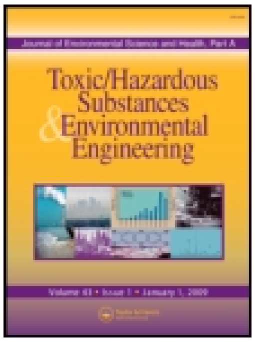

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Journal of Environmental Science and Health, Part A
Toxic/Hazardous Substances and Environmental Engineering

ISSN: 1093-4529 (Print) 1532-4117 (Online) Journal homepage: http://www.tandfonline.com/loi/lesa20

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To cite this article: David R. Brown, Celia Lewis & Beth I. Weinberger (2015) Human exposure to unconventional natural gas development: A public health demonstration of periodic high exposure to chemical mixtures in ambient air, Journal of Environmental Science and Health, Part A, 50:5, 460-472, DOI: 10.1080/10934529.2015.992663

To link to this article: http://dx.doi.org/10.1080/10934529.2015.992663

Published online: 03 Mar 2015.

Journal of Environmental Science and Health, Part A (2015) **50**, 460–472

ISSN: 1093-4529 (Print); 1532-4117 (Online)
DOI: 10.1080/10934529.2015.992663

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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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Directional drilling and hydraulic fracturing of shale gas and oil bring industrial activity into close proximity to residences, schools, daycare centers and places where people spend their time. Multiple gas production sources can be sited near residences. Health care providers evaluating patient health need to know the chemicals present, the emissions from different sites and the intensity and frequency of the exposures. This research describes a hypothetical case study designed to provide a basic model that demonstrates the direct effect of weather on exposure patterns of particulate matter smaller than 2.5 microns ($PM_{2.5}$) and volatile organic chemicals (VOCs). Because emissions from unconventional natural gas development (UNGD) sites are variable, a short term exposure profile is proposed that determines 6-hour assessments of emissions estimates, a time scale needed to assist physicians in the evaluation of individual exposures. The hypothetical case is based on observed conditions in shale gas development in Washington County, Pennsylvania, and on estimated emissions from facilities during gas development and production. An air exposure screening model was applied to determine the ambient concentration of VOCs and $PM_{2.5}$ at different 6-hour periods of the day and night. Hourly wind speed, wind direction and cloud cover data from Pittsburgh International Airport were used to calculate the expected exposures. Fourteen months of daily observations were modeled. Higher than yearly average source terms were used to predict health impacts at periods when emissions are high. The frequency and intensity of exposures to $PM_{2.5}$ and VOCs at a residence surrounded by three UNGD facilities was determined. The findings show that peak $PM_{2.5}$ and VOC exposures occurred 83 times over the course of 14 months of well development. Among the stages of well development, the drilling, flaring and finishing, and gas production stages produced higher intensity exposures than the hydraulic fracturing stage. Over one year, compressor station emissions created 118 peak exposure levels and a gas processing plant produced 99 peak exposures over one year. The screening model identified the periods during the day and the specific weather conditions when the highest potential exposures would occur. The periodicity of occurrence of extreme exposures is similar to the episodic nature of the health complaints reported in Washington County and in the literature. This study demonstrates the need to determine the aggregate quantitative impact on health when multiple facilities are placed near residences, schools, daycare centers and other locations where people are present. It shows that understanding the influence of air stability and wind direction is essential to exposure assessment at the residential level. The model can be applied to other emissions and similar sites. Profiles such as this will assist health providers in understanding the frequency and intensity of the human exposures when diagnosing and treating patients living near unconventional natural gas development.

Keywords: Diagnostic tools, dispersion air model, exposure patterns, health impacts, unconventional natural gas.

Introduction

Technological advances in directional drilling and hydraulic fracturing have spawned the shale gas boom across the United States and around the globe. Progress in the oil and gas industry has brought industrial activity in close proximity to residences, schools, day care centers and other places where people spend their time. The short, and even not-so-short, distances between unconventional natural gas development (UNGD) and everyday human activity allow for emissions from natural gas extraction, processing, and transport to reach individuals in the areas where UNGD activities take place.

The emissions that occur within several miles of residences (sometimes less than 500 feet) pose challenges for health care providers seeing patients from these areas. Health care providers (as well as patients

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/lesa.

themselves) have very little information on the contents of UNGD emissions and the concentration of toxics that could be reaching people where they live or work. Currently patients go to physicians with health concerns but are unable to identify chemical or particulate exposures, if they exist. Physicians unfortunately often find themselves with similarly imprecise exposure conceptualizations. Guidance provided by public agencies is often insufficient to protect the health of individuals, yet, there is an increasing amount of data collected on UNGD emissions; and there is existing research on the toxicological and clinical effects of *some* substances emitted by UNGD activities.

In the present study we consider estimates of emissions from well pads, compressor stations and processing plants to gauge individuals' possible exposures and the health risks those exposures pose. This is necessary because much of the publicly accessible emissions data has been collected to provide average exposures over a lengthy period of time and because the data collection is intended to document compliance with regional air quality standards. To assess health impacts, it is, therefore, necessary to look at human exposures in the short term. What matters from a health perspective is the content and intensity of exposures at the individual level. The critical questions are: What is a person, in a given household, exposed to? How high do those exposures climb? How often is that resident exposed to these high levels? What happens physiologically when a particular toxic comes in contact with the body? This set of questions pertains to individuals living in shale gas regions across the country and is at the core of the public health problem of UNGD.

The objective of this article is to provide a structure for understanding patterns of air exposures resulting from shale gas activity. Our aim is to provide a method for understanding the fluctuations and degree of predictability of peaks in exposure. It is not to achieve precise emissions estimates. Current emission data is too sparce to do that level of modeling. To illustrate the patterns, we present a case study of a hypothetical residence located in southwestern Pennsylvania. The residence is situated near a well pad, a compressor station and a processing plant.

The Southwest Pennsylvania Environmental Health Project's ground-level experience with individuals, along with continual assessment of the literature on UNGD emissions, leads us to propose several essential criteria for evaluating individual exposures. These are: 1) proximity of well pads, compressor stations, production facilities or other operations associated with UNGD; 2) varied stages of operations occurring at the just the well pads; 3) the presence of chemical mixtures in air emissions; 4) the role of weather in dispersion of air pollutants; 5) the resulting chemical composition and concentrations exposing the individual; 6) the frequency and duration of exposures.[1]

The present study demonstrates that households near UNGD sites are subjected to variable particulate and chemical air exposures that may reach potentially dangerous levels. Furthermore, it broadens the concern to the whole lifetime of shale gas development rather than primarily focusing on hydraulic fracturing as the predominant polluter. Hydraulic fracturing itself occurs over a matter of weeks, while compressor stations and gas processing plants, also located near people's homes, pollute 24 hours a day for as long as gas is flowing through the pipeline. These parts of the process produce significant air contaminants and deserve more attention than they have received thus far.

Background

Emissions and the process of gas extraction and post-extraction activities. There are numerous stages to the natural gas extraction and development process. They begin with the development of a well site and end with the transport of natural gas to its final destination. The well pad itself includes multiple activities that occur prior to the gas production phase. Once natural gas (and other substances) flow up the well and into on-site tanks, several more stages follow. These stages involve an array of machinery and facilities including pipelines, condensate tanks, compressor stations, dehydrators, and processing plants.[1] During these stages gas is moved, filtered, compressed, and treated. Emissions – fugitive, smokestack and accidental – are released into the air at every stage of UNGD.

Documented air emissions from UNGD sources. As a group, emissions from one part of the process differ from those produced by another. The particular mix of emissions from a processing plant is different in kind and quantity, from that of a compressor station, which is different from emissions produced by the drilling of a well. That said, there are certain contaminants that are common across many, if not all, parts of the process; two of the most notable being VOCs and particulate matter.

Six air pollutants whose regional ambient air levels are regulated by the Environmental Protection Agency (EPA), are generally found at UNGD sties and are frequently discussed in the literature and identified by public agencies. These are: ozone, particulate matter (PM), carbon

[1]The Southwest Pennsylvania Environmental Health Project is a nonprofit public health organization established to respond to individual and community needs for access to accurate health information and health services associated with UNGD. The southwest region of the state is among the fastest growing areas for this industry because it lies over the Marcellus shale deposits.

Table 1. Variation in ambient air measurements of five VOCs near a compressor station in Hickory, PA, reported in ug m^{-3}*.

	May 18		*May 19*		*May 20*		
Chemical	Morning	Evening	Morning	Evening	Morning	Evening	3-day Average
Ethylbenzene	No detect	No detect	964	2015	10,553	27,088	13,540
n-Butane	385	490	326	696	12,925	915	5,246
n-Hexane	No detect	536	832	11,502	33,607	No detect	15,492
2-Methyl Butane	No detect	230	251	5137	14,271	No detect	6,630
Iso-butane	397	90	No detect	1481	3,817	425	2070

*The PA DEP collected data on many more chemicals than those listed above; the authors selected these chemicals specifically to highlight variation in emissions. See Reference 12, Appendix A. p. 31.

monoxide (CO), nitric oxides (NOx), sulfur oxides (SOx), and lead. Also frequently discussed in the emerging literature on UNGD are volatile organic compounds (VOCs) which include aromatic hydrocarbons, halogenated compounds, aldehydes, alcohols, and glycols.[2-4] VOCs are released into the atmosphere during the production and processing of natural gas and as a component of diesel and exhaust.[5] They also are released from gasoline, solvents, paints and other industrial and domestic products.

The Pennsylvania Department of Environmental Protection (PA DEP) inventory of emissions from natural gas facilities includes CO, NOx, PM10 (particulate matter less than 10 microns), $PM_{2.5}$ (less than 2.5 microns), SOx, the VOCs, Benzene, Ethyl Benzene, Formaldehyde, n-Hexane, Toluene, Xylenes (isomers and mixture), and 2,2,4-Trimethylpentane.[6] In Washington County, Pennsylvania, the PA Department of Environmental Protection (PA DEP) has collected data on 214 natural gas facilities. The highest levels of emissions reported were of benzene, $PM_{2.5}$, NOx, formaldehyde, trimethyl pentene, and ethyl benzene.[7] Additionally, a study conducted for the City of Fort Worth, Texas found acetaldehyde, butadiene 1,3, carbon disulfide, carbon tetrachloride, and tetrachloroethylene.[8] The Texas Commission on Environmental Quality collects data on NOx, VOCs and HAPs (hazardous air pollutants regulated based on emissions rather than regional air levels).[9] There are many other known, suspected, and as yet unknown air emissions from UNGD.[1,8,10,11]

Fluctuations in emissions and ambient air dispersal. Well pad emissions vary in content and concentration over time. In the lead up to a producing well, different activities occur: drilling, hydraulic fracturing, flowback, flaring and, finishing. In contrast other UNGD facilities operate in a more uniform way over time (such as compressor stations and processing plants) but still emissions measured nearby also vary (see Findings section). In addition to differing releases of contaminants, emissions disperse from their sources in varied patterns due to weather and atmospheric conditions. Characterizing these variations– their intensity, frequency, and duration – is critically important from a public health perspective. Little attention has been paid to these fluctuations, particularly the high spikes in exposures.

Three short-term air reports from the PA DEP provide a set of compounds found at well sites, impoundment ponds and compressor stations.[12-14] The PA DEP developed its list of air contaminants after consulting with the Texas Commission on Environmental Quality, New York Department of Environmental Conservation, data from research in Dish, TX, the Federal Register, and TERC.[12] As seen in Table 1, measurement data reveal the variation in emissions even from a single source over only three days. Such variability makes accurate exposure estimates difficult. An examination of the compressor station measurements below also illustrates the seriousness of the problem posed by averaging out emissions data.

Table 1 illustrates the information lost when combining and averaging emissions over time. Looking at ethylbenzene, for instance, we see that its detection varies from zero to over 20,000 ug m^{-3} in just 3 days.

Residential VOC exposures. A small number of studies have been published documenting UNGD-generated air exposures near residences. McKenzie et al.,[15,16] analyzing data from Garfield County, CO, documented concentrations of benzene, ethylbenzene, toluene, and m-xylene/p-xylene 2.7, 4.5, 4.3, and 9 times higher within 0.8 km of sites near well completion activities than were concentrations further out. Also in Garfield County, Colorado, Colborn et al.[16] sampled air outside a residence 1.1 km from UNGD in 2010 and 2011 (and where there was no other nearby industrial activity). Detected in 60% to 100% of the samples were VOCs including methane, ethane, propane, toluene, isopentane, n-butane, isobutene, acetone, n-pentane, n-hexane, methylcyclohexane, methylene chloride, m/p-xylenes: and carbonyls, including formaldehyde, acetaldehyde, crotonaldehyde, 2-butanone (MEK) and butyraldehyde.

Researchers working with Earthworks sampled air near residences in nine counties in Pennsylvania during 2011 and 2012. For households between 0.1 km and 8 km from gas facilities 94% of the samples that were tested for 2-butanone detected it; 88% of those tested for acetone and 79% of those tested for chloromethane detected it. Also frequently but not as consistently found were 1,1,2-Trichloro-1,2,2-trifluoroethane, carbon tetrachloride and trichlorofluoromethane.[17]

In 2009, Wolf Eagle Environmental, a consulting firm working for the town of Dish, Texas, sampled air on seven residential properties near compressor stations. Chemicals identified in the samples drawn included a number that were found above Texas's Effective Screening Levels (levels which cause concern for health effects). These included benzene, dimethyl disulfide, naphthalene, m & p xylenes, carbonyl sulfide, carbon disulfide, methyl pyridine, and dimethyl pyridine.[11]

Health problems identified in the literature. The onset of the acute actions of VOCs and $PM_{2.5}$ can be very brief, within days, hours or minutes.[18] Many of the studies listed below find illnesses reported that appear to be short term but recurring (Table 2). For instance, burning eyes and throat irritation were found in the research of Bamberger,[19] Steinzor et al.,[17] and Subra.[20,21] Episodic nausea was reported by residents in studies by Ferrar et al.,[22] Subra,[20] and Bamberger and Oswald.[19] Rabinowitz et al. documents reports of dermatologic and upper respiratory symptoms close to well sites.[23]

Rationale. To understand the potential health effects and risks to residents, it is necessary to conceptualize the intensity and patterns of residential exposures to UNGD air emissions. To do this source term estimates needed to be developed and then applied to a pollution dispersion model. There is little measurement data providing emission rates for the central UNGD operations: four stages of well development at the well pad, compressor stations, and processing facilities. Further, there is great variability in emissions over time and among activities and between sites that is not captured by existing research or by the PA DEP. The model provides estimates of exposures at different distances from UNGD sites. The emissions estimates used here are provisional; when accurate measurements and estimates–which reflect the variability–are available those could be used.

Materials and methods

Development of the case study. A model is presented for a hypothetical residence in southwest Pennsylvania. The residence has one well pad with five wells 1 km to the west, a compressor station 2 km to the south and a processing station 5 km to the north. This "typical" scenario is based on a dataset of 276 households in Washington County, Pennsylvania.[28] [2] It includes two common UNGD facilities – a well pad with multiple wells and a compressor station. We chose to include a processing plant at the furthest distance (5 km) because they are less common yet large enough to pose potentially significant health risks.

Assumptions. To move forward with a basic screening model, we have made several assumptions:

I. Compressor stations and processing plants are assumed to emit at constant rates and concentrations.
II. Each phase of the drill pad development is assumed to emit at a constant rate. That is, the drilling phase is assumed to generate constant emissions, the hydrofracking phase is assumed to generate constant emissions, etc.
III. Terrain is assumed to be flat.
IV. Pollutants such as $PM_{2.5}$ and VOCs are assumed to travel in the same manner.

EHP exposure model. Considering a hypothetical residence with three different sources at 1 km, 2 km and 5 km, we model the movement and dilution of emissions from each point source to the residence over a period of 14 months. We applied weather conditions reported from the Pittsburgh International Airport from February 2011 through March 2012. The rates of dilution, based on known weather effects and distance from the source, are calculated in 6-h increments. Six-h increments capture the four time periods that are generally responsive to diurnal weather-based dilution patterns. The 6-h increments are designated Night: 12 midnight – 6:00 am; Morning: 6:00 am – 12 noon; Afternoon: 12 noon – 6:00 pm; Evening: 6:00 pm – 12 midnight. The short time intervals also reflect our interest in capturing the short time periods in which onset of health reactions can occur.

Calculation of weather/diurnal effects. The exposure model is intended to be of use to health care providers and residents living in shale development areas. It is a basic "box" air pollution dispersion model, based on the seminal work of Pasquill.[29] Much more complex, accurate air dispersion models are available to use. Highly accurate data on UNGD emissions is not yet available and our data is based on estimates. The simple box model best fits our purpose of providing a simple conceptual model that describes

[2]Two hundred and fourteen of these residences were found to have between 1 and 77 UNGD well pads at a distance of 2–5 km. Eighty-five residences had from 1 to 17 well pads located between 1–2 km. Thirty-one homes had from 1 to 7 well pads within 1k km. Two hundred and sixty residences had between 1 and 5 compressor stations 2–5 km distant. Fifteen homes had 1–2 compressor stations within 1–2 km. Five residences had one to two compressor stations less than 1 km distant. Washington County currently has two processing stations.

Table 2. Evidence for health effects from UNGD found in the literature.

Category	*Researcher/author*
Behavioral/mood/stress	Steinzor et al.[17]
	Ferrar et al.[22]
	Perry [24}
	Resick et al.[26]
	Subra[20]
Birth outcomes	Hill[26]
	McKenzie et al.[27]
Cancer risk	McKenzie et al.[15]
Dermal	Steinzor et al.[17]
	Rabinowitz et al.[23]
	Subra[33]
Ear, nose, mouth, throat	Steinzor et al.[17]
	Subra[21]
	Subra[20]
Eye	Bamberger and Oswald[19]
	Steinzor et al.[17]
	Subra[21]
	Subra[20]
Gastrointestinal	Bamberger and Oswald[19]
	Steinzor et al.[17]
	Ferrar et al.[22]
High blood pressure	Subra[21]
Muscle/joint pain	Steinzor et al.[17]
	Subra[21]
	Subra[20]
Neurological	Bamberger and Oswald [19]
	Subra[21]
	Subra[20]
Respiratory	Bamberger and Oswald[19]
	Steinzor et al.[17]
	Rabinowitz et al.[23]
	Subra[20]

in general how residents near UNGD are at risk of episodic exposures. See Appendix A for full discussion of the calculation of effects.

The model posits that the emissions at the source are released into a defined volume of air (the theoretical "box"). We use a "box" 100 meters at the base. The length is determined by wind speed (meters per minute) The height is dependent on weather and other atmospheric conditions. The box increases in volume as the air flow carries it away from the site, raising the height of dilution and the width of the plume. A new volume calculation and emission concentration is made at each distance point reported (in this case, at 1 km, 2 km and 5 km). The larger the volume of the "box" the more dispersed the pollution. In the model, emissions are assumed to be constant within every stage. The terrain is assumed to be flat.

Cloud cover, wind speed, wind direction, and portion of the day (day or night) are factored into the model and affect the dilution of the contaminants and the intensity of exposures at different distances. Pasquill categorized these atmospheric variations into six "stability classes" A, B, C, D, E and F, with class A being the most unstable or most turbulent class, and class F the most stable or least turbulent class (Table 3).[29] The more stable the atmosphere, the less likely emissions will mix and dilute with the ambient air and the greater the risk that higher ambient concentrations will lead to exposure at the residence.

One stability class is assigned to each 6-h period. This determines the mixing of the pollutant in the air column at the relevant distance between a source and the residence. For the well pad, which is 1km west of the residence, days with winds from the west or with calm conditions are expected to carry emissions toward the home. Winds from the south and north are relevant for emissions moving from the compressor and processing station, respectively. Winds reported as zero at the airport are calculated at 0.2 mph since air movement is always present. Further information on the EHP exposure model can be found on the Southwest Pennsylvania Environmental Health Project website.[30]

Development of source terms used in the case study

Table 4 shows the emissions estimates (in grams per minute) developed for this case study. The values from the literature are adjusted to avoid underestimating the day-to-day high levels. To develop more precise source terms it would be necessary to collect site specific short term emissions. The model is designed to be conservative in terms of health protection and may represent an upper bound of what is emitted.

Table 3. Air stability classes as related to wind speed, cloud cover, day and night.*

Wind Speed	*Day*	*Day*	*Day*	*Day*	*Night*	*Night*
	Clear or just a few clouds	< 50% cloud cover	>50% cloud cover	Overcast >80% cloud cover	>50% cloud cover	< 50% cloud cover
< 5 mph	A	AB	B	D	E	F
5 to 7 mph	AB	B	C	D	E	F
7 to 11 mph	B	BC	C	D	D	E
11 to 13 mph	C	CD	D	D	D	D
>13 mph	C	D	D	D	D	D

*Adapted from Pasquill.[29]

Table 4. Estimated emissions in grams/minute used in the EHP exposure model.

Source	*VOCs Estimate*	*$PM_{2.5}$Estimate*
Drilling stages	400	125
Hydraulic fracturing	160	50
Flares and finishing	300	100
Producing well pad	80	25
Compressor Station	300	100
Processing Station	1500	500

Two of the air contaminants produced by UNGD, particulate matter ($PM_{2.5}$) and volatile organic compounds (VOCs), are used to gauge risk for an individual in the hypothetical residence. The two pollutants pose risks, both individually and synergistically, and they serve as surrogates demonstrating how other hazardous air pollutants resulting from UNGD activity may be dispersed.

Modeling. A short averaging time, (6 h) was used as opposed to 24-h averages. Short averaging times over long periods allowed time specific peak concentrations of exposures to be identified.

To demonstrate the impact of weather on exposure to UNGD emissions we model the exposures from four stages of well pad development, a compressor station, and a processing plant using estimated source terms chosen by EHP based on a review of UNGD emissions monitoring research. Appendix C provides an explanation of EHP's choice of source terms and a table of data from the research EHP reviewed to develop estimated emissions. As valid and reliable emissions data become available the source terms could be adjusted.

Modeled well pad stages using EHP estimated emissions rates

The 11 months after the first well on a pad begins to be drilled encompass four stages of development. We model the first 5 months as "drilling stages"; vertical drilling (small rig) followed by vertical drilling (large rig), horizontal drilling, and preparation for hydraulic fracturing. The next activity is hydraulic fracturing, followed by flaring and finishing processes. Well production, when natural gas is flowing up the well, is then modeled for three months.[3] We base these stages on data provided by the industry to New York State (Table 5).[1] For the 14-month case study, the stages are shown in Figure 1.

For each well pad stage, the source terms for $PM_{2.5}$ and VOCs are applied to the air screening model using weather data for the corresponding number of days and over a distance of 1 km. The same method is applied to the compressor station and processing plant emissions data for 12 months over distances of 2 km and 5 km, respectively.

Results and discussion

The findings show how exposures to VOCs at a residence will vary, in the short-term and over the course of a year or more, due to weather and diurnal conditions. Results for $PM_{2.5}$ emissions mimic the pattern of VOC emissions at scaled levels based on the emission rates presented in Table 4. Not all results are presented.

Results using EHP estimated emissions source terms

Well pad development. Figures 2–5 show the patterns of 6-hour exposures to VOCs at the residence 1 km from the well pad for four stages of development: drilling stage February–June 2011 (Fig. 2): hydraulic fracturing stage July 1–15, 2011 (Fig. 3): flaring and finishing stage August – December 2011 (Fig. 4): and producing well stage January–March 2012 (Fig. 5). (Note that the values on the vertical axis for Fig. 3 vary from the vertical axis values on Figs. 2, 4 and 5). Inspection of the charts shows 6-h periods of high exposures during all four stages. Differences in intensity of exposures are related to the type of activity at the well pad in conjunction with weather conditions for the specified time period.

Figures 2–5 depict the ambient air concentration of well pad emissions that reach the residence on days with west winds or during times when the wind is calm. The figures show that maximum VOC peaks for hydraulic fracturing (the stage of development that often draws the most attention) reached 186 ug m^{-3}, compared to 465, 349 and 425 ug m^{-3} for drilling, flaring and finishing, and production. Low values are also found at each stage. However some level of exposure is always present albeit low compared to peaks.

A "peak" in exposure is defined as two standard deviations above the 6-h mean for the exposure, averaged over the time period of each stage of development. A comparison of average and maximum peaks of exposure levels is found in Table 8. The results show that the drilling, flaring and finishing, and producing stages release higher pollutant concentrations than the hydraulic fracturing stage (Figs. 2, 4, 5).

Compressor station and processing plant. Unlike well pad development, compressor station emissions are assumed to be relatively constant over a 1-year period, operating 24 h a day and seven days a week. The varied patterns of 6-h

[3]The very first stage of well pad development, access road and well pad construction, is omitted from this case study, although there are public health implications for this stage because of truck traffic, diesel exhaust emissions and particulate matter (PM) effects on air quality.

Table 5. Estimated length of time per stage of development*.

Stage of Well Pad Development	*Number of Days or Months**	*VOC Source Term ug m***	*$PM_{2.5}$ Source Term ug m***
Drilling stages	5 months	400	125
Hydraulic fracturing	15 days	160	50
Flares and finishing processes	5 months	300	100
Producing well pad	Indefinite	80	25
Compressor station	Indefinite	300	100
Processing station	Indefinite	3,000	1,000

*Based on NY Revised Draft SGEIS 2011.[1]
**see Table 4.

exposures to VOCs at the residence 2 km from the compressor station are shown in Figures 6 and 7. Figure 6 shows the variability in exposures experienced over the period of one year (2011) and Figure 7 shows the results for a representative month (May 2011) to provide a closer look at the day-to-day variability. The maximum peak exposure value for the compressor station was 169 ug m^{-3}. Low values are also found throughout the year.

Similar to compressor stations, processing plants are assumed to have relatively constant emissions, although there is variation depending on, among other things, the type of gas (wet vs. dry). We use a high estimate for VOCs to reflect an uncertainty factor we associate with the processing facility. The gas processing plants are known to have multiple, frequent, and large scale flaring. In addition, there are more opportunities for fugitive emissions over and above those at the smaller compressor stations. The source term we use for the processing plant is the most complicated and potentially problematic. See Appendix C for a full discussion of the reasoning behind our emissions estimate.

The varied patterns of 6-h exposures to VOCs at the residence 5 km from the processing station are shown in Figures 8 and 9. Although this source is further away than the compressor station, exposure values are higher, with maximum peaks reaching 450 ug m^{-3}. These findings, along with those of the compressor station, show that even with relatively constant emissions from a source there will be high variability in the frequency, duration and intensity of exposures at a nearby residence. The results also indicate that processing station emissions will impact a broader geographic range than well pads or compressor stations.

Frequency of peaks. Examining frequency of peaks (two standard deviations above the mean for each stage), Table 6 shows that during the 15-day hydraulic fracturing stage, there would be two 6-h periods with peak exposures at the residence. From the compressor station there would be 118 6-h peak periods – or 708 h of peak exposures – over the 1-year period modeled. From the processing plant there would be 99 6-h peak periods – or 594 h. These findings suggest that the residence could experience as many as 300 6-hour peaks of VOC exposure over the course of the modeled 14-month period. They also indicate that average intensity over the course of a year is a poor measure for risks to individuals near facilities and operations. Table 7 summarizes peak exposures for $PM_{2.5}$.

Diurnal variation. Residents tend to be more at risk at night when they are also less likely to be aware of the exposures. At night there is usually less mixing within the air column than during the day. The two 6-h periods at night (6:00 pm – 12 midnight and 12 midnight – 6:00 am) tend to carry higher exposure values. For example, in May 2011 the average values of exposure from a producing well pad for evening, night, morning and afternoon periods were 51 ug m^{-3}, 58 ug m^{-3}, 12 ug m^{-3} and 10 ug m^{-3}, respectively. This pattern indicates that residents may be most at risk at night when they are also less likely to be aware of the exposures.

Discussion

The findings of the case study show that residents are exposed to air contaminants at different intensities over

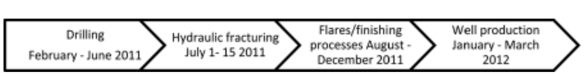

Fig. 1. Stages of well pad development modeled in the case study and corresponding dates for each stage.

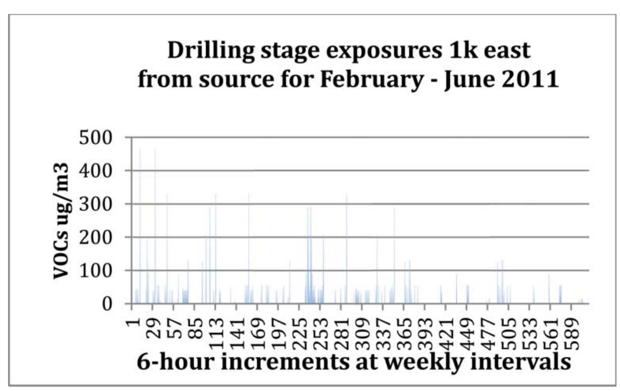

Fig. 2. Changes in the modeled ambient air levels of VOCs from the drilling stage of well pad development.

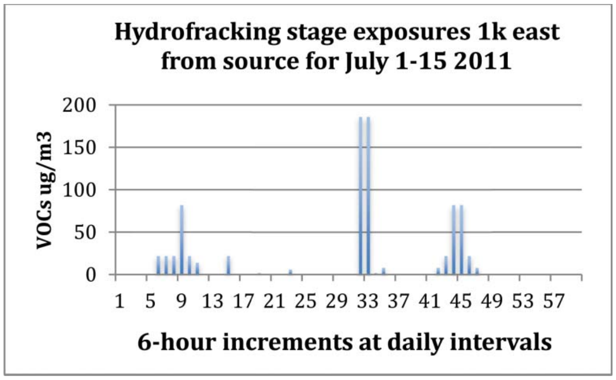

Fig. 3. Changes in the modeled ambient air levels of VOCs from the hydrofracking stage of well pad development. Note variation in vertical axes.

time. Predicting and monitoring these exposures provides important information to residents, health care providers, and policymakers on local health impacts from UNGD. The study shows that it is necessary to consider all nearby sites and the activities at those sites. The effects from one site are compounded by those of another. By bringing together estimates of UNGD emissions, the timing of activities, and weather patterns over a year, a more plausible prediction about an individual's exposures to airborne pollutants can be made.

Health care providers evaluating patients in shale development regions are faced with complex environmental exposures, capable of inducing multiple physiological responses, and non-specific health complaints. It is important for patients and providers to understand that exposure levels and patterns vary predictably and, moreover, exposures can sometimes reach levels that are immediately dangerous to human health.

The study further suggests that the approach commonly taken to estimate average exposures, based on intermittent 24-h sampling, underestimates the hazard at residences near the sites and can mislead the health care provider.

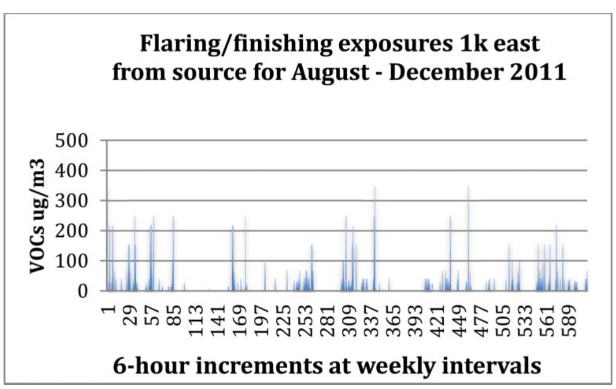

Fig. 4. Changes in the modeled ambient air levels of VOCs from the producing well pad.

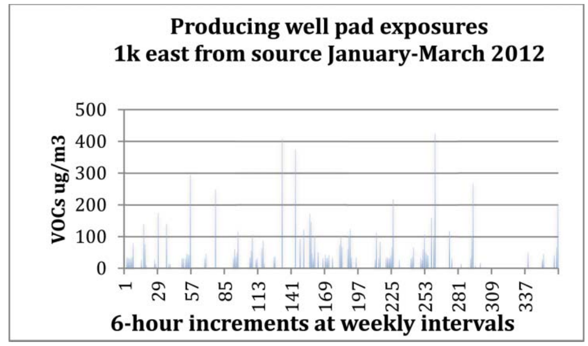

Fig. 5. Changes in the modeled ambient air levels of VOCs from the flaring/finishing stage of well pad development.

Implications of the Model and Findings

Intensity and variability of exposure. The intensity of exposures during UNGD activity at the well pad is determined by 1) the process underway (e.g., drilling, hydraulic fracturing, flaring, producing); 2) wind speed and direction; diurnal and seasonal air dilution; and 3) emission rate from the source.

Fourteen months of modeled data using 2011-12 weather conditions reported from the Pittsburgh airport show that the exposures to PM and VOCs at the hypothetical residence are highly variable and that the variability is predictable with regard to weather patterns.

Periods and patterns of peak exposures. The modeled data show that exposure levels increase most often during nighttime hours when there is usually less mixing within the air column. Residents appear to be most at risk at night when they are also less likely to be aware of the exposures. This is consistent with anecdotal reports from residents who often think that nighttime air is *less* polluted than daytime air. They are often inclined to open windows at night before going to bed. Poorer air quality at night, however, may in part explain why people complain of waking up feeling sick, but improve as the day goes on.[31]

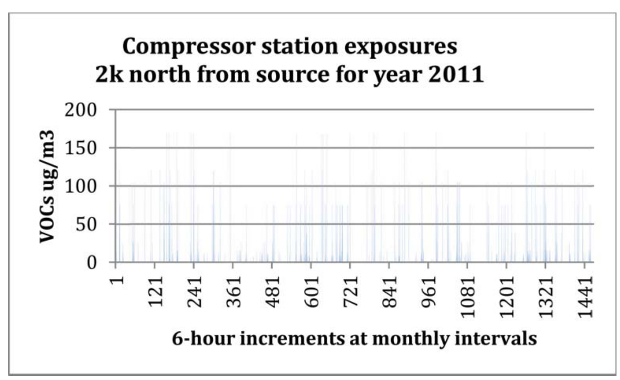

Fig. 6. Changes in the modeled ambient air levels of VOCs from a compressor station over a year.

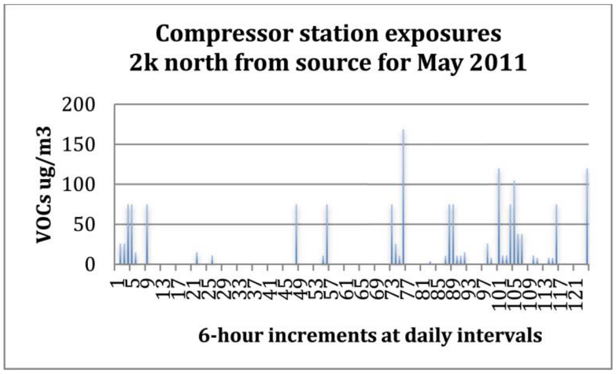

Fig. 7. Changes in the modeled ambient air levels of VOCs from a compressor station over one month.

Tables 8a and 8b show evidence of episodic extreme exposures. In fact, Tables 8a and b and the earlier figures show that 10% of the time or less a peak exposure could occur. The episodic nature of peak exposures points out the difficulty of adequately measuring and documenting exposures at residences and why, anecdotally, residents note odors and symptoms of exposures but air samples days later reveal nothing. Although there may be peaks present, a random air sample has a 75% or more chance of showing little impact of emissions at a residence.

VOC and PM exposures vary with the source

Well pad (Figs. 2–5). Drilling stage emissions are characterized by frequent 6-h episodes of low to moderate VOC exposures and instances of extreme exposures. The hydraulic fracturing stage is similar but is less frequently intense. Flaring and finishing produce high level exposures which continue at lower levels during production. These profiles are consistent with residents' reports of periodic odors and sensory and respiratory irritation. A patient near a well pad would have periods of low exposure some weeks, but higher, more dangerous exposures other weeks.

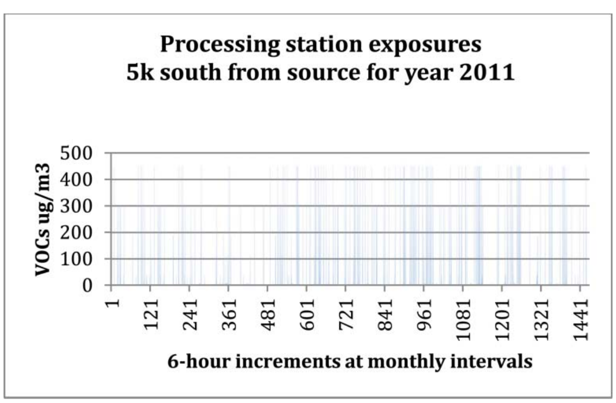

Fig. 8. Changes in the modeled ambient air levels of VOCs from a processing plant over a year.

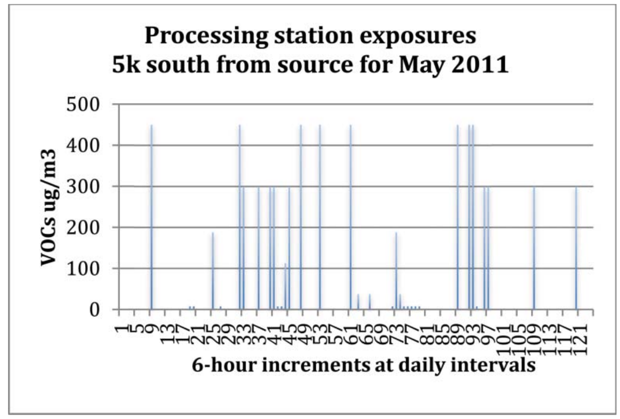

Fig. 9. Changes in the modeled ambient air levels of VOCs from a processing plant over one month.

Compressor station (Figs. 6 and 7). In contrast to well pads, compressor stations more consistently produce emissions. Thus, variability in exposures is largely, but not entirely, due to weather and air stability.

Processing plant (Figs. 8 and 9). The gas processing plant, despite its being five kilometers north from the residence, produced exposures consistently higher than those produced by well development activities or the compressor station, which are closer. The plant has the largest toxic footprint of the three sites and poses the most danger to residents.

Physicians who understand the fundamental aspects of the route of exposures will be able to communicate risks or reassurances to the resident, explaining that he or she is not exposed to high levels all the time. Some days are better, some are worse. Those days that are 'worse' deserve attention and over time they are numerous.

Exposures occur from multiple sources at overlapping times

Figure 10 provides a 1-week snapshot of exposures at the hypothetical residence in September 2011. In the week featured the highest residential exposures are from the well pad during its flaring/finishing stage. As this occurs, however, the residence is also receiving lower but still significant emissions from the other two facilities.

Health implications of episodic exposures to shale emissions

It is important to consider the toxic actions of periodic exposures to high doses of these chemicals.

Table 6. Average intensities and peak values of VOCs in 6-hour increments.

UNGD Source	*Average Intensity*	*Threshold of Peak Value*[*]	*Maximum 6-h Peak Value*	*Frequency of 6-h Peaks*
Drilling	19	125	465	26/5 months
Hydraulic fracturing	13	88	186	2/15days
Flaring/finishing	19	118	349	30/5 months
Producing	21	130	425	25/3 months
Compressor	10	69.3	169	118/1 year
Proc. Station	56	318	450	99/1 year

*This represents the minimum value that is considered a "peak" – defined as 2 standard deviations above the mean. Maximum peak values represent the highest peaks found in the analysis. All values are in ug m^{-3}.

Effects from high exposures to VOCs. *VOCs* are a varied group of compounds which can range from having no known health effects to being highly toxic. Short-term exposure can cause eye and respiratory tract irritation, headaches, dizziness, visual disorders, fatigue, loss of coordination, allergic skin reaction, nausea, and memory impairment. Long-term effects include loss of coordination and damage to the liver, kidney, and central nervous system. Some VOCs, such as BTEX (benzene, toluene, ethylbenzene and xylene, which are often emitted together), have been detected near natural gas development and specifically noted by Wolf Eagle, McKenzie et al., Colborn et al., and Steinzor et al.[12,16-18] Acute exposures to high levels of BTEX have been associated with skin and sensory irritation, central nervous system depression, and negative effects on the respiratory system. The case for elevated risk of cancer from UNGD VOC exposure has been made by McKenzie et al.[15]

Effects from high exposure to particulate matter. Exposure to $PM_{2.5}$, in conjunction with other emissions, is of core concern. Fine particulates interact with the airborne VOCs increasing their absorption into the lung. Reported clinical actions resulting from $PM_{2.5}$ inhalation affect both the respiratory and cardiovascular systems. Inhalation of $PM_{2.5}$ can cause decreased lung function, aggravate asthma symptoms, cause nonfatal heart attacks and high blood pressure.[32] Research reviewing health effects from highway traffic, which, like UNGD, has especially high particulates, concludes, "[s]hort-term exposure to fine particulate pollution exacerbates existing pulmonary and cardiovascular disease and long-term repeated exposures increases the risk of cardiovascular disease and death."[33] $PM_{2.5}$, it has been suggested, "appears to be a risk factor for cardiovascular disease via mechanisms that likely include pulmonary and systemic inflammation, accelerated atherosclerosis and altered cardiac autonomic function. Uptake of particles or particle constituents in the blood can affect the autonomic control of the heart and circulatory system."[33]

High levels of diesel exhaust from engines during well pad activity. Health consequences of diesel exposures include immediate and long-term health effects. Diesel emissions can irritate the eyes, nose, throat and lungs, and can cause coughs, headaches, lightheadedness and nausea. Exposure to diesel exhaust also causes inflammation in the lungs, which may aggravate chronic respiratory symptoms and increase the frequency or intensity of asthma attacks. Long-term exposure can cause increased risk of lung cancer.[34-37]

Mixtures increase the hazards. Mixtures of pollutants are a critically important topic in addressing the public health implications of UNGD. While this report has focused separately on two pollutants, in fact, a very large number of chemicals are released together. Moreover many of the chemicals have little or no tested health data – alone or in conjunction with others. In fact, medical reference values do not take the complex nature of the shale environment,

Table 7. Average intensities and peak values of PM peaks are defined as 2 standard deviations above the mean, in 6-h increments.

UNGD Source	*Average Intensity*	*Threshold of Peak Value*[*]	*Maximum 6-h Peak Value*	*Frequency of 6-h Peaks*
Drilling	6	37	140	26/5 months
Hydr. fracturing	4	26	56	2/15days
Flaring/finishing	6	39	116	30/5 months
Producing	6	39	128	25/3 months
Compressor	3	23	56	118/1 year
Proc. Station	19	106	150	99/1 year

*This represents the minimum value that is considered a "peak" – defined as 2 standard deviations above the mean. Maximum peak values represent the highest peaks found in the analysis. All values are in ug m^{-3}.

Tables 8a and b. Comparison of 75th and 90th percentiles for 6-h levels of VOCs and $PM_{2.5}$ in ambient air at the modeled residence.

a). $PM_{2.5}$			
UNGD Source	*75th Percentile*	*90th Percentile*	*Threshold of Peak*
Drilling	3	16.5	37
Hydraulic fracturing	2	7	26
Flaring/finishing	5	14	39
Producing	8	19	39
Compressor	0	9	23
Proc. Station	2.5	100	106
b). VOCs			
UNGD Source	*75th Percentile*	*90th Percentile*	*Threshold of Peak*
Drilling	10	55	125
Hydraulic fracturing	8	22	88
Flaring/finishing	15	41	118
Producing	35	81	130
Compressor	0	26	69
Proc. Station	7.5	300	318

All values are in ug m^{-3}.

the multiple emissions and interactions, into full consideration.[38] The shale gas industry is not alone in emitting multiple pollutants simultaneously, but this industry is unusual in doing so as close as 500 feet from residences.

Children and pregnant women are vulnerable. Children and pregnant women are especially sensitive to pollution and are of high public health concern. Many studies confirm a range of adverse effects of air pollution on children's lung function and respiratory symptoms, especially for asthmatics. Studies often point, specifically, to fine particles as having an association with respiratory symptoms.[39]

Research on $PM_{2.5}$ suggests that in pregnant women, the high particulate highway pollution (which has many commonalities with shale gas pollution) "may provoke oxidative stress and inflammation, cause endocrine disruption, and impair oxygen transport across the placenta, all of which can potentially lead to or may be implicated in some low birth weight . . . and preterm births." These are immediate consequences in infancy, but further on "low birth weight and preterm birth can affect health throughout childhood and in adulthood."[40] Two studies on birth outcomes and UNGD exposures find correlations between exposures and risk to newborns. Hill found an association between proximity to wells and low birth weight, small for gestational age, and reduction in APGAR scores.[26] McKenzie et al. found an association between proximity and density of nearby wells and congenital heart defects and possibly neural tube defects.[27]

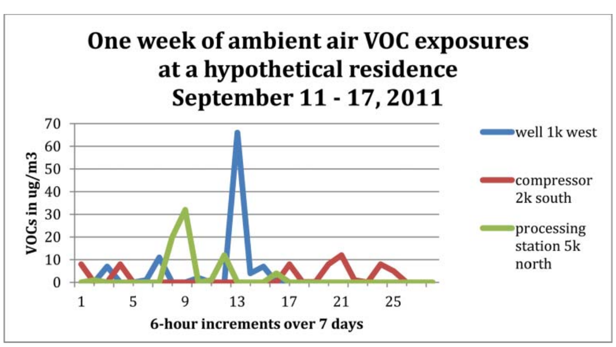

Fig. 10. One week of estimated ambient air exposures from three UNGD sources during a 7-day period.

Limitations of the research

The study of shale gas activity emissions and their possible health consequences is in its early stages. Thus the case study presented has limitations. These include:

1. There is a need for comprehensive source term data based on measurements, especially at processing stations. EHP's source terms were in response to the small number of measurements currently available. Further, the limited source data available are averaged over one year which underestimate the peak emissions that are of particular public health concern.
2. Full assessment of health effects is hindered by emissions uncertainties in the identification of emissions, their mixtures and consequent health impacts. We chose to look at $PM_{2.5}$ and VOCs because they are consistently found in UNGD emissions and because there are known health effects from human exposure. These contaminants, however, are emitted with a wide and not entirely identified mix of other chemicals whose combined effects cannot be determined.
3. The basic screening model was designed to be straightforward and understandable to the public. More complex models would reveal more precise estimates of periods of dangerous levels of exposure.

4. In providing a basic rather than more sophisticated model, we held topography constant, flat surfaces. Failure to account for topography may result in an underestimate of exposures under certain circumstances.
5. We did not incorporate background levels of PM and VOCs in our study. In the future, with precise emissions levels, models should account for the additional background levels of air contaminants.
6. For some acute health assessments it may be necessary to model for less than 6 h. Even shorter averaging times would reveal the highest peak exposures, which might be lost in 6-h averaging time.
7. The exposure model, as applied, does not account for intermediate weather conditions nor does it account for vacillating winds within the 6-h periods. While the model could be extended to account for further variability, the findings hold as the emissions reaching the residence are still proportional to the wind direction and speed.

Conclusions

Exposures must be understood to be time- and location-dependent; and it is important to convey this perspective to residents and health care providers. An exposure model of pollution dispersion provides the opportunity to evaluate the intensity and frequency of exposures that are high enough to produce acute health effects at some residences. Moreover, assessing air quality over long stretches of time reveal days when weather conditions are favorable for contaminants to rise and be diluted.

In addition to weather conditions, it is important to consider the time frame for Unconventional Natural Gas Development, which begins with the clearing of land for a well pad and can go on indefinitely as wells produce gas which is transported, separated, pressurized, vented, and treated. Each stage of natural gas development produces its own emissions and a given household can be subjected to exposures from more than one part of the gas development process at once.

The model and findings provide a possible explanation for the episodic nature of health complaints and symptoms in gas drilling and processing areas. From this conclusion, we generate three recommendations: Our strongest recommendation to the research community is to measure emissions in very short time intervals while also measuring over a long period of time. Our strongest recommendation to the health care community is to consider the possibility that a patient is suffering from intermittent industrial exposures, some of which can be estimated when they live or work near UNGD sites. And, lastly, our strongest recommendation to individuals living in shale gas areas is to monitor weather conditions to understand when the air is likely to be particularly polluted and when it is likely to be less polluted. This can provide some small measure of control and warning.

The public health, medical and regulatory communities must be vigilant in assessing risk across time, distance, and activity.

Acknowledgments

The authors thank the residents in Washington County, Pennsylvania, who shared information with SWPA-EHP. We gratefully acknowledge the support and assistance of the staff at SWPA-EHP, Dr. Kathy Nolan and Earl Ivan White.

Funding

This research was supported by the Heinz Foundation and the Colcom Foundation.

Supplemental material

Supporting information for this paper can be viewed at environmentalhealthproject.org.

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