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Human Exposure to Unconventional Natural Gas Development: A public health demonstration of periodic high exposure to chemical mixtures in ambient air

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SUPPORTING INFORMATION

Appendix A

Mathematical depiction of EHP air exposure model terms and inputs

<u>Box volume</u>
The initial volume of the "box" is calculated by defining a box of
A x B x C cubic meters where:

'A' = Length = meters of air that pass over the site in 1 minute (based on wind speed in meters/minute)
'B' = Width = 100 meters (assumed dimension of typical site)
'C' = Height = mixing depth for the specific stability class shown in Table 3 and in Pasquill's stability chart showing height in meters and down wind distance in kilometers

A x B x C = Initial volume of the box

<u>Initial chemical concentration</u>
The chemical emissions rate at the source is provided in grams/ minute or ug/minute.

The initial air concentration of the source term, 'S', is determined by dividing the emissions rate by the initial volume of the box.

S = ug/minute/AxBxC = initial air concentration in ug/m^3

<u>Dilution</u>
Downwind volume is determined by a recalculation of the box size at set distances down wind: A x B* x C*

Length A (constant)
Width B * (B + the expansion of box in meters based on Pasquill stability chart) x
Height C * (C + increased height for downwind distance based on Pasquill stability chart)

Thus the concentration downwind = S (ug/m^3) x initial volume/ downwind volume.
S x (AxBxC/AxB*xC*)

Appendix B

A note about emissions estimates (source terms) used in the article

EHP estimates are based on a review of UNGD emissions monitoring research from regions with UNGD (See Appendix C Table 2S). We did not find long-term hourly emissions data from Pennsylvania but there are yearly emission estimates reported by industry to PA DEP. These PA DEP estimates demonstrate the extreme variability in ranges of releases between UNGD sites, but provide insufficient detail for estimation of exposures at individual residences.

Our interest is in understanding the likelihood of hazardous peaks in exposure for residents near UNGD sources. The hypothetical case study provides one way of estimating these exposures. Current reliable emissions data are limited and the published literature and publicly available data show inconsistencies. We chose to use source terms that are derived from real time monitoring studies and reflect our best assessment.

EHP's estimated source terms are higher than those reported by the shale gas industry to the PA DEP. We chose higher values for the following reasons:

1) The PA DEP publicly available emissions data for UNGD facilities are reported as long term averages (tons per year) that underestimate the high levels of episodic emissions individuals are exposed to.[1]

2) The PA DEP data are based on estimated emissions factors, using algorithms recommended by the EPA or that the industry has developed internally.[2] They are reported to the PA DEP by the owners and operators of UNGD facilities.

3) The long term averaging in the case of well pads also ignores the various stages of well pad development during which different chemical mixtures are emitted at different concentrations as well as for varying lengths of time (duration).

4) Future research needs to address impact of emissions on exposure variability

<u>The need for future research to address the impact of emissions on the exposure variability</u>

The residential profile presented here shows that greater precision in air monitoring is needed in future research on related public health impacts from UNGD. Adequately assessing exposures to nearby residents requires local, short-term monitoring because each

[1] "Emission Inventory." Pennsylvania Department of Environmental Protection. Available at http://www.dep.state.pa.us/dep/deputate/airwaste/aq/emission/emission_inventory.htm (accessed Jan 2014).

[2] Personal communication, Dean Van Orden, Assistant Director, PA DEP Bureau of Air Quality. May 6, 2014.

residence will have a unique exposure profile. Not only is each home located near different types and numbers of industrial facilities, but the variability of emissions from UNGD sources is high. In order to understand specific residential exposures, site specific and activity specific information is needed.

1) The annual PADEP data show high variability in source emissions. A review of the PA DEP reported emissions from unconventional natural gas facilities in Washington County shows that in 2011 compressor station emissions for VOCs ranged from 3.884 – 22.7110 TPY. In 2012 the range was 1.93 – 31.4 TPY. At processing plants VOC emissions ranged from 13.16 - 29.88 TPY in 2011 and 9.4 – 28.9TPY in 2012. For well pads emissions, reports ranged from 0.0001 - 14.7 TPY in 2011 and 0.00001–-34.3 TPY in 2012.

   Variability is also evident in reported emissions between each well on a well pad, which has multiple wells. For a well pad spudded on 1.24.2011, Table 1S shows the values reported for the year 2011, demonstrating that emissions from individual wells will vary in chemical mixture and amount. In terms of this effort to model the concentrations of chemicals in air in nearby residences, one can see the inadequacy of using TPY calculations. We acknowledge that the EHP model does not account for the full extent of emissions variability but it t begins to address this complex problem.

   Table 1S. Well Pad Emissions (spud date 1.24.2011, 5 wells)

Well pad Unit	Chemical Emissions tons /year (TPY)	Chemical Emissions grams/minute
1	Formaldehyde 0.0032	0.005
	VOCs 0.2444	0.421
	PM2.5 0.2188	0.377
2	Formaldehyde 0.0031	0.003
	VOCs 0.2377	0.264
	PM2.5 0.2128	0.236
3	Formaldehyde 0.0020	0.003
	VOCs 0.1534	0.264
	PM2.5 0.1373	0.236
4	Formaldehyde 0.0029	0.005
	VOCs 0.2227	0.384
	PM2.5 0.1993	0.343
5	Formaldehyde 0.0020	0.003
	VOCs 0.1522	0.262
	PM2.5 0.1363	0.235

2) Another critical aspect of the episodic nature of emissions from UNGD facilities is found in the form of flares, venting, 'intentional blowdowns', fugitive emissions, leaks and spills. The peaks caused by these events, if reported as part of yearly emissions, would be lost in the averaged data. Yet, importantly, the peak exposures can cause the most harm.

3) It should be noted that only two of the many chemicals that are emitted have been modeled, the exact number of chemicals present is not known. The dispersion pattern for these known emissions is driven by weather and is the same as it would be for the other chemicals being released into the environment.

4) Finally, the authors acknowledge that this model should be validated by others. As more accurate short-term measurements are available, the modeling of exposures will improve.

Irrespective of the above points, the profiles that can be developed would substantially reduce the uncertainty in assessment of the health risk.

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Appendix C

Rationale for the development of EHP estimated source terms

Source terms for UNGD drilling, hydraulic fracturing, flares and finishing, well pad production, compressor stations and processing stations are not currently available and the estimates and measurements found in the literature are inconsistent. See, for instance, a recent review that compares findings from Texas, Pennsylvania and Colorado to data collected in West Virginia in "Potential Public Health Impacts of Natural Gas Development and Production in the Marcellus Shale in Western Maryland (July 2014 p.29 – 31).[3] However, there are estimates made in tons/year from publicly available data and monitoring studies. A few studies report data in ppbv or ug/m^3. There are also data that show the variability in the emissions between facilities of the same type and variation within a facility from day to day (e.g. PA DEP oil and gas reported emissions on wells, compressors and processing stations and the PA DEP short-term monitoring study).[4,5,6,7,8] Therefore, default values for emissions in grams per minute were derived for use of the EHP air model. These values serve as a starting point. Real-time values, when accurately measured, are expected to vary widely. The emissions estimates can be factored up or down as more precise information is made available. This method of factoring correlates to uncertainty factors used in health risk assessments when working with incomplete data.

Emission estimates in tons/year were collected from UNGD monitoring research (see Table 2S). Monitored values are also shown in some cases. Because emissions from these sites vary in the short-term (hour to hour and day to day) it is necessary to assign a factor to the variation. The relative differences in variability between the sites and between facility types were also considered to determine the factors to use and to make informed estimates when data is lacking (for certain well pad stages and PM values).

<u>VOC estimates:</u>

The four factors used for VOCs were 2, 3, 4 and 10. The factors were applied to the TPY values reported in the literature.

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[3] Potential Public Health Impacts of Natural Gas Development and Production in the Marcellus Shale in Western Maryland. Maryland Institute for Applied Environmental Health School of Public Health University of Maryland, College Park. July 2014.

[4] "Emission Inventory." Pennsylvania Department of Environmental Protection. http://www.dep.state.pa.us/dep/deputate/airwaste/aq/emission/emission_inventory.htm

[5] Southwestern Pennsylvania Marcellus Shale Short-Term Ambient Air Sampling Report. Pennsylvania Department of Environmental Protection. November **2010**.

[6] Northcentral Pennsylvania Marcellus Shale Short-Term Ambient Air Sampling Report. Pennsylvania Department of Environmental Protection. May **2011.**

[7] Southeastern Pennsylvania Marcellus Shale Short-Term Ambient Air Sampling Report. Pennsylvania Department of Environmental Protection. November **2010**.

[8] Northeastern Pennsylvania Marcellus Shale Short-Term Ambient Air Sampling Report. Pennsylvania Department of Environmental Protection. January **2011**.

Well pad stage estimates:

- The factor of 2 was applied to the upper bound value for VOC well pad production emissions of 22 TPY, rounded to 80 grams/minute.
- For drilling, the factor of 4 was applied to the upper bound value for VOC well pad production emissions of 22 TPY, rounded to 400 grams/minute. This factor was derived from a review of Colburn's assessment that drilling stages produce higher rates of VOC emissions than other stages of well pad development. [9]
- Relative estimates were chosen for hydrofracturing, primarily based on Colburn.[10]
- Relative estimates were chosen for flaring and finishing processes, based on the assumption that flaring and finishing processes involve numerous sources of VOCs. Emissions are likely to be more that a producing well pad and slightly less than a well pad in the drilling phase.

Compressor station estimate:

- The factor of 3 was applied to the upper bound value for VOC compressor station emissions of 22 to 42 tons/year. The estimated source term is rounded to 300 grams/minute.

Processing station estimate:

- The factor of 10 was applied to the upper bound value for VOC processing station emissions of 80 TPY, showing a source term of 1500 grams per minute.

The larger factor for the processing station is based on the following:

- These facilities are assumed to have greater emissions variability than compressor stations, thus have higher levels of uncertainty.
- More flaring occurs at processing stations than at other facilities
- The processing of wet gas in PA potentially creates higher emissions
- Processing stations carry a higher risk for fugitive emissions because of their size and the number of possible sites for leaks (valves, vents, etc.)
- The reported value of total organics (TOC) is higher than TOCs for compressor stations by a factor of 10

$PM_{2.5}$ estimates:

When published TPY measurements are calculated back to g/m to develop a source term we find the measurements in the literature to be very low, based on what is known about the activities that take place at UNGD facilities and during various stages of development and production. A case in point is provided in the table for PM during well pad development. If a measurement of 1-24 ug/m^3 is taken at one point in time during a process that may occur for 5 months (drilling), then a TPY of 0.37 is not plausible. We also know that many sources

[9] Colborn, T.; Schultz, K.; Herrick, L.; Kwiatkowski, C. An exploratory study of air quality near natural gas operations. Human and Ecological Risk Assessment **2014**; *20*(1):86-105.

[10] Ibid.

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on a site can potentially emit PM, though onsite monitoring may not track all the sources. During well development, diesel truck traffic will at times be quite high. Flaring, which produces PM, is common at different phases of development and especially at processing stations. Thus assigning a value of 1TPY (or 2g/m) to a processing plant seems implausible. We derived our PM values based on our best reasoning, primarily on an assessment of the relative differences between well pad development stages and facility types.

Well pad stages:

Drilling – 125 g/m - This stage involves large diesel emissions from truck traffic and onsite engines. The remaining values are estimated in relation to this value.
Hydrofracturing - 50 g/m
Flaring and finishing - 100 g/m
Production - 25 g/m

Compressor station estimate:

100g/m – This value is based on the increasing size of engines used at compressor stations for the transport of natural gas.

Processing station estimate:

500 g/m – Based on the larger size of these facilities in relation to compressors and the assumption of flaring, we used a factor of 5 above the compressor station estimate.

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Table 2S. Source Terms from UNGD research literature reviewed by EHP for the development of EHP estimated emissions.

SOURCE TYPE	Total Organics	VOCs	PM	Carbonyls and aldehydes
Compressor station	99 -276 TPY3	22 - 42 ppbv [66 - 126 ug/m3]1 17-43 TPY3 18.6 tpy6	PM 10 2.22 TPY6 PM 2.5 2.2 TPY6 PM 0.0-1.61 TPY3	6.5 -8.5 ppbv [19.5 – 25.5 ug/m3]1
Well pad development		900 ppbv [2700 ug/m3]1	drilling: 0.37 TPY3 1-24 ug/m3 (PM2.5) 7	8.2 ppbv [24.6 ug/m3]1
Fracking (1 site)		0.05 TPY3	0.5 TPY3 Diesel PM on-site: 20-40 ug/m3, 4	.2 -.44ppm4
flare		300mg/m3 2		
Wellpad in production	68 -4433 TPY3 (with compressors)	2-22 TPY2	0.2 TPY5 0.0 – 0.85 TPY3	
Condensate tank		2500 -7100 ppbv [7500 – 21,300 ug/m3]1		8.5 -10.5 ppbv [25.5 – 31.5]1
Fugitives	Compressor: 16 TPY Tanks & valves: 4483 TPY pneum.valves: 3,003 TPY storage tank vents: 2,076 TPY 3			
Processing facility	1,293 TPY3	80 TPY3 24 ppbv [72 ug/m3]1	1.0 TPY3	9.9 ppbv [29.7 ug/m3]1

1. Zielenska, Barbara, E Fujita and D Campbell (2010). Monitoring of Emissions from Barnett Shale Natural Gas Production Facilities for Population Exposure Assessment. Prepared for Mickey Leland National Urban Air Toxics Research Center Houston, Texas by Desert Research Institute. (page 3-4, Table 3-1B) [46]

2. Strosher, M. (1996). Investigations of Flare Gas Emissions in Alberta. Final Report to Environment Canada. (page 112) [47]

3. City of Fort Worth Natural Gas Air Quality Study (2011). Eastern Research Group and Sage Environmental Consulting, for the City of Fort Worth. (VOCs: compressor station, processing facility – p. 3-33; fugitives -Appendix 3.7, p. 3-99) (PM: Table 3.5-3 pp 3-35 – 3-58).[8]
4. Essweine, E., M Breitenstein (2012). NIOSH Field Effort to Assess Chemical Exposure Risks to Oil and Gas Workers. Powerpoint presentation.[48]
5. Buys and Associates (2004). Emissions Inventory for the Wind River Natural Gas Field Development Project. For the Bureau of Indian Affairs Wind River Agency, Fort Washakie, Wyoming. (pp. EI 16, EI 17) [49]
6. Texas Commission on Environmental Quality Point Source Emissions Inventory, http://www.tceq.texas.gov/airquality/point-source-ei/psei.html [50]
7. McCawley, M. Air, Noise, and Light Monitoring Results For Assessing Environmental Impacts of Horizontal Gas Well Drilling Operations (2013) for West Virginia Department of Environmental Protection Division of Air Quality Charleston, WV 25304. (page 27) [51]

Also reviewed: Armendariz, A. (2009). Emissions from Natural Gas Production in the Barnett Shale Area and Opportunities for Cost-Effective Improvements. Department of Environmental and Civil Engineering Southern Methodist University, for The Environmental Defense Fund, 44 East Avenue Suite 304 Austin, Texas, 78701. [52]

Colborn et al. [17] This study serves as the basis for the estimates used for drilling stages. Colburn et al monitored VOCs for one 4-6 hour period per week for one year.

Glossary of Terms

mg/m^3 = milligram per meter cubed
ppbv = parts per billion by volume
ppm = parts per million
TPY = tons per year
ug/m^3 = micrograms per meter cubed

Conversions

1 ppv = 3 ug/m^3
1 TPY = 1.9 grams/min