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Perspective

Practical measures for reducing the risk of environmental contamination in shale energy production

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Abstract

Gas recovery from shale formations has been made possible by advances in horizontal drilling and hydraulic fracturing technology. Rapid adoption of these methods has created a surge in natural gas production in the United States and increased public concern about its environmental and human health effects. We surveyed the environmental literature relevant to shale gas development and studied over fifteen well sites and impoundments in West Virginia to evaluate pollution caused by air emissions, light and noise during drilling. Our study also characterized liquid and solid waste streams generated by drilling and hydraulic fracturing and evaluated the integrity of impoundments used to store fluids produced by hydraulic fracturing. While most shale gas wells are completed with little or no environmental contamination, we found that many of the problems associated with shale gas development resulted from inattention to accepted engineering practices such as impoundment construction, improper liner installation and a lack of institutional controls. Recommendations are provided based on the literature and our field studies. They will address not all but a great many of the deficiencies that result in environmental release of contaminants from shale gas development. We also identified areas where new technologies are needed to fully address contaminant releases to air and water.

Introduction

Organic shale formations contain enormous hydrocarbon reserves. However, these unconventional reserves have very little or no natural permeability and gas production requires horizontal well placement and hydraulic fracturing in order to achieve economic production rates. In West Virginia alone about 3,000 such wells have been developed since 2008. These reserves are believed to contain more than 2.8 trillion m^3 of recoverable natural gas[1]. At current consumption rates, this would meet the energy needs of the United States for several decades. Natural gas from unconventional resources currently accounts for nearly half of U.S gas production[2]. The Marcellus shale formation in the eastern United States has been developed since 2008 and is important due to its size and its proximity to major markets in the northeastern United States [3,4].

The Marcellus shale basin is thought to be among the largest natural gas reserves in the world. It covers approximately 246,000 km^2 underlying much of the Appalachian Basin stretching from West Virginia in the south through New York in the north. The Marcellus Shale is a Middle Devonian-age shale, a member of the Hamilton Group; found at depths of 1500 to 2700 m. It ranges in thickness from 15 to 60 m and is bounded by limestone below and an additional shale layer above[5]. It is considered an organic rich source rock, the remnants of an ancient river delta containing trapped gas, mostly methane. Hydraulic fracturing typically involves pumping about 19,000 m^3 of water, sand and additives under high pressure into a shale formation to create sufficient porosity to allow gas production. Horizontal drilling installs a well casing that follows the horizontally bedded formation. Steel casing and cement are designed to conduct gas to the surface while preventing contamination of groundwater along the well bore. Over 2000 m typically separate the top of the fracture zone from the nearest potable aquifer in the Marcellus region.

Under ideal conditions the liquid, solid and gaseous waste streams generated during hydraulic fracturing are confined within a managed handling system. In most cases this is largely true. However, the care exercised by the various production companies and their contractors also varies. As a result, contaminant leakage occurs at some undefined rate across the basin. Our objective was to evaluate those leakage points and recommend practices that will improve environmental performance for all operators.

As pressure for gas production grows, the proximity of communities to exploration and extraction operations increases along with the potential for human exposure to potential hazards and pollution. Shale gas development in the eastern United States involves a widely distributed network of well sites, access roads, pipelines and compressor stations. These facilities are often located within a few hundred meters of homes and farms, many of which are supplied by shallow water wells. As a result, many of the public's concerns focus on air and groundwater pollution as well as light and noise associated with drilling and well completion.

To a large extent the current public policy debate over shale gas reflects the dialectic between self-regulation and external (governmental) regulation. The industry recognizes the need to maintain its social license and the unconventional gas industry's Marcellus Shale Coalition has developed an exhaustive listing of recommended practices[6]. Needed are objective measures of compliance and environmental performance so that weaknesses can be identified and appropriate regulatory schemes implemented that encourage innovation and productivity without compromising the environment or public health.

Methods

The authors recently completed a study of multiple Marcellus shale facilities in northern West Virginia. In this paper we summarize our findings and those of other investigators with regard to waste streams, their origins and measures to control environmental and human exposure. The study focused on waste characterization and methods for managing surface and near surface water contamination, pit and impoundment safety and air, light and noise effects on nearby residents. Flowback was sampled at four pits and impoundments and seven well sites. Air, light and noise were sampled at seven well sites and fifteen pits and impoundments were evaluated for construction integrity. Drill cuttings and muds were sampled in the vertical sections of two wells. Technical articles covering the technical components of this project are being prepared. This article outlines our results and recommendations regarding water and waste characterization, impoundment integrity and air, light and noise pollution resulting from shale gas well development and completion.

Solid and liquid fractions were separated by filtration and digested according to USEPA method 3050b prior to analysis. For most samples, the method is not considered by USEPA as a total digestion technique. However, it will result in dissolution of almost all elements that could become "environmentally available." The method is not intended to liberate elements bound in silicate structures as they are not considered to be mobile in the environment.

Findings

Water Management

Fluid and solid waste streams generated at unconventional gas wells consist of flowback and produced waters, precipitates, spent drilling fluids and drill cuttings. Other than produced water and its associated precipitates, all of these waste streams are associated with the drilling and well completion phases of the well. Figure 1 illustrates the fluid streams in a typical shale gas well completion.
Frac fluid comprises about 0.5% hydraulic fracturing additives and 99.5% makeup water. Additives may contain a wide variety of proprietary blends to carry proppant (generally sand) into the fractures and otherwise enhance the well completion process. Makeup water can be any combination of stream water, recycled flowback, produced water or municipal water. In the Marcellus field, between 10 and 30% of injected frac fluid returns to the well head and about 80% of that fluid is currently recycled as makeup water. The remainder of the recovered flowback/produced water is sent to disposal-generally deep well injection. The rate at which flowback/produced water returns to the wellhead is not well characterized in the literature. Figure 2 summarizes estimated return rates used by one West Virginia company for its Marcellus wells. It forecasts the cumulative return and the flow rate over a ten year period following well completion. The flowback return rate decreases rapidly from an initial monthly average of 52 m^3/day to 4.3 m^3/day within about 60 days. The factors determining the flowback rate likely include release of injected fluid pressure, fluid absorption into the formation and released gas pressure. Thereafter, flowback yields to produced water as gas production begins and fluid recovery rates gradually decline to less than 1 m^3/day. Trends in both fluid recovery rate and cumulative recovery are well described by power equations as shown on figure 2 with correlation coefficients of 0.92 and 0.98 respectively.

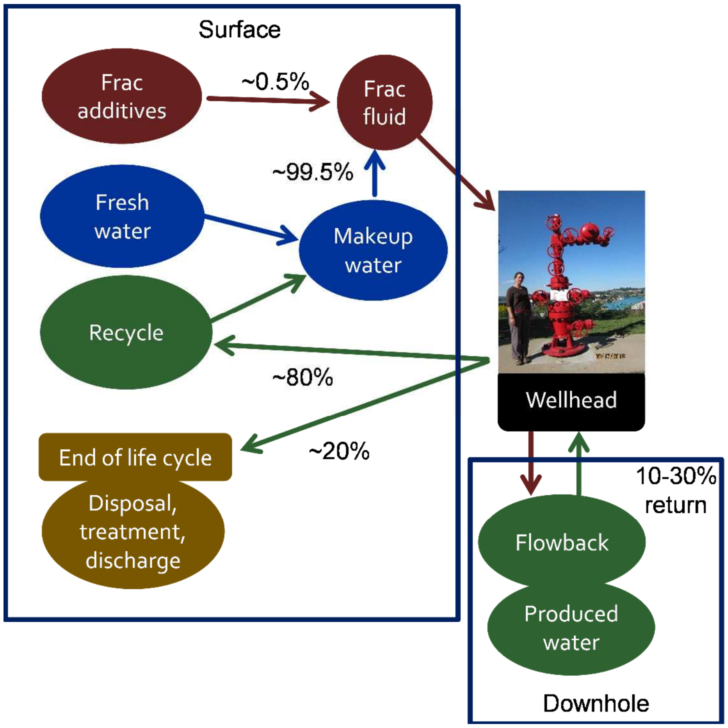

Figure 1. This diagram shows the key water management components of a typical shale gas well.

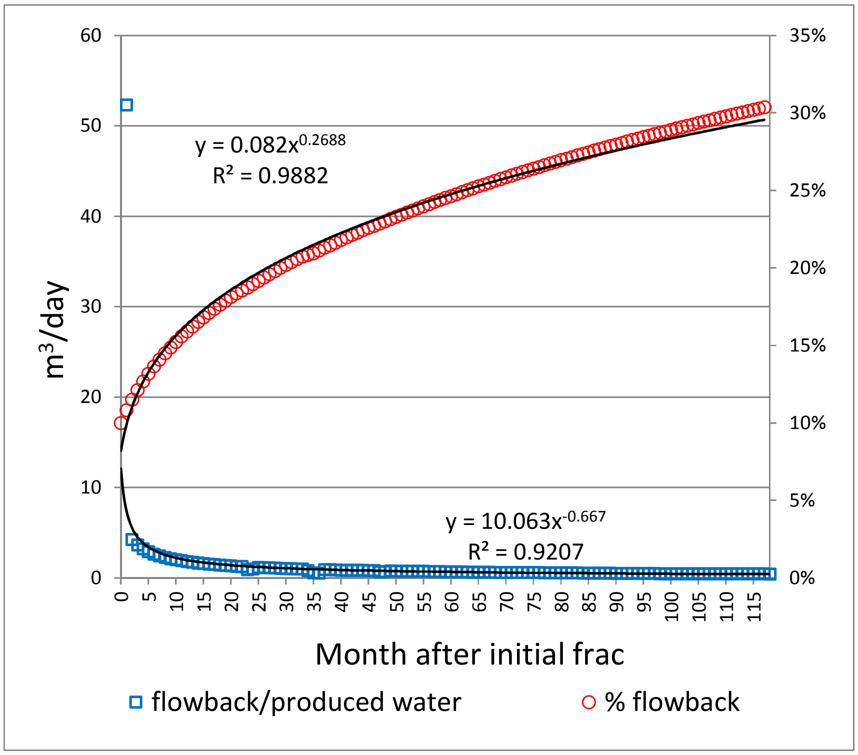

Figure 2. Predicted recovery rates of flowback and produced water in Marcellus shale gas wells. The two curves show the cumulative recovery as a proportion of initially injected fluid (red) and the

volumes (m^3/day) returning to the wellhead over a ten year period (blue). Prediction equations and resulting curves (solid lines) are included.

Marcellus formation flowback, while variable, is consistently saline with sodium the dominant cation and chloride the dominant anion. Strontium, barium and bromide are all present at consistently high concentrations. Table 1 summarizes reported values for Marcellus flowback composition.

Table 1. Marcellus formation flowback water compositions from the literature. All units other than pH are in mg/L.

Source:	A[7]	B[8]	C[9]	D[10]	E[11]	F[12]
	Median	Median	Median	Mean	Median	Mean
TDS	63800	110847	20900	106390	157000	74711
pH	6.6	5.9	7.5	6.6	6.2	6.6
Cl	56900	68000	12400	57447	98300	42683
SO_4	1	20	205	71	<50	56
Br	607	-	356	511	872	466
Na	23500	34548	4340	24123	36400	26202
Ca	4241	6800	739	7220	11200	7269
Mg	177	1707	52	632	875	835
Sr	1115	-	22	1695	2330	1365
Ba	1450	112	-	2224	1990	515
Fe	29.2	92.0	2.4	76.0	47.0	67.0
Mn	1.9	1.8	2.4	-	5.6	5.5
Pb	0.04	-	0.02	-	-	0.10
Ni	0.07	-	0.09	-	-	-
Zn	0.07	-	-	-	0.09	0.15

Solid Waste

Drilling a typical, 3700 m horizontal well in the Marcellus will generate about 500 t of rock cuttings in addition to precipitated solids and those recovered with the drilling mud. This is a low volume relative to the liquid wastes generated during unconventional gas well development but is significant in that the drilling solids are generally severely contaminated. Table 2 summarizes the composition of drilling solids recovered from the vertical section of a Marcellus well in northern West Virginia. (It was not possible to obtain samples from the horizontal section which would have been the Marcellus formation). Both inorganic and organic contaminant concentrations were substantially higher than would be expected in regional soils. Contaminant mobility in the solid fraction, however, is poorly understood.

Table 2. Drill cuttings and muds were sampled at an active Marcellus drilling site. The data indicate the average of ten samples[12]. Confidence intervals (CI) were developed using student's t test. Values represent total ion concentrations. Analysis was preceded by digestion according to USEPA method 3050b.

Vertical Drilling
Drill cuttings: solids analysis

	mg/kg			µg/kg	
inorganics	avg	95% CI	organics	avg	95% CI
Ca	50,798.1	41,982.8	m,p-Xylene	1,839.1	1,357.2
Cl	19,696.6	28,336.7	Toluene	892.4	658.4
SO_4	17,252.2	19,099.1	o-Xylene	409.7	328.7
Fe	15,691.0	5,545.8	Ethylbenze	203.5	164.4
Na	6,803.3	9,898.1	Benzene	126.2	93.1
Al	6,802.0	2,061.2	Styrene	1.0	2.1
K	4,136.0	2,102.8			
Mg	3,842.0	1,481.0			
Ba	2,518.2	2,064.2			
Mn	387.6	128.5			
Sr	297.7	216.9			
Zn	60.8	23.2			
Pb	33.4	20.0			
Ni	27.4	8.8			
Cr	15.6	5.8			
As	14.9	5.6			
Br	8.3	5.2			
Se	1.2	1.1			
Ag	0.2	0.1			
Hg	0.1	0.1			

The results indicate that handling and disposal options for these materials should address the potential release of contaminants to shallow ground and streams. In most cases, appropriate handling will require either treatment or permanent containment.

Pits and Impoundments: Design and Construction

Much of the liquid waste that is generated during unconventional gas development cycles through temporary storage facilities. Those can be either pits and impoundments or mobile tanks. Stored volumes at the well site are typically about 20,000 m^3. The integrity of these storage facilities is critical to groundwater and surface water protection. In the vernacular, pits contain flowback and produced water while impoundments contain only makeup water.

In the mountainous topography of West Virginia, pits and impoundments are located in valleys, hill sides and ridges. We conducted an engineering evaluation of the integrity of liquid containment and transfer systems in northern West Virginia[13]. The engineering evaluation considered fifteen pits and impoundments illustrated in Figure 3 chosen based on criteria such as age, size, use, construction materials and method of placement. Figure 4 shows a typical pit that was incised into a ridge-top subgrade with low berm heights and a geomembrane liner.

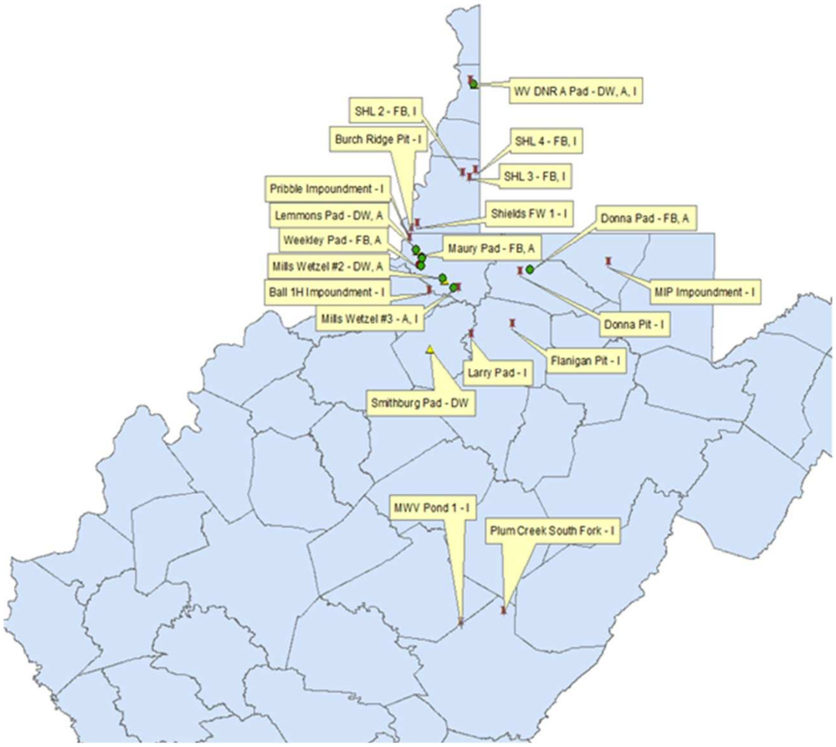

Figure 3: Study site locations in West Virginia

The engineering evaluation of the fifteen pits and impoundments was based on an evaluation form developed for the study, which used a quantitative system to collect field observations reflecting problem occurrence and severity. The method produced data in the form of problem identifiers (No or Yes) and severity rankings of Low, Moderate, or High. The evaluation form consisted of nineteen questions and functioned as a hazard-based field data collection tool[13].

Figure 4: Hill top pit incised into subgrade with geomembrane liner

The study identified several common problems associated with structural integrity (slope stability), containment competency (geomembrane liner deficiencies), and safety (emergency preparedness and response).

Perhaps as a result of the rapid growth of the shale gas industry and the large number of well completions, the investigators found that construction practices, inspection and enforcement lagged. Most problems were related to construction and maintenance deficiencies. Inspection of the structures indicated that they often had larger capacities, narrower berm widths and steeper slopes than were authorized in the construction permit. Each state develops dam safety standards and regulations. West Virginia's most recent regulations[14] are specific to large pits and impoundments for unconventional gas development. We found that the resulting structures often failed to meet those engineering design standards and safety factors. In addition, quality control and assurance were often lacking during construction of the structures e.g. no field compaction testing, use of improper soil types, excessive slope lengths, insufficient erosion control and buried debris. The placement of pipelines and geomembrane liners were often found to be inconsistent with permit requirements and industry practices, posing potential safety and environmental hazards.

Air, Noise and Light

West Virginia's steep, complex terrain and microclimatology are prone to concentrate airborne contaminants in ways that are unique to a given site. Volatile organic compounds are the primary contaminants of concern: methane, benzene, toluene, ethylbenzene and xylene. The latter four, known collectively as BTEX are volatile, water soluble and are known toxins. They can escape the well site during completion and production through flaring, leakage in the fluid handling system, as outgassing from impoundments and as venting from liquid storage tanks. During well completion at one site, idling trucks generated consistent noise levels in excess of 60 dBA with peaks above 95 dBA[15]. These were some of the highest noise levels measured during the study.

Recommendations

Environmental and Human Health Risks

The following recommendations are meant to suggest general practices that, we feel, would address the majority of releases and human exposures.

1. On-site containment. Active well sites are congested and fluid handling systems are typically complex. Leakage of toxic fluid is always a possibility and may range in scale from tens of liters to hundreds of cubic meters in the event of tank failure or well blowout. A blowout is a massive fluid rejection during well drilling and completion. We suggest that well pads be constructed such that the maximum fluid release will be captured by a properly constructed containment structure protected by a geomembrane liner. The liner system should include a sump for removal of accumulated fluids.

2. Blowout Preventers. All wells should include blowout preventers (BOPs) so that any uncontrolled fluid release would be brought under control almost immediately. BOPs may be automatic, responding to drastic pressure changes, or manual. The latter can be engaged in the event the automatic BOP fails. Some degree of redundancy is recommended.

3. Wellbore Integrity. Flowback, as well as production gasses, may escape the wellbore as a result of casing failure or inadequate cement bonding between the casing and the borehole. We recommend pressure testing of the completed, vertical well bore in advance of hydraulic fluid injection. Test pressures should be equal to design operating pressures with an adequate margin of safety. Downhole

tools including bond logs are also available to indicate the integrity of the well bore. Procedures for ensuring wellbore integrity should be identified that are suitable for the prevailing geological conditions.

4. Waste Transportation Plans. Careless and illegal handling of shale gas wastes has resulted in stream pollution and criminal prosecution. To ensure compliance with the law the planned disposition of flowback, produced water, spent drilling fluids and cuttings should be a required and enforceable component of the well's permit. Transportation plans should specify the receiving facility's name and location and the types and volumes of material to be transported to each.

5. Solid Waste Characterization. At present little is known about the risks associated with the solid wastes from hydraulic fracturing in the Marcellus: spent drilling mud, drill cuttings and filtrates/precipitates from flowback. Characterization of their inorganic, organic and radioactive contaminants is at present, incomplete. A systematic study including worker, environmental and community risks is needed.

6. Pits and impoundments. The design and construction of pits and impoundments would be significantly improved by better training for regulatory and industry field inspectors. We also recommend implementation of quality control and assurance standards for pit and impoundment construction. These would include soil classification and compaction analysis to determine geotechnically suitable materials prior to construction. Geomembrane pit and impoundment liners should be tested prior to service to ensure that welds are secure.

Air, light, noise

1. Install air monitors and sound meters at sensitive locations, such that the sites are connected to a central monitoring station by cellular phone or Wi-Fi to record sound levels 24 hours a day. When the desired levels are exceeded engineers should investigate to seek the source and report not only the cause but also the steps taken to prevent a recurrence. This approach to monitoring of all pertinent hazards should be considered for future regulations.

2. Noise reduction, particularly from traffic may be abated by several well-established methods used in highway construction. These include:

- Where possible, route truck traffic away from residences. Since sound intensity decays exponentially with distance from the source, increased distance between the noise source and receiver reduces the noise impact. It may also be possible to obtain attenuation by depressing the roadway slightly to produce a break in the line of sight from the source to the receiver. Potential noise reduction should be considered with the many other factors that influence the selection of roadway alignment.

- Better use of roadway wetting agents would reduce many of the peak dust exposures seen in roadside samples that were taken during our survey. The amount of fine dust that had collected at the sites and the levels in excess of the annual PM2.5 U.S. National Ambient Air Quality Standards (NAAQS), though for shorter time periods than the standard allows, were visible proof that improved dust suppression was needed. The short-term nature of the drilling process was apparently not envisioned by the developers of the NAAQS, which requires a minimum of a year's data during which the site is active. It remains an open question as to how to apply intermittent exposures to prevailing standards.

- Hydraulic fracturing is an intermittent, intensive process rather than a continuous process. As a result, heavy trucks idle at the well site while waiting to deliver or receive loads. Methods are needed for staging this traffic to reduce local concentrations of diesel exhaust while reducing noise.

3. One or all of the BTEX compounds were found in the air at all drilling sites[15]. These compounds could come from diesel emissions or from wastes generated by hydraulic fracturing. Better characterization of the source of these airborne contaminants is needed in order to effectively manage emissions. Some benzene concentrations were found to be above what the U.S. Centers for Disease Control and Prevention calls the "the minimum risk level for no health effects." This is a concern for potential health effects that might arise due to these exposures.

4. Current regulatory approaches often favor proscriptive approaches for health protection such as a fixed setback distance from a residence to the drill pad. On the contrary, our research[15] recommended performance based standards for air, light and noise. This would require placement of continuous monitoring instruments near sensitive locations for feedback and process control at the drill site. Advantages include quicker responses to upset conditions and much improved accountability. Performance based regulatory approaches also provide greater siting flexibility for the industry, incentives for technical improvements in both the drilling process, monitoring and process control tools. The resulting technologies might include solar powered lights, improved sound dampening, use of gas turbines rather than diesels on the well site and better truck scheduling to minimize congestion and idling. Studies are currently underway to establish these criteria. More, long-term studies are needed.

Exposure Pathways and Prevention

Shale gas development generates large volumes of liquid, solid and gaseous wastes. Many are hazardous. Yet, there is nothing inherently unsafe in hydraulic fracturing and horizontal drilling. For example, the vast majority of wells are completed and operated without significant environmental repercussions. However, some wells and operators are problematic. Our experience suggests that most environmental and human exposures occur through careless handling, leakage or failure to use accepted engineering practices and institutional controls. Table 3 summarizes the major waste streams, their contaminants, release points and recommended prevention measures. While this list is not exhaustive, we expect that it addresses the majority of environmental and health issues that policy makers and the public face when considering unconventional gas development.

Table 3. Summary of major waste streams found in unconventional gas development, their major contaminants, sources and recommended prevention measures.

Waste Streams contaminants	**location**	**source**	**control measures**
Liquid wastes			
Flowback/produced water			
salts, metals organic compounds radioactivity	well site	impoundment leakage surface spills well blowout	EC*-impoundment integrity on-site containment blowout preventers
	off site	pipeline breaks improper disposal	EC-pipeline integrity regulatory/enforcement
	off site shallow groundwater	leakage around well casing	well integrity testing-pre production well integrity testing-post production improved well completion methods
Solid wastes (Drilling mud/cuttings/filtrates)			
salts, metals organic compounds radioactivity	well site	poor storage integrity surface spills	EC-storage integrity on-site containment
	off site	improper disposal	management and disposal according to risk regulatory/enforcement
Airborne emissions			
dust volatile and semi-volatile organic compounds (VOC)	off site airborne	drilling, construction truck traffic off gassing from flowback pits venting from condensate tanks leakage at piping and valves	dust suppression VOC containment performance based standards improved real time air monitoring feedback to process controls

*EC=use conventional engineering controls

Most of the identified releases can be controlled by using existing techniques such as containment procedures, conventional engineering controls or regulatory enforcement authorities. In some instances, new technologies are required, particularly with regard to water treatment and air monitoring. However, the most immediate benefit would result from sound regulation focusing on established best industry practices combined with diligent enforcement on the part of the designated regulatory agencies.

Conclusions

Each jurisdiction and region will have specific needs with respect to regulating the environmental and health aspects of shale gas development. Those needs will be determined by well completion technology, waste streams, existing regulatory structures, geologic, environmental and social factors. Without a focused research agenda, characterization of those factors will be a slow process. For example, while extensive development of the Marcellus Shale began in 2008,we are only now beginning to understand its environmental, human health and social implications. While significant problems have been identified with respect to liquid and solid waste handling, impoundment construction and airborne emissions, we found that most could have been managed using strategies that are in place in other industries and regulatory programs. Many of the problems that we found resulted from the lag between extensive shale gas development and the regulatory standards and controls required to ensure safe practices. We recommend that waste stream characterization, development of standards and controls be expedited in jurisdictions contemplating large scale shale gas development.

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Environmental impact statement

Hydraulic fracturing coupled with horizontal well placement is the key technology facilitating development of otherwise inaccessible shale gas reserves. The lack of native porosity and permeability in these shale formations is overcome by hydraulic pressure creating a fissure network which allows movement of gas to the well. The Marcellus Formation gas play of the eastern United States is one of the Nation's major natural gas reserves. Though developed only since 2008, thousands of wells have already been completed in Ohio, Pennsylvania and West Virginia. Its rapid growth, high volume waste streams and proximity to population and infrastructure have drawn attention to its effects on air quality, light, noise and water. We report on findings of recent studies and offer recommendations that will significantly reduce environmental and human risk. Areas requiring additional study are also identified.

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TOC text

Recommended practices to reduce environmental and human health risk during shale gas development.