Environmental Science & Technology
Critical Review
pubs.acs.org/est

Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development

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ABSTRACT: The rapid increase in unconventional natural gas (UNG) development in the United States during the past decade has brought wells and related infrastructure closer to population centers. This review evaluates risks to public health from chemical and nonchemical stressors associated with UNG, describes likely exposure pathways and potential health effects, and identifies major uncertainties to address with future research. The most important occupational stressors include mortality, exposure to hazardous materials and increased risk of industrial accidents. For communities near development and production sites the major stressors are air pollutants, ground and surface water contamination, truck traffic and noise pollution, accidents and malfunctions, and psychosocial stress associated with community change. Despite broad public concern, no comprehensive population-based studies of the public health effects of UNG operations exist. Major uncertainties are the unknown frequency and duration of human exposure, future extent of development, potential emission control and mitigation strategies, and a paucity of baseline data to enable substantive before and after comparisons for affected populations and environmental media. Overall, the current literature suggests that research needs to address these uncertainties before we can reasonably quantify the likelihood of occurrence or magnitude of adverse health effects associated with UNG production in workers and communities.

I. INTRODUCTION

The U.S. holds large reserves of on-shore natural gas in many regions, including but not limited to the Barnett Shale in Texas, the Denver-Julesberg Basin in Colorado, and the Marcellus Shale in the northeast.[1,2] Technological advances in directional and horizontal drilling and hydraulic fracturing (referred to herein as unconventional natural gas, UNG) have eased access to shale and tight gas reserves that were previously uneconomical to recover, resulting in a "shale gas boom" at the beginning of the 21st century.[3,4] In the U.S., the number of UNG wells rose from 18 485 in 2004 to 25 145 in 2007 and it is estimated that over 11 000 wells are hydraulically fractured each year.[5,6] As of 2011, 95% of the natural gas consumed in the U.S. was produced domestically and production is projected to increase from 23 trillion cubic feet in 2011 to 33.1 trillion cubic feet in 2040, with almost all the projected growth in UNG production.[7] The most recent worldwide estimates of natural gas reserves are 2.6−5.7 times greater than what was estimated in the 1990s.[8]

As UNG development grows, it is expected to become more common near where people live and work, increasing the likelihood of human exposure to associated pollutants and related chemical and nonchemical stressors as well as transport of pollutants to nearby cities.[1,9−13] With any fossil fuel development, there is a potential for release of air and water pollutants, physical and public safety hazards, and a range of psychosocial stressors. At present the potential risks from UNG development are more uncertain than risks from conventional natural gas development.[1,6,10,12−19] This is because hydraulic fracturing fluid contains potentially hazardous chemicals, well fracturing requires large volumes of water and sand, and the overall process creates air pollution and large volumes of wastewater containing dissolved chemicals and contaminants of subterranean origin.[4] While unconventional technologies allow for consolidation of several wells on one well pad, multiwell pads focuses an intense industrial activity in one area for several months.[3,12] To maintain gas flows, wells may also be fractured more than once.[3,20] Because UNG development is a recent phenomena, relatively little peer-reviewed public health research exists. Nonetheless, there are potential health risks because production is rising and increasingly occurring near where people live and development is transforming both the population and character of nearby communities.[1,10,12,21] The lack of research on population health effects has led to broad public concern about the potential consequences of the UNG development process.

Special Issue: Understanding the Risks of Unconventional Shale Gas Development

Received: October 15, 2013
Revised: February 4, 2014
Accepted: February 10, 2014

Table 1. Relationships between Sources, Processes and Hazards That May Lead to Human Exposure, Health Effects or Population Health Effects[a]

		chemical hazards					
source	process	air	ground water	surface water soil/ sediments	physical hazards	safety hazards	water scarcity hazard
large trucks	all	DE			noise, vibration	spills and accidents	
heavy equipment	well pad construction, drilling, and well abandonment	DE			noise, vibration	spills and accidents	
dust	well pad construction, well abandonment	PM					
drilling mud	drilling	DMV	DM	DM			
fracturing fluid	hydraulic fracturing, flowback	Silica, FFV	FF	FF		spills	removes water from hydrological cycle
generators	drilling, hydraulic fracturing	DE			noise		
produced water	drilling and construction, flowback	DMV, PHC	DM, PHC, IN	DM, PHC, IN		spills	
drill cuttings	drilling and construction	PM, DMV, PHC	DM, PHC, IN	DM, PHC, IN		spills	
flowback water	flowback	FFV, PHC	FF, PHC, IN	FF, PHC, IN			
deep injection	flowback				seismic activity		
gas venting	drilling, flowback, production	CH_4, H_2S, PHC				accidents	
gas flaring pigging[b]	drilling, flowback, production	NO_X, CO_2,			noise		
	production	CH_4, PHC				accidents	
pipelines	production	CH_4, PHC				accidents	
condensate tanks	production	CH_4, PHC					

[a] **CH_4**: methane; **CO_2**: carbon dioxide; **DE**: diesel emissions, including particulate matter (**PM**), nitrogen oxides (NO_x), polyaromatic, aliphatic, and aromatic hydrocarbons, aldehydes, and sulfur dioxides (SOx); **DM**: drilling muds, e.g., boric acid, borate salts, rubber-based oil, synthetic oil; **DMV**: drilling Muds, Volatile, e.g., rubber-based oil, synthetic oil, aluminum tristearate, choline chloride; **FF**: fracturing fluids, e.g., lauryl sulfate, guar gum and others (see Table 2); **FFV**: fracturing fluids, volatile: e.g., glutaraldehyde, ethylene glycol, methanol,, petroleum distillate; **H_2S**: hydrogen sulfide; **IN**: inorganic chemicals; barium, strontium, bromine, heavy metals, salts and NORM (naturally occurring radioactive materials); **NO_X**: nitrogen oxides; **PHC**: aromatic and aliphatic petroleum hydrocarbons. Refs: King, G.E., Hydraulic Fracturing 101: What Every Representative, Environmentalist, Regulator, Reporter, Investor, University Researcher, Neighbor and Engineer Should Know About Estimating Frac Risk and Improving Frac Performance in Unconventional Gas and Oil Wells. *SPE Hydraulic Fracturing Technology*; Woodlands, TX, 2012; Jiang, M., et al. Life cycle greenhouse gas emissions of Marcellus shale gas. *Environ. Res. Lett.*. 2011. 6(3); United States Department of Energy, *Modern Shale Gas Development in the United States: A Primer*; Oklahoma City, OK, 2009. [b]The process of using gauges to perform maintenance on gas lines without stopping the flow of gas in the pipe line.

This review takes a systems approach to exploring main sources, hazards, exposures, and potential population health effects associated with UNG development in the US. We summarize the strengths and limitations of the existing literature on exposure pathways, environmental media concentrations, and potential risks for workers and communities as well as evaluate existing and potential approaches for assessing population health effects. We also identify risk mitigation strategies and related public health research needs.

II. HAZARDS AND SCALE OF EXPOSURES

As with any complex industrial process, UNG development is a series of steps best viewed as a system: (1) well pad and infrastructure preparation; (2) drilling and construction of well pipelines and facilities; (3) hydraulic fracturing; (4) "flow back" of gas, fracturing fluids, and produced water during well completion; and (5) subsequent connection of the well to the natural gas distribution system.[3] During the 20−30 year production life of a well petroleum byproducts are collected for sale and wastes (e.g., drilling cuttings, flowback and produced water) are treated, recycled and/or disposed offsite. Table 1 summarizes the relationship between major sources, development processes and hazards that may lead to human exposures and health effects. In addition to the chemical, physical, and safety hazards specified in Table 1, Figure 1 outlines the major psychosocial stressors associated with UNG development that may affect the health of nearby populations.

Chemical and nonchemical stressors found in and around UNG development sites may affect both workers and communities. The overall effect of these stressors on population health depends on the hazards, exposure pathways, and temporal and spatial reach of each stressor and its impacts, which may range from the well pad to local, regional, and global scales. The key exposure pathways and health effects are governed by the rate of release, fate and transport, persistence, and frequency and duration of human contact with each stressor, as well as the human behavioral factors that increase or decrease the likelihood of exposure (Figure 1). At the well site itself, the most imminent potential public health effects are accidents and injuries to workers who may also be exposed to acute (e.g., H_2S) and chronic (e.g., silica) stressors.[6,22] Stressors that exert their impacts at the local scale include chemical

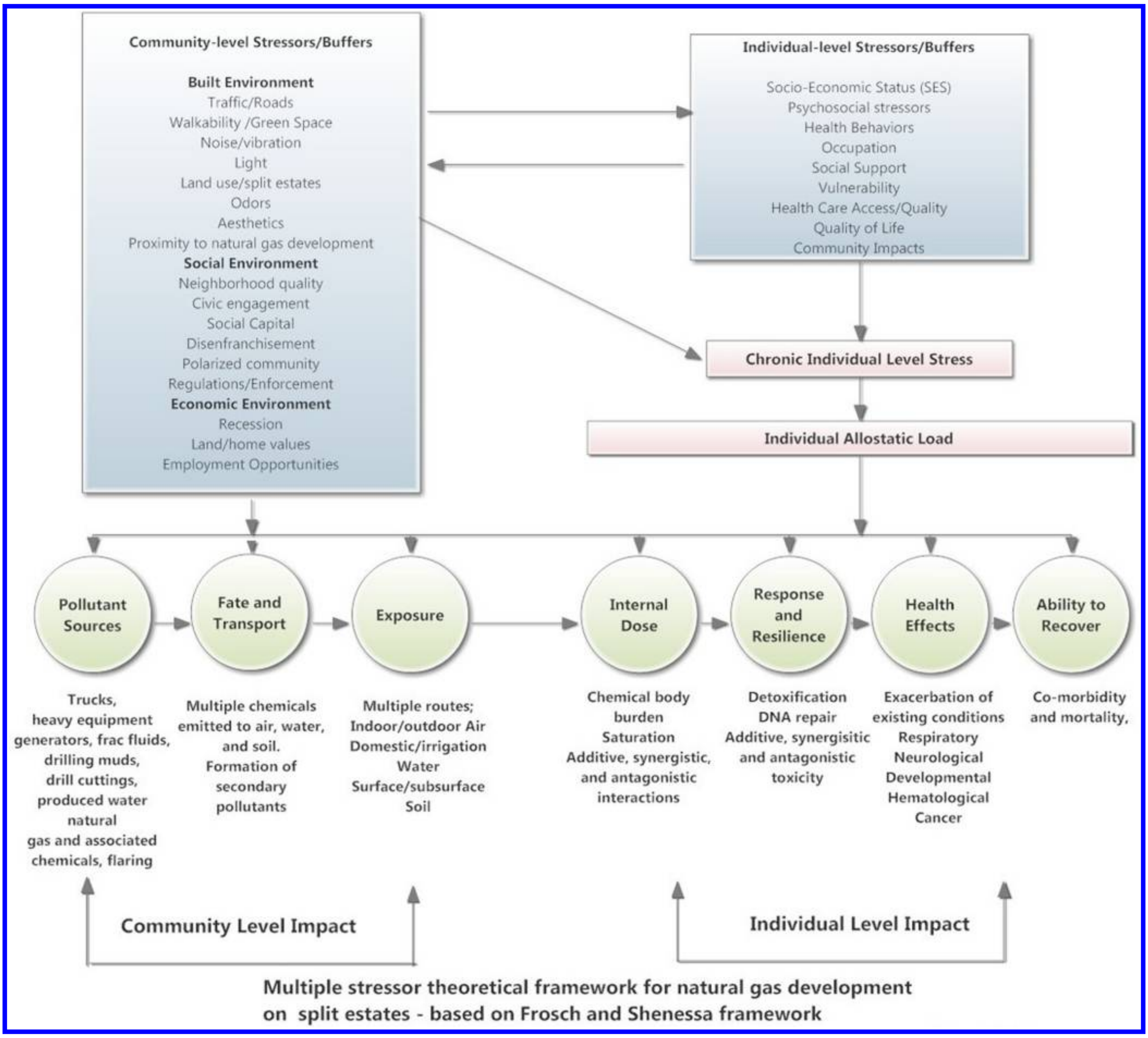

Figure 1. Allostatic load conceptual model describing community and individual level stressors and their relationship with psychosocial stress.

hazards transported offsite, such as volatile organic compounds (VOCs), diesel exhaust, fracturing fluids, and drilling and hydraulic fracturing wastes that migrate offsite through spills, leaks, or accidents (Table 1). Though there are potentially mitigating factors, such as increased tax revenue or income for leaseholders, nearby residents may complain of odors, noise, light, or psychosocial stress from declining land values or decreased housing availability.[10,23,24] The development of intracommunity differences in the perception of risk and rewards may also lead to stress in some residents.[25] Some local stressors may also be regional issues, such as water availability, ground level ozone, and water quality. At the global scale, the contribution of UNG development to methane and carbon dioxide levels in the atmosphere has broad implications for population health.[26,27]

The following sections describe existing mortality and morbidity outcomes that may stem from the major chemical, physical and psychosocial stressors that exist in and around UNG development as well as the pathways by which these stressors may affect workers and communities.

III. EXPOSURE PATHWAYS AND HEALTH EFFECTS

A. Occupational. *1. Fatalities and Injuries.* Industrial incidents, malfunctions, and worksite and traffic accidents put workers at increased risk of exposure to fires, explosions, and uncontrolled chemical releases. While there are no data specific to UNG production, data on the oil and gas industry indicate that it has a high occupational fatality rate. Between 2005 and 2009, the fatality rate was two and a half times the rate in the construction industry and 7-fold higher than the general industry rate.[22,28] Bureau of Labor Statistics data indicate that the fatality rate for oil and gas workers was more than 8-fold higher than in other occupations.[28] Nearly a third of the deaths were due to traffic accidents and single-vehicle rollovers were the most common accident type. Mortality rates are also related to the size of the company, with smaller companies having higher fatality rates compared to medium and large-sized operators.[29] Although the mortality rate data are aggregated across petroleum and natural gas workers, state-level data collected in Wyoming during the recent gas production boom suggest that the recent increase in natural gas development had a major impact on mortality trends. Between 2001 and 2008, Wyoming had 32 fatalities from drill rig accidents and 25 transportation-related fatalities in the oil and gas sector.[30] Wyoming also had the highest workplace fatality rate in the country in five of the six years between 2003 and 2008, and in 2010 its occupational fatality rate was three and half times the national average.[30,31] In contrast to worksite fatalities, nationwide rates of reportable injuries in the oil and gas industry were ∼3 folder lower than in the construction industry, though this may be a result of under-reporting.[16,22,28] Under-reporting would be consistent with the findings of Mendeloff and Burns (2012), who found an unexpected negative correlation between reported fatalities and nonfatal injuries in the similarly decentralized construction industry, which the authors suggest was due to under-reporting of nonfatal injuries when fatalities were high.[32]

2. Air Pollution. Unconventional natural gas development and production workers are at risk from air pollution exposure because they work in and around major emission sources. Air pollution from UNG development originates from (1) direct and fugitive emissions of methane and nonmethane hydrocarbons from the well and associated infrastructure (e.g., production tanks, valves, pipelines, and collection and processing facilities); (2) diesel engines that power equipment, trucks, and generators; (3) drilling muds, fracturing fluids, and flowback water; and (4) deliberate venting and flaring of gas and related petroleum products.

Hydrogen sulfide (H_2S), which is naturally occurring in natural gas reserves, is an explosion risk and is arguably the greatest acute toxicity hazard for natural gas workers.[33−35] Significant irritant and other central nervous system health effects occur at or above 100 ppm, and these effects gradually increase in severity with duration of exposure, with immediate death occurring at ∼1000 ppm.[34] Little data exist on the frequency of occupational exposure to H_2S, but many companies require use of alarmed personal monitors to prevent fatalities.[16,22]

Among the hundreds of chemicals used to drill and fracture wells, silica is the most common additive to the process. Silica is also one of the key occupational hazards for workers because mechanical handing of crystalline silica, which is used as a proppant during hydraulic fracturing, creates large clouds of respirable dust.[16,36] Esswein et al.'s recent study of workers in Colorado, Texas, North Dakota, Arkansas, and Pennsylvania found that 8 h time weighted average breathing zone silica concentrations in 111 samples ranged from 0.007 mg/m^3 to 2.76 mg/m^3.[37] Nintey-three (84%) of the samples exceeded the American Conference of Industrial Hygienists threshold limit value (TLV) of 0.025 mg/m^3, 76 (68%) exceeded the National Institute of Occupational Safety and Health (NIOSH) recommended exposure limit (REL) of 0.05 mg/m^3, and 57 (51%) exceeded the Occupational and Safety Health Administration's (OSHA) current permissible exposure limit (PEL) for respirable silica-containing dust. Increasing evidence of the toxicity of silica has led OSHA to recently propose dropping its PEL to match the NIOSH REL.[38] Respirable silica can cause silicosis and lung cancer and has been associated with tuberculosis, chronic obstructive pulmonary disease (COPD), kidney disease, and autoimmune disease.[16] Exposure to silica dust also poses a hazard to workers in industries supporting shale gas development, such as sand mining and transport.[39]

Workers also may be exposed to petroleum hydrocarbons, such as aromatics (e.g., benzene, toluene, ethyl benzene, and xylenes; hereafter BTEX) and aliphatic compounds during well development and production.[27] The health effects most often associated with benzene include acute and chronic nonlymphocytic leukemia, acute myeloid leukemia, chronic lymphocytic leukemia, non-Hodgkins lymphoma, anemia and other blood disorders and immunological effects.[40,41] Occupational exposure to petroleum compounds is also associated with increased risk of eye irritation and headaches, asthma symptoms, and multiple myeloma and non-Hodgkins lymphoma.[42−47] Many of the common petroleum hydrocarbons measured in and around UNG sites, such as BTEX, have robust toxicity databases and health-based standards, while toxicity information for others, such as heptane, octane, and diethylbenzene, is more limited, thereby hampering the assessment of risks for these compounds.[48]

We found no published studies on exposures of UNG workers to other compounds used on site, though there are potential exposures from vaporization or aerosolization of drilling muds and hydraulic fracturing fluids that contain a range of neurological, respiratory and skin toxicants.[14,49−51] Workers are also exposed to diesel exhaust emitted from trucks and generators used to power operations. While diesel exhaust emissions vary by engine type and controls, exposure to diesel exhaust in other industries is associated with respiratory and cardiovascular disease.[52−54] The International Agency for Research on Cancer has classified diesel exhaust as a human carcinogen, while U.S. EPA classifies it as likely to be carcinogenic in humans.[41,55]

There is relatively little published research on other occupational stressors associated with UNG development, such as particulate matter from diesel engines or other combustion sources. Noise exposure is a significant hazard due to the presence of multiple sources, including heavy equipment, compressors, and diesel powered generators. Loud continuous noise has health effects in working populations.[56] It is likely that exposure to noise is substantial for many workers, and this is potentially important for health because drilling and servicing operations are exempt from some sections of the OSHA noise standard.[22] In addition to these direct exposures, peri-occupational issues, such as incidents of childhood lead poisoning from "take home" exposure to pipe dope on work clothes, increased rates of sexually transmitted infections, and steep increases in the demand for and price of rental housing are all adverse outcomes related to the rapid increase in the workforce in locales where development is occurring.[10,23,51] These work and life issues are addressed in greater depth in the Community effects section.

B. Community. While workers may be exposed to a wide range of hazards during well development, residents and community members living, attending school and working adjacent to UNG development sites may experience many of the same chemical or physical exposures. Although concentrations in the environment are likely lower further from development sites, the round-the-clock development cycle means that cumulative exposures may be of concern for people living near UNG development activities.

1. Accidents and Injuries. Reports to state agencies indicate that traffic and industrial accidents occur in the course of UNG development and operations.[23,57,58] Increased truck traffic in residential areas raises the likelihood for traffic accidents and may decrease residents walking and exercising in areas of development.[12] The average multistage well can require hundreds to more than a 1000 truck round trips to deliver equipment (e.g., bulldozers, graders, pipe), chemicals, sand, and water needed for well development and fracturing.[13,59] Truck counts in Bradford County, PA, for example, were approximately 40% higher than a comparable 5-year average prior to UNG development, with a proportional increase in accidents involving large trucks. [59] Preliminary analysis of data from the Pennsylvania Department of Transportation's Crash Reporting System indicates a significant increase in the number of total accidents and accidents involving heavy trucks between 1997 and 2011 in counties with a relatively large degree of shale gas development compared to counties with no development.[58] Similarly, the Texas Department of Transportation noted a 40% increase in reported fatal motor vehicle accidents from 2008 to 2011 in 20 Eagle Ford Shale counties.[57] Additional research on the impact of increased truck traffic on residential accident and fatality rates is needed.

While not extensively addressed in the peer-reviewed literature, industrial accidents and natural disasters involving well infrastructure and pipelines may put nearby residents at increased risk of exposure to fires, explosions and hazardous chemicals, which is a concern in many communities.[23] The September 2013 catastrophic flood in northeastern Colorado, for example, resulted in 13 notable releases of oil, totaling 43 134 gallons, and 17 releases of produced water, totaling 26 385 gallons.[60] The limited monitoring conducted after the flood indicated that the releases were extensively diluted to concentrations below detection limits by the large volumes of floodwater, and that bacterial contamination of water supplies due to nonfunctional water treatment plants was likely a bigger public health concern than spills originating from petroleum development infrastructure.[61]

2. Air Pollution. Increased traffic from industrial operations can degrade air quality due to diesel exhaust, road dust, and nitrogen oxides (NOx) (Table 1). In addition to traffic-related pollutants, people living near UNG development sites may be exposed to VOCs, silica, and other chemicals used during fracturing and well completion as well as fugitive emissions of VOCs from pipes and valves. While there are few studies characterizing the emission and distribution of pollutants from well pads, there are many documented instances of odor complaints and increased air concentrations of VOCs and other compounds at or near well pads during development.[25,62,63] People living within $^1/_2$ mile of a multiwell pad complained of odors during well completions in Garfield County, CO, and 81% of respondents to a self-reporting survey in active shale gas development areas in Pennsylvania reported odors.[15,62] Hydrogen sulfide has a very low odor threshold and a 10 h half-life, so it may be responsible for some odor complaints.[34]

Pilot studies in Colorado's Piceance Basin, Pennsylvania's Marcellus, and Texas's Barnett Shale indicate that VOCs, including C2−C8 alkanes, aromatic hydrocarbons, methyl mercaptan, and carbon disulfide, are emitted during well completions as well as from compressors, condensate storage tanks and related infrastructure.[17,64−66] Natural gas development may be the primary source of ambient benzene concentrations in the Dallas Fort Worth Area and Garfield County, CO.[17,67] One of the few community pollution studies with near-well pad measurements during well completion found that VOCs were detected more often and at higher concentrations compared to regional ambient air samples.[15] In that study, benzene concentrations ranged from 0.94 to 69 $\mu g/m^3$ and C_5 to C_8 aliphatic hydrocarbon concentrations ranged from 24 to 2700 $\mu g/m^3$ in 24 samples collected 130 to 500 feet from the center of five well pads in western Colorado during the high-emission period of uncontrolled flowback. A second study in western Colorado collected 24 h integrated air samples 0.7 miles from a well pad and found that emissions were higher during drilling compared to levels found during a closed loop ("green") completion.[36] A study in eastern Colorado collected 36, 3 h integrated air samples during morning hours at 850 and 1650 feet from a well pad during a green completion.[68] Benzene concentrations ranged from 0.73 to 2.06 $\mu g/m^3$, and the highest toluene and speciated nonmethane organic carbon concentrations were observed when multiple trucks were at the well pad.[69] In addition to these three studies, regional scale air quality studies suggest that oil and gas operations are a significant source of ambient benzene and alkanes on the northern Colorado Front Range.[70,71]

Studies in Texas, Oklahoma, and Colorado have attributed emissions of light alkanes from oil and gas development to the formation and transport of ozone to nearby urban areas.[70−72] Ground level ozone concentrations in the Haynesville Shale region of East Texas and Louisiana are projected to increase by up to 9 and 17 ppb under low- and high-emission scenarios, respectively. The area affected by high ozone levels under the high-emission scenario is twice that of the low-emission scenario.[73] Increases in ozone levels in either scenario are sufficient to push some counties in the study area beyond the current U.S. EPA 8 h National Ambient Air Quality Standard (NAAQS) for ozone (75 ppb). Monitoring in the Dallas Fort Worth area indicates that decreases in mean annual 8 h ozone concentrations from 1997 to 2011, which coincided with dramatic increases in the number of shale gas wells after about 2007.[65] Additional study is needed to determine if this trend is attributable to decreasing emissions from unconventional gas development or if controls on other sources of VOCs are responsible for the observed change.[74,75] A modeling study of the Barnett Shale region of Texas predicts that VOC emissions associated with compressor engines and NOx emissions from flaring natural gas could increase peak 1 h ozone concentrations by up to 3 ppb and 8 h concentrations by several ppb.[76] A group at Rand Corporation has developed estimates of air emissions from operations related to the shale gas industry in Pennsylvania and utilized an EPA model to monetize estimated health effects. Their region-wide estimate of damages was \$7.2−35 million in 2011. Of note is that aggregate NOx emissions in some counties were 20−40 times higher than allowable for a single minor source.[77] Researchers in Colorado are conducting comprehensive studies designed to characterize shale gas emissions, with results expected in 2014 and 2015.[78]

Winter ozone concentrations above the 8 h NAAQS were observed in relatively remote areas in Utah's Uintah Basin and Wyoming's Upper Green River Basin in recent years.[79−81] Peak ozone concentrations reached 149 ppb and 8 h averages reached 134.6 ppb in the Uintah basin, and emissions inventories indicate that oil and gas operations were responsible for 98−99% of the VOCs and 57−61% of the NOx ozone precursors.[82] In the Upper Green River Basin, photolytic ozone production resulted in peak ozone concentrations >140 ppb when NOx and VOCs from the production of UNG become trapped at the surface by intense, shallow temperature inversions.[80] A modeling study indicates that wintertime ozone production in this region is most sensitive to VOC emissions, suggesting that emission controls on UNG development will likely play an important part in addressing concerns about elevated ozone.[83]

The recent Allen et al. study examining methane releases during the drilling cycle of cooperating industries in different areas of the United States is also pertinent to community air pollution.[84] The study observed a very wide range of total methane emissions as well as a wide range in the rate of release for wells right next to each other that were developed by the same company. Methane emissions during the flowback period ranged from 0.01 to 17 Mg, and the rate of methane emissions during an uploading event varied by about 100-fold. While the authors did not measure BTEX or other VOCs, it is likely that the same degree of variability would be expected for these compounds assuming they are emitted with the measured methane. The work of Allen et al. suggests that local hot spots of both methane and possibly nonmethane air pollutants exist. As not all companies or production areas have cooperated with methane emission measurements, and as emission control practices vary across the industry, there is legitimate concern that local air pollution may produce adverse effects in individuals who live near the high emitting sites or processes.[85]

Apart from the direct effects of these pollutants on human health, UNG development also has the potential to positively or negatively affect global climate. Burning natural gas is far more energy-efficient than burning other fossil fuels, particularly coal, and results in lower emissions of carbon dioxide.[86] Methane itself is a potent greenhouse gas and any released to the atmosphere that otherwise would be locked up underground contributes to global climate change. Direct methane emissions occur during drilling and well completion, and fugitive methane emissions occur along pipelines, valves, and other related infrastructure. Although controversial, the emerging consensus in the scientific literature is that the advantage conferred by burning natural gas is a net benefit compared to burning coal, even considering methane losses to the atmosphere from UNG production.[70,84,87−93] Any further reduction in direct and fugitive methane emissions would be a further net benefit if natural gas permanently replaces coal that otherwise would be produced and burned.

3. Water Pollution. Intense public interest has been focused on possible contamination of drinking water sources with hydraulic fracturing chemicals and other pollutants associated with drilling and production (Tables 1 and 2). Potential pathways of surface and groundwater contamination from UNG development are transportation spills, well casing leaks, migration through fractured rock, abandoned wells, drilling site discharge, and wastewater disposal. [94]

The existing scientific literature has limited information indicating that UNG development may contaminate domestic ground or surface water supplies for individuals or communities.[19,95] Direct attribution of contamination from the fracturing process is hindered by lack of baseline data, the widespread presence of methane and petroleum byproducts in many gas-bearing basins, and nondisclosure agreements that limit the reporting of contamination after legal settlements.[1,3,96] Current scientific consensus is that accidents and malfunctions, such as well blowouts, leaking casings, and spills of drilling fluids or wastewater, are more likely to contaminate surface and groundwater supplies than the process of high-volume hydraulic fracturing itself.[19,94]

Table 2. Types of Additive, Example Chemicals, And Their Purpose in the Hydraulic Fracturing Process[a]

additive	example chemical	purpose
acid	hydrochloric or muriatic acid	helps dissolve minerals and initiate cracks in the rock
antibacterial agent	glutaraldehyde	eliminates bacteria in the water that produces corrosive byproducts
breaker	ammonium persulfate	allows a delayed break down of the fracturing gel
clay stabilizer	potassium chloride	brine carrier fluid
corrosion inhibitor	n,n-dimethyl formamide	prevents corrosion of pipes
cross-linker	borate salts	maintains fluid viscosity
defoamer	polyglycol	lowers surface tension and allows gas escape
foamer	acetic acid (with NH_4 and $NaNO_2$)	reduces fluid volume and improves proppant carrying capacity
friction reducer	petroleum distillate	minimizes friction in pipes
gel guar gum	hydroxyethyl cellulose	helps suspend the sand in water
iron control	citric acid	prevents precipitation of metal oxides
oxygen scavenger	ammonium bisulfate	maintains integrity of steel casing of wellbore; protects pipes from corrosion by removing oxygen from fluid
pH adjusting agent	sodium or potassium carbonate	adjusts and controls pH of the fluid
proppant	silica, sometimes ceramic particles	holds open (props) fractures to allow gas to escape from shale
scale inhibitor	ethylene glycol	reduces scale deposits in pipe
solvents	stoddard solvent, various aromatic hydrocarbons	improve fluid wettability or ability to maintain contact between the fluid and the pipes
surfactant	isopropanol	increases viscosity of the fracturing fluids and prevents emulsions

[a]Sources: Colborn, T., et al. Natural Gas Operations from a Public Health Perspective. *Human and Ecological Risk Assessment: An International Journal*. 2011. 17(5): p. 1039−1056; Earthworks. *Hydraulic Fracturing 101*. 2011 [cited 2012 Jan 11] Available from: http://www.earthworksaction.org/issues/detail/hydraulic_fracturing_101; Encana Corporation. Chemical use. [cited 2013 Sep 25] Available from: http://www.encana.com/environment/water/fracturing/chemical-use.html; EnergyIndustryPhotos. What is Hydraulic Fracturing and What is it Used for? . 2008 [cited 2012 Jan 11] Available from: http://www.energyindustryphotos.com/what_is_hydraulic_fracturing.htm; King, G.E., Hydraulic Fracturing 101: What Every Representative, Environmentalist, Regulator, Reporter, Investor, University Researcher, Neighbor and Engineer Should Know About Estimating Frac Risk and Improving Frac Performance in Unconventional Gas and Oil Wells. *SPE Hydraulic Fracturing Technology*; Woodlands, TX, 2012; Jiang, M., et al. Life cycle greenhouse gas emissions of Marcellus shale gas. *Environ. Res. Lett.*. 2011. 6(3); United States Department of Energy, *Modern Shale Gas Development in the United States: A Primer*; Oklahoma City, OK, 2009.

Aside from accidents and malfunctions, the evidence for contamination of groundwater wells with methane, fracturing chemicals, or other process wastes is mixed.[97−100] EPA studies in Pavilion, Wyoming, and Dimmick, Pennsylvania that have suggested associations between UNG development and drinking water contamination are controversial because of uncertainties about whether the chemicals present in these aquifers are there as a result of the hydraulic fracturing process.[96,101,102] Residents of both towns have been provided replacement drinking water by authorities.[101] An extensive report by the Ground Water Protection Council exploring drinking water contamination from UNG development in Texas and Ohio found evidence of leakage from orphaned wells and disposal pits, but no evidence of contamination from site preparation or the well stimulation process.[85] Osborn et al. used a convenience sampling approach to explore water quality in 60 samples collected in areas of active drilling in the Marcellus Shale.[18] While they did not find evidence of hydraulic fracturing chemicals in their samples, they did find that methane levels were higher in drinking water wells closer to UNG wells. Similarly, analysis of private well water quality in aquifers overlying the Barnett Shale has revealed that arsenic, selenium, strontium and total dissolved solids (TDS) exceeded the EPA's maximum contamination limit (MCL) in some samples located within 3 km of active natural gas wells.[103] Overall, the existing peer-reviewed literature lacks studies with substantive comparisons of water quality before and after natural gas development due to a lack of baseline data on water quality prior to the advent of UNG development. There is at least one documented case of contamination of water supplies from abandoned natural gas wells, but a comprehensive analysis of the effect of plugged or abandoned wells as a potential exposure pathway is a research need.[104]

Produced water is the largest component of the UNG development waste stream and is distinct from flowback water, which is primarily fracturing fluids that come out after immediately after well stimulation.[105,106] Produced water is water present in gas-bearing formations that comes to the surface over the life of the well . Given the high pressure and temperature in the underlying strata, both flowback and produced waters have the potential to contain transformation products that originate from the drilling muds and fracturing chemicals as well as methane, petroleum condensate, salts, metals, and, depending on the formation, naturally occurring radioactive materials (NORM). Flowback and produced water is stored in surface pits or sealed tanks prior to reuse and/or disposal.[87] Studies assessing composition of Marcellus Shale produced water found that most metals and salt ion concentrations increased with time after fracturing and were correlated with the composition of the underlying strata.[107,108] Current evidence suggests that wastewater is more effectively treated onsite because effluents discharged to publicly owned treatment plants may not be able to provide sufficient treatment for this waste stream.[109,110]

Potential for groundwater contamination from surface spills at wastewater storage and treatment facilities at active well sites has received increased attention. From July 2010 to July 2011, Gross et al. noted 77 reported surface spills (~0.5% of active wells in the region) impacting the groundwater in Weld County, CO.[111] Measurements of BTEX exceeded EPA maximum contaminant limits in most cases, and actions taken to remediate the spills were effective at reducing BTEX levels.[111]

C. Potential Health Effects and Population-Based Studies. At present, there are no population-based studies of health effects from water contamination, and relatively few studies exploring the impact of airborne exposures. Nonetheless, the potential for health effects can be inferred for specific chemicals from known health effects of contaminants if data exist on their potential potency that can then be linked to measured or estimated human exposure.

Exposure to ozone is associated with several adverse health effects, including respiratory, cardiovascular, and total mortality as well as decreased lung function, asthma exacerbation, COPD, cardiovascular effects and adverse birth outcomes.[112] People with asthma, children, and the elderly are at increased risk, and adverse health outcomes have been observed at concentrations as low as 41 ppb.[112] The overall relationship between ozone concentration and response to multiple outcomes appears to be linear with no indication of a threshold.[112] While there are many studies documenting the health effects of ozone exposures and several studies that suggest an association between unconventional oil and gas development and ground level ozone production, we found only one population-based study on ozone- and health effects in a UNG development region. That study found that between 2008 and 2011, Sublette County, Wyoming observed a 3% increase in the number of clinic visits for adverse respiratory-related effects for every 10 ppb increase in the 8 h ozone concentration the previous day.[113]

Populations living near UNG operations report odors and, in some cases, upper respiratory, neurological, and dermatological symptoms.[1,23,62,114] While these studies lack scientific rigor because they are volunteer or convenience samples of the local population, these effects are consistent with known health effects associated with petroleum hydrocarbons exposure. For example, inhalation of trimethylbenzenes and xylenes can irritate the respiratory system with effects ranging from eye, nose, and throat irritation to difficulty in breathing and impaired lung function.[115,116] Inhalation of xylenes, benzene, and aliphatic hydrocarbons can adversely affect the nervous system with effects ranging from dizziness, headaches, fatigue, and limb numbness to a lack of muscle coordination, tremors, temporary limb paralysis, and unconsciousness at high levels.[40,115−119] Maternal exposure to ambient levels of benzene has been associated with an increase in birth prevalence of neural tube defects.[120]

There is a growing epidemiological literature on the health effects associated with UNG development. A retrospective study of 124 862 births in rural Colorado indicated an association between maternal proximity to natural gas well sites and birth prevalence of congenital heart defects and neural tube defects, but no association with oral clefts, term low birth weight or preterm birth.[121] A working paper exploring 1 069 699 births in Pennsylvania reported increased prevalence of low birthweight and small for gestational age births, as well as reduced appearance, pulse, grimace, activity, respiration (APGAR) scores in infants born to mothers living within 2.5 km of a natural gas well compared to infants born to mothers living further than 2.5 km from a well.[122] While these preliminary epidemiological studies are hindered by a lack of spatial and temporal specificity in exposure and individual level risk factors, they underscore the need for a better understanding of exposures and health effects in populations living in UNG development and production areas. Another study compared standardized incidence rates (SIRs) for childhood cancer in Pennsylvania counties, but found no difference in SIRs for all cancer types except central nervous system (CNS) tumors, which the authors attributed to a large number of excess tumors in counties with the fewest wells.[123] The scientific validity of this ecological study is questionable because it chose before and after comparison periods that are not relevant to current concerns about UNG development.[124] It is also limited by lack of an individual level assessment of relevant confounders and the assumption that individual exposures to hydraulic fracturing are uniform within a county or confined by county boundaries. Additional epidemiological studies are needed to shed light on the existence and nature of disease patterns that might be associated with UNG development.

D. Socioeconomic Impacts, Psychosocial Effects and Human Health. In addition to the potential for public health benefits from lower regional and global air pollution levels resulting from replacing coal with natural gas in power plants, there are potential economic benefits that could contribute to the overall health of a community.[125] Natural gas development may bring economic growth through increased employment. Though estimates are uncertain, unconventional oil and natural gas development is estimated to employ up to 1.7 million people in the U.S. and is projected to support nearly 3 million jobs by 2020.[126] Various reports and a leading industry association, America's Natural Gas Alliance (ANGA), state that the benefits of natural gas include local infusion of funds to leaseholders, jobholders, and the providers of ancillary services, as well as the economic value to the general public of lower prices of natural gas and electricity.[86,126−128]

There are also negative economic effects, however, which often fall on community members least able to bear the loss. A substantial body of literature indicates negative social effects from energy extraction in small "boomtowns" during the 1970s and 1980s that are similar to the 21st century UNG boom.[10]

Studies in Colorado and Canada finding increases in crime, substance abuse, and sexually transmitted infections corresponding to periods of increased natural gas development activity substantiate these concerns.[10,12,23,129] The influx of UNG industry workers has led to rapid rental price increases, particularly in rural counties with low populations and limited housing stock.[130] The effect has been greatest on low and fixed income individuals who can no longer pay for their homes. As a result, local social services, including the need to develop homeless shelters, may be strained.[131] Community resilience, defined as the ability of a community to sustainably utilize available resources to withstand, respond to, and/or recover from adverse events, may be affected by UNG development, as was evident when social services were further strained by a major storm in central Pennsylvania in 2011.[130] The economic value of lost ecosystem services in areas that rely on tourism and second homes has not been fully assessed, although one estimate suggests a loss of between $11 and $27 million per year in Pennsylvania.[132] A study in Washington County, PA, a semirural area, has reported at least a transitory loss in property values in areas immediately surrounding shale gas drilling sites.[130] In view of the broad social effects and the community divisiveness that has attended UNG development, health effects attributable to stress are not surprising and are consistent with previous studies of boomtowns.[10,127,133−136]

Many of the nonspecific symptoms associated with UNG development may reflect psychosocial stress. Contributing to this stress is a lack of trust and transparency concerning industry and government action. Ferrar et al. (2013) noted that those who believe their health has been affected report higher stress levels due to loss of trust and perceived lack of transparency. More than half these subjects report they have been denied or provided with false information (79%), that their concerns/complaints have been ignored (58%), and that they are being taken advantage of (52%).[25] It is notable that these psychosocial stressors are reported more frequently than physical stressors such as noise (45%) and odors (13%). Perceived secrecy about hydraulic fracturing agents and the makeup of produced water are contributing to this lack of trust.[130] Social amplification of risk perception is commonly noted in situations in which there is a lack of trust.[137,138] A recent review of the many factors involved in risk perception found that the two major determinants were familiarity and trust; with other factors, such as gender, age, media coverage, and socioeconomic status being far less important.[139]

IV. HEALTH RISKS FROM SHALE GAS DEVELOPMENT

To date observational studies exploring the association between human health and UNG development have had a number of scientific limitations, including self-selected populations, small sample sizes, relatively short follow-up times and unclear loss to follow-up rates, limited exposure measurements and/or lack of access to relevant exposure data, and lack of consistently collected health data, particularly for noncancer health effects. Given these limitations, the lack of observational studies and the public's demand for answers, it is likely that human health risk assessments will be needed to provide projections of potential future harm for both short-term catastrophic and long-term human health risks.

Risk Governance, Risk Estimates, and Cumulative Risk. Natural gas development is governed by a mix of federal, state, and local laws and regulations.[1,13] The Federal government has relatively little direct authority over natural gas development and production, as the permitting authority lies with states and, in some cases, local authorities.[13] Companion papers in this volume address the key risk governance issues around UNG development, so we focus on the current estimates of public health risk and related issues and research needs.

Human health risk assessments published to date have focused on risks to communities from only air exposure. McKenzie et al.'s screening-level human health risk assessment is the only study to utilize measurements collected near well pads during the high emission well completion process, and found that residents living nearest to the well pad were at increased risk of acute and subchronic respiratory, neurological and reproductive effects.[15] They also estimated lifetime excess cancer risks, which were in the range of concern but below the range where action is typically taken. Other risk assessments conducted to date are largely in agreement with these observations, indicating slightly elevated excess lifetime cancer risks driven by benzene, some indication of acute or subchronic noncancer risks for those living closest to well sites, and little indication of chronic noncancer risks.[69,96,140−143] Few studies have attempted to use biomonitoring to explore risks from shale gas-related pollutants. Blood and urine samples collected from 28 adults living in Dish, Texas, a town with large numbers of gas wells, storage tanks, and compressor stations near residences, found no indication of community wide-exposure to VOCs.[144] These results likely reflect the multiple potential sources and the short half-lives of most VOCs in urine and blood, especially since the sampling did not coincide with known or perceived exposures, and concurrent air samples were not collected for study subjects.

This limited collection of risk studies underscores the overall lack of and need for substantive research on the human health effects stemming from UNG development. Given the broad range of chemical and nonchemical stressors present in and around UNG development sites and public demand for explication of the real and perceived risks, more substantive cumulative risk research is needed to address public concerns about the effects of UNG development on human and ecosystem health.[145,146] Figure 1 outlines a potential cumulative risk assessment approach that incorporates chemical, physical, and psychosocial stressors that contribute to stress-related health effects in populations living near UNG development sites. This cumulative risk approach uses an allostatic load conceptual model to incorporate the various stressors and buffers that act on individuals and communities.[145,147] Additional research is needed to both produce cumulative risk estimates and judge their utility for local, state, and federal decision-makers.

V. PUBLIC HEALTH RESEARCH NEEDS

The major uncertainties that should be addressed in future research on the effects of UNG development are the magnitude and duration of human exposure to stressors as well as the lack of baseline data to enable substantive before and after comparisons in affected populations and environmental media.[13] Additional process uncertainties include the location and extent of future UNG development as well as the cost, feasibility, and success of future emission control and mitigation strategies. Overall, the current scientific literature suggests that there are both substantial public concerns and major uncertainties to address before we can reasonably quantify the likelihood of occurrence or magnitude of adverse health effects in workers and communities where UNG development will likely occur.

Occupational health and safety research needs include both disease surveillance and exposure characterization. This includes tracking of fatalities, injuries, and health effects data in a defined population of unconventional resource workers, with particular focus on benzene, toluene, and silica related disease, hearing loss, and other traffic and worksite safety issues as well as health-based standards for poorly characterized compounds, such as aliphatic hydrocarbons.[22,29] Exposure data is also needed in workers to characterize the magnitude, frequency, duration of exposure to the wide range of chemical and physical stressors present at the worksite. Measurements should focus on continuous exposure monitoring to characterize acute and chronic worker exposure to aliphatic and aromatic hydrocarbons, diesel exhaust, fracturing chemicals, silica, produced water, H_2S, NORM, and noise over the wide range of UNG development activities.

Given the lack of systematic tracking of exposure and health effects in communities, there are little data to inform risk mitigation and risk management activities. For air quality, key unknowns include characterization of baseline air quality prior to development in new areas as well as characterization of the variability in exposure during high emissions processes, specifically drilling, hydraulic fracturing, and well completion activities. For water quality, unknowns include characterization of baseline water quality and impacts during each of the process steps that use water, that is, chemical mixing, hydraulic fracturing, flowback, and storage of flowback and produced water and wastewater treatment and disposal. Research on other stressors, including noise and light, traffic, and other safety hazards needs to be conducted in the context of understanding the overall effect of the mixture of these chemical and physical stressors. The interaction with the stress created by rapid change and community disruption is a key research need for characterizing health effects in locales where development is encroaching. Better understanding of cumulative risk issues will help inform UGD control policies and mitigate adverse community effects.[148]

At present, relatively little funding for independent research is available from federal, state, foundations, industry, or public-private partnerships to address these public health research needs. Given the high level of mistrust observed between citizens and the natural gas development industry it is important that research is designed and conducted by scientists that are not perceived as biased in favor of or against the industry.[95] Public-private partnerships (e.g., the Health Effects Institute) that solicit and fund rigorous research are a model that has worked for contentious public health issues in the past and may be effective in the future.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

Drs. Adgate and McKenzie were supported, in part, by funds from the National Science Foundation (NSF CBET-1240584), Research Partnership to Secure Energy for America/Department of Energy (EFDTIP2-TIP213), and the Colorado School of Public Health. We thank Nathan De Jong for his support in developing the manuscript.

LIST OF ACRONYMS

APGAR	appearance, pulse, grimace, activity, respiration
BTEX	benzene, toluene, ethyl benzene, xylenes
CNS	central nervous system
COPD	Chronic obstructive pulmonary disease
H_2S	hydrogen sulfide
MCL	maximum contamination limit
Mg	megagram
NAAQS	National Ambient Air Quality Standard
NIOSH	National Institute of Occupational Safety and Health
REL	recommended exposure limit
NOx	nitrogen oxides
NORM	naturally occurring radioactive materials
OSHA	Occupational and Safety Health Administration
PEL	permissible exposure limit
SIR	standardized incidence rate
TDS	total dissolved solids
TLV	threshold limit value
UNG	unconventional natural gas
U.S. EPA	United States Environmental Protection Agency
VOC	volatile organic compound

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