found can vary from surface outcroppings to as deep as 7,000 feet or more below the ground surface along the Pennsylvania border in the Delaware River valley,[11] and as deep as 9000 feet in Pennsylvania[12].

Marcellus shale underlies a vast section of the United States, as seen in Figure 1. The USGS study analyzed seventeen cores from wells in Pennsylvania, New York, Ohio, West Virginia, Kentucky, Tennessee, and Illinois. The researchers collected a variety of geochemical data to be used for resource assessment and identification of possible environmental problems. It is important to note the method of analyzing cores.

Rather than the direct gamma spectroscopy employed by gas industry consultants[13], in the USGS study uranium was measured in each core with a more appropriate and precise method. This is called delayed-neutron analysis. In contrast, the oil and gas industry consultants employed a non-ELAP-certified lab that cannot do this more precise analysis. Nevertheless, DEC's contractor, Alpha Environmental, quotes these measurements in Appendix 1. The Alpha Environmental report does not even cite the USGS study. Since USGS is a reputable and objective government agency, DEC should request an explanation why this reference was omitted.

Although the cores varied in thickness and in depth, geologists identified the Marcellus Shale stratum in several cores using data on the organic matter (carbon), sulfur, and uranium content of the samples. Table 1 below summarizes the results from four cores that tapped into the radioactive Marcellus formation. The depths at which the layer was found as well as the uranium measurements are presented.

Location of the Core	Depth of Sample (feet)	Uranium Content (ppm)
Allegheny Cty, PA	7342 – 7465	8.9 – 67.7
Tomkins Cty, NY	1380 – 1420	25 – 53
Livingston Cty, NY	543 – 576	16.6 – 83.7
Knox Cty, OH	1027 – 1127	32.5 – 41.1

Table 1. Uranium Content and Depth of Marcellus Shale in Four Cores

The four cores were taken from different geographical locations, but the characteristics of the identified Marcellus shale layer, specifically the high uranium and carbon content, are consistent. DEC reports uranium content up to 100 ppm, that is, higher than we assume. The thickness of the Marcellus shale formation varies between 0 and 250 feet, according to isopach maps.

To compare the uranium content in parts per million (weight) to radioactive concentration in picocuries per gram, we use the correspondence[14]:

$$2.97 \text{ ppm} = 0.037 \text{ Bq/m}^3 \text{ (1 pCi/g) U-238}$$

Using this relationship, the U-238 ranges up to 1.04 Bq/m^3 (28 pCi/g), or 33 times background for radium-226, assuming U-238 and Ra-226 are in secular equilibrium, as it is in the Marcellus Shale formation. That is, the USGS measurements and the GAPI logs are consistent. The range of 0.24 to 1.11 Bq/m^3 (6.6 to 30 pCi/g) is our starting point for the concentrations of Ra-226 in the natural Marcellus Shale formation, to determine radon concentrations at the wellhead.

Numerical simulation shows the high concentrations of radon that will be found at the wellhead for Marcellus Shale gas, based on a variety of realistic assumptions. These assumptions

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include the rate at which radon is generated by radium-226 which, in turn, depends on the radium concentration in the shale. Otherwise there are no major uncertainties about the rate at which radon is produced. The radon's ability to escape from the rock matrix and be entrained by the natural gas flowing inward toward the well bore is less certain, but it can be estimated reasonably well. Our assumptions in the model we employed are listed in Table 2.

PARAMETER	Value	Unit
Depth of Horizontal Bore [27]	5000	feet
Gas Temperature [28]	105	°F
Well Bore r(min)	0.5	feet
Max gas-yielding radius r(max)	200	feet
Length of horizontal well bore	4000	feet
Gas Production Rate	10000	MCFD
Flowing pressures at r(min) [29]	2000	psi
Flowing pressures at r(max) [30]	1500	psi
Standard pressure for gas	1	atm
Standard temperature for gas	59	°F
Porosities at r(min) [31]	10 - 50	%
Porosities at r(max)	4	%
Radium Activity	6.6 - 30	pCi/g
Rock Density [32]	2.55	g/cm^3
Radon Emanation Factor [33]	10 - 30	%

Table 2. Input Parameters for Well Simulation

A description of the Fortran model we developed is in Appendix A. Numerical simulation thus shows – for typical flow rates, well dimensions, and other reasonable assumptions – that the radon concentrations in natural gas at the wellhead (expressed in pCi/liter) range between 1,367 to 95,407 Bq/m^3 (36.9 to 2576 pCi/L). The two high values in Table 3, 68,837 Bq/m^3 (1,858.6 pCi/L) and 95,407 Bq/m^3 (2576 pCi/L), are based on a radium concentration of 1.11 Bq/m^3 (30 pCi/g). For the radon concentration 31,780 Bq/m^3 (858.6 pCi/L), we assume a porosity of 30% and an emanation rate of 30%. The highest value assumes a porosity of 10% and an emanation rate of 30%.

All these are reasonable values and indicate the need for independent testing of production wells in the Marcellus shale formation. These radon concentrations in gas at the wellhead are far higher than the 1,481 Bq/m^3 (40 pCi/liter) wellhead concentration estimated by ATSDR[15] or the 1,370 Bq/m^3 (37 pCi/liter) concentration that Raymond Johnson *et al.* considered average in pre-fracking days, though Johnson *et al.* did find a maximum of 53,704 Bq/m^3 (1450 pCi/L). More recently, the pipeline operator, Spectra Energy, through its contractor, measured radon concentrations of 630 Bq/m^3 (17 pCi/L) taken at a pipeline intersection 70 miles from New York City.[16] The geology of the producing wells was not identified.

NY Baseline	Table 3. Approximate NY Range for Marcellus gas				
4.2	100	151	858.6	2576	pCi/l of radon in gas at wellhead
1500	400	500	400	400	miles from wellhead to customer
11	11	11	11	11	mr/hr typical speed of gas in pipeline
5.68	1.52	1.89	1.52	1.52	days transit time in pipeline
0.3576	0.76	0.7089	0.758528828	0.758528828	fraction of Rn-222 remaining after transit time
1.50192	75.85	107.0439	651.27	1953.97	pCi/l in natural gas delivered to customer
7111	4053	7111	4053	4053	Dilution factor
0.000211211	0.019	0.015053284	0.161	0.482	pCi/l lifetime exposure level in living space
1.23E-06	9.94E-05	8.75E-05	8.54E-04	2.56E-03	Lifetime risk (excess deaths per capita)
21	1183	1465	10160	30484	Excess deaths per 11.9 million residents
<1{.27)	17	20	145	435	Excess deaths per year per 11.9 million residents
Johnson, p. 14 for NYC distribution lines*	Numerical Similation Low-End values	Gogolak pp.5-26 Devonian shales*	Numerical Simulation High-End Values	Numerical Simulation High-End Values	**Basis for Radon Concentration**

*based on 16.76 million residents

	porosity 10%, emanation 10%, radium 30 pCi/g	porosity 10%, emanation 30 %, radium 30 pCi/g

In addition and in response to a preliminary report by this author, the USGS sampled radon from several natural gas wells in Pennsylvania.[17] Two samples were from the Middle Devonian Shale formation. It is not clear these samples were taken from Union Springs (Black Mudrock) formation. While the authors state the data were preliminary and the uncertainty was 25%, one well had radon concentrations from 37 Bq/m^3 (1 pCi/L) to 2,926 Bq/m^3 (79 pCi/L), a considerable spread. The well locations were not identified. It would be important for the USGS to continue this project by sampling hydraulic fractured wells in Black Mudrock and to discuss the geology of each well.

III. TRANSPORT FROM WELLHEAD TO HOUSEHOLD

Marcellus Shale gas and the accompanying radioactive gas, radon, would be transported from the natural gas wellheads in Pennsylvania and New York to apartments and homes via pipelines. With a travel time of 10 mph in the pipeline[18], only about 25% of the initial radon from the Gulf Coast remains to enter homes. Since gas from the Marcellus shale travels a much shorter distance, a greater fraction will remain, all things being equal. The natural gas piped in from the Gulf Coast allows a radon decay up to two half-lives. The distance from Marcellus shale to New York City is much shorter; we are estimating this distance at the conservative figure of 400 miles. We estimate closer to 76% of the initial concentration of radon at Marcellus Shale wellheads will arrive at New York State residences, as shown in Table 3.

Thus, over and above the effects of increased well concentrations of radon, the shorter transit time for Marcellus Shale gas will increase the risk compared to the risk that Raymond Johnson *et al* calculated for New York residents.

IV. RADON DILUTION IN THE HOME AND POTENTIAL HEALTH IMPACTS

Given the radon concentration in natural gas arriving at the kitchen stove, the next issue is the dilution of radon within the apartment or home. This will allow us to determine the radon concentration within the home and the health impact to residents who use natural gas.

Johnson bases his dilution factor of 7111 on two values. First, he assumes the volume of a home, which he estimates at 8000 cubic feet (or 226.6 cubic meters). Secondly, he figures the expected number of air exchanges as one per hour. An air exchange is the amount of time to replace the entire air volume of a dwelling.

We base our calculations on data from the US Environmental Protection Agency. On the basis of the EPA Factors Handbook[19], we take the volume of a dwelling as 183 cubic meters, rather than 226.6 cubic meters used by Johnson. This smaller volume is more representative of the size of an urban apartment in New York City or Philadelphia.

For the number of air exchanges per hour, rather than one per hour, we take 0.71 air exchanges per hour. This is also more representative of New York City apartments[17]. With these changes, the dilution factor of 7111 is substantially modified. The factor of 7111 is multiplied by 0.57 and becomes 4053. This increases the radon concentration within a dwelling, as compared to Johnson's calculations.

To obtain the radon concentration within the home, we divide the radon concentration entering the home via a kitchen stove by the dilution factor of 4053, as seen in Table 3, the indoor concentrations range between 0.69 Bq/m^3 (0.0187 pCi/L) to 17.85 Bq/m^3 (0.482 pCi/L). Since the average radon concentration in a multi-family unit[20] is 24.11 Bq/m^3 (0.651 pCi/L), at the upper concentration, this is a considerable increase to radon concentrations in an apartment.

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The concentration 24.11 Bq/m^3 (0.651 pCi/L) is comparable to a recent survey of apartments in New York City[21], 17.78 Bq/m^3 (0.48 pCi/L).

Assuming a person resides in the home 70% of the time, we can determine the risk to a resident of developing lung cancer. The risk is based on a U.S. Environmental Protection Agency analysis[22]. As seen in Table 3, the risk of developing cancer in a lifetime ranges from 1 in 10,000 to 1 in 391, an extremely high number. One then multiplies this risk by the number of persons who are potentially at risk.

The number of persons potentially at risk in New York State can be roughly determined by the number of kitchen stoves fueled by natural gas in New York State multiplied by the number of persons in a household. According to the U.S. Department of Energy[23], the number of households with natural gas fueled stoves in New York State is 4.4 million. We have not identified how many stoves are unvented. In New York City, most gas stoves were installed before the city code required venting.

From the 2010 Census, the average number of persons per household in New York State is 2.69. Thus 11.9 million persons in New York State are potentially at risk. Multiplying the lifetime risk of inhaling radon gas by the number of persons in New York State at risk, we finally determine the potential number of lung cancers as ranging between 1183 to 30,484, out of a population at risk of 11.9 million. This major environmental impact, which does not include unvented space heaters, must be carefully assessed by State regulators.

V. UNCERTAINTIES

Natural gas from the Marcellus shale formation may or may not require processing to remove impurities such as sulfur compounds and heavier hydrocarbons such as ethane, propane, n- and i-butane and i-pentane. Processing will substantially remove radon, since radon is preferentially concentrated in the ethane and propane streams[2]. However, according to DEC, "Not all natural gas requires processing, and gas that is already low in higher hydrocarbons, water, and other compounds can bypass processing."[5] Whether natural gas from the Marcellus formation in New York State is wet or dry needs to be better determined. A map developed by Penn State geologists, Figure 4, shows the approximate wet-dry line.[24]. It's not clear whether the gas industry would find it economic to separate propane and whether DEC would require propane removal in order to lessen the radon concentrations in natural gas.

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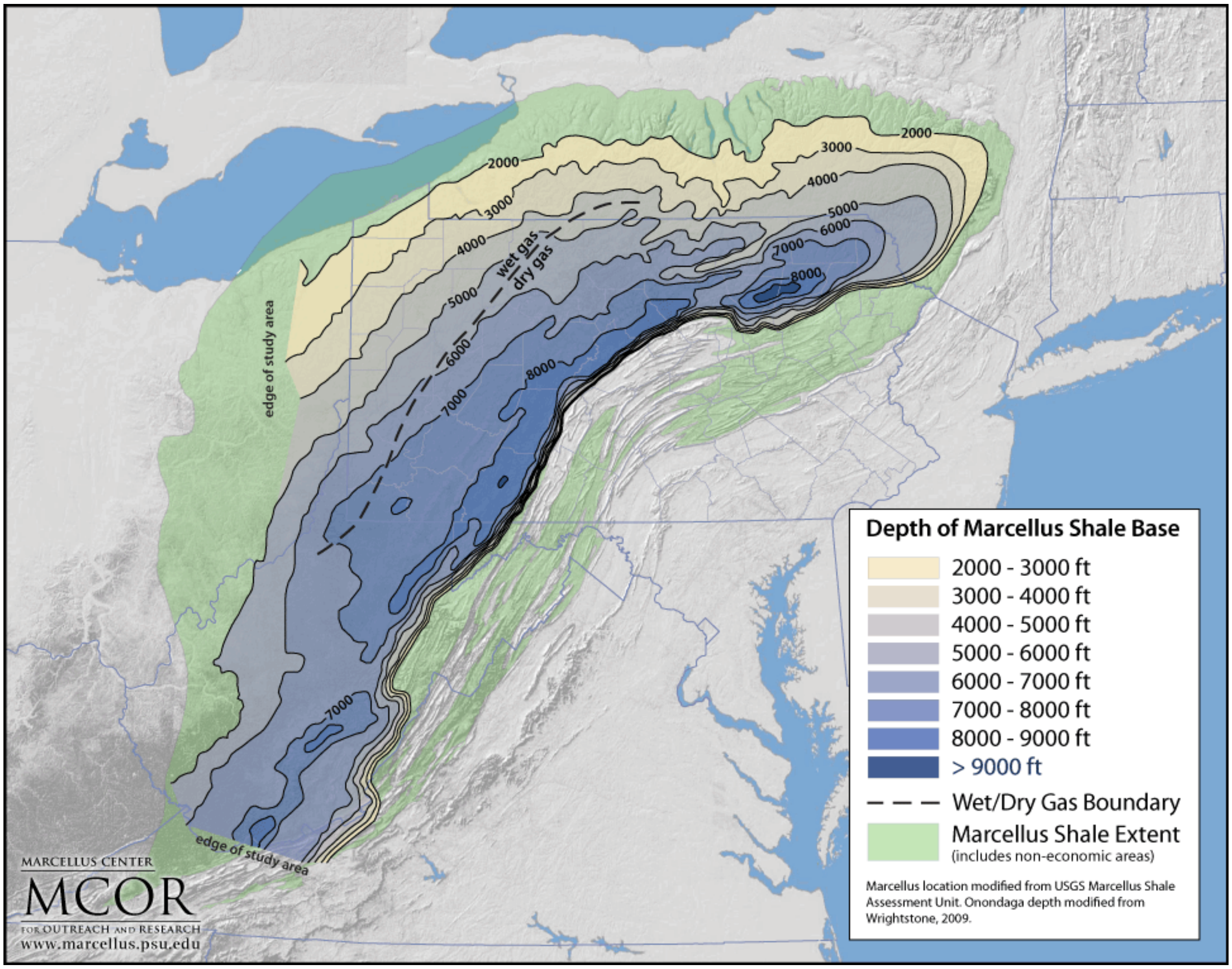

Figure 4. Map of wet-dry line for Marcellus shale gas[24]

Another issue involves pressurization and storage of natural gas from the Marcellus formation. Any additional storage time would lessen the radon concentrations. The gas industry requires some storage capacity since natural gas use varies with the season. How much and how long affects the radon concentrations reaching homes.

In addition, gas from Marcellus shale would be mixed with natural gas from other locations, thereby lessening the concentration reaching urban areas, but also increasing the potential number of natural gas customers. Over time, as more wells are developed in the Marcellus shale formation, less mixing from other locations will occur.

Finally, the New York City code requires that remodeled and new kitchen stoves be vented outside the apartment. It is not clear how many kitchen stoves in New York City apartments are vented since a major fraction of apartment buildings were constructed before the building code went into effect.

VI. MITIGATION OF IMPACTS

Because radon is an inert gas, it cannot be chemically removed from the natural gas stream when natural gas is burned in kitchen stoves or gas heaters. But since radon has a 3.8 day half-life, the radioactive gas could be potentially stored for a sufficient period of time to allow the

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radon to decay to safe levels. In order to adequately protect residents of New York State, the material could be stored at wellhead locations for several months. If the gas was stored for two months, there would be a significant diminution of the hazard. Over this time period, the hazardous radioactive gas, radon, will decay by a factor 100,000.

From Gogolak[2], the estimated cost is on the order of $10 billion (1980 dollars) to develop sufficient pressurized storage in tanks. Some lag storage will be required in any case, since use of natural gas will not be uniform over the seasons. The estimated costs for mitigating the environmental impact of radon is beyond the scope of this article.

VII. CONCLUSION

The potential environmental and public health impact of radon in natural gas from the Marcellus Shale formation is large. This paper has calculated the number of lung cancers in New York State as ranging between 1,182 and 30,448, which is significant, though far less than lung cancers caused by background radon and smoking. This calculation is based on reasonable assumptions for a gas well in the Marcellus Shale, including the concentration of radon at the wellheads, the transit time between wellheads and homes, the dilution expected in a typical household, and reasonable risk factors drawn from studies by the U.S. Environmental Protection Agency.

In its 1400-page rdGEIS, New York DEC has devoted one sentence to the issue of radon. The sentence states "Radon gas, which under most circumstances is the main health concern from NORM [Normally Occurring Radioactive Materials], is produced by the decay of radium-226, which occurs in the uranium-238 decay chain".

Clearly, this one sentence does not constitute an adequate or thorough analysis of the potentially serious risks associated with the impacts of transporting radon-contaminated natural gas into the apartments and homes of New York State residents. In its final version, hopefully DEC will more seriously consider the issue. As a first and crucial step the DEC must make certain that radon at the wellheads from the Marcellus Shale formation in presently operating wells is independently measured. Tests must be conducted by independent experts and agencies. Such tests also must be scientifically rigorous in their design and be conducted with full transparency to assure public confidence in the validity of the testing.

The long-term environmental risks and public health concerns of radon in Marcellus Shale natural gas formations should not be sacrificed to short-term, economic policies or to unrealistic and/or inaccurate assessments of the benefits of natural gas development in New York State.

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APPENDIX A. CALCULATIONS OF RADON AT THE WELLHEAD

Numerical simulation of radon production to the well bore is set up as a family of concentric cylindrical shells of radius r, the innermost of which is the well bore of radius r_o. Radon escapes from the rock matrix into pores and fractures, is entrained by natural gas and continues inward toward the well bore at the same mean velocity as the gas. However, the continuity of the inward flow of radon is limited by its radioactive decay, with half-life 3.83 days. When radon decays, it reverts to a solid and ceases its inward flow.

In this model, the concentration of radium-226 per unit mass of rock is assumed to be the same within each of the annular volumes; the radium concentration is specified by the user. As seen earlier, the highest radium concentration leading to the highest radon concentration is taken to be 1.11 Bq/m^3 (30 pCi/g). The emanation fraction is taken as a range from 10 to 30%, based on radon production in mill tailings. The length of the gas producing interval within the well bore is defined by the function $f = kr^n$, the gas production rate per unit volume at every radius r (in cm^3/second at 15 ^oC and 1 atm pressure). The parameter n can be set between -1 to +2. The well production rate is also specified (cubic feet of gas per day). The specified information, together with the porosity, fixes both the mean gas velocity across each cylindrical shell and the transit time through any interval $\Delta r = r - r_o$.

The computer source code is written in Fortran95, and is compiled with Lahey95 compiler. All the inputs specified in Table 2 appear in a separate input file and is altered for each of the computer runs. A copy of the source code can be obtained by writing the author. It should be emphasized that this is a simulation of radon production and transit and it is important that State regulators gather actual measurement data at the wellhead.

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