Air Pollution from Shale Gas Industry Compressor Stations: Updated Report for Pennsylvania

Cynthia Walter, Ph.D. 2/28/2020

Executive Summary

Compressor Stations (CS) in the gas industry are permanent and significant sources of serious air pollutants known to harm humans. CS transport gases from wells to major pipelines and within pipelines. CS are also the location for additional equipment that emit toxins. In the last 20 years, CS abundance and sizes have dramatically increased in shale gas extraction areas across the US. This report will focus on CS in and near Southwestern Pennsylvania. Numbers there have risen more than 10-fold in the last decade in response to well completions and pipelines after the local fracking boom began in 2005. For example, Westmoreland County, PA, had two CS before 2005 and now with about 300 active shale gas wells, has 50 CS. In Pennsylvania. CS are allowed 750 ft. from homes, schools and businesses and emission monitoring relevant to public health exposure is limited or absent.

Current PA policies allow rapid CS expansion. Also, regulations do not address public health risks due to several major flaws. First, permits allow annual totals of emitted toxins using models assuming constant releases, but substantial emissions from CS occur in bursts that expose citizens to concentrations likely to impair health, ranging from asthma to cancer. Second, permits do not address the fact that CS simultaneously release many serious air toxins including benzene and formaldehyde, particulates that carry toxins into lungs and large amounts of lung irritants. This allowance of multiple toxin release does not reflect the well-established science that public health risks multiply when people are exposed to several toxins at once. Third, permit reviews rarely consider nearby known air pollution sources contributing to aggregate air toxin exposures that can occur in bursts and continually. Fourth, permits do not require operators to provide public access to real-time reports of air pollutants released by CS.

The annual cost of air pollution from CS was estimated at $4 million-$24 million in PA as one component of the shale gas industry in its early stages in 2011. As CS and gas infrastructures expand, air pollution and costs increase, especially in shale gas areas. These costs must be compared with benefits of using alternative energy sources. In a neighboring state, New York, shifting to renewable energy will save $33 billion annually in air pollution costs, prevent 4000 premature deaths each year, and trigger substantial job creation, based on peer-reviewed research using US government data.

<u>Recommendations</u>:

1. Constant air monitoring must occur at current compressor stations and nearby sites important to the public, such as schools. The peak concentrations and totals for substances relevant to public health must be recorded and made available to the public in real time.
2. Air pollution from compressor stations must become an important part of measuring and modeling pollution exposures from all components of the shale gas industry.
3. Permits for new compressor stations must be revised to better protect the publi in ways including, but not limited to the following:
   a) Location, e.g., increased general set-back limits and expanded limits for sensitive sites such as schools, senior homes and hospitals
   b) Emissions, especially limits for peak concentrations and annual totals
   c) Monitoring air quality within the station, at the fence-line and in key sites nearby, such as schools, using information from air movement models to select locations and heights.
   d) Limit CS size based on aggregate pollution from other local air pollution sources.
4. Costs of harm from CS and other shale gas activities must be compared to alternatives.

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Chemistry of Compressor Station Emissions

CS emissions contribute major air pollutants to totals from unconventional gas development (UCGD), but their role in regional air quality problems has not always been noted. In 2009, when UCGD operations were only a few years in this region and many CS had not yet been built, CS emissions were estimated to be a small component. Now, in 2020, gas transport requirements have increased, many more and larger CS are in place and these sources of emissions have greatly increased, based on estimates by Carnegie Mellon University atmospheric researcher, Robinson (Fig. 1). Also, looking forward, CS will remain a major pollution source because they run constantly in contrast to machinery for well development and trucking that fluctuate with the market for new wells.

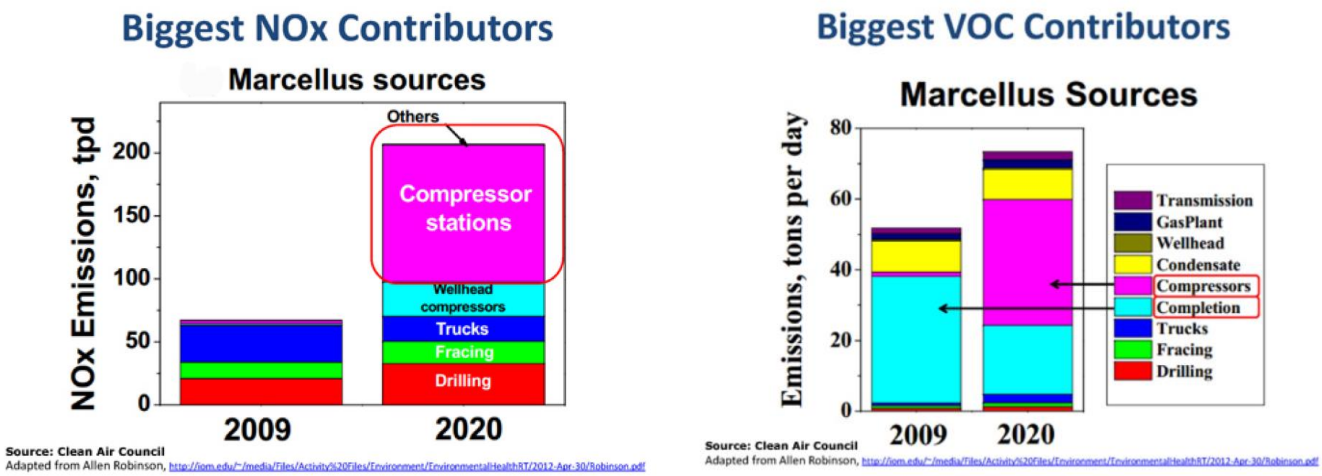

Fig. 1. Relative contribution of compressor stations and other components of shale gas industry to NOx and VOC. Source: Clean Air Council- adapted from webinar by Alan Robinson cited in figure.

Air pollutants in CS emissions vary substantially in chemistry and concentrations during days and weeks due to shifts in operations (Table 1). Emissions in CS can come from several types of sources described below.

1) **Engines:** Compression engines powered with methane release NOx, CO, VOCs and HAP. Diesel engines release those pollutants as well as SO2 and substantial particulate matter. In addition, diesel storage on site is a hazard. Electric engines would produce less pollutants, but they are much less common than fossil fuel engines in SWPA. Depending on demands for gas movement, compressor engines can be partially or fully shut down, or the source of the fuel can be changed.

2) **Blow-downs**: Toxic emissions dramatically increase during blow-downs, a procedure that is scheduled or used as needed to release the build-up of gases. Blow-down frequency and

emitted chemicals vary with the rate of gas transport and the chemistry of transported gases. The full extent of emissions from any CS, therefore, is not known. Blow-downs can release a wide range of substances, and when flaring is used to burn off gases, the combustion creates new substances and additional particulates. Blow-downs are the most likely source of peaks in emissions at continuously operated CS. Brown et al. (2015) used PA DEP measures of a CS in Washington Co., PA, likely blowdown frequencies and weather models to predict peak emission frequency. They estimated nearby residents would experience over 118 peak emissions per year.

3) **Non-compression Procedures:** CS facilities are often the location for equipment that separates gases, removes water and other fluids, and run pipeline testing operations called pigging. These activities can be constant or intermittent and release a wide range of substances which may or may not be included in estimates for a permit. In addition, some of the processing releases gases which are flared at the facility, thus releasing a range of combustion by-products and small particles. For example, the Shamrock CS operated by Dominion Transfer Inc. includes equipment for dehydration, glycol processing and pigging. The Janus facility operated by EQT includes dehydration and flaring. Emissions for those facilities are listed in Table 1.

4) **Storage Tank Emissions**: CS often include storage tanks that hold substances known to release fumes. For example, the Shamrock CS was permitted to have an above ground storage tank of 3000 gallons for drip gas and a 1000-gallon tank for used oil, both of which release volatile organic compounds. The EQT Janus CS has two 8,820-gallon tanks. Gas releases from such tanks could be controlled and recorded or fugitive and never noted in operator reports.

5) **Fugitive emissions**: Gases easily leak from many components in CS facilities; such problems will increase as equipment ages. A study of CS stations in Texas is an example. “In the Fort Worth, TX area, researchers evaluated compressor station emissions from eight sites, focusing in part on fugitive emissions. A total of 2,126 fugitive emission points were identified in the four month field study of 8 compressor stations: 192 of the emission points were valves; 644 were connectors (including flanges, threaded unions, tees, plugs, caps and open-ended lines where the plug or cap was missing); and 1,290 were classified as Other Equipment. The Other category consists of all remaining components such as tank thief hatches, pneumatic valve controllers, instrumentation, regulators, gauges, and vents. 1,330 emission points were detected with an IR camera (i.e. high-level emissions) and 796 emission points were detected by Method 21 screening (i.e. low-level emissions). Pneumatic Valve Controllers were the most frequent emission sources encountered at well pads and compressor stations.”
Eastern Research Group (2011).

Table 1. Examples of air pollutants allowed for release by compressor stations. Air pollutants (pounds/year) are estimates provided by the companies for permits in West Virginia and Pennsylvania in recent years. Total compressor engine horsepower (hp) is noted.

Pollutant	**Term**	**Janus (WV) 22,000 hp**	**Tonkin (WV) 4390 hp**	**Shamrock* (PA) 4140 bhp**	**Buffalo ** (PA) 20,000 hp + 5,000 bhp**
Nitrogen Oxides	NOx	254,400	248,000	170,000	155,800
Volatile Organic Compounds	VOC	191,200	30,000	66,000	77,000
Carbon Monoxide	CO	118,200	80,000	154,00,0	144,400
Sulfur Dioxide	SO2	1,400	400	10,000	5,400
Hazardous Air Pollutants	HAP	48,200		19,400	30,000
	Formaldehyde		1,080	12,800	12,200
	Benzene		540		
	Ethylbenzene		60		
	Toluene		140		
	Xylene		200		
	Hexane		500		
	Acetaldehyde		600		
	Acrolein		160		
Total Particulate Matter (<10 um)	PM	18,200	11,000	32,000	PM-10 32,000 PM-2.5 32,000
TOTAL TOXINS		**631,600**	**372,680**	**417,400**	**444,600**
Carbon Dioxide Equivalents	CO2-e	29,298,000	27,200,000	367,000,000	214,514,000

Sources for table:

- Janus and Tonkin CS Permits at WV DEP website.
- Shamrock CS permit: https://www.dep.pa.gov/About/Regional/SouthwestRegion/Community%20Information/Pages/Laurel-Mountain-Midstream.aspx
- Buffalo CS, Washington, Co PA - PENNSYLVANIA BULLETIN, VOL. 45, NO. 16 APRIL 18, 2015

Health Effects of Compressor Station Emissions

Several toxic chemicals are released by individual CS in amounts that range from a few thousand pounds to a quarter of a million pounds per year (Table 1& 2) as described below.

- The largest amount of the pollutants is usually a category called Nitrous Oxides (NOx). These oxides are formed when a fossil fuel such as methane or diesel is combusted to produce the energy to compress and propel gases. NOx contributes to acid rain. Excess acids in rain lower the pH of waters, in some cases to levels that dissolve toxic metals in drinking water supplies. NOx also triggers the formation of ozone, a substance well known to impair lungs.
- Ozone exposure can trigger asthma and heart attacks in sensitive individuals, and for healthy people, ozone causes breathing problems in the short term and eventual scarring of lungs and impaired function.
- Volatile Organic Compounds (VOC) include components toxic in themselves (Figure 2 and Table 3). Also, several VOC react to form ozone. Other VOC, such as methane, contribute to global warming.
- Carbon Monoxide (CO) is another product of fossil fuel combustion and another contributor to ozone formation. CO is directly toxic because it prevents oxygen from binding to the blood.
- Sulfur Dioxide (SO2) adds to lung irritation. It also contributes to acid rain, lowering the pH of water and increasing the ability of toxic metals to dissolve in water supplies.
- Hazardous Air Pollutants (HAP) include highly toxic substances such as formaldehyde and benzene, which are known carcinogens, and other substances listed in Table 1 and Fig. 2, a table listing HAP for a CS. Additional HAPs have been observed in emissions from CS including MTBE, iso-Butane, methyl mercaptan, n-Butane, n-hexane, n-octane, nitrous-acid, styrene, 2-methyl butane, 2 methyl pentane, 3 methyl pentane, and naphthalene, toluene and xylenes.
- Particulate Matter (PM) is usually monitored for particles that are smaller than 2.5 microns and less than 10 microns. Particles in those size ranges are not visible, but highly damaging because they travel deep into the lungs where they irritate tissues and impair breathing. Also, these tiny soot particles carry toxins from air into the blood passing through the lungs. This blood transports substances directly to the brain where toxins can quickly impair the nervous system and subsequently impact other organs.

Health impacts from many of the substances released by CS are well-known in medical research. For example, many of the VOC and HAP compounds permitted for release by state agencies are known carcinogens (Fig. 2). Many of these substances also impact the nervous system as shown in the organic compounds measured in CS in PA and listed in Tab.3 Also, a study of 18 CS in New York by Russo and Carpenter (2017) found that all 18 CS released substances with known impacts on the nervous system and total annual emissions were over 5 million pounds, among the highest of all types of emissions (Fig. 3). Russo and Carpenter also found high annual emissions of over 5 million pounds was also found for substances known to be associated with each of the following other health problems: digestive problems, circulatory disorders, and congenital malformations.

Congenital defects were significantly more common for mothers living in a 10-mile radius of denser shale gas development in Colorado compared to reference populations (MacKenzie et al. 2014). Currie at al. (2017) examined over a million birth records in Pennsylvania and found a statistically significant increased frequencies of low birth weight and negative health scores for infants born to mothers within 3 km of unconventional gas wells compared to matching populations more distant from shale gas developments. Such developments include a wide range of gas infrastructure including CS and also high truck traffic and fracking. One plausible mechanism for harm to developing babies is exposure to VOCs such as benzene, toluene and xylene associated with CS and well operations. These VOC's are classified by the Agency for Toxic Substances and Disease Registry as known to cross the placental barrier and cause harm to the fetus including birth deformaties.

Table. 2. Health effects of air pollutants permitted for release by compressor stations.

Pollutant	Health Effects
Particulate Matter	Impairs lungs and transfers toxins into body when microscopic particles carry chemicals deep into lungs and release into bloodstream.
Nitrogen Oxides	Forms ozone that impairs lung function, which can trigger asthma and heart attacks and scars lungs in the long term. Forms acid rain that dissolves toxic metals into water supplies.
Volatile Organic Compounds	Composed of many gaseous organic compounds, some of which cause cancer. Many VOC react to form ozone that impairs lungs as noted above.
Carbon Monoxide	Blocks ability of blood to carry oxygen. Also forms ozone that impairs lungs as noted above.
Sulfur Dioxide	Irritates lungs, triggering respiratory and heart distress. Forms acid rain that dissolves toxic metals into water supplies.
Hazardous Air Pollutants	Category of various toxic compounds many of which impact the nervous system. Includes formaldehyde, benzene and several other carcinogens.
TOTAL TOXINS	Combined toxins in short and long-term exposure are known to exacerbate harm directly through impairment of lungs and circulatory system and indirectly through injury to detoxification mechanisms, such as liver function.
Carbon Dioxide Equivalents	Calculated mostly from CO2 and Methane released. These gases trap heat and worsen climate change & related harm to health when increased air temperatures directly cause stress directly and indirectly accelerate ozone formation.

Table 4: Potential HAPs - Carcinogenic Risk

HAPs	Type	Known/Suspected Carcinogen	Classification
Acetaldehyde	VOC	Yes	B2 - Probable Human Carcinogen
Acrolein	VOC	No	Inadequate Data
Formaldehyde	VOC	Yes	B1 - Probable Human Carcinogen
Methanol	VOC	No	No Assessment Available
Biphenyl	VOC	Yes	Suggestive Evidence of Carcinogenic Potential
1,3-Butadiene	VOC	Yes	B2 - Probable Human Carcinogen
Naphthalene	VOC	Yes	C - Possible Human Carcinogen
n-Hexane	VOC	No	Inadequate Data
Benzene	VOC	Yes	Category A - Known Human Carcinogen
Toluene	VOC	No	Inadequate Data
Ethylbenzene	VOC	No	Category D - Not Classifiable
Xylenes	VOC	No	Inadequate Data
2,2,4-Trimethylpentane	VOC	No	Inadequate Data

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Fig. 2. List of carcinogenicity rating for Hazardous Air Pollutants (HAPs) known to be released by compressor stations in a factsheet prepared by EQT for Janus compressor, WV. 2015 dep.wv.daq/Documents/January%202015%20Draft%20Permits/3269-Eval.pdf

Table 3 Health effects for volatile organic carbons measured by PA DEP near compressor station.

Substance	Exposure Symptoms	Target Organs
Ethylbenzene	irritation eyes, nose; nausea, headache; peripheral neuropathy: numb extremities, muscle weak; dermatitis; dizziness;	Eyes, skin, respiratory system, central nervous system, peripheral nervous system
n-Butane	Drowsiness	Central nervous system
n-Hexane	Irritation eyes, skin, respiratory system; headache, dizziness; nausea	Eyes, skin, respiratory system, central nervous system
2-Methyl Butane	na	na
Iso-butane	drowsiness, narcosis, asphyxia;	Central nervous system

Source: https://www.cdc.gov/niosh/npg/npgd0322.html

Table 3.17b.

Congenital Malformations, Deformations & Chromosomal Abnormalities by ICD Code Group

NYS Natural Gas Compressor Stations, 2008-2014

ICD-10			Facilities				Chemicals				Pounds			
#	Description		'08	'11	'14	Tot	'08	'11	'14	Tot	2008	2011	2014	Total
1	Q00-Q89	Congenital malformations and deformations	18	18	17	18	57	54	54	57	4,393,806	6,607,676	5,900,691	16,902,175
1.1	Q00-Q07	Nervous system	18	18	17	18	16	16	16	16	4,068,877	5,882,704	5,258,344	15,209,926
1.2	Q10-Q18	Eye, ear, face and neck	15	15	12	15	4	4	4	4	5,825	19,569	11,475	36,869
1.3	Q20-Q28	Circulatory system	18	18	17	18	10	10	10	10	4,269,779	6,336,905	5,651,896	16,258,581
1.4	Q30-Q34	Respiratory system	14	8	7	14	4	4	4	4	150	107	113	372
1.5	Q35-Q45	Digestive system	18	18	17	18	17	17	17	17	4,386,043	6,586,345	5,884,324	16,856,713
1.6	Q50-Q56	Genital organs	6	7	8	8	2	2	2	2	1,399	4,373	2,612	8,385
1.7	Q60-Q64	Urinary system	18	17	16	18	9	9	9	9	119,382	254,922	237,359	611,663
1.8	Q65-Q79	Musculoskeletal system	18	18	16	18	19	19	19	19	122,314	262,300	243,932	628,547
1.9	Q80-Q89	Other	18	18	17	18	55	52	52	55	2,124,445	3,614,575	3,413,375	9,152,395
2	Q90-Q99	Chromosomal abnormalities, nec	18	18	16	18	30	31	31	32	120,669	256,739	239,709	617,118
	Q00-Q99	**Total**	**18**	**18**	**17**	**18**	**57**	**56**	**56**	**59**	**4,393,806**	**6,607,676**	**5,900,691**	**16,902,175**

Fig. 3. Amounts of pollutants known to be associated with health impacts in a review of 18 New York compressor stations. Emissions were grouped and tallied based on their impacts on disorders classified by ICD codes as defined by the International Statistical Classification of Diseases and Related Health Problems (ICD), a medical classification list by the World Health Organization (Copied from Russo and Carpenter 2017.)

Regional Air Toxins and Cancer Risk

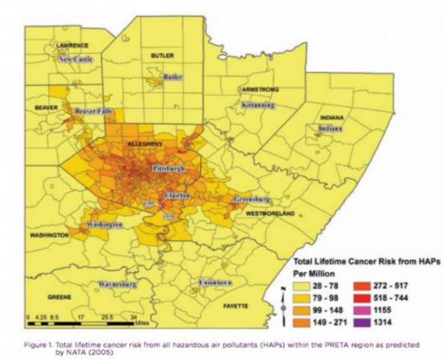
Cancer risks from Hazardous Air Pollutants (HAP) have been elevated for many years in several areas of Southwestern PA, as noted in maps from 2005 (Fig. 4), when unconventional gas development (UCGD) had just begun in the region and more recently in 2014 (Fig. 5). Such maps are likely to be under-reporting risk levels, however, in both the amount rates of risk and also the locations. These maps are constructed by the EPA office of National Air Toxics Assessment using models of reported air toxics and their relationship to cancer, not direct observations of cancer incidence in a region.

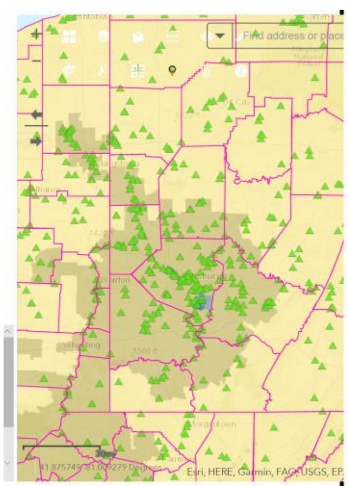
Cancer risk from serious air pollutants cannot be properly mapped for several reasons. First, reports on concentrations of HAP in emissions are limited. HAP emissions are in accounts required only from large facilities, and thus, smaller operations, such as many CS, are likely be ignored. Second, general air quality monitoring stations are limmited in location and do not measure HAP. For example, the PA DEP maintains 47 air quality stations dispersed among over 60 counties (http://www.dep.state.pa.us/dep/deputate/airwaste/aq/aqm/pollt.html). Most report hourly measures of Ozone and PM-2.5 and only a handful also monitor one or more other substances such as CO, NOX, SO2 or H2S. One couty, Allegheny, has a county health department that maintains 17 stations to report real-time air quality based on Ozone, SO2 or PM-2.5 (https://alleghenycounty.us/Health-Department/Programs/Air-Quality/Air-Quality.aspx).

In sum, cancer risk estimates from air pollution fall short in the following ways:

1) Estimates of air quality do not reflect the reality of air pollution from CS as well as many other new sources such as increased truck traffic associated with shale gas development.
2) Tallies of annual emissions do not represent the actual exposures of individuals to pulses of toxins.
3) Models of air pollution and cancer are not sufficiently based on real world studies of impacts from multiple toxins in short and long-term exposures.

Figure 4. Right--Cancer risk map in Southwestern Pennsylvania in 2005 from the National Air Toxics Assessment program in the EPA (https://www.epa.gov/national-air-toxics-assessment)





Legend

Green triangles- Facility level information

Colored sections:

Cancer Risk – Total Risk

Light Pink 0-25

Gray 25-50

Blue 50-100

Figure 5. Cancer risk map in Southwestern Pennsylvania in 2014 from the National Air Toxics Assessment in the EPA. Source: https://gispub.epa.gov/NATA/. Facilities are locations where air quality information was available for modeling. Total Risk of cancer from all causes is assumed to be 1/1,000,000 for most areas. Thus, Cancer Risk-Total Risk from air pollution is 0-1-24/1,000,000 in Light Pink areas, 25-49/1,000,000 in Gray areas, and 50-74/1,000,000 in Blue areas.

Measurements of Compressor Station Emissions

Studies of concentrations of air pollutants from CS in real world locations are lacking, but some reports exist. Of these, a few are in peer-reviewed studies, and these are described below. They all show the high variation over time for CS emissions and the occurrence of peak concentrations.

Macey et al. (2014) observed ambient air near CS contained toxins at concentrations that impair health. They collected grab samples of air from industrial sites including CS in Wyoming and Arkansas and analyzed them for toxins using EPA approved methods. Figure 6 (Copy of Table 4 from article) shows most of the CS studied in Arkansas released formaldehyde at amounts associated with a cancer risk of 1/10,000. This is 100 times greater than the broadly accepted baseline cancer risk of 1/1,000,000. Formaldehyde and benzene were found at similar amounts and cancer risks near Wyoming CS. Some observed toxins are less well studied than formaldehyde and benzene. For example, 1,3-butadiene is classified by the EPA as a known human carcinogen, but a calculation of cancer risk for this substance is lacking. Air samples in the Macey study were collected close to the CS (e.g., 30-42m) and at greater distances (e.g., 254-355m). Those distant samples were well beyond the 750-foot set-back rule for Pennsylvania. At all these distances, air movement modeling predicts that toxins released from a source such as a CS are likely to travel downwind within the air mass under most weather conditions, thus exposing residents near and further from CS. Many people, therefore, in homes, schools and businesses that are downwind of CS are likely to experience serious air toxins at concentrations that harm their health.

Air toxins were also measured by the Pennsylvania Department of Environmental Protection in 2010 in a variety of unconventional gas extraction facilities including one CS in Washington County PA. Brown et al. (2015) reported these data, showing the concentrations that citizens could experience near a compressor station varied greater than 10-fold within a day and among consecutive days (Fig. 7). The length of time for peak concentrations was unknown, but Brown et al. used a model of weather including wind patterns to estimate citizens are likely to experience 118 peak concentrations per year.

Goetz et al. (2015) sampled air in Marcellus shale regions of PA for short periods (1-2.5 hrs.) at distances 480-1100 meters from eight CS, four with relatively small capacity (5,000-9,000 hp) and four with moderate capacity (14,000-17,000 hp). They found that each CS had a different pattern of relatively higher concentrations of some pollutants versus other pollutants. For example, among the eight CS, the one with the lowest NOX measure had the highest measure of a VOC (Ethane). Other CS showed different patterns. Also, totals of all pollutants did not correlate with compressor engine capacity, probably because the CS they sampled include a mix of engines using fossil fuels and electric power. Goetz et al. concluded with recommendations for more comprehensive and longer term monitoring to better understand air pollution from CS and all components in shale gas development.

Methane is the substance tracked most often in emissions from CS and other gas industry facilities because of its central role in operations, requirements to avoid explosive concentrations, and readily available measurement technology, compared to other substances emitted from CS. Although methane emissions from CS are not always correlated with amounts of other, more toxic emissions, patterns observed in plumes of methane from CS are likely to reflect elevated concentrations of other toxic substances from CS.

Nathan et al (2015) sampled methane emissions from one CS in the Barnett shale region using a sensor carried on a model aircraft. The open-path, lazer sensor produced measures with a precision of 0.1 ppmv over short intervals allowing researchers to see variation in time and space as the aircraft changed position. Based on 22 flights during one week, they observed a substantial range in methane released from 0.3 – 73 g CH_4 per second. These values calculate to 0.02 – 6.3 metric tons per day, a range that matches that estimated by Goetz of 0.5 -9 metric tons per day. In addition, Nathan et al. found high variability in concentrations at different heights, as the emission plumes shifted in response to wind velocity, direction and topography. They recommend caution in interpretations of ground-based emission monitors and called for more monitoring of air movements and emissions at different elevations.

Payne et al. 2017 confirmed these ideas when they mapped plumes of methane in CS in New York and PA using a sensor capable of recording methane in parts per million (ppm) every 0.25-5 seconds . The sensor was located on a mobile unit that marked GPS location. They found high variability in the shape and extent of plumes. For example, one of most extensive plumes was recorded near Dimock, PA in a local with CS as the only major source of methane. Researchers recorded the highest concentrations of methane in the study, 22 ppm, at 500 m from the CS, with a second peak of 0.6 ppm noted over 1 km from the CS and elevated methane as far as 3 km from the site (Fig. 8). Wind direction did not always predict the shape of the plume, but data collection was restricted by the path of the sensor and the transport vehicle (Fig. 8). Most importantly, they found that …"during atmospheric temperature inversions, when near-ground mixing of the atmosphere is limited or does not occur, residents and properties located within 1 mile of a compressor station can be exposed to rogue methane from these point sources." These residents are likely to also experience excess toxins from CS as well, especially under such weather conditions.

Exposure to peak concentrations of air pollutants have dramatic effects on health for several reasons. First, lungs carry toxins into the blood within seconds, and the blood quickly transfers compounds to the brain and other vital organs. Many of the substances released by compressor stations impact the central nervous system as seen in Table 3, and these toxins are released simultaneously. Citizens, therefore inhaling a plume of emissions will have impacts from the total of these compounds. The health impacts for these combined toxins are unknown, and especially of concern during pregnancy and child development. Exposure studies in animals and humans test individual substances and the Center for Disease Control and NIOSH use these to develop exposure guidelines for a healthy adult in a work-place. In contrast, residents near compressor stations will include citizens of all ages with various health conditions. For example, the American Lung Association determined that over 50% of the 30,000 residents of Westmoreland County are at greater risk for health impairment due to air pollution because they have one or more of these conditions: asthma, diabetes, heart disease, respiratory illness, advanced age (https://www.lung.org/our-initiatives/healthy-air/sota/key-findings/people-at-risk.html).

In sum, the research on CS emissions of methane, air pollutants such as NOx, and hazardous air pollutants such as formaldehyde and benzene, all indicate exposures to the general public from CS emissions pose a threat to public health, but the emissions have not yet been fully quantified and modeled. Documenting CS contributions to harmful ambient air quality is feasible, however. The published studies from as back as 2011 indicate that instrumentation to record substances and weather are readily available. Activities within a station such as compressor function, blowdowns, venting and flaring are all recorded by operators, but such reports are not released to researchers or the public. The science of models that predict public health risks in response to air pollution exposure are highly developed. In sum, operators of CS have the technology to measure emissions and ambient air quality and scientists have the models, but lack of industry data prevents the public from knowing impacts from CS.

Table 4 Concentrations of volatile compounds exceeding health-based risk levels in samples collected in Arkansas

State/ID	County	Nearest infrastructure	Chemical	Concentration (μg/m^3)	ATSDR MRLs exceeded	EPA IRIS cancer risk exceeded
AR-3136-003	Faulkner	355 m from compressor	Formaldehyde	36	C	1/10,000
AR-3136-001	Cleburne	42 m from compressor	Formaldehyde	34	C	1/10,000
AR-3561	Cleburne	30 m from compressor	Formaldehyde	27	C	1/10,000
AR-3562	Faulkner	355 m from compressor	Formaldehyde	28	C	1/10,000
AR-4331	Faulkner	42 m from compressor	Formaldehyde	23	C	1/10,000
AR-4333	Faulkner	237 m from compressor	Formaldehyde	44	C, I	1/10,000
AR-4724	Van Buren	42 m from compressor	1,3-butadiene	8.5	n/a	1/10,000
AR-4924	Faulkner	254 m from compressor	Formaldehyde	48	C, I	1/10,000

C = chronic; I = intermediate.

Figure 6. Air toxins found in grab samples near compressor stations including concentrations, the Agency for Toxic Substances and Disease Registry (ASTDR) Minimum Risk Level (MRL) exceedance, and the Environmental Protection Agency (EPA) Integrated Risk Information System (IRIS) cancer risk. Copied from Macey et al. 2014

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

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

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

Fig. 7. Variation in air pollutants measured in ug/cubic meter by PA DEP during two sampling times per day for three consecutive days near a compressor station in Southwest PA. Copied from Brown et al. 2015 based on data from Southwestern Pennsylvania Short Term Marcellus Ambient Air Sampling Report, Pennsylvania Department of Environmental Protection, Nov. 2010.

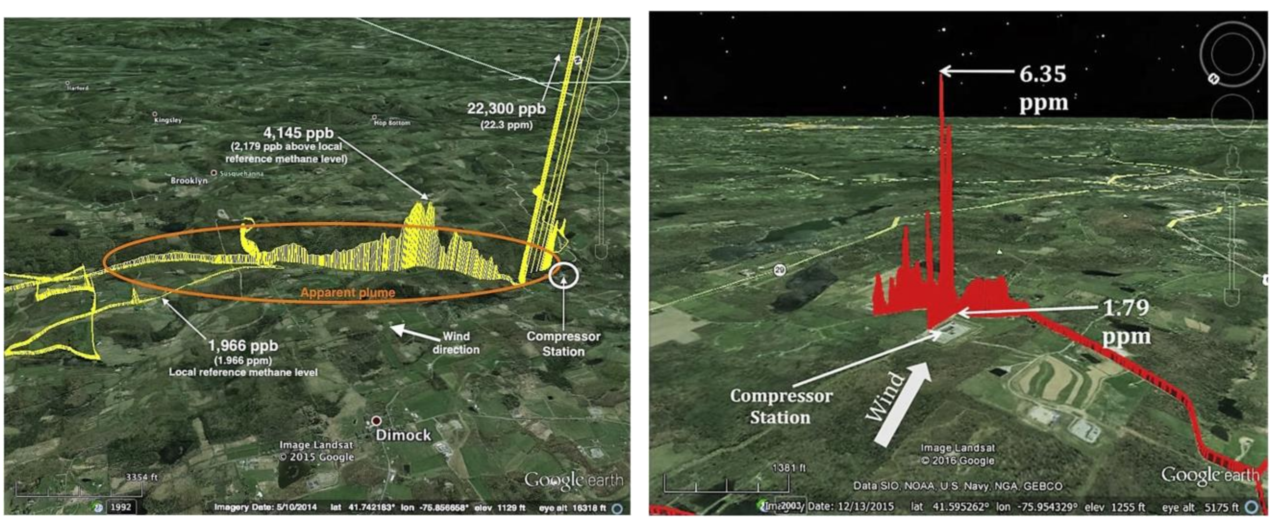


Fig. 8. Methane emission plumes from compressor stations near Dimock, PA (left) and Springvale, PA (right). Copied from Payne et al. 2017.

Compressor Station Locations

Prior to 2008, compressor stations were infrequent with one or a few per county broadly distributed across PA as part of gas transport from locations outside of PA (Fig. 9). These pipelines were mainly an issue for public health in the case of explosions. Major transmission pipelines use pressures up to 1500 psi. Leaks, therefore, release large amounts of gas much of which is not noticed because it lacks the mercaptan odorant added to household methane. For example, the 30-inch Spectra gas pipeline that exploded in 2016 in Westmoreland County caused a hole 12 ft deep 1500 ft square and burned 40 acres. The PA DEP claimed to have measured air quality, but they did not arrive until long after the plume from the fire traveled downwind. This pipeline was transporting gas from one of the largest gas storage facilities in the country, the Sunoco Gas Depot in Delmont, PA to New Jersey as part of over 9,000 miles of pipelines in the Texas Eastern system from the Gulf Coast to the Northeast. That section of pipeline was built in 1981 and had recently been increased in pressure, probably using older or newer compressors in nearby locations. Faulty joints between pipeline sections were blamed for the catastrophic release of gas. (Phillips, S. 2016. State Impact, NPR). Immediately after the explosion, while gas continued to pour out of the pipeline, emergency workers needed at least one hour to locate shut-off locations. In general, pipeline shut-offs are sited at compressors stations or at intervals along a pipeline.

CS abundance in counties with shale gas extraction increased over 10-fold in the decade after 2005 when the gas industry obtained exemptions to the Clean Water Act and began unconventional gas extraction in PA (Fig 10). Permit applications for new wells, pipelines and CS continue throughout SW PA. The development of the gas industry involves substantial air pollution sources that add to the air pollution from CS.

Each stage of gas extraction involves emissions that can be close or far from the well pad. Most emissions involve diesel engines. Diesel engines are well-known to produce substantial amounts of VOC's, NOx and particulate pollution (PM-2.4, PM-10). Well pad construction requires intense activity by diesel trucks and earth moving equipment. Well drilling uses diesel engines. From 3-5 million gallons of water are used for each fracking event and up to 300 truck visits are needed to transport water for the many wells that are not close to water supplies from piped sources. Trucks are used to transport the 1-2 million gallons of produced water that emerges from the well for disposal in injection wells likely to be distant from most wells. Additional waste is carried long distances as well, including drill cuttings and sludge. For example, shale gas industry waste was handled for years in Max Environmental, one of the largest industrial waste sites in the eastern US located in Yukon, Westmoreland County since the 1960's. Within one mile of Yukon is Reserved Environmental, a waste facility with operations focused since 2008 on processing sludge from fracking into solid cakes to be trucked to other landfills. In sum, all stages of shale gas industry contribute to many poorly documented sources of air pollution likely to be near CS.

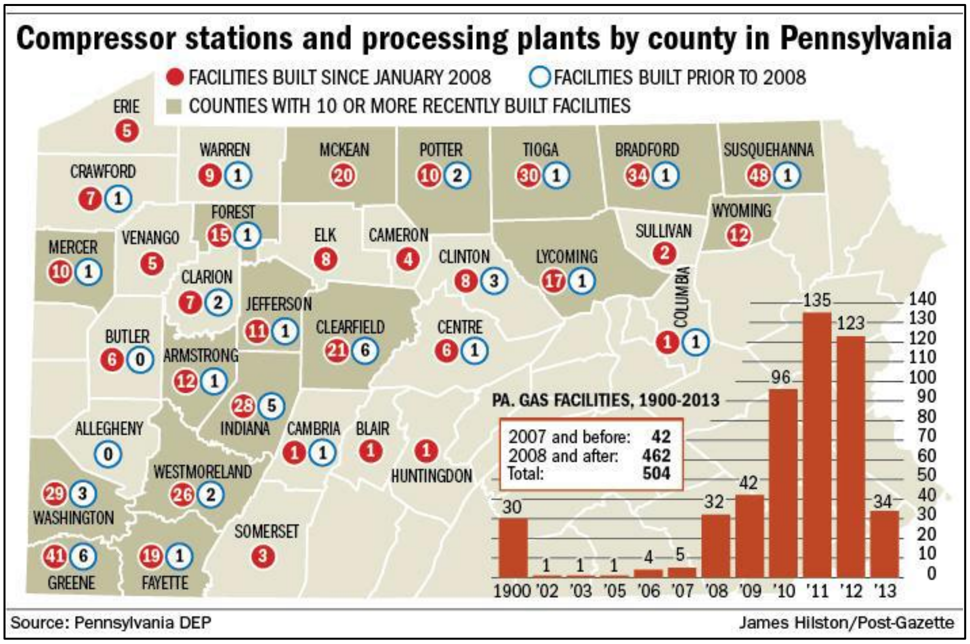


Fig.9 Compressor Stations prior to 2008 and in around 2013. Copied from article by James Hilton in Pittsburgh Post-Gazette.

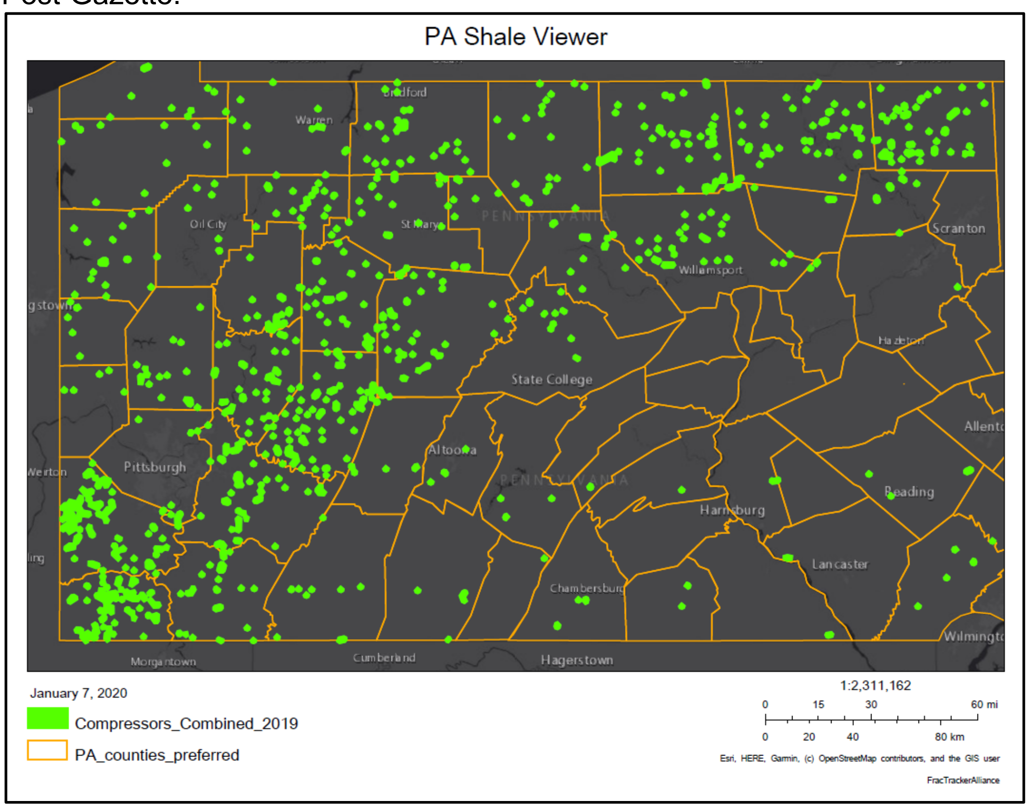


Fig.10. Compressor Stations in Pennsylvania mapped in 2019 (Source: Fracktracker 2000)

The density of CS in some areas such as SWPA impacts the local air quality and sites downwind. For example, people in Westmoreland County receive emissions from CS in their immediate vicinity and possibly additional air pollutants from CS and other industries in neighboring counties. Wind patterns shown in Figure 11 indicate Westmoreland County is frequently downwind from Washington County, a county with a very high density of shale gas operations, and Eastern Allegheny County where large industries such as coke works release large amounts of air pollutants.

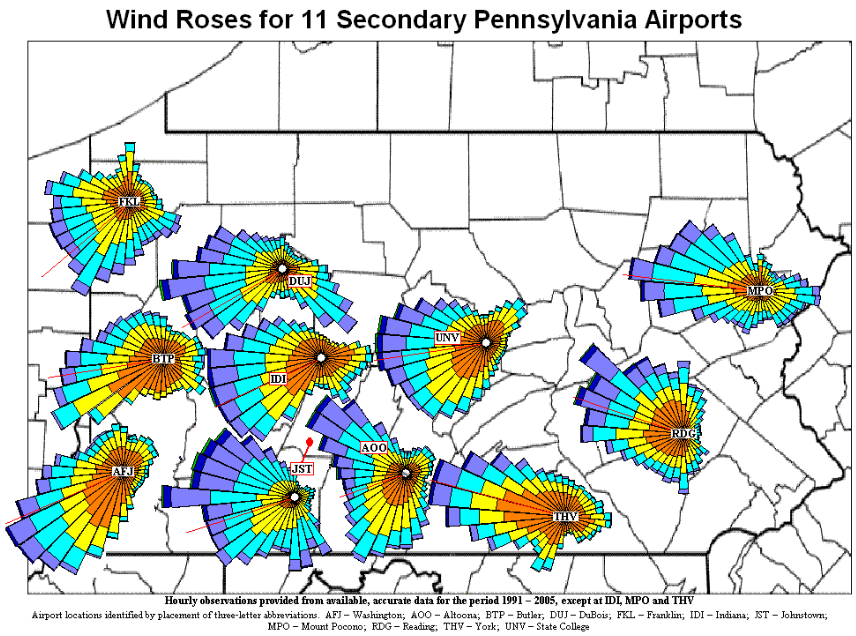


Figure 11. Wind patterns at small airports around Pennsylvania showing predominant direction of wind and velocity in knots (Orange 0-4, Yellow 4-7, Turquoise 7-11, Medium Blue 11-17, Dark Blue 17-21)

Costs of Compressor Stations and Air Pollution

As permanent, constant sources of air and noise pollutantion and safety risks, CS add a significant cost to communities. Poor air quality alone is well-established as an economic drain for a region due to many factors including increased health care, lower property values, a declining tax base, and difficulty in attracting new businesses or housing development. Litovitz et al. (2013) estimated that, compared to other activities of shale gas extraction, CS made up the majority of the annual emsissions of important air toxins in 2011, and therefore a majority of the damages from air pollution, totalling 4-24 million dollars of the 7-32 million dollars of the aggregate air pollution damages (Fig. 12). Given that CS increased even faster than new well construction in some areas from 2011 to the present, CS are likely to be an even greater component of air pollution damages.

Litovitz and others recognizec that, in 2011, emissions from shale gas activities on a state-wide basis in may appeared to be small compared to other industries such as coal burning power plants and coke production, but that appearance deserves a second look. First, shale gas extraction actvities are concentrated in a few regions of Pennsylvania, and local air quality is most relevant to public health and local economics such as property values. Second, emissions from gas extraction in 2011 was only in its early stages in Pennsylvania and will expand greatly unless regulations change, while coal-fired power plants are declining due to the advanced age of most facilities. For example, in Westmoreland County, PA alone there are over 50 CS in 2020, the number currently in the entire state of New York, where unconventional gas development was suspended due, in large part, to concerns for public health. Costs from one aspect of an energy sector can be viewed in the context of economic and other benefits of alternative energy efforts. For example, Jacobson et al. (2013) estimated that shifting to renewable energy in NY state would prevent 4000 premature deaths each year and save $33 billion/year through air pollution reductions in health care and related costs.

Table 5. Statewide emissions estimates for shale gas development and production in 2011.

Activities	Statewide annual emissions (metric tons per year) VOC	NO_x	$PM_{2.5}$	PM_{10}	SO_x
(1) Transport	31–54	550–1000	16–30	17–30	0.82–1.4
(2) Well drilling and hydraulic fracturing	260–290	6600–8100	150–220	150–220	6.6–190
(3) Production	71–1800	810–1000	15–78	15–78	4.8–6.2
(4) Compressor stations	2200–8900	9300–18 000	280–1100	280–1100	0–340
Total[a]	2500–11 000	17 000–28 000	460–1400	460–1400	12–540

[a] These totals are reported to two significant figures, as are all intermediate emissions values in this document. The activity emissions may not exactly sum to the totals.

Table 6. Estimates of regional air pollution damages from Pennsylvania extraction activities in 2011.

Activities	Timeframe	Total regional damage for 2011 ($2011)	Average per well or per MMCF damage ($2011)
(1) Transport	Development	$320 000–$810 000	$180–$460 per well
(2) Well drilling, fracturing	Development	$2 200 000–$4 700 000	$1 200–$2 700 per well
(3) Production	Ongoing	$290 000–$2 700 000	$0.27–$2.60 per MMCF
(4) Compressor stations	Ongoing	$4 400 000–$24 000 000	$4.20–$23.00 per MMCF
(1)–(4) Aggregated	Both	$7 200 000–$32 000 000	NA

Fig. 12. Costs of damages due to air pollution from shale gas extraction in PA.Table 5 and 6 copied from Litovitz et al. 2013.

Major Studies Cited in Text:

Brown, David, Celia Lewis, Beth I. Weinberger and Heather Bonaparte. 2014. Understanding air exposure from natural gas drilling put air standards to the test. Reviews in Environmental Health DOI 10.1515/reveh-2014-0002

Brown, David, Celia Lewis and Beth I. Weinberger. 2015. Human exposure to unconventional natural gas development; a public health demonstration of high exposure to chemical mixtures in ambient air. Journal of Environmental Science and Health (Part A) 50: 460-472.

Currie, J, M Greenstone and K Meckel. 2017. Hydraulic fracturing and infant health: New evidence from Pennsylvania. Science Advances 2017;3:e1603021

Eastern Research Group, Inc. and Sage Environmental Consulting, LP. City of Fort Worth natural gas air quality study: final report. 2011. Available at: http://www.edf.org/sites/default/files/9235_Barnett_Shale_Report.pdf . July 13, 2011.

Goetz, J.D. E. Floerchinger,E., C. Fortner, J. Wormhoudt, P. Massoli, W. Berk Knighton, S.C. Herndon, C.E. Kolb, E. Knipping, S. L. Shaw, and P. F. DeCarlo. 2015. Atmospheric Emission Characterization of Marcellus Shale Natural Gas Development Sites DOI: 10.1021/acs.est.5b00452
Environ. Sci. Technol. 49, 7012−7020

Jacobson, MZ, RW Howarth, MA Delucchi, ST Scobie, JH Barth, M Dvorak, M Klevze, H. Hatkhuda, B. Mirand, NA Chowdhury, R Jones, L Plano, AR Ingraffea. 2013.
Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight. Energy Policy 57: 585-601.

Litovitz, A., A. Curtright, S. Abramzon, N. Burger and C. Samaras. 2013. Estimation of regional air-quality damages from Marcellus Shale natural gas extraction in Pennsylvania
Environ. Res. Lett. 8; 014017 (8pp) doi:10.1088/1748-9326/8/1/014017

Macey, G.P., Breech, R., Chernaik, M. (2014) Air concentrations of volatile compounds near oil and gas production: a community-based exploratory study. *Environ Health* **13,** 82 (2014). https://doi.org/10.1186/1476-069X-13-82

McKenzie, LM, G Ruisin, RZ Witter, DA Savitz, LS Newman, JL Adgate. 2014.
Birth Outcomes and Maternal Residential Proximity to Natural Gas Development in Rural Colorado. Environmental Health Perspectives Vol 22. http://dx.doi.org/10.1289/ehp.1306722.

Nathan BJ, LM Golston, AS O'Brien , K Ross, WA Harrison, L Tao, DJ Larry, DR Johnson, AN Covington, NN Clark, MA Zondlo. 2015. Environ Sci Technol. 2015 Near-Field Characterization of Methane Emission Variability from a Compressor Station Using a Model Aircraft. Environ Sci Technol. 2015 Jul 7;49(13):7896-903 doi: 10.1021/acs.est.5b00705.

Payne, RA, P Wicker, ZL Hildenbrand, DD Carlton, and KA Schug. 2017. Characterization of methane plumes downwind of natural gas compressor stations in Pennsylvania and New York. Science of The Total Environment 580:1214-1221

Russo, PN and DO Carpenter 2017. Health Effects Associated with Stack Chemical Emissions from NYS Natural Gas Compressor Stations: 2008-2014 Institute for Health and the Environment, A Pan American Health Organization / World Health Organization Collaborating Centre in Environmental Health, University at Albany, 5 University Place, Rensselaer New York.
Https://www.albany.edu/about/assets/Complete_report.pdf