Marcellus Shale Development: Analysis of Air Quality Data and Public Health Studies

Prepared by

Christopher M. Long, Sc.D., DABT

Prepared for
Range Resources – Appalachia, LLC
3000 Town Center Blvd.
Canonsburg, PA 15317

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GRADIENT

www.gradientcorp.com
20 University Road
Cambridge, MA 02138
617-395-5000

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Abbreviations

AAPG	American Association of Petroleum Geologists
ACHD	Allegheny County Health Department
ATSDR	Agency for Toxic Substances and Disease Registry
BRS	Bradford Ranger Station
BTEX	Benzene, Toluene, Ethylbenzene, and Xylenes
CARB	California Air Resources Board
CO	Carbon Monoxide
CREG	Cancer Risk Evaluation Guide
CRS	Chronic Rhinosinusitis
CWS	California Well Stimulation
DABT	Diplomat of the American Board of Toxicology
DMF	N,N-dimethylformadide
ESL	Effects Screening Level
ELCR	Estimated Excess Lifetime Cancer Risk
GC/MS	Gas Chromatography/Mass Spectrometry
GC-FID	Gas Chromatography-Flame Ionization Detector
H_2S	Hydrogen Sulfide
HC	US Forest Service Hearts County Campground
HI	Hazard Index
HEI	Health Effects Institute
HHRA	Human Health Risk Assessment
IDW	Inverse Distance Weighted
KEF	Kane Experimental Forest
MRL	Minimal Risk Level
NAAQS	National Ambient Air Quality Standards
NCEI	National Centers for Environmental Information
NETL	National Energy Technology Laboratory
NGAAMI	National Gas Ambient Air Monitoring Initiative
NGD	Natural Gas Development
NGL	Natural Gas Liquid
NOAA	National Oceanic and Atmospheric Administration
NO_2	Nitrogen Dioxide
O_3	Ozone
OP-FTIR	Open Path Fourier Transform Infrared
ORs	Odds Ratios
PADEP	Pennsylvania Department of Environmental Protection
PAH	Polycyclic Aromatic Hydrocarbon
PELs	Permissible Exposure Limits
PM	Particulate Matter
PPB	Parts Per Billion
RfC	Reference Concentration
RSL	Regional Screening Level
SGA	Small for Gestational Age

SIR	Standardized Incidence Ratio
SO_2	Sulfur Dioxide
TCEQ	Texas Commission on Environmental Quality
TVOCs	Total Volatile Organic Compounds
US DOE	United States Department of Energy
US EPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound
WAM	Wireless Air Monitoring Station
WVU	West Virginia University

1 Introduction

1.1 Qualifications

My name is Christopher M. Long. I am a principal scientist at Gradient, where I specialize in air pollution exposure assessment and inhalation risk assessment. In my 16 years at Gradient, I have worked on a wide variety of indoor and outdoor air quality projects. Prior to joining Gradient, I received my doctorate in Environmental Health from the Harvard School of Public Health, where I conducted a research study to characterize particulate matter mass concentrations, size distributions, and chemical composition inside and outside residential homes. I have prepared approximately 30 peer-reviewed journal articles or book chapters in the general areas of indoor and outdoor air pollution and exposure/risk assessment. I am certified as a Diplomate of the American Board of Toxicology (DABT). My full CV is attached as Appendix A of this report.

1.2 Introduction and Scope

I have been retained, as an employee of Gradient, by Range Resources – Appalachia, LLC to provide an overview of the science bearing on the potential community-level air quality impacts and public health risks associated with natural gas development activities in Mount Pleasant Township within Washington County, Pennsylvania, including the proposed development of the Yonker well pad located on the Yonker property at 86 Baker Road. There are 6 wells scheduled to be drilled in the short term on Yonker well pad. It is my understanding that Range Resources' Cowden well pad to the southwest is the only other well pad within 1 mile of the Yonker well pad.[1] The Fort Cherry School District campus is to the northwest of the proposed location of the Yonker well pad, with an estimated distance of approximately 3,800 feet from the center of the proposed pad to the closest building on the school property. For perspective, Range Resources' Chiarelli well pad, a 6-well pad that was the subject of the comprehensive Maskrey *et al*. (2016) air monitoring study discussed in Section 4.2.1, is located approximately 2,800 feet to the north of the school campus. Figure B.1 in Appendix B illustrates the low frequency of southeasterly winds in this area that would blow from the Yonker well pad towards the Fort Cherry School District campus.

It is my understanding that there are typically four phases of natural gas development (NGD) for new well pad sites, such as the Yonker well pad, with the following approximate timeframes:

- **Well Pad Construction:** includes both construction of an access road (~ 2 weeks) and construction of the well pad itself (~7 weeks).
- **Well Drilling:** consists of vertical drilling (~1 week per well) and horizontal drilling (~2 weeks per well).

[1] The Cowden well pad is a 2-well pad that was drilled in 2009 and completed in 2010. The Cowden Impoundment formerly located adjacent to the Cowden well pad was closed in the spring of 2016.

- **Well Completion:** consists of two phases, namely hydraulic fracturing and flowback, with the entire completion process expected to take an average of one month.[2]
- **Production:** natural gas is transported *via* pipeline, and condensates and natural gas liquids (NGLs) are removed *via* truck, for the lifetime of the producing well.

With the exception of the production phase, any air emissions associated with each of the phases of NGD activity will thus be relatively short-term and transient in nature, with durations on the order of weeks to at most several months.

Each of these NGD phases is associated with potential sources of air emissions. For example, diesel-powered equipment that would be used at any construction project, including trucks, backhoes, and graders, can be sources of air emissions during the well pad construction phase. During the well drilling phase, sources of air emissions can include diesel-powered trucks, generators, compressors, and backhoes; diesel- and/or natural gas-powered drill rigs; as well as a flare stack and drilling muds. During the well completion phase, sources of air emissions can include diesel-powered trucks, diesel- and/or natural gas-powered hydraulic fracturing pumps, hydraulic fracturing fluids, flowback water, and sand handling operations. Finally, air emission sources during the production phase can include well-head compressors or pumps, well pad equipment bleeding and leaks (*e.g.*, condensate tank vents, dehydrators), flaring[3], and diesel-powered trucks.

Besides methane and other natural gas constituents (*e.g.*, propane, ethane, butane) that are of low direct toxicity to humans (Goldstein *et al*., 2014; McKee *et al*., 2014), NGD-related air emissions can include United States Environmental Protection Agency (US EPA) criteria air pollutants such as particulate matter (PM; *i.e.*, $PM_{2.5}$ and PM_{10}), sulfur dioxide (SO_2), carbon monoxide (CO), and nitrogen dioxide (NO_2); non-methane hydrocarbons such as benzene, toluene, ethylbenzene, xylenes, and trimethylbenzenes; aldehydes such as formaldehyde and acetaldehyde; and other air pollutants, such as silica and hydrogen sulfide (H_2S). These substances are also ubiquitous in indoor and outdoor air due to numerous common indoor and outdoor sources that are both anthropogenic (manmade) and natural in origin. Manufacturing operations (*e.g.*, steel, aluminum, machinery), construction, coal mining, fossil fuel combustion, conventional oil and gas development activities, motor vehicles, and forest fires are common examples of air emission sources. Thus, the presence of a constituent does not necessarily implicate a particular source. Given that these constituents are common in indoor and outdoor air, they have been well-studied in other contexts and have health-based exposure guidelines and limits (*e.g.*, US EPA Reference Concentrations [RfCs], US Agency for Toxic Substances and Disease Registry [ATSDR] Minimal Risk Levels [MRLs], Texas Commission on Environmental Quality [TCEQ] Effects Screening Levels [ESLs]).

Although recent studies have constructed air emissions inventories and totaled emissions of various air pollutants associated with Marcellus Shale development (*e.g.*, Roy *et al*., 2014), air emissions data in terms of tons per unit time (*e.g.*, tons per day or tons per year) or tons per well cannot be used to assess potential community exposures to NGD-related air pollutants. Due to factors such as the pattern of emissions (*i.e.*, whether emissions are continuous or only occur at certain times), the location of emissions (*i.e.*, whether emissions occur at ground-level or from stacks or vents high in the air), and air dispersion (*i.e.*, the amount of dilution that occurs as pollutants spread out in the air during travel away from the source, based largely on meteorological conditions and terrain properties), air emissions provide little

[2] Note that there will not be a flowback water impoundment at the Yonker pad, as flowback water will be removed for off-site disposal.

[3] While a temporary flare stack may be used at the Yonker pad during the drilling phase to safely eliminate natural gas released during the drilling phase, it is my understanding that Range Resources does not plan to conduct open flaring during the production phase at the Yonker pad.

information on concentrations of pollutants (masses of pollutants per unit volume of air, *e.g.*, micrograms per cubic meter or $\mu g/m^3$) that can potentially be inhaled. Together with exposure frequency (*i.e.*, how often) and exposure duration (*i.e.*, how long), air concentrations (and not air emissions) are a key determinant of air pollutant exposures.

Importantly, there has emerged a sizable body of air quality data specific to the Marcellus Shale region that can be used for evaluating the nature and health significance of potential community-level air exposure levels posed by NGD-related air emissions in the Marcellus Shale. Air quality data are available from regulatory agency monitoring programs and studies, peer-reviewed published studies, and other commissioned study reports. Much of these data are for ambient air monitoring conducted at or in close proximity to NGD sites, and thus provide information more representative of upper-bound community air exposure levels than typical air exposure levels, due to the frequent location of monitors on or very close to well pads and other emission sources. As discussed in Section 4, data are available to characterize short-term episodic (*e.g.*, 1-minute to 1-hour) air concentrations at locations on or nearby to NGD sites; in addition, a number of studies provide targeted data for specific NGD phases (*e.g.*, baseline, hydraulic fracturing, production), including for Range Resources sites in Washington County.

While the number of Marcellus Shale health studies has also dramatically grown in recent years, these studies continue to be affected by major methodological limitations and study shortcomings. In particular, there remains an absence of any Marcellus Shale epidemiological studies that have used actual exposure measurement data (*e.g.*, air monitoring data) in their exposure assessments, as all published studies have instead relied on crude exposure surrogates such as proximity to the nearest gas well and inverse distance weighted well counts. As discussed in Section 5, even the more rigorous of the available Marcellus Shale epidemiological studies are at best hypothesis-generating studies and cannot be used to make or support causal conclusions regarding NGD activities and adverse human health impacts.

As described in this report, the accumulated Marcellus Shale air quality data do not provide evidence of widespread community air exposures of public health concern for typical NGD operations in the Marcellus Shale. In fact, there is consistency in the available air quality data and studies in providing a general absence of evidence for either significant short-term or long-term air exposures of health concern for typical Marcellus Shale NGD operations. Some studies have reported evidence of elevated episodic air quality impacts for certain air pollutants nearby to well pads and emission sources; however, these site-specific findings are not indicative of broader community exposure concerns across NGD operations, nor are they different from the kinds of near-source air quality impacts common to other air emission sources, such as traffic exhaust, conventional oil and gas development, manufacturing, construction, coal mining, and fossil fuel combustion. Moreover, while Marcellus Shale epidemiological studies have been interpreted by some (*e.g.*, Webb *et al*., 2016) as providing evidence linking NGD activities with increased human health risks, it is important to highlight the major methodological limitations and study shortcomings that preclude their use for making any causal conclusions regarding NGD activities and adverse human health impacts. As discussed in Section 5, human health risk calculations conducted to date predominantly provide evidence supporting a lack of adverse health effects from NGD air emissions in the Marcellus Shale.

Below, in Section 2, I begin with some brief historical context on oil and gas development activities in Pennsylvania, because air emissions from oil and gas development activities, including hydraulic fracturing, are not a new and unknown phenomenon in Pennsylvania and are, instead, very familiar to regulators and the region. In Section 3, I then provide some background on safe threshold doses and exposure assessment. Section 4 is focused on the body of available Marcellus Shale air quality data and studies, while Section 5 discusses epidemiological studies and human health risk assessments that have been conducted for populations in the Marcellus Shale region. I do not discuss the literature regarding methane air emissions and air quality impacts from NGD activities, since methane is considered to be relatively nontoxic to humans (Goldstein *et al*., 2014).

2 Historical Perspectives on Oil and Gas Development and Hydraulic Fracturing in Pennsylvania

The State of Pennsylvania has a long and rich history of oil and gas development. The first commercially successful oil well drilled for production was completed in 1859 and located in Venango County, where it became known as the "Drake Well." This was, in fact, the first commercial oil well in the US. The earliest gas wells in Pennsylvania were drilled in 1860 in the northwest part of the state (Erie County), and the first commercial production well came online in 1872, in Crawford County (Carter *et al*., 2011). The Pennsylvania Department of Environmental Protection (PADEP) has estimated that, since the construction of the Drake Well in 1859, more than 350,000 oil and gas wells have been drilled in the state (PADEP, 2013). Following the initial development in the mid- to late-1800s, several important gas fields were discovered in the central and western portions of the state – most prominently, the Oriskany Sandstone in the 1950s to 1960s (Fettke, 1951) and, later, in the 1970s, the Medina Sandstone, which is considered a "tight" (*i.e.*, low permeability) gas play (Carter *et al*., 2011).

Following the advent of hydraulic fracturing by Stanolind Oil and Halliburton in 1949 (Montgomery and Smith, 2010), the technology was systematically used to develop Pennsylvania's natural gas resources decades before the introduction of horizontal drilling and the economic production of gas from the Marcellus Shale. For example, the first reported use of hydraulic fracturing in Pennsylvania was conducted in 1953 in Elk County (Fettke, 1954). Later, hydraulic fracturing was used extensively in shallow gas-bearing sandstones of Warren County, in addition to deep gas-bearing formations, where it was estimated that, by 1963, more than 70% of deep gas-bearing sandstones were hydraulically fractured (Lytle, 1964; Lytle *et al*., 1966). After these early applications of hydraulic fracturing in Pennsylvania, subsequent NGD activities continued to use hydraulic fracturing on a routine basis, prior to more recent public awareness of the technology's use with respect to development of the Marcellus Shale.

The first Marcellus well hydraulically fractured in Pennsylvania was completed in 2004 by Range Resources and was located in Washington County, more than five decades after the first recorded use of hydraulic fracturing in the state. Since that time, it is estimated that more than 16,000 Marcellus Shale wells have been completed in Pennsylvania (Marcellus Center for Outreach and Research, 2016). The number of gas wells installed in the Marcellus Shale over the past decade represents only a fraction of the wells historically drilled in the state. Thus, although hydraulic fracturing activities in the Marcellus Shale region have garnered much public attention over the past decade, NGD in general, as well as the use of hydraulic fracturing, have occurred historically throughout the state over an extended period. Accordingly, relevant regulatory frameworks have been developed against the backdrop of these kinds of activities and air emission sources.

3 Background on Safe Threshold Doses and Exposure Assessment

Information on airborne exposure levels is an essential piece of information for determining whether an exposure to an airborne substance may be excessive and associated with potential adverse health effects. This is because the body's response to contact with chemicals (*e.g.*, health restoration, health maintenance, neutral, or health impairment) depends on the amount taken in, or in other words, the dose. It is in fact a basic tenet of toxicology. Moreover, it is also a basic principle of toxicology that there are safe threshold levels that reflect the doses below which no adverse health effects are expected to occur. As any medical doctor and public health professional knows, we would not be able to use over-the-counter and prescription drugs if safe thresholds and thresholds of efficacy did not exist. Quite simply, for both contaminant chemicals that we contact in the environment as well as other types of chemicals that we routinely encounter in our daily lives (such as natural chemicals in food), excessive amounts can be harmful, while smaller quantities are not.

Exposure assessment, which is one of the four main components of the human health risk assessment (HHRA) process,[4] is a well-established and generally accepted process for estimating chemical concentrations in environmental media and predicting chemical exposures/doses that may be received *via* exposure routes that include inhalation, ingestion, or dermal contact (US EPA, 1992, 2016; Paustenbach and Madl, 2014). Recognizing that they often reflect the combined air quality impacts of multiple sources beyond just the source(s) of interest, environmental measurements such as ambient air monitoring data are often used to represent exposure levels. Source-specific exposure can be determined by transport modeling of how chemicals from a particular source are released, dispersed, and transported from the source, through the environment, to a person's location, which then allows for calculation of an exposure-point concentration for an individual. Exposure-point concentrations, which reflect the intensity of exposure, are then typically paired with individual-specific information on frequencies and durations of exposure to characterize exposure.

Given that substances such as benzene and H_2S must exceed safe threshold levels prior to eliciting adverse health effects, understanding airborne exposure levels in communities nearby to NGD activities is a critical step in determining whether NGD-related air emissions may be associated with increased health risks. Exposure estimates are also a key input to epidemiological studies that attempt to associate environmental impacts from NGD activities with changes in health measures, such as asthma exacerbations or adverse birth outcomes. As discussed later in this report, to date, no epidemiological studies of NGD-impacted areas have used actual environmental exposure data, such as air monitoring data, in exposure assessments.

Before discussing the body of available Marcellus Shale air quality data and studies, it is important to highlight several challenges to the interpretation of ambient air measurement data collected at or near well pads, compressor stations, and other NGD source types. First, the air pollutants of health concern in these studies are typically ubiquitous in indoor and outdoor air, due to a number of common exposure sources (as illustrated in Table 3.1 for a few constituents potentially associated with NGD activities). Since baseline air quality data (*i.e.*, air measurement data collected prior to the widespread occurrence of NGD

[4] The other three components of the HHRA process are Hazard Identification, Dose-Response Assessment, and Risk Characterization.

development activities) are rarely available for NGD-impacted areas, it is often very difficult to quantify the fraction of ambient air concentrations that is due to NGD-related air emissions *versus* the fraction that is due to other common sources.

Table 3.1 Common Sources for Several Air Pollutants Linked with NGD Activities

Pollutant	Common Sources
Benzene	Vehicle exhaust, gasoline vapors, tobacco smoke, wood smoke, power plants, manufacturing facilities, household products (glues, paints, adhesives, lubricants).
Formaldehyde	Vehicle exhaust, tobacco smoke, wood smoke, gas stoves, kerosene space heaters, power plants, manufacturing facilities, incinerators, cooking, building materials and home furnishings containing pressed wood products (hardwood plywood wall paneling, particleboard, fiberboard), carpets and permanent press fabrics, glues and adhesives, paints and coating products.
H_2S	Sewer gas, hot springs, manure holding tanks, pulp and paper mills, Chinese drywall, well water containing sulfur-reducing bacteria, landfills, bad breath.
$PM_{2.5}$	Outdoors: A variety of natural and human sources, including windblown dust, volcanoes, forest fires, sea spray, bioaerosols, vehicle exhaust, road debris, and power plant and other industrial emissions. Indoors: A variety of ordinary daily activities, such as cooking (baking, frying, grilling, barbecuing, toasting, etc.), dusting, vacuuming, folding clothes, making a bed, mowing the lawn, driving a car, heating a home, smoking, burning candles, *etc.*

Notes:
H_2S = Hydrogen Sulfide; NGD = Natural Gas Development.

For example, short-term peak $PM_{2.5}$ concentrations in excess of the 24-hour $PM_{2.5}$ National Ambient Air Quality Standard (NAAQS) of 35 μg/m^3 are common both indoors and outdoors, due to $PM_{2.5}$ emissions from a variety of indoor and outdoor sources. Even near an NGD site, possible sources of transient peak ambient $PM_{2.5}$ concentrations could include traffic exhaust, diesel emissions from farm equipment, wood smoke, construction-related diesel emissions or fugitive dust, *etc*. As shown in Table 3.2, cooking and cleaning activities can result in elevated short-term indoor $PM_{2.5}$ impacts ranging up to more than 100 μg/m^3 (Long *et al*., 2000).

Table 3.2 Average Short-term Peak $PM_{2.5}$ Impacts During Various Cleaning, Cooking, and Other Activities in Boston-area Homes

Activity	$PM_{2.5}$ Concentration (μg/m^3)
Baking (electric)	15
Baking (gas)	101
Toasting	54
Broiling	29
Sautéing	66
Stir-frying	37
Frying	41
Dusting	23
Vacuuming	7
Cleaning with Pine Sol	11
Walking vigorously over carpet indoors	12
Burning candles	28

Another key challenge to the interpretation of the available air exposure data, as they relate to potential community exposures, involves the fact that many of these air measurement data have been collected either on-site or very close to well pad sites or other air emission sources, like compressor stations. They are, thus, not necessarily representative of community-level exposure levels. Some of the available data, such as personal breathing zone samples and workplace area samples from occupational exposure studies, provide little information regarding community exposure levels. This is because air concentrations typically decrease very rapidly with distance from air emission sources; this has been demonstrated specifically for NGD-related air emission sources by Zielinska *et al*. (2014) who reported relative concentration gradients for measurements at different distances from NGD sites in Texas's Barnett Shale region. Ambient air data for on-site sampling locations that are not immediately adjacent to emission sources can be viewed as providing information more representative of upper-bound community air exposure levels than typical community air exposure levels. Notwithstanding uncertainties regarding the relationship between the existing ambient air data and actual air exposure levels, it is also important to distinguish air exposure levels from actual inhaled doses. Ambient air exposure levels themselves represent an upper-bound measure of actual inhaled dose since they assume the presence of people at the monitoring location, and are not representative of the reduced time- and spatially-averaged exposures to NGD-related emissions that would be anticipated as an individual moves among different locations (*e.g.*, home, workplace, commercial buildings, *etc.*) within a community. In fact, people typically spend more than 90% of their time indoors, which is important from an air exposure perspective, since indoor levels of outdoor-generated pollutants can often be substantially less than outdoor levels.

Finally, air exposure data representative of both short-term (*e.g.*, 1-hour, 24-hour) and long-term (*e.g.*, annual) exposure periods are needed when assessing the potential health significance of NGD-related air emissions. A recent study (Brown *et al*., 2014) concluded that there is a general absence of appropriate short-term air exposure data for assessing the health significance of transient peak exposures associated with NGD activities. Arguably, this conclusion was not consistent with the body of available air quality data and studies available at the time this article was published; however, as discussed in the next section, there are now multiple Marcellus Shale air quality studies with short-term air measurement data that provide information on potential episodic peak air exposure levels associated with various NGD activities.

4 Overview of Marcellus Shale Air Quality Studies

This section provides an overview of key findings from the rich nucleus of air quality data for areas with extensive NGD activities that are now available for the Marcellus Shale region. As grouped below, Marcellus Shale air quality data are available from regulatory agency monitoring programs and studies, peer-reviewed publications, and other commissioned study reports. Table 4.1 provides a summary of the available Marcellus Shale air quality data, showing the frequent availability of months to years of data for NGD-impacted sampling locations, including short-term (*e.g.*, minutes to hours) measurement data that provide insights on the occurrence of any episodic short-term peak concentration impacts of NGD activities. As shown in this table, air quality data are available for a comprehensive set of air pollutants, including both US EPA criteria air pollutants and air toxics. Much of these data are for ambient air monitoring conducted at or in close proximity to NGD sites, and thus provide information more representative of upper-bound community air exposure levels than typical air exposure levels, due to the frequent location of monitors on or very close to well pads and other emission sources. A number of studies provide targeted data for specific NGD phases (e.g., baseline, hydraulic fracturing, production).

As indicated in Table 4.1, a number of the available datasets are focused on sites in Washington County, including nearby to Range Resources well pads.[5] In particular, the Maskrey *et al*. (2016) peer-reviewed publication summarizes a comprehensive air monitoring study that was conducted on behalf of the Fort Cherry School District board to determine the air quality impacts of NGD activities at Range's Chiarelli well pad at both the Fort Cherry High School and a downwind residence in Mount Pleasant Township. As compared to the proposed Yonker well pad, the Chiarelli well pad is located in closer proximity to the Fort Cherry School District buildings (approximately 2,800 feet *versus* approximately 3,800 feet). This study, which is described in detail in Section 4.2.1, included continuous air quality monitoring during four phases of operations: 1) a baseline period before hydraulic fracturing commenced (16 days), 2) the hydraulic fracturing period (28 days), 3) the flaring period (10 days), and 4) an inactive period following flaring (21 days). As shown in Table 4.1, air quality data specific to certain NGD phases- *e.g.*, during construction, drilling, hydraulic fracturing, and production phases- are now available from a number of studies.

Overall, as demonstrated in this section, this body of Marcellus Shale air quality studies does not provide evidence of widespread community air exposures of public health concern for typical NGD operations in the Marcellus Shale. In fact, there is consistency in the available air quality data and studies in providing a general absence of evidence for either significant short-term or long-term air concentrations of health concern for typical Marcellus Shale NGD operations. This is the case across a fairly disparate body of studies that differ in terms of study investigator backgrounds (academics, regulator, governmental scientists, consultants), sampling designs, study locations and time periods, and potential emission sources. Some studies (*e.g.*, the WVU Air, Noise, and Light Monitoring Study (McCawley, 2013)) have reported evidence of elevated episodic air quality impacts for certain air pollutants nearby to well pads and emission sources; however, these site-specific findings are not indicative of broader community exposure concerns across NGD operations, nor are they different from the kinds of near-source air quality impacts common to other air emission sources, such as traffic exhaust, conventional oil and gas development, construction, coal mining, and fossil fuel combustion.

[5] Note that Table 4.1 is a comprehensive summary of Marcellus Shale air quality studies that includes studies with measurements nearby to sources such as impoundments, compressor stations, and production flare stacks that are not of direct relevance to potential air emissions associated with development of the Yonker or other well pads.

Table 4.1 Summary of Key Aspects of Marcellus Shale Air Quality Studies

Study or Dataset	Geographic Study Location(s)	Study Time Period	Air Monitoring Locations	Target Analytes	Frequency of Sampling/Approx. Number of Total Samples	Averaging Time(s) for Reported Pollutant Conc.	Phases of Well Pad Activity with Targeted Air Monitoring Data
Regulatory Agency Data and Studies							
PADEP Air Monitoring Data	Multiple locations downwind of oil & gas development sites, including in Washington, Wyoming, Tioga, Greene, Bradford, and Susquehanna Counties	Generally multiple years up to the present (2016)	Off-site ambient/community locations	Criteria air pollutants including $PM_{2.5}$, NO_2, O_3; VOCs; carbonyls	Continuous sampling for criteria air pollutants; VOC and carbonyl sampling typically every 6 days	1-hour (criteria air pollutants) to 24-hours (VOCs, carbonyls)	Assumed to be all phases
Allegheny County Health Department Deer Lakes and Imperial Pointe Air Monitoring Studies	Allegheny County near NGD activity	2014 to present	Deer Lakes Park and the Imperial Pointe neighborhood	VOCs (Imperial Pointe); VOCs and NO_2 (Deer Lakes)	Once every 6 days (Imperial Pointe) and continuously over 14-day periods (Deer Lakes)	24-hours (VOCs) and 14-days (VOCs, NO_2)	Baseline, construction, drilling, and hydraulic fracturing periods
US EPA Region III (2015) Natural Gas Ambient Air Monitoring Initiative in Southwestern PA	Residential community near the Brigich Compressor Station in Washington County	August to November 2012	Three sites near community residences	$PM_{2.5}$ and VOCs	At least 30 samples per site	24-hours	Compressor station operations (but also nearby well pads, impoundments, gas processing plant)

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ATSDR (2015) Health Consultation for Potential Air Pollutant Exposures at the Brigich Compressor Station	Residential community near the Brigich Compressor Station in Washington County	July to October 2012	Six sites near community residences	Carbonyls, hydrogen sulfide	Continuous sampling for hydrogen sulfide, and sampling every other day for carbonyls during a 3-month period	5-minutes (carbonyls) and 24-hours (hydrogen sulfide)	Compressor station operations (but also nearby well pads, impoundments, gas processing plant)
PADEP (2010, 2011a, 2011b) Short-term Ambient Air Sampling Studies	Multiple locations in southwestern, northeastern, northcentral PA, including a Range Resources well pad site and impoundment in Washington County	April to December 2010	On-site locations at 15 different sites including well pads, compressor stations, impoundments, and condensate tank farms	Criteria air pollutants including CO, NO_2, SO_2, and O_3; VOCs	Continuous sampling for all analytes over a total of 12-13 sampling weeks; also multiple VOC canister samples collected at each site	2-5 minutes (all analytes) to 24-hours (VOC canister samples)	Well completion, flaring, production
Peer-reviewed Published Studies							
Maskrey *et al.* (2016)	Residential community near the Range Resources Chiarelli well pad in Washington County	November 2011 to January 2012	A high school and a private residence	CO, explosive gases, hydrogen sulfide, TVOCs and VOCs	7 samples tested for individual VOCs, and continuous sampling for all other target analytes during a 75-day period	24-hours (individual VOCs) and 1-minute (all other analytes)	Baseline, hydraulic fracturing, flaring, inactive period following flaring

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Study or Dataset	Geographic Study Location(s)	Study Time Period	Air Monitoring Locations	Target Analytes	Frequency of Sampling/Approx. Number of Total Samples	Averaging Time(s) for Reported Pollutant Conc.	Phases of Well Pad Activity with Targeted Air Monitoring Data
Goetz *et al.* (2015)	Sullivan and Bradford Counties in Northeast PA, and several Southwestern PA Counties including Washington County	Summer 2012	At fence lines of multiple NGD sites including production well pads, a well pad with a drill rig, a well pad undergoing a well completion, and compressor stations	NO_2, NO, alkane and non-alkane VOCs, ultrafine and submicrometer particles	Continuous sampling for all analytes over a total of 28 total sampling hours	Seconds to minutes	Production, well drilling, completion (also compressor station operations)
Swarthout *et al.* (2015)	Southwestern PA including Washington County	June 2012	Hundreds of off-site community locations	VOCs	Hundreds of samples over a few day period	2-minutes	Presumably production; possibly other phases
Macey *et al.* (2014)	Susquehanna and Washington Counties	August and September 2013	Off-site locations of "community concern," including nearby to compressor stations and a PIG launching station	VOCs and formaldehyde	Total of 4 VOC samples and 10 formaldehyde samples	VOCs: 2-3 minutes; formaldehyde: 8 hours	None specified
Pekney *et al.* (2014)	Pennsylvania's Allegheny National Forest	Between July 2010 and June 2011	Multiple locations differing in proximity to oil & gas development activities	Criteria air pollutants including $PM_{2.5}$, PM_{10}, NO_2, SO_2, and O_3; VOCs; elemental and organic carbon	Continuous sampling for all analytes over a 7-month period	1-minute to 2-hour	Presumably production; possibly other phases

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Study or Dataset	Geographic Study Location(s)	Study Time Period	Air Monitoring Locations	Target Analytes	Frequency of Sampling/Approx. Number of Total Samples	Averaging Time(s) for Reported Pollutant Conc.	Phases of Well Pad Activity with Targeted Air Monitoring Data
Other Commissioned Studies							
WVU Air Noise, and Light Monitoring Study (McCawley, 2013; Pekney *et al.*, 2016)	Three West Virginia Counties (Brooke, Marion, Wetzel)	July to November 2012	~250 to 1,300 feet from well pad centers at seven NGD sites	Criteria air pollutants including $PM_{2.5}$, PM_{10}, NO_2, SO_2, and O_3; VOCs	Continuous sampling for all analytes for 1 to 4 weeks per site; also, multiple VOC canister samples taken at each site	1-minute to 3-days	Well pad construction, vertical drilling, horizontal drilling, hydraulic fracturing, and flowback/ completion
US DOE NETL Greene County Well Pad Monitoring Study (Pekney *et al.*, 2013; Hammack, 2015)	Greene County, Pennsylvania	March to June 2012	On a Greene County well pad	Criteria air pollutants including $PM_{2.5}$, PM_{10}, NO_2, SO_2, and O_3; VOCs; elemental and organic carbon; ammonia	Continuous sampling for all analytes over a 3.5-month period	1-minute to 2-hour	Hydraulic fracturing (two different periods of 3 wells at a time); periods of no to low well pad activity
TechLaw (2012) Air Quality Measurements at Sky View Elementary School	Morgantown, West Virginia	August to October 2011	Six sites at Sky View Elementary School	VOCs, aldehydes, and hydrogen sulfide	At least one VOC sample per site during 3 sampling periods, and one aldehyde sample and 4-8 hydrogen sulfide samples per site for 2 sampling periods	Instantaneous (hydrogen sulfide) and 24-hours (aldehydes, VOCs)	Baseline and well completion (specifically hydraulic fracturing)

4.1 Regulatory Agency Monitoring Programs and Studies

4.1.1 PADEP Continuous $PM_{2.5}$ Monitoring Data for Oil and Gas Areas

The Pennsylvania Department of Environmental Protection (PADEP) manages an extensive network of ambient air monitors across 39 counties (PADEP, 2016).[6] In response to the widespread growth of natural gas extraction in the Marcellus Shale, PADEP is expanding its monitoring in the shale gas regions of the state, including adding 10 $PM_{2.5}$ monitors (PADEP, 2016). With the expansion, PADEP will manage 37 $PM_{2.5}$ monitoring sites throughout the state. The first phase of this expansion is now complete, with the 2016 addition of the Towanda and Holbrook monitors in Bradford and Greene counties, respectively. PADEP will install new monitors in Fayette, Indiana, Lycoming, Susquehanna, and Wyoming counties by the end of 2016, and in 2017, PADEP expects to install the remaining proposed $PM_{2.5}$ monitors in Clarion, Jefferson, and McKean counties. Figure 4.1 below shows the locations of these new and proposed PADEP $PM_{2.5}$ monitors.

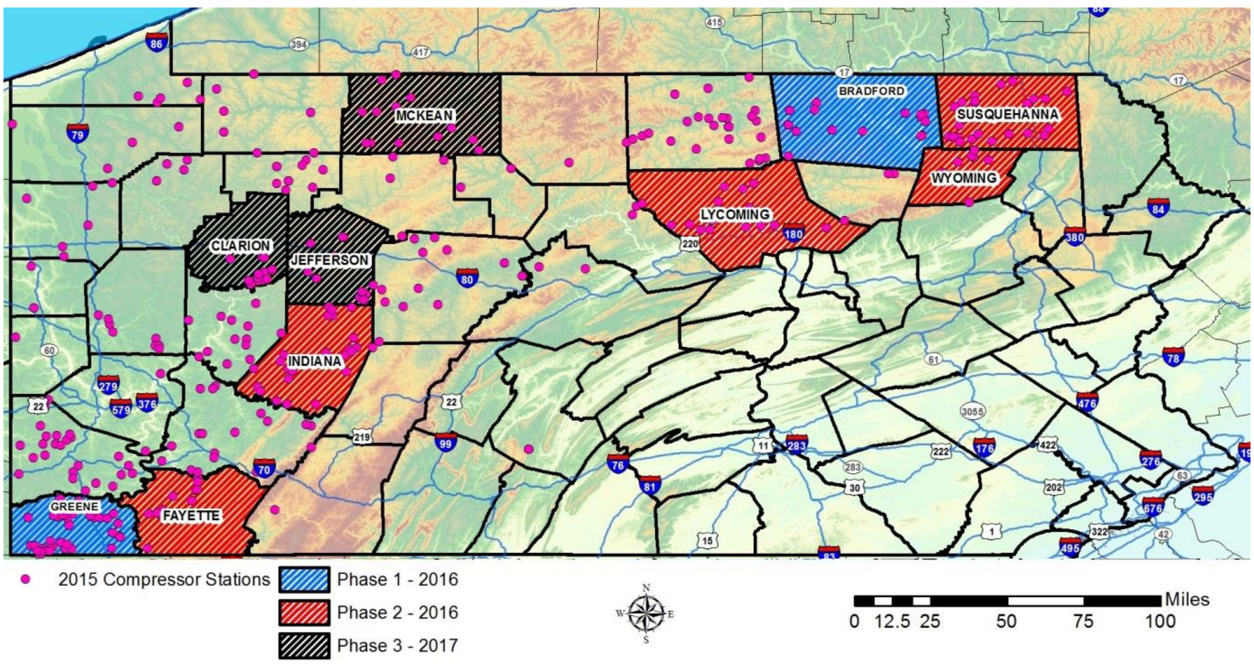

Figure 4.1 Locations of New and Proposed PADEP $PM_{2.5}$ Monitors. Source: PADEP (2016).

Figure 4.2 shows hourly $PM_{2.5}$ measurements from the Holbrook (Greene County) and Towanda (Bradford County) monitors, which were installed in early 2016 to measure any air quality impacts of emissions from shale gas activities. This figure also shows one year of recent data from the Tioga County monitor, which is located just west of Bradford county, as an example of a longer-term record of $PM_{2.5}$ measurements in a shale gas area. In comparison, Figure 4.3 shows $PM_{2.5}$ data from two monitors outside of the region of extensive shale gas activity. Specifically, this figure shows measurements from the Arendtsville (Adams County) and Carlisle (Cumberland County) monitors, which are located in the southeastern quadrant of the state. The Arendtsville monitor is an example of a site measuring

[6] In addition to the PADEP-operated air quality monitors, there are additional monitors in Pennsylvania that are operated by the Allegheny County Health Department (ACHD) and the City of Philadelphia Health Department's Air Management Services (AMS) within their own jurisdictions, as well as several Clean Air Status and Trends Network (CASTNET) monitors operated by US EPA within the state.

background $PM_{2.5}$ (*i.e.*, $PM_{2.5}$ concentrations in an area without major emission sources) and the Carlisle monitor is an example of a monitor focused on $PM_{2.5}$ exposure within an urban neighborhood. These plots show similar hour-to-hour variation in $PM_{2.5}$ levels, including slightly higher peak and average $PM_{2.5}$ levels for the monitors in the two non-shale gas areas. Overall, Figures 4.2 and 4.3 show no discernible differences in $PM_{2.5}$ levels between shale gas areas and non-shale gas areas in Pennsylvania.

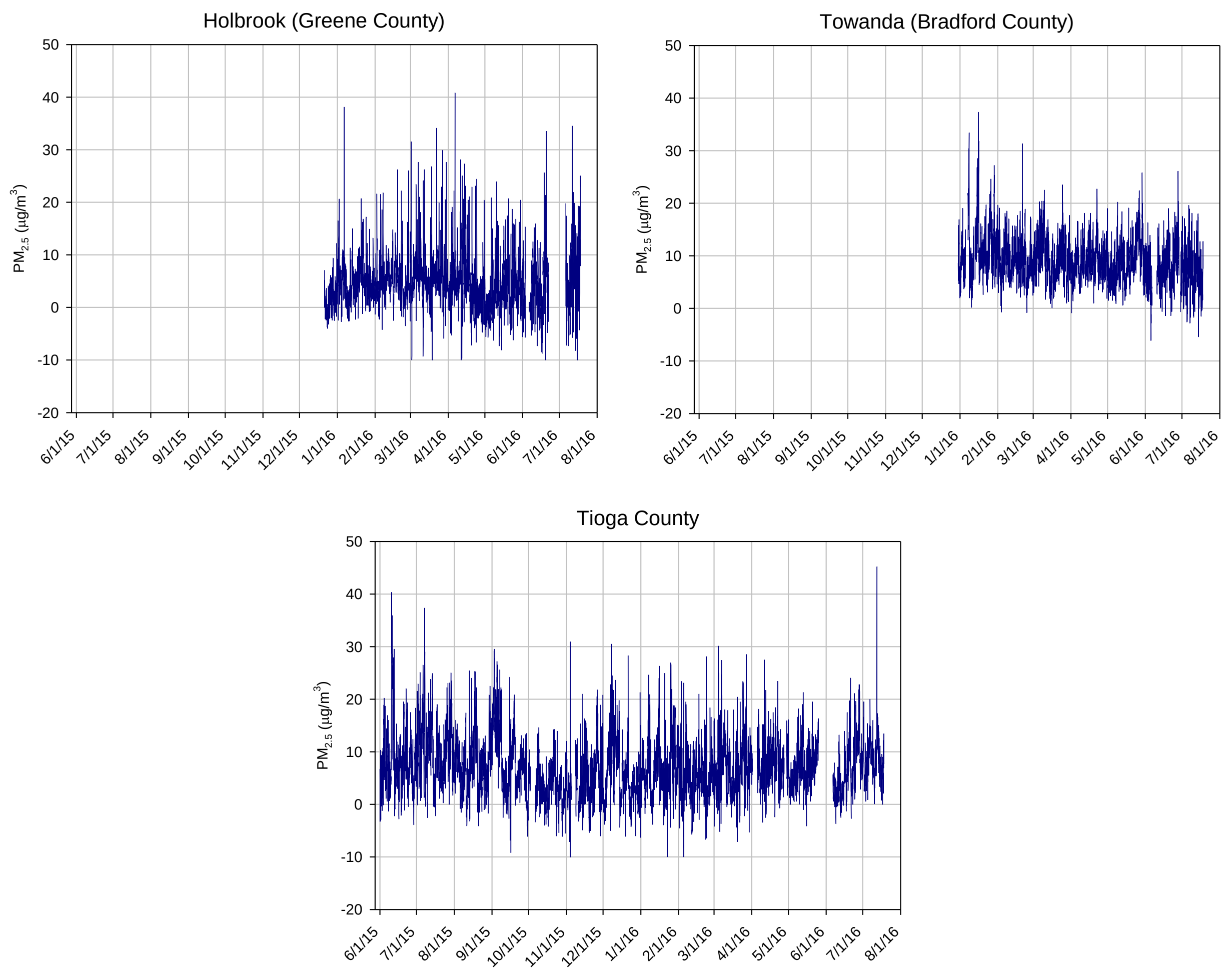

Figure 4.2 Hourly $PM_{2.5}$ Concentrations at the Holbrook, Towanda, and Tioga County Monitors in Shale Gas Areas. Source: PADEP (2015-2016).

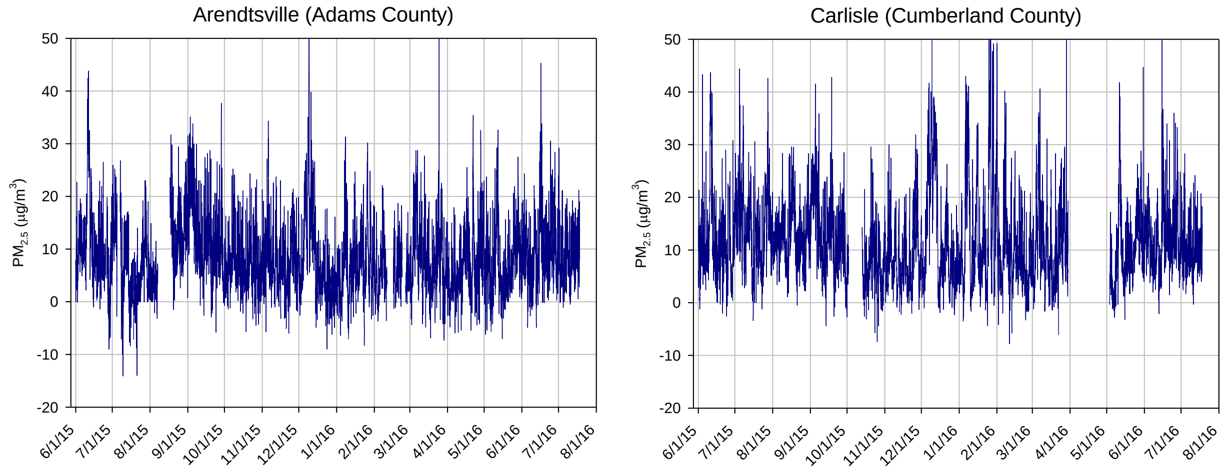

Figure 4.3. Hourly $PM_{2.5}$ Concentrations at the Arendtsville and Carlisle Monitors Located Outside of Shale Gas Areas. Source: PADEP (2015-2016).

4.1.2 PADEP NO_2 Monitoring Data for Oil and Gas Areas

Data from PADEP air quality monitors also provide insights on NO_2 air quality impacts from oil and gas-related emission sources. More than three years of hourly NO_2 data are now available for three PADEP monitors classified by PADEP as being nearby to natural gas production and/or processing facilities, namely the Houston, Tioga County, and Towanda monitors. Figure 4.4 below shows no exceedances of the US EPA 1-hour NO_2 NAAQS of 100 ppb for the most recent three years of data available for these monitors, with most hours having NO_2 concentrations that are a small fraction of the NAAQS. Despite a high density of production wells and the presence of other gas-related NO_2 sources (*e.g.*, the Markwest Houston gas processing facility nearby to the Houston monitor), these data thus indicate a lack of NO_2 concentrations of public health concern in these areas from natural gas development activities.

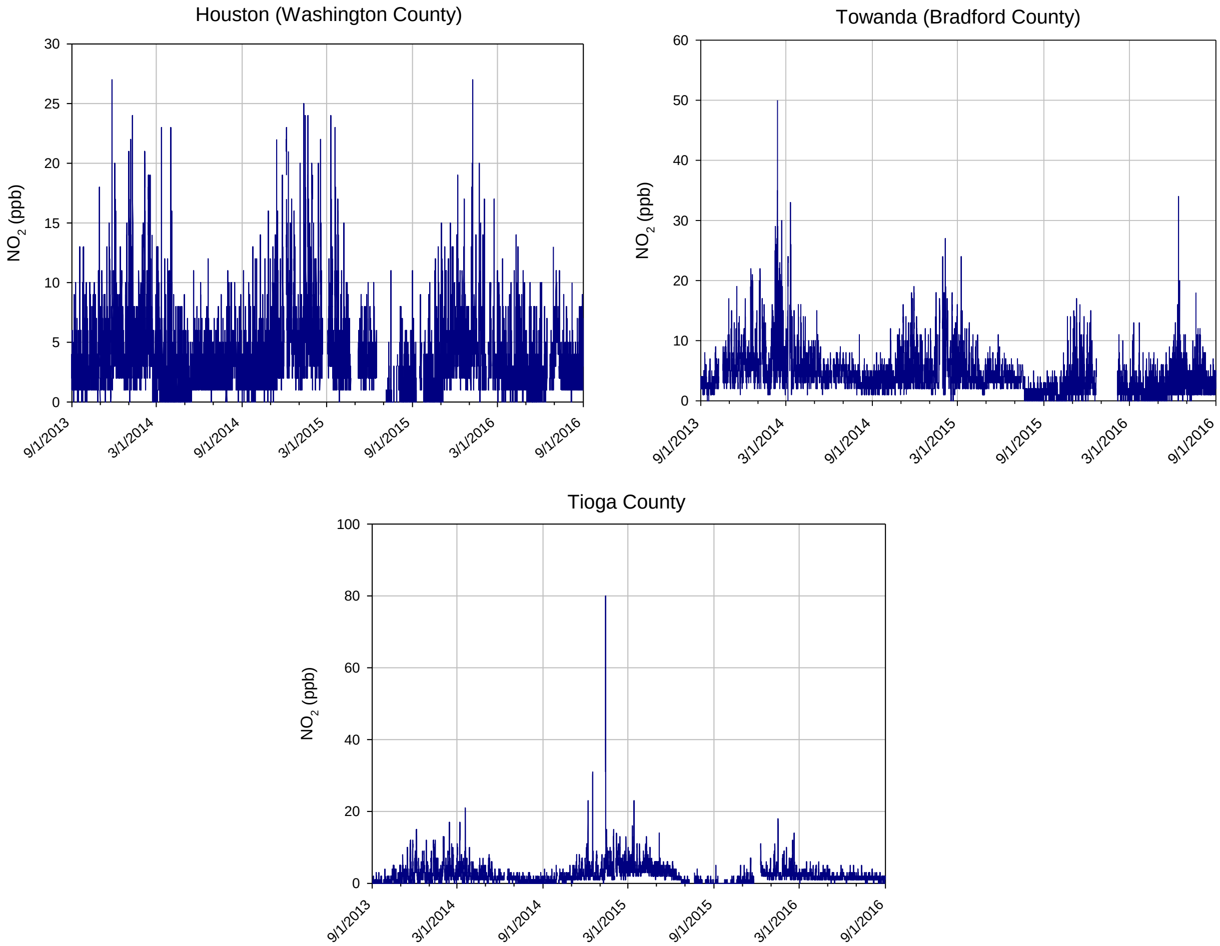

Figure 4.4. Hourly NO_2 Concentrations at the Houston, Towanda, and Tioga County Monitors in Shale Gas Areas. Source: PADEP (2013-2016).

4.1.3 PADEP Air Toxics Monitoring Data

PADEP maintains an extensive statewide network of air toxics monitors, including several monitors in locations considered by the state to be potentially impacted by NGD activities. Air toxics monitors in areas with extensive NGD activities include the Houston, Mehoopany, and Springville monitors in Washington, Wyoming, and Susquehanna Counties, respectively. An extensive list of volatile organic compounds (VOCs) as well as carbonyl compounds (*e.g.*, formaldehyde, acetaldehyde) are measured at each of these locations, although only VOC data are currently available on the PADEP website.[7] Figure 4.5 below compares measured benzene concentrations at these sites from the most recent data available on the PADEP website with data available for three other air toxics monitoring sites in areas without oil and gas development activities that are considered to represent either rural or urban background sites. This figure shows that benzene concentrations measured at the Houston, Mehoopany, and Springville monitors are similar to concentrations measured at rural and urban background sites in counties without extensive oil and gas development activities. This figure also contains the US EPA risk-based regional screening level (RSL) concentration for residential air of 0.11 ppb (0.36 $\mu g/m^3$) for

[7] http://www.dep.pa.gov/Business/Air/BAQ/MonitoringTopics/ToxicPollutants/Pages/Toxic-Monitoring-Sites-in-Pennsylvania.aspx

benzene in residential air that is based on 1 in a million excess lifetime cancer risk, showing that ambient air benzene concentrations at all of these monitoring locations, including the monitors in rural or urban background areas without extensive oil and gas-related activities, routinely exceed this concentration. As discussed more in Section 4.3.1, benzene is a ubiquitous pollutant in both indoor and outdoor air due to a number of common sources that include vehicle exhaust, gasoline vapors, tobacco smoke, wood smoke, and household products (glues, paints, adhesives, lubricants).

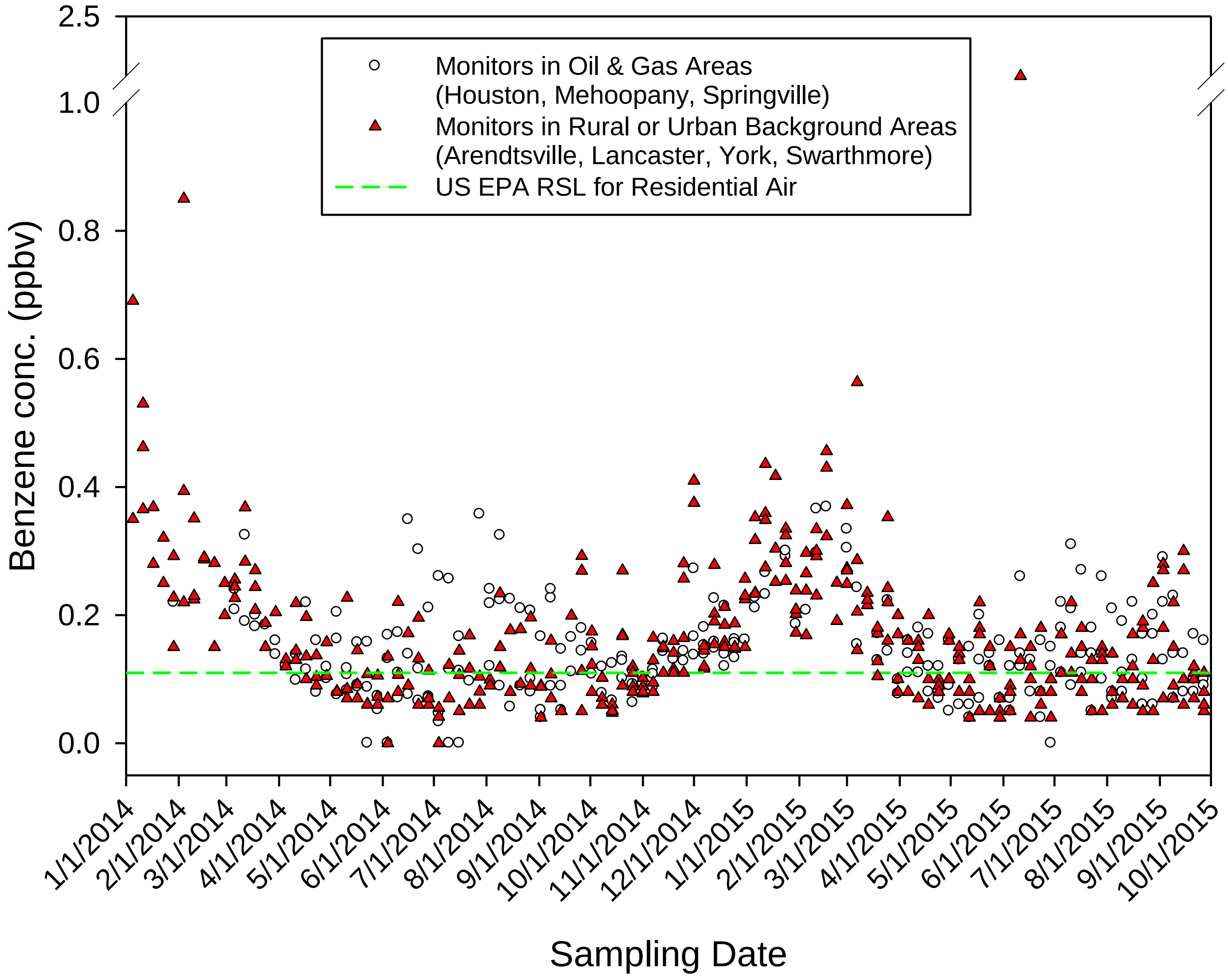

Figure 4.5 24-hour Ambient Benzene Concentrations for PADEP Monitors in Oil and Gas Development Areas *versus* in Urban and Rural Background Areas without Oil and Gas Development Activities. Data available from the PADEP website between the years 2013 to 2015 are shown, including data for the time period 5/2014 to 9/2015 for the Houston monitor, 2/2013 to 9/2015 for the Springville monitor, and 3/14 to 9/15 for the Mehoopany monitor. Samples are generally collected over 24-hour periods once every six days.

4.1.4 Allegheny County Health Department (ACHD) Deer Lakes and Imperial Pointe Air Monitoring Studies

The Allegheny County Health Department (ACHD) established the Imperial Pointe and Deer Lakes air monitors in 2014 to specifically measure the community-level air quality impacts of local unconventional natural gas well activity (ACHD, 2015). The Imperial Pointe monitor is located within a neighborhood, and the Deer Lakes monitor is located in a county park that is "heavily utilized by the local community" (ACHD, 2015). Monitoring began at Imperial Pointe in March 2014, and at Deer Lakes Park in June 2014; although described by ACHD as temporary monitoring sites, both sites remain active air monitoring sites at this time. At both sites, measurements have been made during baseline periods (*i.e.*, the time period immediately preceding construction and drilling activities), and also during three well pad activity periods (construction, drilling, and hydraulic fracturing periods). Figure 4.6 shows the locations of the two monitors in relation to local well pads.

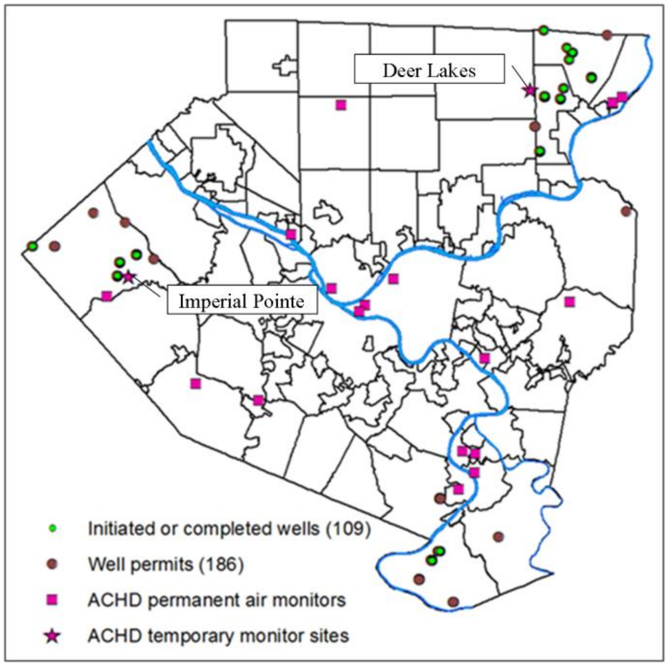

Figure 4.6 Locations of Imperial Pointe and Deer Lakes Air Monitors (pink stars) Relative to Unconventional Natural Gas Well Activity in Allegheny County.
Source: http://www.achd.net/shale/.

ACHD has collected 24-hour VOC canister samples every six days at the Imperial Pointe site since March 2014. Based on the available data from March 2014 to September 2016 (ACHD, 2016a)[8], 16 compounds have been detected on at least one occasion during the baseline, construction, drilling, and/or hydraulic fracturing periods, and a further 20 compounds have been tentatively identified on at least one occasion. Eight of the 16 detected compounds have been reported for all four periods: acetone, 2-butanone, chloromethane, dichlorodifluoromethane, ethanol, ethyl acetate, isopropyl alcohol, and toluene. The average concentrations of these eight compounds during the well pad activity periods are similar to the average concentrations during the baseline period. Of the additional eight detected compounds, most were detected infrequently during the well pad activity periods at very low concentrations (*e.g.*, less than or around 1 ppb). More specifically, m,p-xylenes was detected once during the site construction period; 1,4-dioxane, chlorobenzene, and 1,4-dichlorobenzene were detected once during the hydraulic fracturing period; methylene chloride was detected once during both the drilling and hydraulic fracturing periods; benzene was detected once during each of the well pad activity periods (site construction, drilling, and hydraulic fracturing); hexane was detected twice during both the drilling and hydraulic fracturing periods; and tetrachloroethene was detected once during the hydraulic fracturing period and in approximately one-third of the construction period samples.

[8] Data for both the Imperial Pointe and Deer Lakes sites are available on the ADHD website: http://www.achd.net/shale/

Since June 2014, ACHD has collected 14-day passive air monitoring samples at the Deer Lakes site for analysis of eight VOCs and nitrogen dioxide, again for time periods classified as either baseline, construction, drilling, and/or hydraulic fracturing periods. Based on the available data from June 2014 to October 2016 (ACHD, 2016b), benzene, toluene, m,p-xylenes, n-hexane, and nitrogen dioxide have been detected. Air samples were only collected for nitrogen dioxide measurement during the baseline period, and this gas was detected in about 60% of the baseline samples. Benzene and toluene have been detected during both the baseline and well pad activity periods, and the average concentrations of benzene and toluene measured during the construction, drilling, and hydraulic fracturing periods are equal to or less than the concentrations measured during the baseline period. The remaining two compounds have been detected infrequently, with m,p-xylenes detected once and n-hexane detected twice during the drilling period. Overall, both the Imperial Pointe and Deer Lakes data collected to date show no evidence of consistent elevations in VOC concentrations as compared to the baseline data, and no concentrations of health concern.

4.1.5 PADEP Short-Term Ambient Air Sampling Studies

Between 2010 and 2011, PADEP conducted three short-term ambient air sampling studies in several regions of Pennsylvania having extensive Marcellus Shale gas operations, including a study in southwestern Pennsylvania from April to July 2010 (PADEP, 2010), a study in northeastern Pennsylvania from August to October 2010 (PADEP, 2011a), and a study in northcentral Pennsylvania from August to December 2010 (PADEP, 2011b). While described as short-term, screening-level air quality sampling studies, these studies together total over 15,000 sampling hours across 12-13 sampling weeks and 15 different NGD sites. The sampled NGD sites include six different compressor stations; six different well sites (including two with completed wells, one with a well undergoing active hydraulic fracturing, one with a recently fractured well during flowback water production, one with a well being flared, and one with an active wastewater impoundment); and one condensate tank farm. Range Resources' Yeager Impoundment (and nearby well pad) was among the sites included in the PADEP (2010) study. In addition, each study included air sampling at background sites considered to be more remote and less impacted by NGD activities.

PADEP used an extensive array of state-of-the-art sampling equipment and instrumentation to measure ground-level air concentrations of several US EPA criteria air pollutants (CO, NO_2, SO_2, and O_3) and ~ 60 VOCs, including the principal natural gas constituents (*e.g.*, methane, ethane, propane, butane) and a number of VOCs that can pose potential health risks at elevated exposure levels (*e.g.*, H_2S, benzene, toluene). VOCs were measured for both 2 to 5 minute air samples, as well as 24-hour air samples, using three different measurement techniques (field Gas Chromatography/Mass Spectrometry [GC/MS], Open Path Fourier Transform Infrared [OP-FTIR] instruments, and canister air samples).

Higher air concentrations of the principal natural gas constituents (*e.g.*, methane, ethane, propane, butane) were generally detected at the various NGD sites as compared to the background sites, but not at levels considered to constitute a public health hazard. Other VOCs (*e.g.*, benzene, ethylbenzene, toluene, 2-hexanone, acetone, n-heptane, propene) were also detected at some of the NGD sites, albeit either at low concentrations or for brief sample durations not considered to be of significant health concern. Sampling for criteria air pollutants revealed no exceedances of the US EPA NAAQS for CO, NO_2, SO_2, and O_3. As a result, each of the three PADEP reports reached similar conclusions regarding the lack of significant health risks posed by the measured air exposure levels (whether from NGD or other sources) to the general public: "In conducting the short-term, screening-level air quality sampling initiative in the southwest, northeast, and northcentral areas of the Commonwealth where a majority of the Marcellus

Shale gas is being extracted, the PADEP has not found an immediate health risk to the general public" (PADEP, 2011b).

4.1.6 US EPA/ATSDR Studies of Air Quality Nearby to the Brigich Compressor Station in Washington County

US EPA Region III assessed air concentrations of pollutants near the Brigich Compressor Station as part of the National Gas Ambient Air Monitoring Initiative (NGAAMI) in Southwestern Pennsylvania (US EPA Region III, 2015). The Brigich Compressor Station, located in Washington County, Pennsylvania, was selected for a number of reasons including that it is located close to homes, it is a large facility that has five compressors and three condensate tanks, and it is located in a region of Pennsylvania that has "wet" gas extraction. "Dry" natural gas is almost completely composed of methane, whereas "wet" natural gas contains a greater percentage of liquid natural gases like ethane and butane. While this investigation was focused on the Brigich Compressor Station, a number of other natural gas-related sites were also located within a mile of this community, including three impoundments, seven or more well pads, and another compressor station; in addition, the Houston Gas processing plant is approximately 2 miles from the Brigich Compressor Station (ATSDR, 2016).

US EPA measured air concentrations of VOCs and fine particulate matter ($PM_{2.5}$) at three residences near the compressor station, as well as at one background site (*i.e.*, a site that is not impacted by emissions from the compressor station). US EPA collected measurements of VOCs and $PM_{2.5}$ one out of every three days from August 4 to November 28, 2012. Sampling canisters were used to collect 24-hour air samples, which were analyzed for individual VOCs. US EPA also collected 24-hour filter samples using an Airmetrics MiniVol™ TAS to measure $PM_{2.5}$ air concentrations.

US EPA concluded that the measured concentrations of $PM_{2.5}$ and VOCs were not at levels of health concern. The $PM_{2.5}$ measurements were compared to the National Ambient Air Quality Standards (NAAQS), which are federal standards established by US EPA for six criteria air pollutants including $PM_{2.5}$ that are protective of human health and public welfare.[9] The 24-hour measurements of $PM_{2.5}$ ranged from 1.0-26.5 $\mu g/m^3$, all of which are below the current 24-hour $PM_{2.5}$ NAAQS of 35 $\mu g/m^3$. US EPA compared the measured VOC concentrations with thresholds US EPA developed in a study of air quality at schools (US EPA, 2009); these conservative thresholds define the upper limit of air pollutant concentrations for which there is minimal risk to human health. US EPA found that all of the measured VOC concentrations were below the thresholds, although the average measured concentration of one VOC, 1,2-dichloroethane, was approximately equal to the threshold. In addition, US EPA compared the measured VOC concentrations to a second set of health benchmarks, the Agency for Toxic Substances and Disease Registry (ATSDR) Cancer Risk Evaluation Guides (CREGs), which are considered to be more conservative (*i.e.*, health-protective) benchmarks than the thresholds from US EPA's schools study (US EPA Region III, 2015)[10]. This comparison showed that the average measured concentrations of four VOCs—1,2-dichloroethane, chloroform, benzene, and methylene chloride—exceeded the CREGs. Overall, given the conservative nature of the benchmarks and the degree of benchmark exceedances, US

[9] Counties, territories, and other areas in the US are evaluated for attainment (*i.e.*, compliance) with the NAAQS through a complex assessment involving several factors (indicator, averaging time, level and form) and only using data from specific air quality monitors. However, in public health evaluations of criteria air pollutant concentrations, it is common practice to compare measured air quality data from any monitor with the level of the health-protective NAAQS (*i.e.*, the concentration that represents the upper limit of the pollutant that is allowable in the air), provided that the averaging time (*e.g.*, 24-hour averages, annual averages) is consistent between the monitored data and the NAAQS.

[10] As defined by ATSDR, CREGs are based on a stringent cancer risk limit of 1 in a million, which is the lower limit of US EPA's acceptable lifetime excess cancer risk range of 1 in a million to 1 in ten thousand. In contrast, the cancer-based thresholds from the US EPA schools study were based on a cancer risk limit of 1 in ten thousand, or the upper end of US EPA's acceptable lifetime excess risk range.

EPA Region III concluded that, "the ambient concentrations near the Brigich Compressor Station in Washington County, PA did not indicate impacts of potential concern" (US EPA Region III, 2015).

In parallel with the US EPA Region III investigators, the US Department of Health and Human Services Agency for Toxic Substances and Disease Registry (ATSDR) evaluated the potential health impacts to the residential community surrounding the Brigich Compressor Station in response to health complaints from nearby residents (ATSDR, 2016). The evaluation was separate from the US EPA Region III evaluation described above, but the agencies collaborated on pollutant measurements and the ATSDR study incorporated the measurements collected by US EPA Region III. ATSDR identified 78 homes within one mile of the Brigich Compressor Station and 30 homes within 0.5 miles of the station.

ATSDR used industry-standard sampling equipment and methods to measure carbonyls, hydrogen sulfide, and reduced sulfur compounds at six sites near the Brigich Compressor Station. All six sites were located at or near residences and were within 0.65 miles of the compressor station, and three of the sites were the same as used by US EPA Region III for their concurrent measurements of $PM_{2.5}$ and VOCs. ATSDR also measured pollutants at a background site (*i.e.*, a site not impacted by emissions from the compressor station) located in Florence, Pennsylvania. ATSDR performed two phases of measurements: Phase 1 from July 7-August 7, 2012 and Phase 2 from August 11-October 10, 2012. In Phase 1, 24-hour concentrations of carbonyls were measured every other day at five sites, and continuous, 5-minute hydrogen sulfide concentrations were measured at all six sites. In Phase 2, continuous, 5-minute hydrogen sulfide concentrations were measured at all six sites. Reduced sulfur compounds and carbonyls were also measured during Phase 2, but issues with the weather conditions during this phase (*i.e.*, rain and high humidity) hindered the proper collection and laboratory analysis of the air samples. As described above, US EPA Region III measured 24-hour average $PM_{2.5}$ and VOCs at three sites during August 4-November 28, 2012.

ATSDR first compared the measured pollutant concentrations to conservative screening level benchmarks to identify which pollutants should be included in a further evaluation of residential community exposures. The source of the health-based benchmarks varied by pollutant, and the set of benchmarks included ATSDR Cancer Risk Evaluation Guides (CREGs) and Chronic Minimum Risk Levels (MRLs), Texas Commission on Environmental Quality (TCEQ) long-term Effects Screen Levels (ESLs), US EPA Reference Concentrations (RfCs), and the levels of the 24-hour and annual average $PM_{2.5}$ National Ambient Air Quality Standards (NAAQS). With the exception of the 24-hour $PM_{2.5}$ NAAQS, each of these health-based benchmarks are intended to be protective of a lifetime of exposure.

Based on the screening-level assessment, ATSDR chose to complete a further assessment of 12 "constituents of potential concern": hydrogen sulfide, $PM_{2.5}$, the six VOCs and three carbonyls, and glutaraldehyde. This further assessment focused on calculation of the risks of developing cancer and of experiencing other non-cancer health impacts.

For the nine VOCs and the three carbonyl compounds, exposure concentrations were found to be below non-cancer health effect levels and estimated excess lifetime cancer risks (ELCRs) were below or within US EPA's acceptable lifetime excess cancer risk range of 1 in 1 million to 1 in ten thousand. Based on these findings, ATSDR concluded, "Exposure to the detected levels of chemicals in the ambient air from residences surrounding Brigich compressor is not expected to harm the health of the general population." ATSDR cited data limitations for both $PM_{2.5}$ and glutaraldehyde:

- Although there were no exceedances of the 24-hour $PM_{2.5}$ NAAQS, there was insufficient data- *i.e.*, less than a year- to compare to the annual average $PM_{2.5}$ NAAQS.

- All 24-hour glutaraldehyde concentrations were less than levels known to cause adverse health effects for chronic exposures, but ATSDR pointed to the absence of short-term data (*i.e.*, for sampling periods of less than 24 hours) that could be used to determine whether there were any peak exposure levels that could cause adverse health effects in sensitive individuals.

Regarding hydrogen sulfide, ATSDR determined average concentrations for each of the six sampling locations that ranged from 0.53 to 0.85 ppb over the two phases of sampling and were thus below the US EPA reference concentration of 1.4 ppb, supporting a lack of health risk from chronic exposures. For averaging times matching the ATSDR MRLs, hydrogen sulfide concentrations also did not exceed the acute and intermediate MRLs of 70 and 20 ppb, respectively. However, citing the occurrence of ten occasions at two of the sampling sites located approximately 0.3 and 0.35 miles from the compressor station when hydrogen sulfide concentrations exceeded 20 ppb for 30 minutes or more, ATSDR concluded that short-term peak concentrations have the potential to irritate sensitive individuals due to objectionable odor or to exacerbate pre-existing respiratory conditions.[11]

4.2 Peer-reviewed Published Studies

4.2.1 Maskrey *et al*. (2016) Study of Chiarelli Well Pad Air Quality Impacts at the Fort Cherry School District

In 2011, the Cardno ChemRisk consulting firm was hired by the Fort Cherry School District board to evaluate the impacts of hydraulic fracturing at the Chiarelli well pad in Mount Pleasant Township on local air quality, and the results of this evaluation were published in a peer-reviewed journal article (Maskrey *et al*., 2016). This study focused on approximately three months of air measurements collected at the following two sites: the local high school, which is located 863 meters (~2,800 feet) south of the well pad, and a private residence located 774 meters (~2,500 feet) east-southeast of the well pad. Wind direction data collected at the two sites showed that the high school was generally upwind of the well pad and the private residence was generally downwind of the well pad. The study included measurements during four phases of operations: 1) a baseline period before the hydraulic fracturing commenced (16 days), 2) the hydraulic fracturing period (28 days), 3) the flaring period (10 days), and 4) an inactive period following flaring (21 days).

Cardno ChemRisk used industry-standard sampling equipment to measure air quality at a height approximating the breathing zone of a person. During each of the four operating periods, they conducted continuous air sampling for carbon monoxide, explosive gases (including methane), hydrogen sulfide, and total volatile organic compounds (TVOCs), which is the combined measurement of a wide variety of VOCs in the air. The continuous air sampling instruments (one MultiRAE Plus and one ppbRAE instrument) collected 1-minute data points, which were converted to 24-hour daily averages by the study authors. Cardno ChemRisk also collected 24-hour canister air samples on seven days during the study period for analysis of 62 individual VOCs. At the high school, the 24-hour canister air samples were collected during all four operating periods, and at the private residence, these samples were collected during the baseline, hydraulic fracturing, and flaring periods.

The TVOC and individual VOC measurements showed that there was little difference between the air concentrations of VOCs during well pad operations (*i.e.*, hydraulic fracturing and flaring periods), as compared to periods of no activity (*i.e.*, baseline and post-flaring periods). At the high school, which was located in a generally upwind direction from the well pad, there were actually lower concentrations of TVOCs measured during hydraulic fracturing and flaring operations than during periods of no activity.

[11] Note that these short-term H_2S events make up less than 0.5% of the total H_2S sampling data.

The individual VOC air concentrations at the high school were similar during the activity and non-activity periods, further demonstrating that the well pad did not contribute to elevated VOCs at the high school during the hydraulic fracturing and flaring operations. At the private residence, which is located in a generally downwind direction from the well pad, the TVOC concentrations during hydraulic fracturing were slightly higher than during the non-activity periods (*i.e.*, baseline and post-flaring periods), and the concentrations during flaring were lower than during non-activity periods. Individual VOC air concentrations at the private residence were similar during all four operating periods. Overall, at both sites, there was no statistically significant difference between the measurements of TVOCs or individual VOCs between well pad operations (i.e., hydraulic fracturing and flaring periods) and periods of no activity (*i.e.*, baseline and post-flaring periods), indicating that there was no discernible impact from the well pad operations on the air quality at the school or the private residence. In addition, the individual VOC measurements at the two sites were compared to VOC measurements at two background sites in Washington County (the Florence and Charleroi PADEP monitoring sites), which have air concentrations of VOCs representative of locations without large sources of VOC emissions. This comparison showed that the VOC concentrations at the high school and the private residence were similar to background VOC concentrations except that the high school, which is generally upwind of the well pad, had higher concentrations of four VOCs (2-propanol, trichlorofluoromethane [Freon 11], toluene, methylene chloride) than the background sites during some operating periods.

While the 1-minute TVOC measurements were not evaluated by Maskrey *et al*. (2016), the supplementary material for that publication contains a plot of the average 1-minute TVOC concentrations during each hour of the day at each site during the four operating periods, and ChemRisk (2012) lists daily average, minimum, and maximum TVOC concentrations. Table 4.2 summarizes the 1-minute TVOC concentration statistics that are reported in ChemRisk (2012).

Table 4.2 Statistics for 1-minute TVOC Concentrations at the Fort Cherry High School

Operating Period	Average (ppb)	Minimum (ppb)	Maximum (ppb)
Baseline	107	0	483
Hydraulic fracturing	7.3	0	56
Flaring	4.6	0	42*

Notes:

ppb = parts per billion

Data are from the ppbRAE instrument; the MultiRAE instrument data are not shown because the instrument is not designed to measure low concentrations of VOCs and the data are considered to be less reliable than the ppbRAE data (ChemRisk, 2012).

* In ChemRisk (2012), the maximum TVOC concentration is reported as both 0.42 ppm (420 ppb) and 0.042 ppm (42 ppb). 42 ppb is reported here because it is the statistic shown in the supplementary table detailing all of the daily statistics (Table 2b), and appears to be the accurate statistic based on these daily statistics.

These 1-minute measurements show that the TVOC concentrations during the hydraulic fracturing and flaring periods were significantly lower than the concentrations measured during the baseline period. This indicates that during the days on which measurements were collected, well pad operations did not contribute to peak TVOC concentrations that exceeded background TVOC concentrations. In their evaluation of the 1-minute measurements, the study investigators (ChemRisk, 2012) stated that, "At no point during any of the three sampling periods did a total VOC measurement approach the action level of 20 ppm" (20,000 ppb).

The study also addressed the potential health risks posed by the individual VOC concentrations at the high school and the private residence by comparing the measured VOC concentrations with US EPA's Regional Screening Levels (RSLs). RSLs, which were available for 13 of the 15 individual VOCs detected in the air at the high school and private residence, are conservative health-based benchmarks that are generally used to screen for whether a more detailed exposure or risk assessment needs to be conducted for a specific chemical. None of the VOC concentrations measured at either the high school or the private residence exceeded the RSLs, and therefore Cardno ChemRisk concluded that there was no measurable health impact from the well pad at either site.

The measurements of hydrogen sulfide and explosive gases are not discussed by Maskrey *et al*. (2016), but the results for the high school site are presented in ChemRisk (2012). Explosive gases (*e.g.*, methane) were not detected at the high school during hydraulic fracturing or flaring activities. The instrument used to measure hydrogen sulfide was not designed to measure the low concentrations that were detected at the high school, and therefore the accuracy of the measured concentrations is not known. All of the 1-minute hydrogen sulfide measurements during the baseline, hydraulic fracturing, and flaring periods were less than the instrument's 1 ppm resolution, meaning that it is only possible to conclude that 1-minute concentrations during the baseline, hydraulic fracturing, and flaring periods were always between 0 and 1 ppm.

4.2.2 Goetz *et al*. (2015) Tracer Release Study

Goetz *et al*. (2015) conducted a series of fenceline tracer release experiments in order to characterize air pollutant emission rates at several types of NGD sites (production well pads, well pad with drill rig, a well completion, and several compressor stations) in two regions of Pennsylvania within the Marcellus Shale Region (Northeast PA centering on Sullivan and Bradford Counties, and Southwestern PA including Washington County). Goetz *et al*. (2015) did not identify the specific names and operators of the sites included in the study. For the well pad sites included in the study (*e.g.*, production well pads numbering 7 to 9 wells, well drilling, and well completion sites), Goetz *et al.* (2015) reported average downwind sampling distances of 560 to 890 meters (approximately 1,800 to 2,900 feet). As part of their study, Goetz *et al*. (2015) employed a comprehensive set of real-time, sensitive instrumentation for measurement of short-term concentrations of criteria air pollutants, alkane and non-alkane VOCs, and both ultrafine and submicrometer particles.

In total, Goetz *et al*. (2015) made fenceline air measurements for 17 short-term (~1 to 3 hours each) tracer release experiments at 13 separate sites, concluding that "In contrast to observations from other shale plays, elevated volatile organic compounds, other than CH_4 [methane] and C_2H_6 [ethane], were generally not observed at the investigated sites." The authors specifically noted the absence of elevated concentrations of light aromatics (*e.g.*, benzene, toluene) at any of the sampling sites. Goetz *et al*. (2015) further observed that "Elevated submicrometer particle mass concentrations were also generally not observed." Some transient elevations in ultrafine particle concentrations were observed downwind of most compressor and transient activity well sites (*e.g.*, drill site and completion), which the authors attributed to natural gas combustion. Acknowledging the small time duration and the limited spatial coverage of their measurements, Goetz *et al*. (2015) concluded that "the extent to which the results can be generalized to the Marcellus basin as a whole remains uncertain."

4.2.3 Swarthout *et al*. (2015) Regional Air Measurement Study

Similar to the Goetz *et al*. (2015) study, the primary objective of the Swarthout *et al*. (2015) study was to estimate emission rates of methane and volatile organic compounds in the Marcellus Shale region rather than to measure air concentrations for assessing human exposure levels. As part of this effort, Swarthout *et al*. (2015) conducted a regional air measurement campaign over a three-day period (June 16-18, 2012) in the southwestern Pennsylvania region of the Marcellus Shale region. Grab air samples were collected over 2-minute periods twice during this time period throughout an 8050 km^2 area surrounding Pittsburgh, PA, which presumably includes parts of Washington County; in addition, a mobile laboratory was deployed at two sites, one remote from natural gas development activities and a second site with 294 unconventional natural gas wells within 10 km. This sampling design thus emphasized detailed spatial coverage, but little temporal coverage.

As discussed by Swarthout *et al*. (2015), they observed higher concentrations of VOCs such as benzene, ethane, and ethyne along the urban corridor extending from Pittsburgh to the northwest and lower concentrations near unconventional natural gas (UNG) wells. They hypothesized that these higher concentrations were associated with combustion and urban emissions rather than NGD-related emissions. Higher concentrations of C_2-C_8 alkanes were observed in areas with dense clusters of UNG wells and particularly recently drilled wells than in the urban corridor. The comparisons of data from the mobile laboratory sampling indicated that some air pollutants (*e.g.*, C_2-C_6 alkanes, methanol, acetaldehyde, acetone, acetic acid, methyl-ethyl ketone) were significantly higher at the UNG-impacted site as compared to the remote site, while other air pollutants (*e.g.*, combustion-related compounds such as the trimethylpentanes, ethyne, ethene, 1-butene, iso-butene, 2-methyl-2-butene, 1-pentene, 2-methyl-1-pentene, and cis-2-hexene) were significantly higher at the remote site. Other alkenes or aromatic compounds, including benzene, were not found to be significantly different between the two sites, and source apportionment calculations confirmed that UNG emissions were not a large source of measured alkenes and aromatic hydrocarbons (*e.g.*, benzene, ethylbenzene, toluene, xylenes).

Swarthout *et al*. (2015) performed some screening-level risk calculations that confirmed the low levels of air pollutants measured during the study, as the highest non-cancer hazard index was below acceptable risk criteria and the highest cancer risks were well within the US EPA acceptable excess lifetime cancer risk range of 10^{-6} to 10^{-4} (1 in a million to 1 in ten thousand). It should be noted that these risk calculations conservatively assumed that the short-term air concentrations measured by the researchers were representative of long-term chronic exposures, and moreover, risks were generally driven by pollutants associated with combustion and urban emissions.

4.2.4 Macey *et al*. (2014) Community-based Exploratory Study

The Macey *et al*. (2014) "community-based exploratory study" purports to provide air monitoring data near unconventional oil and gas operations demonstrating "elevations in concentrations of hazardous air pollutants under a range of circumstances." It included a small amount of air monitoring data for the Marcellus Shale region together with a limited dataset for other shale gas plays in Arkansas, Colorado, Ohio, and Wyoming. In total, the study included just 35 grab (2-3 minute) air toxics samples and 41 8-hour formaldehyde badge samples. In contrast to the majority of the available air monitoring data for NGD areas that have been collected by either regulators, academic researchers, or professional air sampling experts, the Macey *et al*. (2014) monitoring was conducted by "trained volunteers" with no prior air sampling experience. Notwithstanding any data quality problems associated with the novice data collection, this study had several major limitations, including: (1) air toxics samples consisted of 2-3 minute grab samples, which provide only a snapshot of air quality conditions at the time of sampling, (2) the volunteer samplers did not collect any upwind air samples or wind direction data that are necessary to link specific sources with the observed air concentrations, and (3) air concentrations from the 2-3 minute grab samples and 8-hour formaldehyde samples were compared to long-term exposure guidelines and risk-based concentrations developed for a lifetime of exposure.

Four of the 35 grab air toxics samples and ten of the 41 formaldehyde badge samples were collected in Pennsylvania, and specifically in Susquehanna and Washington Counties.[12] As described by Macey *et al*. (2014), these and other samples were collected at times when volunteers observed odors, could see emissions, or experienced what they believed to be health symptoms. As discussed by Macey *et al*. (2014), only one of these four grab air toxics samples was found to have a benzene concentration (5.7 $\mu g/m^3$, or 1.8 ppb) exceeding the US EPA 1/100,000 cancer risk level of 4.5 $\mu g/m^3$ (1.4 ppb). However, it is not appropriate to compare a 2-3 minute grab sample to a risk-based concentration based on a lifetime of exposure. Moreover, we are commonly exposed to airborne benzene concentrations in excess of 1.8 ppb in our everyday lives, such as in urban environments, in our cars, in our homes, and at gasoline service stations (ATSDR, 2007; HEI, 2007).

Macey *et al*. (2014) further reported that six of the ten passive formaldehyde samples collected in close proximity (reported distances of 230 to 790 meters, which is equivalent to approximately 750 to 2,600 feet) to compressor stations in Pennsylvania had formaldehyde concentrations exceeding either US EPA cancer risk levels or other health-based exposure guidelines. Notwithstanding the apples-to-oranges nature of these comparisons due to large differences in the sample durations *versus* the averaging times of the health-based exposure guidelines, it is important to note that these formaldehyde concentrations (7.6 to 61 $\mu g/m^3$, or 6.2 to 49.7 ppb) are well within the ranges common to indoor environments (HEI, 2007; Logue *et al*., 2011; Weisel *et al*., 2005; ARCADIS 2001). Formaldehyde is in fact ubiquitous in residential indoor air due to a number of common indoor sources that include building materials such as composite wood, coatings, fiberglass insulation, and paper products (Hult *et al*., 2014). Other indoor formaldehyde sources include cooking activities, permanent press fabrics, personal care products, natural gas combustion, and tobacco smoke (Hult *et al*., 2014; Logue *et al*., 2014; Missia *et al*., 2010; Nazaroff and Singer, 2004; ARCADIS, 2001). For example, ARCADIS (2001) demonstrated that significant quantities of formaldehyde are generated by cooking using both natural gas and electric ranges, reporting formaldehyde concentrations of 129.3 and 129.4 $\mu g/m^3$ in a kitchen for cooking experiments where fish was broiled using a gas range or an electric range, respectively. For 5-hour oven cleaning tests of gas and electric ranges, ARCADIS (2001) reported formaldehyde concentrations of 417.3 and 224.5 $\mu g/m^3$, respectively.

4.2.5 Updated Paulik *et al*. (2016) Study of Polycyclic Aromatic Hydrocarbons (PAHs)

Although specific to the Utica Shale and not the Marcellus Shale, the recently updated Paulik *et al*. (2016) bears mentioning for two reasons: (1) It is one of few studies to investigate levels of polycyclic aromatic hydrocarbons (PAHs)[13] in areas with NGD development, and (2) the original Paulik *et al*. (2015) publication that received media attention as providing evidence of PAH health risks from NGD-related air emissions was recently retracted and many of its conclusions altered due to a serious calculation error, illustrating the importance of weighing the body of study findings rather than findings from a single study.[14] Paulik *et al*. (2016) reported corrected data for vapor-phase PAH measurements made at 23

[12] Four air toxics grab samples and five passive formaldehyde samples were also collected in three Ohio counties (Athens, Carroll, and Trumbull) that are likely influenced by Utica Shale development activities, but possibly by Marcellus Shale development activities. Macey *et al*. (2014) do not provide any specific air concentration data for these samples, but simply note that there were no air concentrations exceeding US EPA cancer risk levels or other health-based exposure guidelines.

[13] Polycyclic aromatic hydrocarbons (PAHs) are a class of over 100 organic compounds that consist of two or more joined aromatic rings of hydrogen and carbon atoms. PAHs occur naturally in coal, crude oil, and gasoline, and they are formed during the incomplete burning of a range of different materials, including coal, oil and gas, wood, garbage, tobacco, and meat and other foods.

[14] This is not meant to imply that findings from other studies in the literature may be erroneous in nature as the original Paulik *et al*. findings, but instead, that it is important that findings from a single study or multiple studies be confirmed through additional study. Conclusions should be drawn from a body of scientific evidence rather than single studies, especially hypothesis-generating studies.

properties in Carroll County, Ohio, each located between 0.04 and 3.2 miles (approximately 210 and 16,900 feet) from an active gas well pad. A total of 23 samples (one per property) were collected over 3 to 4 week sampling periods in February 2014 and analyzed for 62 PAH species. Although Paulik *et al*. (2016) reported some evidence of increased concentrations of certain PAH species for samplers closer to active wells, they acknowledged in their corrected publication that all PAH concentrations were either comparable to or lower than most published PAH data for other areas, including both urban and rural areas. In other words, for all of their sampling data including those closest to active wells, only very low PAH concentrations were measured.[15] Risk calculations performed by Paulik *et al*. (2016), which assumed that the highly limited number of 3-4 week average air samples collected in the study were representative of chronic exposure levels, confirmed the low levels of PAHs measured in the study. For example, the highest excess lifetime cancer risks estimated by the authors (0.04 in a million) were well below the US EPA acceptable excess lifetime cancer risk range of 1 in a million to 1 in ten thousand.

4.3 Other Commissioned Study Reports

4.3.1 West Virginia University (WVU) Air, Noise, and Light Monitoring Study

As described in both a May 2013 final report from the lead WVU investigator (McCawley, 2013) and more recently in a June 2016 data report recently finalized by the U.S. Department of Energy (US DOE) National Energy Technology Laboratory (NETL) (Pekney *et al*., 2016), the WVU air, noise, and light monitoring study was conducted to provide data for evaluating the effectiveness of a 625-foot set-back from the center of a NGD well pad. As part of this study, a comprehensive air sampling program was conducted between July and November 2012 at seven drilling sites operated by three different companies in three West Virginia counties. Between 1 to 4 weeks of air sampling was conducted at each site, with all sampling locations situated within close proximity (~ 250 to 1,300 feet) to well pad centers and possible air emission sources (McCawley, 2013; Pekney *et al*., 2016). Sampling occurred at times when a variety of different NGD activities were occurring at the different sites, including well pad construction, vertical drilling, horizontal drilling, hydraulic fracturing, and flowback/completion. Using both solar-powered wireless air monitoring stations (WAMs) and the US DOE NETL mobile air monitoring laboratory (the mobile air monitoring laboratory was used at 6 of the 7 sites), a number of different instruments and samplers were deployed at the NGD sites for collection of a comprehensive air monitoring dataset. Similar to the PADEP air sampling studies, data representative of transient peak exposures (1-hour Gas Chromatography-Flame Ionization Detector [GC-FID] sampling) and longer-duration exposures (3-day canister samples[16]) were collected for a standard set of VOCs. Continuous instruments were used for collection of 1-minute NO_2, SO_2, and O_3 concentrations and hourly average $PM_{2.5}$ and PM_{10} concentrations.

McCawley (2013) highlighted both the measurement of detectable levels of PM and VOCs at the 625-foot set-back distance, as well as the large variability in detected air concentrations, as key study findings. Based on a simple and highly conservative comparison of measured VOC concentrations from the 72-hour air canister samples with risk-based limits for chronic (365 days and longer) exposures, the study

[15] Interestingly, for samples grouped by their proximity to active wells, corrected summed PAH concentrations for 14 PAHs commonly measured in air samples (acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, benzo[g,h,i]perylene, and indeno[1,2,3-cd]pyrene) in the updated Paulik *et al*. (2016) publication are approximately 0.4% of the corresponding summed PAH concentrations reported in the original Paulik *et al.* publication. The calculation error referred to in Paulik *et al*. (2016) appeared to significantly inflate all reported PAH concentrations in the study, necessitating major revisions to the findings and conclusions of the original manuscript.

[16] While the McCawley (2013) final report does not provide information on the sampling duration for the VOC canister samples, a prior monitoring plan report (McCawley, 2012) indicated that canisters were to be deployed over 72-hour periods.

investigators concluded that only benzene was found to be present near well pad centers at concentrations posing potential health risks. The study investigators emphasized the conservative nature of their assumption that a small number of 72-hour canister air samples were representative of ≥ 1-year chronic exposures, stating that "It is unlikely that any single drill site would expose any location to the levels found in this study for a period of a year or more" (McCawley, 2013). Moreover, benzene was detected in less than 10% of the 1-hour GC-FID samples, and only one site (the Maury Pad in Wetzel County) was found to have 72-hour benzene concentrations more than 10 times higher than the risk-based limit for ≥ 1-year chronic exposures (McCawley, 2013). Pekney *et al*. (2016) observed that diesel and gasoline engine emissions from both equipment used on well pads as well as from local traffic emissions are common sources of benzene and other BTEX (benzene, toluene, ethylbenzene, xylenes) compounds. Regarding $PM_{2.5}$, McCawley (2013) noted some episodic hourly concentrations in excess of the 24-hour $PM_{2.5}$ NAAQS of 35 $\mu g/m^3$, but 24-hour average concentrations ranged from 1-24 $\mu g/m^3$ and were, thus, well below the NAAQS for $PM_{2.5}$. For the NETL mobile air monitoring data, Pekney *et al*. (2016) concluded that no VOCs were detected at levels exceeding OSHA permissible exposure limits (PELs) over the duration of monitoring, and that of the criteria air pollutants monitored by NETL ($PM_{2.5}$, PM_{10}, O_3, SO_2, NO_2), only O_3 was found to exceed its corresponding NAAQS on a single occasion.

4.3.2 TechLaw Report of Air Quality Measurements at Sky View Elementary School

At the direction of US EPA Region III, TechLaw performed three sets of air quality measurements at Sky View Elementary School in Morgantown, West Virginia in 2011 to evaluate the impact of nearby Marcellus Shale natural gas drilling operations (TechLaw, 2012). Measurements were taken at six locations within the school grounds: two outdoor, ground level locations; two indoor locations; and two outdoor, rooftop locations. The first two sets of air quality measurements, which took place on August 11-12, 2011, and September 19-20, 2011, represented background air quality conditions prior to the initiation of shale gas hydraulic fracturing activities near the school. The final set of air quality measurements on October 6-7, 2011, represented air quality conditions during hydraulic fracturing. During each of the three sampling events, a 24-hour canister air sample was collected at each of the six sampling locations and analyzed for VOCs, and a duplicate 24-hour canister sample was collected at one of the locations for quality assurance purposes. On August 11-12 and October 6-7, two additional sets of air quality measurements were collected: 1) one adsorbent tube sample per location for aldehyde analysis, and 2) continuous hydrogen sulfide measurements at each location. TechLaw (2012) reported that the data logger used to record continuous hydrogen sulfide measurements failed to operate on at least one of the measurement days, but that TechLaw staff manually recorded hydrogen sulfide measurements periodically during the measurement time periods.

Overall, the Sky View Elementary School measurements did not show significant increases in any compounds during the hydraulic fracturing period, as compared to the background measurements. A number of aldehydes were detected during both the background and the hydraulic fracturing periods, specifically formaldehyde, acetaldehyde, acetone, methyl ethyl ketone/ butyraldehydes, m,p-tolualdehyde, and hexanal. The measured concentrations of these compounds were similar for the background and hydraulic fracturing periods, and there were no aldehydes detected during the hydraulic fracturing period only. The VOC measurements showed that acetone and ethanol were detected during both the background and hydraulic fracturing periods in several of the measurement locations, and chloromethane, heptane, and toluene were detected during both periods in the indoor locations. The concentrations of all of these VOCs were similar during the two periods. A number of other VOCs were detected during both periods, but the measured concentrations were so low that they fell below the "level of quantitation" (*i.e.*, the concentration at which the amount of the compound is large enough that it can be accurately quantified). Small concentrations of heptane and toluene were also detected at the outdoor locations during the hydraulic fracturing period, although several of these detections fell below the level of quantitation. In addition, small concentrations of isopropyl alcohol and m,p-xylenes were detected at indoor locations during the hydraulic fracturing period, although the m,p-xylenes detection was below the level of quantitation. Hydrogen sulfide measurements ranged between 0 and 2 parts per billion (ppb) in the background measurements and between 0 and 4 ppb during the hydraulic fracturing period.

4.3.3 US DOE's NETL Mobile Air Monitoring Studies

Utilizing the state-of-the-art NETL mobile air monitoring laboratory and the same comprehensive set of target analytes, US DOE scientists have been actively collecting air monitoring data at multiple locations in the Marcellus Shale region besides just the WVU Air, Noise, and Light Monitoring Study locations. For example, in 2012, NETL conducted air monitoring at a Greene County (PA) well pad, both prior to and during hydraulic fracturing activities of a number of wells. Only preliminary results are available for this air monitoring study, with Pekney *et al*. (2013) summarizing the air monitoring findings as follows: "Preliminary results from this project suggest that although measurements did not at any time exceed applicable exposure limits or air quality standards, there were discernible differences in measurements collected during the various phases of operation at the well pad." Specifically, for their on-pad monitoring location, Pekney *et al*. (2013) reported evidence of some episodic short-term increases in methane, PM_{10}, and NO_x concentrations during hydraulic fracturing activities; however, they observed more modest short-term increases, and sometimes no discernible changes, in concentrations of $PM_{2.5}$, NO_2, and VOCs like benzene (*e.g.*, as compared to an average baseline concentration of 0.3 ppb, average benzene levels during a first and second hydraulic fracturing event were 0.4 and 0.2 ppb, respectively).

In addition, as described in the Pekney *et al*. (2014) peer-reviewed publication, US DOE scientists conducted seven months of air sampling between July 2010 and June 2011 at three locations in Pennsylvania's Allegheny National Forest differing in their proximity to oil & gas development activities:

- **Kane Experimental Forest (KEF):** 8 to 9 km downwind of Sackett oilfield;
- **Bradford Ranger Station (BRS):** 1 to 2 km downwind of extensive oil and gas activity; and the
- **US Forest Service Hearts County campground (HC):** "[R]elatively removed from existing wells and new development."

Although portions of both the Marcellus Shale and the Utica Shale underlie the Allegheny National Forest, Pekney *et al*. (2014) noted that there were only four Marcellus wells and no Utica wells at the time of their study; this study was thus designed to examine the air quality impacts of historic oil and gas development activities and to provide baseline air quality data prior to more extensive deep shale gas development in this area. At each of these locations, short-term air concentrations were measured for a suite of particulate and gaseous pollutants, including VOCs (52 specific compounds), NO_2, SO_2, O_3, $PM_{2.5}$, and PM_{10}.

Despite marked differences in the proximity to and intensity of oil and gas development activity at the three sites, the study investigators observed only "slight site-to-site differences" in air pollutant concentrations. Criteria air pollutant concentrations were found to all be below applicable NAAQS. Based on these findings, the study investigators concluded that the NETL mobile air monitoring laboratory was located at sufficiently downwind locations from oil and NGD activities for localized plumes to be effectively dispersed with background air, rendering them largely undetectable. In other words, these findings support the rapid diminishment of NGD-related air quality impacts with distance from sources.

5 Marcellus Shale Health Studies

For the past five years or so, the potential health risks posed by unconventional natural gas development activities in the United States have been investigated using two types of public health studies, namely statistical (health survey and epidemiological) studies of selected populations nearby to NGD activities and human health risk assessments (HHRAs). While these studies have been interpreted by some as providing evidence linking NGD activities with increased human health risks (*e.g.,* Webb *et al*., 2016), it is important to highlight the major methodological limitations and study shortcomings that preclude their use for making any causal conclusions regarding NGD activities and adverse human health impacts (see Table C.1 and discussion below). In particular, none of the health survey and epidemiological studies are based on actual exposure measurement data, including air concentration data; as discussed previously in Section 4, the available air exposure data do not support the conclusion that NGD-related air emissions would be expected to cause adverse health effects. These major methodological limitations and study shortcomings extend to the recently published epidemiological studies of the associations between asthma exacerbation and NGD activities in the Marcellus Shale region (Rasmussen *et al*., 2016) and between nasal and sinus, migraine headache, and fatigue symptoms and NGD activities in Pennsylvania (Tustin *et al*., 2016) that are discussed in detail below. Despite media reports to the contrary, neither of these studies provide causal evidence linking NGD activities with increased health risks, and they instead reports statistical associations that are of uncertain causal implication. As also discussed more below in Section 5.2, human health risk assessments conducted to date predominantly provide evidence supporting a lack of significant adverse health effects from NGD air emissions in the Marcellus Shale.

5.1 Epidemiological Study Findings

Environmental epidemiological studies typically report statistical associations linking an exposure of interest with specific adverse health impacts, but due to large differences in the rigor of their design and methodology, they can widely vary in their probative value and cause-and-effect interpretation. As summarized in Table C.1, the earliest health studies of Marcellus Shale communities in the published literature consist primarily of surveys of health symptoms among community members living near NGD operations (Ferrar *et al.* 2013, Saberi *et al.* 2014, Steinzor *et al.* 2013). These studies have reported increased prevalences of a variety of common health complaints (*e.g.*, headaches, stress, nausea, sinus problems, rashes, *etc.*) registered by community members. However, the results do not provide useful insight into associations between NGD-related pollutions and health effects because all involved "convenience samples" for subject participation, likely resulting in a high degree of recall bias; all depended upon subject self-reporting of health status without verification by health professionals; reported health complaints are very common and have a number of other causes; and none conducted an appropriate statistical analysis of health effects relative to an NGD-related exposure metric. Steinzor *et al*. (2013) attempted to analyze patterns between frequency of health symptoms and distance to nearest drilling sites, but their analysis did not include any control for important confounding variables and did not account for clustering of responses within households. In the words of Saberi *et al.* (2014), their own survey-based research can be described as an "exploratory descriptive analysis"; the works of Steinzor *et al.* (2013) and Saberi *et al.* (2014) fit this description as well. Collectively, the value of these studies is in their demonstration that some community members living in the Marcellus Shale region are highly concerned about potential public health impacts of NGD activity; they do not provide any cause-and-effect evidence.

Other recent epidemiological studies of Marcellus Shale communities, including the Casey *et al*. (2016) and Stacey *et al*. (2015) birth outcome studies and the Rabinowitz *et al*. (2014) random-sample survey study, have employed more sophisticated study designs, but still have major methodological limitations and study shortcomings (Table C.1). Importantly, none of these studies (nor the Jemielita *et al*. (2015) ecological study of hospital inpatient prevalence rates or the Fryzek *et al*. (2013) ecological study of childhood cancer incidence) utilized measures of actual exposures or any environmental monitoring data at all, and instead relied on crude exposure surrogates. For example, Rabinowitz *et al*. (2014) and Stacey *et al*. (2015) relied on proximity to the nearest gas well and inverse distance weighted well counts as crude exposure surrogate, respectively. Casey *et al*. (2016) developed an aggregated NGD activity index based on four exposure surrogates corresponding to different NGD phases (number of well pads per square meter for the well pad development phase, the number of drilled wells per square meter for the well drilling phase, total well depth for the hydraulic fracturing or stimulation phase, production volume for the production phase), but provided no validation of these four exposure surrogates (*i.e.*, how well they are correlated with actual exposures to NGD-related pollutants). For example, Casey *et al.* (2016) used total well depth as a surrogate for truck trips and hydraulic fracturing fluid volume, and production gas volume as a surrogate for air pollution emissions, without any demonstration of the validity of these surrogates, which are themselves surrogates of exposure concentrations, such as ambient air concentrations. In other words, they are using surrogates of surrogates.

Overall, while employing more rigorous methods than the earliest survey-based studies, these studies remain at best hypothesis-generating studies. Rabinowitz *et al*. (2014) and Stacey *et al*. (2015) themselves described their studies as hypothesis-generating studies. However, Casey *et al*. (2016) attached no such caveat to their study and instead appeared to make a causal interpretation of their findings, concluding, "This study adds to limited evidence that unconventional natural gas development adversely affects birth outcomes." In fact, in a recently published letter to the editor regarding the Casey *et al*. (2015) study, Cox (2016) called out Casey *et al*. for making an "unwarranted causal interpretation of associational results." Cox (2016) highlighted the lack of any explicit causal analyses in the Casey *et al*. (2016) study, as well as its major study limitations that include the use of exposure surrogates, the lack of any model validation or diagnostics, and the failure to include more appropriate statistical methods for spatial and longitudinal data (*e.g.*, kriging or panel data analysis) or to address model uncertainty. Cox (2016) concluded, "In light of these limitations, positive associations observed in selected models between an unvalidated exposure index and two (of several) birth outcomes examined do not provide valid evidence of a causal relation between unconventional natural gas development and adverse health impacts in newborns."

Even the most recently published health studies conducted for the Marcellus Shale region, namely the Rasmussen *et al*. (2016) asthma exacerbation study and the Tustin *et al*. (2016) study of self-reported nasal and sinus, migraine headache, and fatigue symptoms, suffer from many of the same limitations and make no specific causal link between NGD activities and increased health risks. As summarized in Table C.1, Rasmussen *et al*. (2016) reported statistically significant associations between four so-called "UNGD [unconventional natural gas development] activity metrics" and three types of asthma exacerbations, including new oral corticosteroid medication orders (mild), emergency department visit (moderate), and hospitalization (severe). The four "UNGD activity metrics", which are surrogates of exposure rather than true measures of exposure (see more discussion below), consisted of a well pad preparation metric, a spud metric, a stimulation metric, and a production metric. However, due to correlations between the four "UNGD activity metrics", Rasmussen *et al*. (2016) could not distinguish between the impacts of any of the specific phases of natural gas development activity. Moreover, due to the use of the "UNGD activity metrics" as exposure surrogates rather than direct measures of exposure, this study provides no insight as to whether the observed associations are in fact causal in nature- *i.e.*, whether the observed associations are indeed caused by some aspect of natural gas development activities rather than by some other confounding factor. This is acknowledged by the authors themselves who stated, "Whether these associations are causal awaits further investigation, including more detailed exposure assessment."

While this study touts itself as the first study of "UNGD and objective respiratory outcomes," it bears similarities to all other health studies of Marcellus Shale activities given its lack of a detailed exposure assessment and its reliance on crude exposure surrogates rather than any direct measures of exposures or even any environmental monitoring data at all (Table C.1). Rasmussen *et al*. (2016) imply that they've developed improved exposure metrics as compared to prior studies, but they provided no validation of their four "UNGD activity metrics", which are all still just exposure surrogates. Are the four "UNGD activity metrics" in fact correlated with NGD-related exposures? It would appear that the principal difference between their approach and that of prior studies is the use of four different activity metrics rather than just a single exposure surrogate, such as inverse distance weighted well counts within 10-miles that has been used by several prior epidemiological studies. However, they are relying on surrogates of exposure which are themselves based on surrogates. For example, Rasmussen *et al*. (2016) stated that total well depth, which is itself just a surrogate for volume of water used during stimulation, was used as a surrogate for truck traffic in their stimulation metric. They also stated that daily gas production volume was used as a surrogate in their production metric for fugitive emissions and compressor engine activity without acknowledging that fugitive emissions and compressor engine activity are themselves surrogates of exposure concentrations, such as ambient air concentrations. In other words, they are using surrogates of surrogates, and I would further argue that ambient air concentrations are themselves surrogates of actual exposures (given that there are a variety of home-specific and individual-behavior-specific factors that can result in significant differences between ambient concentrations and personal exposure levels), meaning that they are using surrogates of surrogates of surrogates of exposure.

The Rasmussen *et al*. (2016) study has other major limitations, including its omission of a number of Pennsylvania counties with extensive NGD development, including Washington County; its control for just a small number of potential confounding factors; its lack of consideration of the actual timing and location of the exposure event triggering the asthma exacerbation (it simply assumes that all exposure events occurred at residential addresses); and an unusual study design that used different event and contact dates for cases and controls, respectively, and that required controls to not have had an exacerbation event up to the year of the event in the frequency-matched case. In addition, Rasmussen *et al*. (2016) reported in a separate analysis focused on counties rather than activity metrics that counties with high NGD activity were not associated with their asthma exacerbation outcomes. Although they cited this finding as evidence that unmeasured confounding is unlikely to account for their findings, this finding indicating that counties with the greatest NGD activity do not have the highest numbers of asthma exacerbation events would seem to go counter to their hypothesis that NGD activities may increase risk of asthma exacerbation.

Given that it shares many of the same study investigators as the Rasmussen *et al*. (2016) study, the Tustin *et al*. (2016) study of self-reported nasal and sinus, migraine headache, and fatigue symptoms also estimated a similar set of natural gas development activity metrics for its exposure assessment rather than relying on air monitoring measurements or other measures of actual exposure. This study reported statistically significant associations between a "summary UNGD activity metric" averaged over 90 days and increased odds of self-reported symptoms among individuals meeting criteria for two or more outcomes. Specifically, Tustin *et al*. (2016) reported adjusted odds ratios (ORs) for their highest quartile of estimated UNGD activity compared to the lowest quartile of 1.88 (95% CI: 1.08, 3.25) for chronic rhinosinusitis (CRS) plus fatigue, 1.95 (95% CI: 1.18, 3.21) for migraine plus fatigue, and 1.84 (95% CI: 1.08, 3.14) for all three outcomes together. Strangely, for analyses of individuals with just a single health outcome (*i.e.*, CRS or migraine or fatigue), there was a general lack of statistically significant associations; this raises questions regarding biological plausibility of the findings since it is unclear why exposure to UNGD-related pollutants would cause two or more symptoms, but not a single symptom.

This observational study also has numerous major methodological limitations that relegate it to the category of hypothesis-generating study. As concluded by the study authors themselves, "Further research, including more sophisticated exposure and outcome measurements, is necessary to evaluate whether these associations are causal and to elucidate the mechanisms for these findings." As documented in Table C-1, key methodological limitations of the Tustin *et al*. (2016) study include:

- no measures of actual exposures, and instead, reliance on exposure surrogates that are themselves based on surrogates (*e.g.*, total well depth, which is a surrogate for volume of water used during stimulation, was used as a surrogate for truck traffic in the stimulation metric)
- the cross-sectional study design that provided little information on temporal relationship between exposure and health outcome (*i.e.*, did symptoms pre-date NGD activity?);
- reliance on self-reported symptoms that are subject to recall bias;
- a low survey response rate (33%), and as reported by the study authors, evidence of selection bias given the poorer health of study participants than survey non-responders;
- adjustment for a very limited set of potential confounders that did not include occupation and workplace exposures, medication usage, meteorology, allergic history, allergen exposures, *etc.*;
- the use of an unmatched case-control analysis that increased the likelihood of potential confounding due to differences in risk factors between cases and controls;
- spatial differences between study participants assigned to the highest exposure quartile *versus* study participants in the other three exposure quartiles; and
- low participant numbers in counties with extensive oil and gas activity, including no participants in PA counties with greatest amounts of oil and gas activity.

While each of these study limitations is an important source of uncertainty affecting the interpretation of the study findings, I would like to provide some additional context on the latter two and their potential impacts on the study findings. As discussed by Tustin *et al*. (2016), they found study participants assigned to their highest exposure quartile lived farther north than those in the other quartiles generated for their exposure surrogates. This spatial difference arose due to the small amount of overlap between the Geisinger catchment area, which is focused on central and northeastern Pennsylvania, and the areas with extensive Marcellus Shale development activities. While Tustin *et al*. (2016) attempted to control for some covariates that could be associated with both location and outcomes (*e.g.*, race/ethnicity and socioeconomic status), the study investigators collected data on only a small number of covariates and it remains quite possible that the observed associations may be due to spatial confounding- *i.e.*, differences between the highest exposure quartile in the north and the lowest exposure quartile besides just the amount of NGD activities. The general lack of statistically significant associations between the 2nd and 3rd quartiles compared with the lowest quartile provides support for the potential impacts of spatial confounding given that study participants for each of these three quartiles were drawn from the same general areas. The authors acknowledge the potential impacts of spatial confounding on the observed associations, stating, "Given the correlation between geography and UNGD, we cannot rule out the possibility that spatial confounding was responsible for the observed associations."

Moreover, either very few or no study participants were drawn from the PA counties with the greatest amounts of oil and gas activity:

- Washington County- none;
- Bradford County- 12 study participants;
- Susquehanna County- 69 study participants;
- Greene County- none;
- Lycoming County- 233 study participants;
- Tioga County- 4 study participants;
- Butler County- none;
- Fayette County- none;
- Westmoreland County- none; and
- Wyoming County- 178 study participants.

As a result, the majority of study participants are from counties with little or no NGD activities, and the associations reported in Tustin *et al*. (2016) for the highest quartile of UNGD activity are based on small sample sizes and thus of uncertain interpretation.

5.2 Human Health Risk Assessment Findings

Human health risk assessment (HHRA) can provide quantitative insight into the likelihood of adverse health effects, based on the answers to such questions as:

- What substance?
- How much exposure?
- For how long?
- What's known about the dose needed for ill effects?

Regulatory HHRA procedures are highly conservative (*i.e.*, health protective). When public-health regulatory agencies develop "screening levels," "guidelines," "precautionary limits," "preliminary remediation goals," and "risk thresholds," they incorporate large uncertainty or safety factors, meaning that exceeding such health-based levels cannot be interpreted as an expectation that actual adverse health effects will occur. For example, typical inhalation "reference concentrations" (RfCs) are developed to assure safety from non-cancer diseases and specify exposure levels that are from several-hundred-fold to several-thousand-fold lower than the exposure at which the actual effect was observed. A non-cancer hazard index (HI) is calculated by comparing the expected exposure concentration to the RfC for the chemical. Thus, $HI < 1.0$ means exposures are less than the RfC, and $HI > 1.0$ means that exposures are above the RfC. However, because of the way RfCs are developed, exceeding $HI = 1.0$ is not evidence that any disease is expected to occur at that dose.

As discussed previously, several studies including the Maskrey *et al*. (2016) study of the air quality impacts of the nearby Chiarelli Pad, the PADEP short-term air sampling studies (PADEP, 2010, 2011a, 2011b), and the WVU air, noise and light monitoring study (McCawley *et al*., 2013) have performed screening-level human health risk assessments, comparing measured air concentrations to health-based exposure guidelines and risk-based concentrations. While not full-fledged human health risk assessments with calculations of non-cancer hazard indices (HIs) and excess lifetime cancer risks (ELCRs), these assessments provide support for measured air concentrations generally being below levels of health concern. Moreover, these screening-level risk assessments have typically compared short-term air monitoring data to health-based exposure guidelines and risk-based concentrations appropriate for chronic long-term exposures; in other words, they are highly conservative given their inherent assumption that the short-term air monitoring data are representative of chronic long-term exposure levels. As discussed previously, as part of its evaluation of the potential health impacts to the residential community surrounding the Brigich Compressor Station, ATSDR (2016) calculated more detailed non-cancer and cancer risk evaluations that included excess lifetime cancer risk calculations for a subset of the constituents of potential concern. ATSDR concluded that, in general, these more detailed non-cancer and cancer exposure evaluations did not support the likelihood of human health harms from these air pollutants, although ATSDR could not rule out that some sensitive subpopulations may experience health impacts from hydrogen sulfide, $PM_{2.5}$, or carbonyls. ATSDR cautioned that sources other than the Brigich Compressor Station, such as automobiles and agricultural equipment, could be contributing to $PM_{2.5}$ and VOC concentrations.

Recognizing that researchers have concluded that there can be large differences in emissions and thus air quality impacts at oil and gas sites in different shale gas plays due to regional differences in such factors as the reservoir characteristics, the types of activities being performed, the nature of the oil, gas, and liquids being produced, processed, and transported, and emissions regulations (Allen *et al*., 2016), it bears mentioning that a small number of human health risk assessments have been conducted for other shale gas plays. In particular, Bunch *et al*. (2014) conducted a comprehensive assessment of community-level ambient air VOC exposure levels in Texas's Barnett Shale region that included comparisons of 1-hour and 24-hour air monitoring data to federal and state acute or short-term health-based air comparison values as well as comparisons of annual average concentrations computed from the 1-hour and 24-hour data to chronic health-based air comparison values. Bunch *et al*. (2014) utilized a large dataset that consisted of 4.6 million data points from six different monitoring locations selected to represent community-wide ambient air exposures in the Dallas-Fort Worth area. Totaling seven fixed-site monitors (two monitors were located at one of the monitoring locations), key elements of the extensive VOC dataset analyzed by Bunch *et al*. (2014) from these six locations included the following:

- More than 4.6 million data points;
- Monitoring locations included areas with the highest densities of wells, minimal urban source impacts, both wet and dry gas production, and different types of natural gas operations (*e.g.*, well drilling and hydraulic fracturing, producing wells, compressor stations, *etc.*).
- Data covering the time period of 2000-2011 (a minimum of one year for each monitor and nearly a decade of data from three of the monitors);
- For five of the locations, 1-hour data for 46 unique VOCs from monitors that collect air samples continuously; and
- For two of the locations, 24-hour data for 105 unique VOCs from canister samples collected every sixth day.

Based on their assessment, Bunch *et al*. (2014) concluded, "The analyses demonstrate that, for the extensive number of VOCs measured, shale gas production activities have not resulted in community-wide exposures to those VOCs at levels that would pose a health concern." For their acute health hazard evaluation (*i.e.*, comparison of 1-hour and 24-hour measurement data to applicable federal and state acute or short-term health-based air comparison values), they found not a single exceedance across the entire period of record from each site. For their chronic health hazard evaluation (*i.e.*, comparison of annual average concentrations computed from the 1-hour and 24-hour data to applicable federal and state chronic health-based air comparison values), they reported only two exceedances out of 2,501 comparisons, both for a single chemical (namely, 1,2-dibromoethane) that is not known to be associated with shale gas operations.

Using air sampling data from a study of NGD-related air quality impacts in Garfield County, Colorado, McKenzie *et al*. (2012) employed similar risk-based techniques as Bunch *et al*. (2014) to investigate the health significance of VOC air concentrations measured at different distances from well pads. However, in contrast to the Bunch *et al*. (2014) study, the data evaluated by McKenzie *et al*. (2012) were highly limited in terms of their quantity, duration, and potential for confounding. That is, < 200 total samples consisting of 163 "natural gas development area samples" were collected at unspecified distances from NGD operations, and an additional 24 "well completion samples" were collected at distances of up to 500 feet from well pad centers. The sample duration (primarily 24-hour samples), the period of time in which the data were collected (between January 2008 and November 2010), and the confounding effects of other air emission sources (the study authors note the presence of Interstate-70 approximately 1 mile from the five well pads where the well completion samples were collected) all limit the usefulness of the data.

While McKenzie *et al*. (2012) highlighted some of these study limitations and described their study results as being preliminary in nature, they still concluded, "These preliminary results indicate that health effects resulting from air emissions during development of unconventional natural gas resources are most likely to occur in residents living nearest to the well pads and warrant further study." This conclusion would appear to be based on the greater subchronic and chronic air exposure levels estimated by the study investigators for residents living ≤ half a mile from the wells *versus* residents living > half a mile from the wells. However, the estimated subchronic and chronic air exposure levels for residents living ≤ half a mile from the wells are highly influenced by the well completion samples collected at distances of up to 500 feet from well pad centers, and no clear justification is provided in the paper for why these samples are representative of air exposure levels at distances of up to half a mile – *i.e.*, distances more than 5 times greater than the maximum distance of 500 feet from well pad centers for the well completion samples, and more than 40 times greater than some of the other well completion samples. In an appendix to the WVU air, noise, and light monitoring study that discusses some results from other studies of NGD air quality impacts, McCawley (2013) similarly questioned the selection of a half a mile distance given the 100- to 500-foot proximity of the well completion samples from well pad centers. Others (Everley, 2012; Bunch *et al*., 2014; Shonkoff *et al*., 2014) have raised a variety of additional concerns with the methods and assumptions employed by McKenzie *et al*. (2012), including potential confounding effects of the nearby major highway, the lack of baseline air quality data, and overly conservative risk assessment assumptions. Based on their substantial concerns with the study, Bunch *et al*. (2014) concluded that "the results reported by McKenzie *et al*. (2012) may not be applicable for characterizing typical exposures and health hazards/risks."

Notwithstanding its study limitations, the health risks reported by McKenzie *et al*. (2012) were in general low. This was the case despite the use of highly conservative risk assessment assumptions, including the assumption that a person had 24/7 exposure at upper-bound concentrations, for 30 years. In addition, even though well development on a given site rarely takes more than 3 or 6 months, the "well-development scenario" exposures were assumed to continue for 20 months. For the authors' "within half mile zone," cumulative chronic-exposure HIs were 1.0 or below, and cumulative lifetime cancer risks 1 in 100,000 or below. For exposure locations beyond a half mile, these indices dropped by a factor of about two. Subchronic exposures "within half mile" did yield a non-cancer HI of 5 due to assumed benzene, toluene, ethylbenzene, and xylenes (BTEX) concentrations; however, given the assumption of a 20-month duration for well completion activities and the conservative nature of subchronic toxicity factors that typically incorporate large uncertainty or safety factors, this level of HI cannot be considered indicative of the actual occurrence of adverse health effects.

6 Conclusions

As described in this report, there is now available a sizable body of Marcellus Shale ambient air monitoring studies that can be used to assess the nature and potential health risks of community-level air exposures that may arise from NGD-related activities. This body of data does not support claims of widespread community air exposures of public health concern for typical NGD operations. For air pollutants such as $PM_{2.5}$ and VOCs, there is a general absence of evidence for either significant short-term or long-term air concentrations of health concern for typical Marcellus Shale NGD operations, and thus a lack of evidence linking these air pollutants with the reports of common health symptoms like headaches, nausea, sinus problems, *etc.* While several of the available studies have themselves reached similar conclusions, my conclusion is based on the body of evidence from the available Marcellus Shale studies, rather than the findings or conclusions from any specific study.

As I have discussed, amidst the greater amount of data that do not support the widespread occurrence of community air exposure impacts of public health concern from NGD-related activities in the Marcellus Shale region, there are some findings of sporadic short-term elevations in air concentrations for certain air pollutants in relatively close proximity to emission sources. These findings are of uncertain relevance to current best practices to be employed by Range Resources. Moreover, these site-specific findings are not indicative of broader community exposure concerns across NGD operations, nor are they different from the kinds of near-source air quality impacts common to other air emission sources, such as traffic exhaust, conventional oil and gas development, construction, coal mining, and fossil fuel combustion. These types of episodic short-term air pollutant exposures are common for numerous other types of emission sources in our everyday lives. For example, we commonly experience short-term peak exposures to benzene from driving/riding in our car, from visiting a gas station, and from adding gasoline to small engine equipment such as lawnmowers and trimmers. Spikes in short-term $PM_{2.5}$ concentrations of hundreds to thousands of $\mu g/m^3$ are common in both indoor and outdoor environments (Baldauf *et al*., 2006; Morawska *et al*., 2003; Long *et al*., 2000; Howard-Reed *et al*., 2000; Olson and Burke, 2006; Wallace *et al*., 2006).

I have also discussed the available body of Marcellus Shale health survey/epidemiological studies and the reported statistical associations between surrogates of NGD-related exposures and adverse health impacts that include asthma exacerbations, adverse birth outcomes, and common health symptoms like headaches, nausea, sinus problems, *etc.* Findings from these studies are not at odds with my conclusion that there is a general absence of evidence for either short-term or long-term community air exposures of health concern in the Marcellus Shale region. This is due to the major methodological limitations, study shortcomings, and inconsistent findings of all of the available Marcellus Shale health survey/epidemiological studies that preclude their use for making any causal conclusions regarding NGD activities and adverse human health impacts. In particular, none of the health survey/epidemiological studies conducted to date have used actual exposure measurement data (*e.g.*, air monitoring data) in their exposure assessments, and instead have relied on crude exposure surrogates such as proximity to the nearest gas well and inverse distance weighted well counts. There thus remain large uncertainties in the proper interpretation of the statistical associations reported by these studies, but the available air quality data, as well as health risk calculations performed using these data, do not support airborne exposures as causal factors underlying the reported associations.

Overall, the body of scientific evidence bearing on potential air exposures and health risks from Marcellus Shale development does not provide evidence of new or unique air pollutant exposures associated with NGD activities; instead, the available studies focus on air pollutant exposures that have been well-studied in other contexts and for which health-based exposure guidelines and effective regulatory frameworks have been developed. Similar to other operations, it is thus expected that NGD-related air emissions and potential air quality impacts can be addressed through current air quality management practices and adherence to applicable state and federal standards and regulations, such that Marcellus Shale operations can be conducted in a manner protective of community air quality.

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Appendix A

Curriculum Vitae of Christopher M. Long, Sc.D., DABT

Appendix B

Comparison of Yonker Well Pad and Fort Cherry School District Campus Locations with Wind Rose Data for Nearby Airports

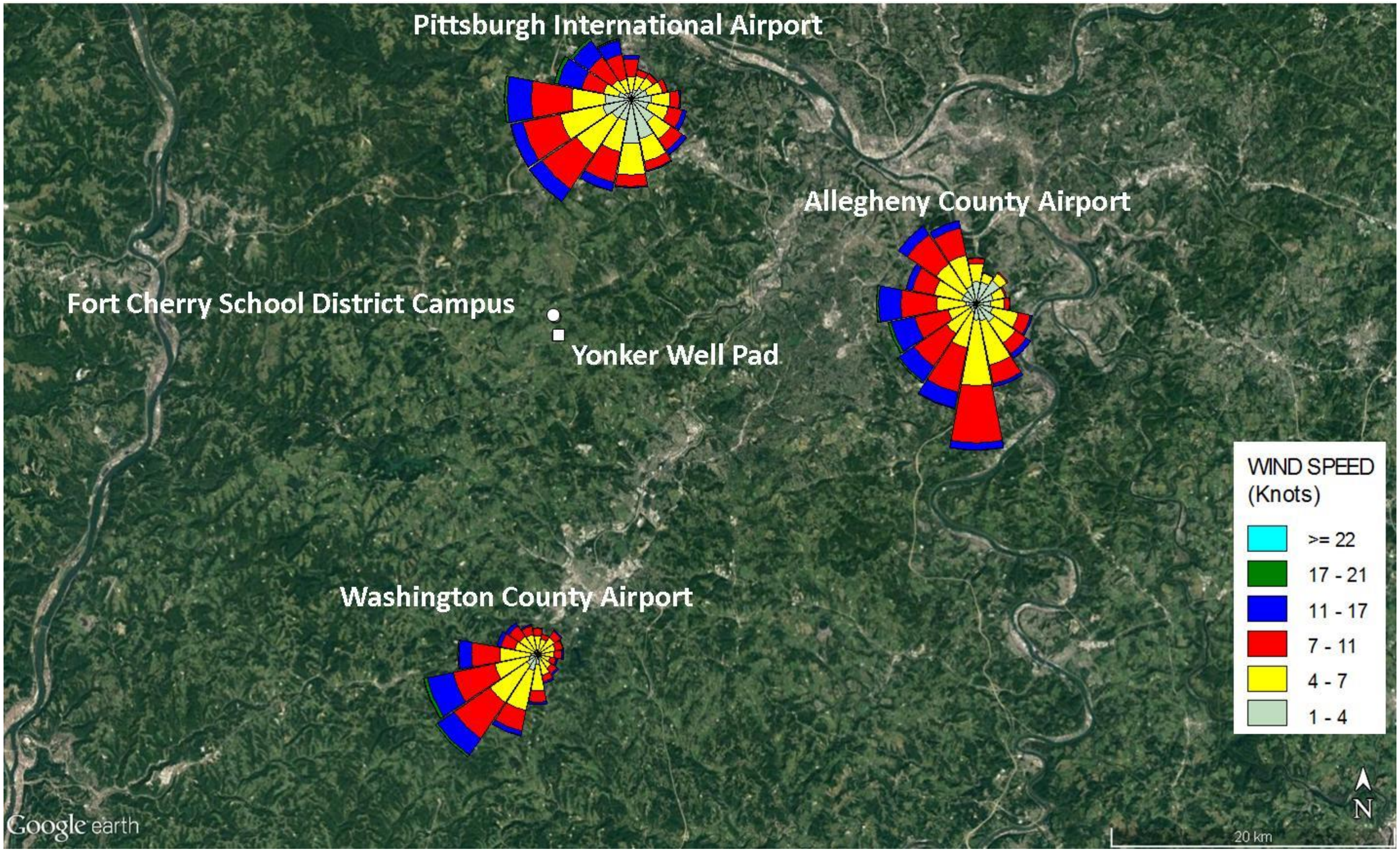

Figure B.1 Comparison of Yonker Well Pad and Fort Cherry School District Campus Locations with Wind Rose Data for Nearby Airports. Wind rose data shown are for three years (2013-2015) and were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI). Hourly and one-minute wind speed and direction data from 2013-2015 were downloaded for the meteorological stations at Pittsburgh International and Allegheny County Airports, and these were input to the US EPA's AERMINUTE meteorological data processing tool to generate hourly average wind data for each site. Only hourly data were downloaded for the meteorological station at Washington County Airport, as one-minute data are not available for this site. The wind roses show the direction from which the winds arrived at the meteorological station- *i.e.*, the direction from which winds were blowing.

Appendix C

Summary of Published Health Survey and Epidemiological Studies for the Marcellus Shale Region

Table C.1 Summary of Published Health Survey and Epidemiological Studies for the Marcellus Shale Region

Reference	Type of Study	Study Population/Size	Exposure Assessment	Outcome Measure	Primary Findings Emphasized by Authors	Other Findings	Selected Key Study Limitations/Caveats
Tustin *et al*. (2016)	Cross-sectional study	7,785 study participants in central and northeastern PA (none in Washington County)	No direct exposure measures or environmental samples; instead, relied on 90-average of cumulative "UNGD activity metric" that summed across activity metrics for each phase of well development (pad preparation, drilling, stimulation, and production)	Self-reported symptoms of chronic rhinosinusitis (CRS), migraine headache, and fatigue	For individuals meeting criteria for two or more outcomes, adjusted odds ratios (ORs) for the highest quartile of UNGD activity compared to the lowest were 1.49 (95% CI: 0.78, 2.85) for CRS plus migraine, 1.88 (95% CI: 1.08, 3.25) for CRS plus fatigue, 1.95 (95% CI: 1.18, 3.21) for migraine plus fatigue, and 1.84 (95% CI: 1.08, 3.14) for all three outcomes together	Study investigators highlighted clear spatial differences between individuals in highest quartile for their exposure surrogate *versus* individuals in other quartiles- *i.e.*, participants in highest quartile lived farther north than participants in other quartiles; lack of statistically significant associations for most models with just a single health outcome	No measures of actual exposures; used exposure surrogates that are themselves based on surrogates (e.g., total well depth, which is a surrogate for volume of water used during stimulation, used as a surrogate for truck traffic in stimulation metric); used cross-sectional study design that provided little information on temporal relationship between exposure and health outcome (*i.e.*, did symptoms pre-date UNGD activity?); relied on self-reported symptoms that are subject to recall bias; authors reported evidence of selection bias as study participants had poorer health than survey non-responders; adjustment for very limited set of potential confounders that did not include occupation and workplace exposures, medication usage, meteorology, allergic history, and allergen exposures; study used unmatched case-control analysis, increasing the likelihood of potential confounding due to differences in risk factors between cases and controls; study had low participant numbers in counties with extensive oil and gas activity, including no participants in PA counties with greatest amounts of oil and gas activity.

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Reference	Type of Study	Study Population/Size	Exposure Assessment	Outcome Measure	Primary Findings Emphasized by Authors	Other Findings	Selected Key Study Limitations/Caveats
Rasmussen *et al.* (2016)	Nested case-control study	35,508 asthma patients in PA and NY (none in Washington County)	No direct exposure measures or environmental samples; instead, relied on several exposure surrogates, namely estimated "activity metrics" for 4 UNGD phases (pad preparation, drilling, stimulation, and production), for the day before the index date	Several measures of asthma exacerbation, including new oral corticosteroid medication orders (mild), emergency department visit (moderate), and hospitalization (severe)	Associations found between the 4 UNGD activity metrics and all 3 types of asthma exacerbations, with odds ratios (ORs) ranging from 1.5 (95% CI: 1.2-1.7) for the association of the pad metric with severe exacerbations to 4.4 (95% CI: 3.8-5.2) for the association of the production metric with mild exacerbations.	In model evaluating associations of counties (rather than activity metrics) with outcomes, counties with high UNGD activity not associated with outcomes.	No measures of actual exposures; used exposure surrogates that are themselves based on surrogates (e.g., total well depth, which is a surrogate for volume of water used during stimulation, used as a surrogate for truck traffic in stimulation metric); authors acknowledge that further investigation, including more detailed exposure assessment, needed to determine whether observed associations are indeed causal in nature; study design provides no insights on mechanisms underlying associations and only addressed small number of potential confounding factors; study did not include PA counties with greatest amounts of oil and gas activity.

Table C.1 Summary of Published Health Survey and Epidemiological Studies for the Marcellus Shale Region

Reference	Type of Study	Study Population/Size	Exposure Assessment	Outcome Measure	Primary Findings Emphasized by Authors	Other Findings	Selected Key Study Limitations/Caveats
Casey *et al.* (2015)	Retrospective cohort study	9,384 mothers linked to 10,946 neonates, primarily from ~40 counties in central and northeast PA	No direct exposure measures or environmental samples; instead, used summed UNGD activity index based on four exposure metrics by phase (pad development, drilling, hydraulic fracturing, production) as exposure surrogate for cumulative exposure.	Several birth outcomes, including term birth weight, preterm birth, low 5-minute Apgar score, and small size for gestational age birth; also, post-hoc analysis of physician-recorded high-risk pregnancy identified from problem list	In adjusted models, only 1 (preterm birth) of the original 4 birth outcomes found to be associated with UNGD activity index; post-hoc analysis also found association between UNGD activity and physician-recorded high-risk pregnancy identified from problem list	No associations found for other birth outcomes, including Apgar score, small for gestational age, and term birth weight; in sensitivity analysis of birth outcomes for infants born in 2006 before extensive UNGD activity that was designed to examine the potential effects of uncontrolled confounding on the study findings, found 1 (lower birth weight) of the original 4 birth outcomes to be associated with UNGD activity index.	Authors themselves acknowledge seven different sets of key limitations, including the absence of any measures of actual exposures and the use of exposure surrogates that likely introduced measurement error; the inability of the study to evaluate phase-specific associations due to collinearity of the individual phase activity metrics; the inability to control for temporal trends due to correlation of UNGD development with year; and uncertainty as to whether the last recorded addresses used in analyses represented residential locations during the course of pregnancy.

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Reference	Type of Study	Study Population/Size	Exposure Assessment	Outcome Measure	Primary Findings Emphasized by Authors	Other Findings	Selected Key Study Limitations/Caveats
Jemielita *et al.* (2015)	Zip code-level ecological study	Hospital inpatients for the 2007-2011 time period for residents of two counties with UNGD wells (Bradford, Susquehanna) and one without any wells (Wayne)	No direct exposure measures or environmental samples; instead relied on numbers of active wells within a zip code or per km^2 as crude exposure surrogates	Inpatient prevalence rates for 25 different medical categories as well as overall inpatient rates	Found statistically significant ($p<0.00096$, based on adjustment for multiple comparisons) increase in cardiology inpatient prevalence rates with both number of wells per zip code and wells per km^2 and for neurology inpatient prevalence rates with wells per km^2. Also found evidence of associations between well density and inpatient prevalence rates for the medical categories of dermatology, neurology, oncology, and urology, but p-values did not meet correction for multiple	For both sets of analyses, the year variable was significantly and negatively associated with inpatient prevalence rates within the medical categories of gynecology and orthopedics; authors did not have an explanation for this unexpected finding, but they hypothesized that it wasn't related to UNGD activity.	No measures of actual exposure, nor any individual-level exposure information; as an ecological study, data included only zip code-level inpatient statistics and no individual-level information on environmental, lifestyle, medical, or other characteristics of the study population; study examined a relatively short time interval and authors caution that unclear whether findings would be valid over longer time periods.

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Reference	Type of Study	Study Population/Size	Exposure Assessment	Outcome Measure	Primary Findings Emphasized by Authors	Other Findings	Selected Key Study Limitations/Caveats
					comparisons.		

Table C.1 Summary of Published Health Survey and Epidemiological Studies for the Marcellus Shale Region

Reference	Type of Study	Study Population/Size	Exposure Assessment	Outcome Measure	Primary Findings Emphasized by Authors	Other Findings	Selected Key Study Limitations/Caveats
Stacy *et al.* (2015)	Retrospective cohort study	15,451 live births in southwest PA from 2007-2010	No direct exposure measures or environmental samples; instead relied on inverse distance weighted (IDW) well count as crude exposure surrogate	Continuous birth weight, small for gestational age (SGA), prematurity (gestational age <37 weeks)	For comparisons of quartiles for most to least exposed, found small but stat. significant associations for lower birth weight and increased likelihood of SGA	No significant association found between proximity and density of UNGD wells and prematurity	Authors acknowledged a number of limitations that relegated their study into the category of hypothesis-generating studies, including semi-ecological nature of study where individual data was available on birth outcomes and risk factors, but mothers were grouped into exposure categories; no measures of actual exposure, with proximity being a "primitive surrogate" that is uninformative on etiologic agent; residence on birth certificates assumed to be representative of location during the entire pregnancy; possibility for unknown confounding; and the lack of a birth month and day in the birth dataset, which allowed the identification of only wells drilled during the birth year of the infant.
Rabinowitz *et al.* (2014)	Cross-sectional random-sample survey	492 people/180 households with ground-fed wells in Washington County	No direct exposure measures or environmental samples; instead, relied on proximity to nearest gas well (<1, 1-2, or >2 km) as crude exposure surrogate	Self-reported dermal, respiratory, gastrointestinal, cardiovascular, and neurological symptoms based on questionnaires	In models adjusted for limited number of potential confounders (age, gender, education, smoking , environ. risk awareness, work, pets), increased numbers of health symptoms (dermal and upper respiratory	Observed association between self-reported environmental awareness with the prevalence of all groups of reported health symptoms, thus providing evidence of a correlation between heightened awareness of health risks and reported health conditions.	No measures of actual exposure; use of crude exposure surrogate (proximity to nearest gas well) that does not account for phase of activity (if any) at well; reliance on self-reports of health symptoms is major limitation and possible source of recall bias- e.g., environmental concerns may have biased recall; data analysis employed many multiple comparisons, leading authors to label their findings as "preliminary and hypothesis generating."

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Reference	Type of Study	Study Population/Size	Exposure Assessment	Outcome Measure	Primary Findings Emphasized by Authors	Other Findings	Selected Key Study Limitations/Caveats
					only) more frequently reported among residents < 1 km from nearest gas well versus >2 km from nearest gas well.		
Saberi *et al.* (2014)	Descriptive study based on survey of community members (convenience sample)	72 respondents, 88% of whom resided in Bradford County	None; subset of subjects had addresses mapped with respect to nearby UNGD facilities	Self-reported symptoms from questionnaires with 29 item check-list	22% identified UNGD as health concern; 13% attributed current health problems specifically to UNGD, 42% to all environmental causes including UNGD	53 subjects consented to mapping of their home location in descriptive spatial analysis, and no pattern of clustering around UNGD facilities was observed.	No measures of actual exposure; very small sample size; no actual epidemiology analysis of any sort was conducted (besides the descriptive spatial analysis); all health outcomes were assessed based on subject self-reports alone, although medical record review was conducted for a small subset of participants (n=6), which revealed poor correlation between self-reported symptoms and medical records.
Fryzek *et al.* (2013)	County-level ecological study	1,874 cancers before any type of drilling versus 1,996 cancers after drilling	None; compared time periods before and after drilling of first well in a county	Childhood cancer incidence	No evidence that cancer incidence was different from expected before and after drilling	Reported a slightly increased standardized incidence ratio (SIR) for central nervous system tumors after drilling	No measures of actual exposure, nor any individual-level exposure information; as an ecological study, data included only area-wide cancer statistics and no individual-level information on environmental, lifestyle, medical, or other characteristics of the study population

Table C.1 Summary of Published Health Survey and Epidemiological Studies for the Marcellus Shale Region

Reference	Type of Study	Study Population/Size	Exposure Assessment	Outcome Measure	Primary Findings Emphasized by Authors	Other Findings	Selected Key Study Limitations/Caveats
Ferrar *et al.* (2013)	Descriptive study based on survey of community members (convenience sample)	33 respondents actively seeking out help for concerns about hydraulic fracturing, including 18 from Washington County	None; compared self-reported symptoms at two time points (2010 and 2012)	Self-reported symptoms and mental and physical health stressors from interviews	Subjects attributed a large number of health problems to UNGD activities near their residences; increase in numbers of reported health concerns between first and second interviews	Stress found to be the most frequently reported symptom.	No measures of actual exposure; study population consisted of a biased convenience sample, as all subjects were actively seeking out help for their concerns about hydraulic fracturing; very small sample size, including only 20 of the original 33 respondents for the second interview; relied on self-reported symptoms, which are subject to potential recall bias; multiple comparison problem, with no adjustment in statistical methods to account for multiple testing.
Steinzor *et al.* (2013)	Descriptive study based on survey of community members (convenience sample)	108 subjects in 55 households across Pennsylvania, with majority (85%) residing in Washington, Fayette, Bedford, Bradford, and Butler counties	Conducted air and water sampling for 35 households, although no rigorous analyses performed to integrate environmental sampling data into analysis of survey results	Self-reported symptoms (20 in total) from questionnaires	Reported that for 18 of 20 symptoms, higher percentage for those living within 1500 feet of a UNGD facility, with statistical significance for 10 of the 20 symptoms	Authors acknowledge that many symptoms commonly reported regardless of distance from UNGD facility (e.g., sinus problems, nasal irritation, increased fatigue, feeling weak and tired, joint pain, and shortness of breath).	Although air and water testing was conducted as part of the study, one-time samples are not representative of long-term exposures; study did not include a control group, which is particularly important given the common symptoms being examined and the ubiquitous nature of the air and water pollutants being quantified; authors acknowledge that additional factors could underlie the reported health conditions; relied on self-reported symptoms, which are subject to potential recall bias; multiple comparison problem, with no adjustment in statistical methods to account for multiple testing.