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INTRODUCTION

Oil and gas development using hydraulic fracturing ('fracking') and horizontal drilling (also known as unconventional oil and gas production) has expanded dramatically in recent years in the United States,[1] putting more wells and other facilities in close proximity to communities and raising concerns about exposure to local and regional pollution and its potential health impacts.[iii] At the same time, there remains a relative paucity of publicly available scientific data on the health hazards, risks, and impacts of hydraulic fracturing. Aside from a small but growing number of observational studies on associations between hydraulic fracturing and health impacts,[2] too little is known about the actual levels of pollutants around unconventional oil and gas production sites and human exposure to them. Pollution concerns – and corresponding demands for more detailed data on pollution sources, types, and exposures – from oil and gas exploration and production arise during all stages of the process, including pad construction, drilling rig set-up, horizontal drilling, hydraulic fracturing, oil or gas production, treatment, storage and transmission, well decommissioning, and land restoration.[3]

Since a growing number of communities in Pennsylvania, Colorado, Texas, and other states are experiencing the large-scale implementation of hydraulic fracturing, there is a need to collect more data and increase scientific understanding on pollutant levels and human exposures in order to develop adequate public health protections. This need is further elevated by the exemption of many oil and gas

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[iii] Hydraulic fracturing and horizontal drilling involve the pumping of large volumes of water mixed with chemicals and proppant (most often sand) under high pressures through long horizontal wellbores into hydrocarbon-rich rock formations with the purpose of creating and propping fractures open to enable to flow of trapped oil and/or gas to the well's surface. The term hydraulic fracturing has become synonymous with all stages of development, production, and post-production rehabilitation of oil or gas wells that use hydraulic fracturing to release hydrocarbons from shale and tight oil and gas reservoirs.

related practices from many federal regulatory and reporting requirements on the use or release of hazardous substances that are applicable in other industrial settings.[4,5] These limitations in federal authority to monitor and regulate the oil and gas sector have resulted in a patchwork of state and local rules that are inconsistent and incomplete.

In response to these concerns and the persistent data gaps, NRDC collaborated with the Harvard Center for Health and the Global Environment, the Mid-Atlantic Center for Children's Health & the Environment (MACCHE),[6] and the Health Effects Institute (HEI) to identify recommended practices for conducting air and water monitoring to inform public health assessments and support adequate protections for communities near hydraulic fracturing operations. The workshop resulted in the publication of a Proceedings report that is publicly available.[7] NRDC also conducted a series of public webinars in June 2014, which shared the findings of the workshop and collected additional feedback from communities impacted by hydraulic fracturing as well as from researchers, public health advocates, and other stakeholders.[8]

We discuss three types of monitoring programs:

- **Community investigations** examining potential exposures that could be linked to reports of health impacts or concerns among residents;
- **State/federal monitoring programs** focused on environmental quality, potential health threats, and compliance of oil and gas sites;
- **Health risk and impact studies** to identify health risks, model exposure pathways, evaluate exposure levels and their association and causal relationships with reported health effects.

(Note that these programs are not designed to address the implications of methane emissions in the context of climate change. Although climate change carries known and serious adverse public health risks, their consideration is beyond the scope of our project.)

OVERVIEW OF HEALTH RISKS FROM UNCONVENTIONAL OIL AND GAS DEVELOPMENT[iv]

As an industrial process, oil and gas extraction using hydraulic fracturing shares many of the steps and processes of conventional oil and gas development and a systems approach is appropriate to assess their threats to human health. Typically, distinction is made between the following life cycle stages.[9]

- Exploration[v], well pad and infrastructure preparation;
- Drilling of the well and construction of associated facilities (e.g., pumps, storage tanks, pipelines);
- Hydraulic fracturing and well completion (including flowback and initial oil or gas flow);
- Production (including produced water and connection of well to transmission infrastructure);
- Well plugging, abandonment, and site rehabilitation

Each of the above steps is associated with potential releases of a range of pollutants into the air, water, and soil at varying times, intensities, and frequencies that pose physical, safety, and health hazards at the local to the regional level.

[iv] Much of the text for this portion of these comments comes from an NRDC report that will be publicly released in mid-October, 2014.

[v] Exploration in this context would refer to activities that help narrow down the location of the well pad prior to drilling the production well, including evaluation of petrology, lithology, and stratigraphy, seismic evaluation, and topographic and other landscape and ecosystem features that may influence well pad siting.

Exploration, well pad and infrastructure preparation

Exploration can include seismic testing as well as drilling of exploratory wells. Initial well site preparation involves the construction of roads, pipelines, pits, and well pads, as well as the transportation of drilling equipment and materials such as the drill rig, well construction materials, pumps, compressors (e.g., for air drilling), storage containers, chemicals, and mixing equipment for drilling fluids and additives. The pollution associated with this stage, therefore, comes largely from combustion engines and includes diesel emissions such as particulate matter (diesel PM), BTEX (benzene, toluene, ethylbenzene, and xylene), other volatile organic compounds (VOCs), including polycyclic aromatic hydrocarbons (PAH), nitrogen oxides (NOx), but also road dust (PM), and potential releases of drilling mud components and storm water runoff.

Prolonged exposure to BTEX compounds has effects on the kidney, liver and blood systems.[10] Benzene is a known carcinogen (e.g., leukemia).[11] VOCs and NO_x contribute to the formation of regional ozone, which causes smog and is very harmful to the respiratory system.[12] [13] [14] Particulate matter can cause respiratory problems including coughing, airway inflammation and worsening of existing respiratory illnesses such as asthma and COPD, and premature death.[15] [16]

Well drilling

Drilling horizontal wellbores can take 3 to 4 weeks of continuous operations and involves boring through thousands of feet of rock and installing and cementing thousands of feet of casing into the borehole. The enormous power required to drill long laterals and run the piping typically requires numerous diesel-powered engines and compressors, resulting in emissions of diesel PM, NOx, BTEX, and PAH. Exposure to these compounds can lead to a range of health impacts, including respiratory and cardiovascular problems ranging from coughs to heart attacks and premature mortality.

The drilling mud used to cool the drill bit, remove drill cuttings, and control subsurface pressure consists of water, oil, synthetic or gaseous base fluids mixed clays, weighting agents, polymers (synthetic thickeners), and other chemical additives, the composition of which depends on well-specific factors. The drilling muds bring rock cuttings and formation components such as stray gases and brines to the surface. After going through a shaker to reuse portions of the drilling muds, the left-over drill cuttings are stored in impoundment pits, where chemicals and formation components may become volatilized. Drill cuttings can be contaminated with drilling mud and hydrocarbons and may contain naturally occurring radioactive material (NORM), heavy metals, and other contaminants of concern. These cuttings may be buried on site, which could lead to soil or groundwater contamination if the pits are not properly sealed or leak over time.

Hydraulic fracturing and well completion

The chemicals used in hydraulic fracturing fluid include carcinogens, mutagens, teratogens, and compounds that have adverse effects on the nervous system, kidneys, liver, as well as the blood and endocrine systems, while others can cause eye, nose, throat irritation, and skin rashes.[17] [18] Prior to mixing they present health threats through unintentional releases such as during road transport, faulty operation of equipment, and leaks from storage containers.[19]

The chemicals are mixed with water and a proppant to manufacture a hydraulic fracturing fluid. The most widely used proppant is silica sand. Each hydraulically fractured well requires on average several thousand tons of silica to hold open the fractures created during the hydraulic fracturing process. Inhalation of respirable silica can cause the irreversible lung disease silicosis and lung cancer. Silica inhalation is now a recognized health hazard among oil and gas workers, who are exposed when silica is moved and blended at the well cite. Some measured concentrations exceeded the maximum use concentration of half-mask air-purifying respirators.[20]

To create pathways for hydrocarbons to flow from the shale rock formation to the wellhead, perforating guns create a series of small holes through the steel and cement casing of the horizontal section of the wellbore. Then up to 20 diesel-powered pump-trucks generate the 10,000 psi needed to inject the hydraulic fracturing fluid into the well. Fracturing is done in 10-100 stages by plugging off sections of the horizontal wellbore from the 'toe' of the well towards the 'heel' (the section where the vertical well moves to a horizontal direction). Once fracturing is completed, the plugs used to separate the various fracture stages are removed. Hydraulic fracturing fluids then return to the surface as 'flow back', which consists of the used hydraulic fracturing fluid combined with some amount of naturally occurring formation water, chemical additives, dissolved metal ions, naturally occurring radioactive material (NORM), and total dissolved solids (TDS). Once a sufficient amount of fracturing fluid and proppant have returned to the surface, production tubing and packers are then run into the well and a wellhead is set up, which controls the flow of formation fluids to the surface and through the flowline to production facilities such as separators and storage tanks. Flowback water is captured on-site in open pits and storage tanks where it can release volatile chemicals and compounds, including benzene and methanol, into the atmosphere and also poses spill and overflow risks to the surrounding area.

Diesel emissions as well as emissions of natural gas associated with the flowback process are significant sources of emissions during these process stages. Natural gas consists of 70-90% methane but also contains other hydrocarbons such as ethane and pentane, and hydrogen sulfide (H_2S). Hydrocarbons and hydrogen sulfide can escape into the atmosphere creating episodic acute exposure risks that could result in headaches, nausea and other neurologic symptoms, as well as eye and respiratory irritation. Hydrogen sulfide is a toxic and explosive gas that is damaging to the central nervous system at low concentrations and can be lethal at higher concentrations (~ 1000 ppm).[21] Oil and gas workers may be required to wear protective respirators but residents living in close proximity to well pads are not protected.

Production

During the production phase – which can last decades and involve repeated work-overs – the well head, condensate tanks, processing equipment on the well pad, compressors, open wastewater storage pits, compressors, and even closed storage tanks can be sources of methane and non-methane VOCs, including numerous toxic air pollutants. Compressor engines are the most significant source of NO_x with 70% of emissions attributed to them. VOCs are mostly released from well pad storage tanks and pneumatic devices at production units (up to 75% of VOC emissions). Pneumatic devices are also estimated to account for more than 50% of fugitive methane emissions.[22] [23]

In contrast to flowback, produced water is naturally present in oil- and gas-bearing formations and is co-produced with the oil and gas throughout the entire lifespan of the well. This water has a wide range of compositions depending on geology but can have high levels of total dissolved solids (TDS) and metals including arsenic, barium, calcium, iron and magnesium. It also contains dissolved hydrocarbons such as methane, ethane and propane along with naturally occurring radioactive materials (NORM) such as radium isotopes (Ra-226 and Ra-228).

Flowback and produced water are sometimes stored in open wastewater evaporation pits or open storage tanks. Exposure of communities and residents to airborne volatile pollutants from evaporation pits (especially those that use misters and vaporizers) has been raised as a concern.[24 25] Another route of contamination and exposure is through ground and surface drinking water sources as a result of overflows and ruptured liners or unlined pits. The majority of wastewater, more than 95%, is disposed of in deep underground injection wells (UIC Class II wells). High-pressure injection in Class II wells has now been linked to contamination of drinking water[26] and induced seismicity, which may cause property damage or injury.[27 28 29 30]

Well malfunctioning, storage and transport spills, and leaks of flowback and/or produced water have been documented.[31,32] Waste water that is sent to treatment plants pose a risk to surface water because these facilities are not always equipped to handle all types, volumes, and concentrations of oil and gas wastewater, which may result in undesirable treatment and disinfection bi-products such as trihalomethanes due to their bromide content.[33 34 35 36 37 38]

Naturally Occurring Radioactive Materials (NORM) create exposure hazards to workers at the well site and to neighboring communities and the environment. It can accumulate in pipes and other well equipment, pass through wastewater treatment facilities and into streams and rivers, and contaminate the air and soil when radioactively contaminated water or other waste is sprayed on roads for dust control and de-icing or applied to or stored on land.[39 40]

An examination of more than 75,000 compliance reports for 41,381 conventional and unconventional oil and gas wells drilled in Pennsylvania between 2000 and 2012 found that the incidence of cement and/or casing integrity failure was six-fold higher for unconventional wells versus conventional wells and also varied by geographical location of the well.[41]

Well plugging, abandonment and site rehabilitation

When the well reaches the end of its productive life span or is temporarily idled, emissions depend on well integrity and proper plugging and site rehabilitation procedures. Loss of well integrity and problems such as sustained casing pressures can lead to leakage of oil, methane, and non-methane VOCs into the air or soil long after the well has been abandoned.[42 43] Failure of well construction materials including casing and cement could allow oil, gas, and naturally occurring toxics and radioactive materials to escape from the well and migrate into shallower groundwater aquifers. Improper or inadequate plugging of abandoned wells can also cause releases into the environment.

Noise and Light Pollution

Well pad preparation, drilling, hydraulic fracturing, and repeated work-overs generate significant noise levels for neighboring residences, schools, and work places. The noise – from trucks, generators, drilling operations, compressors, pumps and other equipment and activities – can occur intermittently for months at a time over several years as wells are hydraulically fractured and reworked many times.[44] Produced gas e.g., during flowback or production that is not captured and sold may be flared 24 hours a day, producing not only additional air pollution but a constant roar and bright light.[45] The health effects associated with noise and light pollution include sleep disturbance, fatigue, reduced school and work performance, hypertension and cardiovascular problems.[46]

Community Safety

Communities are impacted by unconventional oil and gas development in a multitude of ways. From a health perspective air and water pollution are among the most direct health hazards, but the rapid increase in the scale of hydraulic fracturing and its encroachment of towns and communities has also generated a substantial traffic problem. Traffic accidents have risen in rural areas across the country as a result of large numbers of heavy trucks moving water, chemicals, sand, and waste to and from well sites as well as from the influx of itinerant workers.[47] [48]

OVERVIEW OF AIR AND WATER QUALITY MONITORING

General principles of air quality monitoring

Air quality monitoring helps to assess the extent of pollution, ensure compliance with national legislation, evaluate control options, and provide data for air quality modeling. In the context of unconventional oil and gas development, air monitoring needs to address two aspects:

- Air emissions monitoring for compliance purposes, including identification of the types and quantities of pollutants emitted from different sources (source attribution), designing effective emission control programs, and ensuring that emissions fall within permissible limits aimed at protecting human health and the environment;
- Air quality monitoring for human health protection.

The design of air monitoring systems, i.e., the selection of the types of air monitors to be used, their siting, and the frequency of sampling, therefore, need to take these two different objectives into account. In addition, protecting human health requires knowledge and information on potential human exposure pathways, the identity and toxicity of the chemical and physical agents that humans may be exposed to, the location of current and anticipated future sources of emissions, as well as their typical operating patterns.

Since unconventional oil and gas development using hydraulic fracturing is occurring in close proximity to towns and residences, it is important to establish a baseline (pre-drilling) assessment of air quality and major sources of air emissions in conjunction with basic population health data. Establishing such a baseline assessment facilitates the identification of subsequent sources of cumulative pollution, source attribution for subsequent pollutants, and epidemiological analyses of changes in population health.

Air quality monitoring for human health protection

Considering the rapid evolution of industrial-scale unconventional oil and gas development over the past decade, air quality monitoring plans should not only include contaminants covered by existing health-related regulations but also newly emerging contaminants of concern, e.g., chemicals and other additives found in hydraulic fracturing fluid. The contaminants that may be of greatest health and safety concern may not be the ones that are regulated or monitored. The current regulatory standards or 'compliance monitoring' is too limited and rigid to form the basis of a comprehensive air quality monitoring program. Sampling requirements are also too infrequent and benchmark values ill-defined to capture and assess potential acute exposure episodes.[49]

Moreover, a single pollutant approach to assessing potential health threats is unsuitable in the unconventional oil and gas development context due to the frequent presence of mixtures of pollutants. Source- or site-specific emissions also need to be viewed in a spatial context and aggregated locally to obtain a more complete picture of the cumulative exposure burden of the population.

Monitoring should also account for vulnerable individuals, including the elderly, infants and children, and the infirmed by locating monitors at or near nursing homes, childcare centers and schools, and hospitals.

General principles of water quality monitoring

Water quality monitoring is done to characterize water conditions for ecological and human health objectives and involves chemical, physical, and biological parameters that are collected on a temporary or seasonal basis. In unconventional oil and gas development the focus is on detecting subsurface and surface pathways of pollution, identifying their causes (e.g., leaks and faulty well casings), and assessing their potential impacts on human health. In addition, compliance monitoring can be conducted for effluents of wastewater treatment plants that receive wastewater from unconventional oil and gas operations.

As is the case in air quality monitoring, the design of water monitoring programs needs to take into consideration information on potential human exposure pathways, the identity and toxicity of the chemical and physical agents, hydrogeology, and the location of current and anticipated future unconventional oil and gas operations in relation to drinking water sources.

<u>Water quality monitoring for subsurface migration of pollutants</u>

Methane contamination of drinking water resulting from unconventional gas development is a well-documented concern.[50] [51] Oil and gas production poses risks for methane contamination of underground drinking water sources through leaking oil and gas wells, migration through hydraulically fractured rock, communication of fractures with existing faults and rock fractures, and with nearby wells that have been poorly constructed, poorly maintained, or abandoned, or which haven't been designed to withstand the pressures used during hydraulic fracturing.[52] [53] [54]

Although the available information is still limited, the emerging consensus appears to be that the probability of the fracturing process itself causing groundwater contamination by creating fractures that extend from depth to drinking water aquifers or that connect to natural faults and fractures that connect to drinking water aquifers is smaller than the likelihood of contamination events from blowouts, improper well construction or operations, and spills and leaks at the surface. Causes of well integrity failure are complex and may be related in varying degrees to poor industry practices, inadequate regulation and enforcement, well age, poor casing and cementing practices, well location and type.[55] [56] To allow the detection and correct attribution of the source of groundwater contamination, a monitoring program should include a pre-drilling baseline assessment, and monitoring throughout the productive life of the well and beyond as contaminants may migrate slowly and hence not be detected for some time.

The analytes to monitor should be selected taking local reservoir formation factors into account and include methane as the main component of natural gas (or equivalently liquid hydrocarbons in oil producing shales and tight sands), hydraulic fracturing chemicals such as methanol and chloride, and formation components such as barium, strontium, and radionuclides (226Ra and 228Ra).[57] Source attribution for contaminated water wells may be possible by using methane-chloride ratios, ethane and propane levels, and noble gas tracers.[58]

Existing regulatory programs for water quality monitoring may not be sufficient. The Safe Drinking Water Act (SDWA), for example, has maximum contaminant levels (MCLs) for only about ninety contaminants, while hydraulic fracturing fluids may contain hundreds of compounds, many of which lack even the most basic health information.[59]

For surface water quality monitoring, monitoring stations or sampling should be conducted downstream from wastewater discharge sites, wastewater treatment plants, and in water bodies that are located down-gradient from oil or gas well locations. Effluent from wastewater treatment should be screened for physical and chemical parameters linked to oil and gas development that the treatment processes may not fully eliminate or may alter in their composition, such as radionuclides and bromides (forming disinfection by-products such as trihalomethanes).[60,61] Flowback and produced water from unconventional oil and gas wells is known to be high in chemicals that inhibit aerobic and anaerobic wastewater treatment processes, so facility operators should monitor for signs of decline in process efficacy.[62]

Water monitoring for accidents, spills and leaks

A recent investigation of spill reports in most states with hydraulic fracturing found a 17% increase in the number of accidental releases from 2012 to 2013.[63] There were at least 7,662 spills, blowouts, leaks and other mishaps in 2013 in 15 top states for onshore oil and gas activity, i.e., more than 20 spills per day with a combined volume of more than 26 million gallons of oil, hydraulic fracturing fluid, hydraulic fracturing wastewater and other substances. The true number and volumes released is likely much larger than this due to inadequate monitoring and reporting practices. An investigation by the Pennsylvania Department of Environmental Protection (PA DEP) found that only about half of all spills that resulted in a fine were detected by on-site workers and personnel, the remainder having been found by residents and inspectors.[64] Leak detection equipment on storage tanks, impoundment ponds, and transportation pipelines can be effective in limiting accidental releases of contaminants into the soil, surface water bodies, and shallow groundwater.

Monitoring Transparency and Community Engagement

Communities experiencing unconventional oil and gas development, especially those that have not had oil and gas development in the past, should be engaged in the monitoring program design and implementation process. They should be informed about why and what monitoring is being planned, where and how it will be conducted, and how the results will be publicly shared. Community engagement is not only a question of community empowerment and trust, but also serves many practical purposes in designing effective monitoring systems. Access to private property, for example, and other siting questions benefit from community transparency and buy-in. In addition, ‘citizen science’ is a rapidly emerging form of affordable data collection on individual exposures, for spill, accident and leak detection, and to increase effective sample sizes in epidemiological studies. Individual and communities should thus be engaged in every step of the monitoring process from development of the plan to collecting the information and sharing the results. States and federal governments should be responsive and accountable to community concerns, by evaluating the use of monitoring as a means of evaluating health threats.

CONCLUSION

There are many significant challenges to developing effective and comprehensive environmental monitoring programs. Overall, the design of effective and comprehensive air and water quality monitoring systems is very resource intensive - financial resources, personnel, time, and equipment - and requires extensive expert knowledge on the physical and chemical agents to be monitored (physical and chemical characteristics, exposure pathways, fate and transport in the environment, and toxicology). Monitoring programs must be tailored for the local context and are therefore often difficult to generalize to other sites. Effective monitoring must take routine and unpredictable emissions and releases into account as well as short and long time frames and cumulative impacts of mixtures of contaminants. All monitoring programs are significantly hampered by confidential business information (CBI) claims and other restrictions on the disclosure of information on chemicals. Ultimately, to provide protection for human health and the environment, strong regulations are required and must be enforced, regulatory loopholes need to be closed, limitations need to be placed on the use of CBI claims, and communities need timely and accurate information about the potential risks they face.

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[6] MACCHE disclaimer: This material was developed by the Association of Occupational & Environmental Clinics and funded under the cooperative agreement award number 1U61TS000118-03 from the Agency for Toxic Substances and Disease Registry (ATSDR). Acknowledgement: The U.S. Environmental Protection Agency (EPA) supports the Pediatric Environmental Health Specialty Unit (PEHSU) by providing funds to ATSDR under Inter-Agency Agreement number DW-75-92301301-0. Neither EPA nor ATSDR endorses the purchase of any commercial products or services mentioned in PEHSU publications.

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