Chemical and Biological Risk Assessment for Natural Gas Extraction in New York

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Summary:

Over the last decade, operators in the natural gas industry have developed highly sophisticated methods and materials for the exploration and production of methane from unconventional reservoirs. In spite of the technological advances made to date, these activities pose significant chemical and biological hazards to human health and ecosystem stability. If future impacts may be inferred from recent historical performance, then:

- Approximately two percent of shale gas well projects in New York will pollute local ground-water over the short term. Serious regulatory violations will occur at more than one of every ten new shale gas projects.

- More than one of every six shale gas wells will leak fluids to surrounding rocks and to the surface over the next century.

- Each gas well pad, with its associated access road and pipeline, will generate a sediment discharge of approximately eight tons per year. If not sequestered from local waterways, these sediments will further threaten federally endangered mollusks and other aquatic organisms.

- Construction of access roads and pipelines will fragment field and forest habitats, further threatening plants and animals which are already species of concern.

- Some chemicals in ubiquitous use for shale gas exploration and production, or consistently present in process wastes, constitute human health and environmental hazards when present at extremely low concentrations. Potential exposure effects for humans include poisoning of susceptible tissues, endocrine disruption syndromes, and elevated risks for certain cancers.

- Exposures of gas field workers and neighbors to toxic chemicals and noxious bacteria are exacerbated by certain common practices, such as air/foam-lubricated drilling and the use of impoundments for flowback fluids. These methods, along with the intensive use of diesel-fueled equipment, will degrade air quality and may cause a recently described "down-winder's syndrome" in humans, livestock and crops.

- State officials have not effectively managed oil and gas exploration and production in New York, evidenced by thousands of undocumented or improperly abandoned wells and numerous incidents of soil and water contamination. Human health impacts from these incidents may include abnormally high death rates from glandular and reproductive system cancers in men and women. Improved regulations and enhanced enforcement may reasonably be anticipated to produce more industry penalties, but not necessarily better industry practices, than were seen in the past.

Overall, proceeding with any new projects to extract methane from unconventional reservoirs by current practices in New York State is highly likely to degrade air, surface water and ground-water quality, to harm humans, and to negatively impact aquatic and forest ecosystems. Mitigation measures can partially reduce, but not eliminate, the anticipated harm.

Introduction:

Natural gas production from hydrocarbon-rich shale formations is probably the most rapidly developing trend in onshore oil and gas exploration and production today. "In some areas, this has included bringing drilling and production to regions of the country that have seen little or no activity in the past. New oil and gas developments bring changes to the environmental and socio-economic landscape, particularly in those areas where gas development is a new activity. With these changes have come questions about the nature of shale gas development, the potential environmental impacts, and the ability of the current regulatory structure to deal with this development." (1)

Prominent features of shale gas development, which distinguish it from conventional gas extraction activity, are the use of horizontal drilling and high-volume hydraulic fracturing. While these technologies certainly lead to well projects which are orders of magnitude larger than traditional gas wells, and enable energy development companies to pursue projects in places which historically weren't commercially viable (such as New York's Southern Tier), gas exploration and production have never been free of risk. No attempt is made here to isolate horizontal drilling or hydraulic fracturing from any other processes used for gas extraction and transportation, inasmuch as the term "fracking" is understood by a majority of Americans as emblematic of the entire shale gas industry (2). Therefore, the objective is to evaluate risk related to the industry as a whole.

The working hypothesis of this work is that recent historical performance may be used to predict future performance of the gas industry. Data sources predominantly include official state, federal or industry reports. Using similar sources, industry analysts have broadly assessed environmental risks for the global oil and gas industry (3, 4). This article focuses on environmental risks which may be peculiar to New York State. Two components of risk imposed by the gas industry are evaluated here: incident frequency and impact. Frequency data are presented in Part 1, and chemical and biological aspects of impact are discussed in Part 2.

Part 1: Incidents of Contamination Related to Natural Gas Extraction

Official incident reports from various jurisdictions are cited below, and to evaluate them together requires application of a uniform context. One approach to context compares gas industry incidents over any period to the total number of gas wells that ever existed in the report region. In the author's judgment, this approach fails to accommodate the facts that many gas wells were "spudded" prior to any official record-keeping (let alone incident reporting), and most reported gas well mishaps arguably occur during initial drilling and stimulation. This author's contextual approach is to compare incident reports to the total active gas wells operating in a jurisdiction at the close of the reporting period, and to offer the number of new gas well projects started in that period, where available, as an alternative comparison.

Other States:

Data from Colorado indicated that there were 1549 spill incidents related to natural gas extraction activities in the period from January 2003 to March 2008; the Congressional Sportsmen's Foundation estimated that 20% of these (310) impacted groundwater (5). The New Mexico Oil Conservation Division recorded 705 groundwater-contaminating incidents caused between 1990 and 2005 by the gas industry (6). Compared to totals of 25,716 and 40,157 producing gas wells in Colorado and New Mexico, respectively (7), these data suggest that 6% of western region gas projects suffer serious mishaps, and that natural gas development in western states degrades groundwater quality at a rate of 1.2 to 1.8 incidents per 100 gas wells. Data from West Virginia lead to a generally similar conclusion of groundwater impacts from approximately 1.5% of active gas wells (6, 7), while Utah reported a violations rate of 11.5% without expressly indicating the extent of documented groundwater contamination (8).

The Pennsylvania Land Trust reported 1610 DEP violations in the Commonwealth between January 2008 and late August 2010, of which 1052 were judged likely to impact the environment (9). The Land Trust report appears to have included incidents related only to those gas wells which targeted the Marcellus shale formation. What fraction of the then-active 57,356 gas wells in Pennsylvania targeted that formation was not reported (7), but 2008 – 2010 records show that 25% of the DEP's gas well inspections were performed on Marcellus wells (10). Comparing 1052 serious incidents to an upper limit of 14,340 Marcellus wells, these data suggest that at least 7% of Pennsylvania's shale gas projects had negative impacts on their environment.

Pennsylvania's gas industry incident data are available for independent review since, responding to Act 15, signed into law by Governor Rendell in March, 2010 (11), the Department of Environmental Protection developed the DEP Oil and Gas Electronic Reporting website (10). **Table I** summarizes incidents from (a) all formations and (b) Marcellus shale formations for the period from January 2008 through the end of 2010.

Table I: Pennsylvania Gas Industry Inspections, Violations and Enforcements

Year	Formations	Inspections	Violations	Enforcements
2008	All	937	1447	662
	Marcellus	130	179	122
2009	All	1801	3159	693
	Marcellus	314	639	190
2010	All	1500	2721	721
	Marcellus	634	1227	308
Total	All	4238	7327	2076
	Marcellus	1078	2045	620

These records indicate that total violations and serious violations (enforcements) correlate well with the numbers of inspections, but Marcellus projects tended to generate violations and enforcements at rates that increased with the passing of time. Compared to a total of 57,356 producing gas wells in the Commonwealth, the data indicate a violations rate of 12.8% and an enforcements (serious violations) rate of 3.6%. Further, they suggest that industry operators became less compliant with regulations as the Marcellus shale projects advanced: more citations produced greater penalties, but not better practices.

It could be argued that not all producing wells pose equal risk: that gas well projects which are under construction contribute greater hazards than completed wells. Compared to 20,698 total *new* gas well projects reported from January 2008 through December 2010 (12), the data in Table I indicate a serious (potentially groundwater-impacting) violations rate of 10.0%. Put another way, about one out of every ten new gas well projects in Pennsylvania has run into serious trouble over the past three years. For a more detailed analysis of incident reports from Pennsylvania, Utah and West Virginia, the reader is referred to the work of Conrad Daniel Volz (8).

New York State:

Gas industry incidents are not systematically reported by New York State, and this state's history of regulating the industry is rather complex. The first domestic gas well was drilled in the stream bed of Canadaway Creek near Fredonia in 1821 (13, 14). New York was the first state to require the plugging of abandoned wells in 1879 (13, 14), and the first New York law to protect public water supplies from contamination was passed in 1885 (15). No particular state entity existed to monitor compliance or enforce these laws, but an 1882 amendment to the well plugging law offered half of any collected fines to informants who reported violations (13). New York's Fisheries, Game and Forest Commission was formed in 1895 (16), and the New York State Health Department was created in 1901 (15). The Fisheries, Game and Forest Commission was reorganized as the Department of Conservation in 1910 – 1911 (16). Legislation was adopted in 1933 to allow leasing of state lands for oil and gas drilling (13). In 1949, the Comprehensive State Water Pollution Control Act was passed (15).

New York repealed all previous oil and gas-related legislation in 1963, and amended Conservation Law to consolidate the Conservation Department's control of that industry's future development in the state. In 1966 the Department began to keep records on oil and gas wells (16). On April 22, 1970 (the first Earth Day), the New York State Department of Environmental Conservation (DEC) was created from the old Conservation Department, elements of the Health Department and a variety of other state commissions. The state's Environmental Conservation Law (ECL) was extensively recodified in 1972 (16).

In 1978, New York passed the State Environmental Quality Review Act (SEQRA), which was revised in 1987 and again in 1996 (17). This law required all state agencies to consider the environmental impact of all activities which they carried out or permitted, issuing environmental impact statements as needed. In response, the DEC's Division of Mineral Resources (DMN) prepared a Generic Environmental Impact Statement on Oil, Gas and Solution Mining (GEIS), issued as a draft in 1988 and finally adopted with revisions in 1992 (18). Although not accompanied by a "rules package" (19), this document became the primary guide for permit conditions attached to new oil and gas well projects until now (16). The DEC is currently revising a draft Supplement to the GEIS (dSGEIS) to address new technologies and issues of scale related to horizontally-drilled high-volume hydraulically fractured (HV/HF) gas well projects (20).

These laws, regulations and guidance documents constitute a diffuse, incomplete and at points inconsistent regulatory framework. For example, mineral resources laws and regulations fail to define process wastes (21, 22); "waste" is defined only as hydrocarbon product loss (23). And whether gas industry waste fluids are managed as liquids or solids depends on whether they are being transported (solids), treated (liquids), re-purposed or disposed (solids) (24 – 27). In any event, they are classified as non-hazardous (28 – 30), regardless of what is in them (31). These exceptions and exemptions contradict the definitions of pollutants found in mineral resources regulations (32) and water resources law (33). Further complicating matters, the GEIS recommended some practices that proved to be so unworkable, they are no longer used. An example was "pitless drilling", for which the rationale was that just letting waste fluids spray out onto the ground would kill fewer trees than would clearing a forested site for a wastewater pit (34). The efforts of field agents with the DEC's Bureau of Oil and Gas Regulation have arguably been hindered by such diffuse, incomplete and sometimes incompatible laws and regulations (35).

Indeed, when New York's regulatory program was reviewed in 1994 by a panel from the Interstate Oil and Gas Compact Commission, a number of deficiencies were noted (19). Among the issues were an estimated annual discharge of 360 million gallons of oil and gas well flow-back fluids directly into streams, onto land and roadways, and a legacy of approximately 60 thousand abandoned oil and gas wells. The DEC had no data on roughly half of them, and two-thirds of the wells for which they had records showed evidence that they were improperly abandoned. But the review panel considered the program's lack of resources to be its greatest deficiency (19).

The DEC Division of Mineral Resources has improved since 1994 (36), but some old problems persist. Their 2008 Annual Report, dominated by production data (consistent with their mandate (37)), estimated that 57,000 abandoned oil and gas wells remain to be dealt with, including approximately 30,000 for which the DEC still has no records (38). They are managing to plug about 200 per year, at which rate the backlog will require more than 280 years to complete if no new wells are improperly abandoned. Their 19 field agents also performed 2445 inspections in 2008, which resulted in 84 enforcement actions (a rate of 3.4%) for a total of $10,500 in fines – an average of $125 per citation (38, 39). The BOGR now has 16 field agents state-wide (39, 40) to monitor the state's 13,217 oil and gas wells – more than 800 wells for every inspector (41).

Walter Hang of Toxics Targeting, Inc. reported 270 ground-water polluting incidents since 1979, based on data from a DEC spills hotline (42). Compared to 13,217 active wells, this would suggest a ground-water pollution rate of 2.0% for oil and gas extraction projects. However, there is controversy about whether all the reported incidents actually impacted ground-water (43). Further complicating this analysis, problems reported directly to DEC field offices or to county health departments (lead investigators of complaints involving the gas industry according to memoranda of understanding with the DEC), were not combined with the hotline data or otherwise reported by the DEC; there were more than a hundred such complaints in Chautauqua County alone (44). Therefore, the actual number and types of gas industry incidents in New York State remain unknown, but a 2% ground-water pollution rate could arguably be considered an under-estimate.

But accidental releases of gas industry process wastes were far outweighed by the intentional discharges of these wastes directly into streams, onto land, and on roadways, as stated above (19). Studies are currently underway to evaluate the scope of harm done to surface streams and shallow aquifers in the western counties of New York where most of the discharges took place (45 – 52). Some possible human health impacts are presented in Part 2 of this article.

Long-Term Impacts:

Short-term collateral damage from gas well development constitutes only part of this industry's hazard profile. In 1992, the US Environmental Protection Agency (EPA) estimated that of 1.2 million abandoned oil and gas wells in the U.S., 200,000 were leaking (53). This represents a 16.7% failure rate; one of every six abandoned wells is releasing its contents to the surrounding area, including the surface. A Canadian research team investigated the mechanisms for these failures, and determined that concrete shrinkage which leads to well casing fissures is essentially inevitable in a fifty-year time frame. They found that this cracking was especially severe at maximum depth, and exposure of steel casings to the hot (140 – 180 °F) brines there accelerated their breakdown, permitting subterranean gases and other fluids to re-pressurize the deteriorating wells (54). Wells in regions containing mobile geological faults, such as Upstate New York (55), are also subject to casing deformation and shear (56). According to the IOGCC panel report and the DEC, New York has a "substantial abandoned wells problem", with more than 57 thousand undocumented or improperly abandoned oil and gas wells (36, 38). USGS scientists judged that some ground-water contamination cases in Chautauqua County were caused by gas wells providing portals for deep pollutants to reach the surface (44). We may reasonably expect higher percentages of gas well casings to fail over time, especially longer than fifty years. Therefore, the probability that a project scope of as few as ten modern gas wells will impact local ground water within a century approaches 100% certainty.

Part 2: Chemical and Biological Hazards From Natural Gas Extraction

Drilling Additives:

Many chemical products are used in the development of a gas well. Some examples, along with their most common applications, are shown in **Table II**.

Table II: Additive Functions in Shale Gas Extraction

Additive Type	Examples	Purpose	Used In
Friction Reducer	heavy naphtha, polymer microemulsion	lubricate drill head, penetrate fissures	drilling muds, fracturing fluids
Biocide	glutaraldehyde, DBNPA, dibromoacetonitrile	prevent biofilm formation	drilling muds, fracturing fluids
Scale Inhibitor	ethylene glycol, EDTA, citric acid	prevent scale buildup	drilling muds, fracturing fluids
Corrosion Inhibitor	propargyl alcohol, *N*,*N*-dimethylformamide	prevent corrosion of metal parts	drilling muds, fracturing fluids
Clay Stabilizer	tetramethylammonium chloride	prevent clay swelling	drilling muds, fracturing fluids
Gelling Agent	bentonite, guar gum, "gemini quat" amine	prevent slumping of solids	drilling muds, fracturing fluids
Conditioner	ammonium chloride, potassium carbonate, isopropyl alcohol	adjust pH, adjust additive solubility	drilling muds, fracturing fluids
Surfactant	2-butoxyethanol, ethoxylated octylphenol	promote fracture penetration	drilling fluids, fracturing fluids
Cross-Linker	sodium perborate, acetic anhydride	promote gelling	fracturing fluids
Breaker	hemicellulase, ammonium persulfate, quebracho	"breaks" gel to promote flow-back of fluid	post-fracturing fluids
Cleaner	hydrochloric acid	dissolve debris	stimulation fluid, pre-fracture fluid
Processor	ethylene glycol, propylene glycol	strip impurities from produced gas	post-production processing fluids

Individual additives are typically used in multiple stages of the drilling process; most hydraulic fracturing additives are also used in drilling fluids (or "muds") (57). Rare exceptions include bentonite and barium sulfate, which are used almost exclusively in drilling muds and packer slurries, and hemicellulase enzyme, used solely in post-fracturing fluids. Even the chemicals used for post-production purification may also be used as solvents in drilling muds (57).

The majority of chemical products used by the gas industry have not been fully tested for human or environmental toxicity (58, 59). Of those which have, a minority (*e.g.,* bentonite, guar gum, hemicellulase, citric acid, acetic acid, potassium carbonate, sodium chloride, limonene, polyethylene glycol and mineral oil) pose no significant hazards to humans or other organisms as utilized in gas extraction processes.

Several other additive chemicals, including ammonia, methanol, ethanol, 2-propanol, 1-butanol, thioglycolic acid, acetophenone, sodium perborate tetrahydrate, diammonium peroxydisulfate and hydrochloric acid, are moderately or acutely toxic to humans or aquatic organisms when encountered in concentrated forms (60 – 69), but as used by the natural gas industry, they end up greatly diluted, and so impose relatively modest hazards (58). More significant issues with these chemicals would be anticipated from storage sites, trucking accidents while they are being transported to remote well sites via rural roads, and staging at well sites.

However, a few chemical products in widespread use, including in exploratory wells, pose significant hazards to humans or other organisms, because they remain dangerous even at concentrations near or below their chemical detection limits. These include the biocides glutaraldehyde, 2,2-dibromo-3-nitrilopropionamide (DBNPA) and 2,2-dibromoacetonitrile (DBAN), the corrosion inhibitor propargyl alcohol, the surfactant 2-butoxyethanol (2-BE), and lubricants containing heavy naphtha. Precisely because of the hazard these chemicals pose even when they are extremely diluted, they are considered in some detail in this section. (Note: CAS No. refers to a unique identifier assigned to every known substance by the Chemical Abstracts Service Registry.)

Glutaraldehyde:

Glutaraldehyde (CAS No. 111-30-8) is a biocide used widely in drilling and fracturing fluids. Along with its antimicrobial effects, it is a potent respiratory toxin effective at parts-per-billion (ppb) concentrations (70); a sensitizer in susceptible people, it has induced occupational asthma and/or contact dermatitis in workers exposed to it, and is a known mutagen (i.e., a substance that may induce or increase the frequency of genetic mutations) (70, 71). It is readily inhaled or absorbed through the skin. In the environment, algae, zooplankton and steelhead trout were found to be dramatically harmed by glutaraldehyde at very low (1 – 5 ppb) concentrations (72).

DBNPA:

2,2-Dibromo-3-nitrilopropionamide (DBNPA) (CAS No. 10222-01-2) is a biocide finding increasing use in drilling and fracturing fluids. It is a sensitizer, respiratory and skin toxin, and is especially corrosive to the eyes (73). In the environment, it is very toxic to a wide variety of freshwater, estuarine and marine organisms, where it induces developmental defects throughout the life cycle. In particular, it is lethal to "water fleas" (*Daphnia magna*), rainbow trout and mysid shrimp at low (40 to 50 ppb) concentrations, and is especially dangerous to Eastern oysters (74). Chesapeake Bay oysters are killed by extremely low (parts-per-trillion, ppt) concentrations of DBNPA, well below the limit at which this chemical can be detected.

DBAN:

Dibromoacetonitrile (DBAN) (CAS No. 3252-43-5) is a biocide often used in combination with DBNPA, from which it is a metabolic product (with the release of cyanide). Its human and environmental toxicity profiles are similar to that of DBNPA, except that DBAN is also carcinogenic (75). DBNPA and DBAN appear to work synergistically. In combination, the doses at which these biocides become toxic are significantly lower than when they are used separately. In other words, it takes much less of these chemicals to exert toxic effects when they are used together, although the specific degree of potentiation has not been publicly reported.

Propargyl Alcohol:

Propargyl alcohol (CAS No. 107-19-7) is a corrosion inhibitor that is very commonly used in gas well construction and completion. This chemical causes burns to tissues in skin, eyes, nose, mouth, esophagus and stomach; in humans it is selectively toxic to the liver and kidneys (76). Propargyl alcohol is a sensitizer in susceptible individuals, who may experience chronic effects months to years after exposure, including rare multi-organ failure (77). It is harmful to a variety of aquatic organisms, especially fathead minnows, which are killed by doses near 1 ppm (78).

2-BE:

2-Butoxyethanol (2-BE), also known as ethylene glycol monobutyl ether (EGBE) (CAS No. 111-76-2), is a surfactant used in many phases of gas exploration and extraction. It comprises a considerable percentage of Airfoam HD, commonly used for air-lubricated drilling (79). Easily absorbed through the skin, this chemical has long been known to be selectively toxic to red blood cells; it causes them to rupture, leading to hemorrhaging (80). More recently, the ability of EGBE at extremely low levels (ppt) to cause endocrine disruption, with effects on ovaries and adrenal glands, is emerging in the medical literature (81). This chemical is only moderately toxic to aquatic organisms, with harm to algae and test fish observed with doses over 500 ppm (80).

Heavy Naphtha:

Heavy naphtha (CAS No. 64741-68-0) refers to a mixture of petroleum products composed of, among other compounds, the aromatic molecules benzene, toluene, xylene, 1,2,4-trimethylbenzene and polycyclic aromatic hydrocarbons including naphthalene. It is used by the gas industry as a lubricant, especially in drilling muds. This material is hazardous to a host of microbes, plants and animals (82). Several of the mixture's components are known to cause or promote cancer. If released to soil or groundwater, several components are toxic to terrestrial and aquatic organisms, especially amphibians, in which it impedes air transport through the skin.

Flowback Fluids:

Irrespective of chemical additives used for drilling, Marcellus shale contains several toxic substances which can be mobilized by drilling. These include lead, arsenic, barium, chromium, uranium, radium, radon and benzene, along with very high levels of sodium chloride (83). These components make flowback fluids hazardous without any added chemicals, and are often among the analytes most easily measured by potential waste fluid treatment plant operators (**Figure 1**).

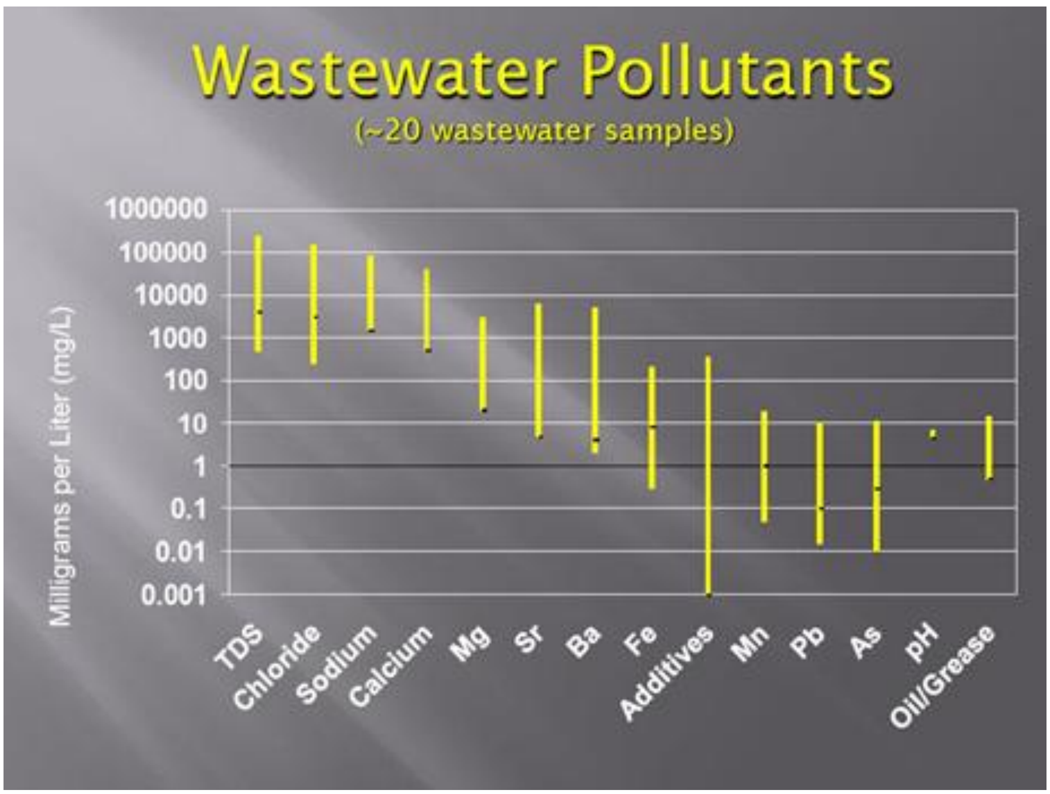

Figure 1: Wastewater Pollutants (84)

Because of to their significant toxicity at low (ppb) concentrations, and the fact that drill cuttings are often not removed, but rather are buried on-site, several of these flowback fluid and cuttings components (83) are discussed below: barium, lead, arsenic, chromium, benzene and technologically enhanced naturally occurring radioactive materials.

Barium (Ba):

Barium is a toxic heavy metal commonly found in Marcellus shale well flowback fluids (85). Exposure to soluble salts (not the sulfate), which may occur by ingestion, absorption or inhalation, may induce drops in tissue potassium levels, and by this mechanism it is selectively toxic to the heart and kidneys (86). Further, barite (barium sulfate), used as a weighting agent in drilling muds, reacts with radium salts in shale, forming radioactive scale on metal parts (such as the drill "string") which then are subsequently brought to the surface (57); in these reactions, barite is converted to more soluble (i.e. more toxic) barium salts.

Lead (Pb):

The poisonous nature of lead has been known for centuries, but its ability to impair neurological development in children at very low (1 ppb) concentrations makes it a toxicant of special concern. The most sensitive targets for lead toxicity are the developing nervous system, the blood and cardiovascular systems, and the kidney. However, due to the multiple modes of action of lead in biological systems, and its tendency to bio-accumulate, it could potentially affect any system or organs in the body. It has also been associated with high blood pressure (87).

Arsenic (As):

Arsenic, another component of black shale (83), has also been known as a poison for hundreds if not thousands of years. The most sensitive target tissue appears to be skin, but arsenic produces adverse effects in every tissue against which it has been tested, especially brain, heart, lung, the peripheral vascular system, and kidney (88). Arsenic is harmful below one part per trillion (ppt) in water, and is a confirmed carcinogen.

Chromium (Cr):

Chromium, also found in Marcellus shale (89), may be an essential nutrient required in extremely small doses (μg per day), but the biological system it supports is not currently known. Exposure to elevated doses by inhalation, ingestion, skin or eye contact may lead to respiratory, gastrointestinal, reproductive, developmental and neurological symptoms

(90). Sensitization-induced asthma and allergy have also been reported. However, at very low concentrations, particularly of potassium dichromate or strontium chromate (the hexavalent form, as found in shale rock) (91), the major hazard posed by chromium is as a carcinogen, especially in stomach and lung tissues (90).

Benzene:

Benzene, a known shale constituent (83), was briefly considered above as a component of heavy naphtha. In ppb concentrations, the primary hazard from this compound is due to its proven ability to cause acute non-lymphocytic leukemia (92).

Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM):

The use of lubricants and "slickwater" additives along with hydraulic fracturing for oil and gas production have been shown to mobilize naturally occurring radioactive materials, including uranium- 238, radium-226 and radon-222 (93). This has been identified as one of the greatest challenges facing the American gas industry today (94). Of these, radon is of special concern because as a gas it is extremely mobile, and it is intensely radioactive (94). Exposure by inhalation or ingestion typically results in migration to the lungs, which are susceptible to damage from its nuclear decay; exposure to radon is considered the second leading cause of lung cancer after tobacco smoking (95). Radon was detected at levels above 300 pCi/L (a drinking water limit proposed by the USEPA), in a majority of groundwater samples collected in New York State by USGS investigators (50 – 52). However, whether the high levels of radon in drinking water may be related to past or present oil and gas development in those locales has never been studied; they could possibly be due to fracture intensification domains in New York's subsurface geology (55).

4-NQO:

In addition to the above shale constituents, one chemical compound was consistently encountered in flowback fluids from Marcellus gas wells in Pennsylvania and West Virginia: 4-nitroquinoline-1-oxide (4-NQO) (96). This is one of the most potent carcinogens known, particularly for inducing cancer of the mouth (97). It is not used as a drilling additive and is not known to occur naturally in black shale; no studies have been published to date with respect to what chemical interactions account for its consistent presence in flowback fluids. However, it is dangerous at parts-per-trillion (ppt) concentrations, well below its levels reported in gas well flowback fluids (96).

Inadequately Treated Drilling Wastes:

Treatment of gas industry process wastes by publically-owned sewage treatment plants or privately-owned industrial waste treatment plants has been found to be not completely adequate to maintain water quality in receiving streams. Pennsylvania's Monongahela River was subject to spikes in total dissolved solids (TDS) in late 2008 and throughout 2009. Seeing that gas drilling wastes constituted up to 20% of the waste treated at some facilities discharging into the basin, the Pennsylvania DEP ordered these facilities to restrict their intake of drilling waste water (98). More recently, elevated levels of bromide in the Allegheny River, ostensibly from gas drilling wastes, have caused concern for a number of water treatment managers in southwestern Pennsylvania (99). Direct tests of effluent from a facility dedicated to treating gas drilling wastes showed that the plant was discharging extraordinary levels of bromide and other contaminants into a tributary of the Allegheny River, in flagrant violation of its permit (100).

Biological Contamination:

Rock strata beneath the earth's surface are populated by microscopic organisms, and the advent of air-lubricated drilling (without biocides) has introduced a risk of contaminating surface (fresh) water zones with bacteria and other microbes from deeper (brine) layers, where they often flourish. Of particular concern are sulfate-reducing bacteria, especially *Desulfovibrio desulfuricans*, a facultative anaerobe that thrives in fresh water where some sulfate (such as is present in pyrite or hematite) is available (101), (**Figure 2)** (102).

Figure 2: Biofilm of *Desulfovibrio desulfuricans* Growing on a Hematite Surface

These bacteria are especially prevalent and aggressive in oil and gas producing regions, where they avidly form living black, sticky films in water wells and other structures (103). There they produce hydrogen sulfide (H_2S), characterized by a "rotten eggs" smell. Rock strata rich in gas are often also rich in this bacterium, and exposure to hydrogen sulfide along with methane raises significant health concerns –neurological syndromes in humans and, in livestock, elevated birth defect rates and diminished herd health. At high concentrations, hydrogen sulfate is lethal (104).

The now-common use of air-lubrication (without biocides) while drilling the top one- to three thousand feet of gas wells (105) risks contaminating fresh water aquifers with sulfate-reducing bacteria from the deeper strata, but there is no clear evidence that this water well fouling mechanism is recognized by New York state regulators.

Transportation Infrastructure:

Gas well development requires the construction of well pads, access roads and pipelines. These structures, as well as the construction projects that produce them, pose significant environmental hazards from accelerated erosion (106, 107). A report for the USEPA determined an average annual sediment yield of 7.4 metric tons per hectare in Denton, Texas (108). After adjusting for the difference in average rainfall amounts in Denton, TX and New York State, and estimating one hectare (2.47 acres) as a typical land disturbance for a gas well pad, access road and pipeline (109), the sediment load for a New York gas well is expected to average 8.5 tons per year. Degradation of existing roads, culverts and bridges by excessive truck traffic also accelerates erosion and increases deposition of road dust into waterways (110). Organisms which are critical for maintaining stream water quality and are especially vulnerable to sediment runoff and siltation damage include filter-feeding macroinvertebrates (111) and bivalve mollusks, including the federally endangered dwarf wedgemussel (112, 113).

In addition to soil erosion issues, all-weather access roads also lead to the fragmentation of fields and forests (104, 114). One consequence is declining critical core populations of Allegheny woodrats, snowshoe hares, and plants such as tamarack and red spruce trees, and yellow lady slipper orchids, all of which require interior woodland habitats (114). Woodland amphibians, including marbled, blue-spotted and Jefferson's salamanders, which are species of special concern, are also sensitive to habitat fragmentation (115). Some grassland species are exquisitely sensitive to habitat fragmentation: over the past forty years, New York has seen a decline of 80 to 99% in the abundance of Henslow's Sparrow, Grasshopper Sparrow, Vesper Sparrow, Upland Sandpiper, Horned Lark, Eastern Meadowlark, Savannah Sparrow, Northern Harrier and Bobolink (116). Therefore, the DEC is developing Grassland Focus Areas in attempts to restore populations of Short-eared Owl and Sedge Wren in addition to the above bird species (116). This begs the question of how much fragmentation from shale gas development can be sustained without compromising these habitat restoration efforts (117).

Air Quality Impacts:

Gas well projects can generate uniquely severe air quality problems, as volatile organic compounds (VOC's) from flowback fluid impoundments, polycyclic aromatic hydrocarbons (PAH's) from incompletely-combusted fuel and fugitive methane emissions combine with nitrous oxides (NOx) from diesel exhaust (118) to form ground-level ozone. To paraphrase the pioneering work of Theo Colborn et al (119): "This ozone can burn the deep alveolar tissue in the lungs, causing its premature aging. Chronic exposure can lead to asthma and chronic obstructive pulmonary diseases (COPD). Ozone combined with [fine] particulate matter produces smog which has been demonstrated to be harmful to humans as measured by emergency room admissions during periods of elevation. Gas field ozone has created a previously unrecognized air pollution problem in rural areas, similar to that found in large urban areas, and can spread up to 200 miles beyond the immediate region where gas is being produced. Ozone not only causes irreversible damage to the lungs, it is similarly damaging to conifers, forage, alfalfa, and other crops commonly grown in the U.S." (119).

In addition to impacts from ground-level ozone, fugitive emissions of methane from wellheads, pipelines and storage facilities, along with combustion (primarily diesel) exhausts related to construction and pipeline pressurization, combine to put the total greenhouse gas emissions from shale gas extraction on par with greenhouse gas emissions from coal (120). Further, Robert Howarth's analysis suggests that "clean" natural gas exerts a greater "carbon footprint" than diesel oil when the intensive efforts required to extract gas from shale are taken into account (120). Therefore, the desirability of natural gas as a "transition fuel" is questionable when the resource must be extracted from unconventional reservoirs by energy-intensive means: it may be no better than coal.

Potential Health Effects:

Hazards that accompany the above chemicals and microbes and physical agents have to this point been considered individually. They clearly don't occur individually. No investigations of interactions among all these materials have been reported to date. However, this author has been contacted by officials with the National Institute of Safety and Occupational Health, Centers for Disease Control (NIOSH/CDC), who requested any information that might shed light on a group of clinical symptoms, presented by patients in southwestern Pennsylvania and the state of West Virginia, which is being tentatively identified as "down-winder's syndrome" (121). These symptoms, including irritated eyes, sore throat, frequent headaches and nosebleeds, skin rashes, peripheral neuropathy, lethargy, nausea, reduced appetite and mental confusion, were also reported in gas field health impact studies conducted by Wilma Subra in Texas (122) and Wyoming (123). These disparate observations are supported by a literature review of potential human health effects from gas drilling activities (124). In response, the Medical Society of the State of New York and the medical societies from Broome, Cayuga, Chenango, Chemung, Herkimer, Madison, Oneida, Onondaga, Oswego, Otsego and Tompkins Counties, and the Sixth District (Delaware and Tioga Counties), have all called for a moratorium on natural gas extraction using high volume hydraulic fracturing in New York State (125).

The proposed practice in New York of using open impoundments for large-scale capture of flowback fluids from gas wells may exacerbate the risk of this syndrome. Although most additives are greatly diluted in the drilling process, organic compounds (with the notable exceptions of DBNPA and DBAN) tend to be lighter than water; therefore they float to the surface of holding pits, where they concentrate to essentially 100% of the top layer. From there they volatilize or aerosolize into the air, from which they may be inhaled by neighbors and on-site industry workers. Partly for this reason, the states of Colorado (126) and New Mexico (127) have prohibited the use of impoundments for flowback fluids.

As mentioned in Part 1, above, the oil and gas industry was responsible for substantial contamination of soil and water in New York, particularly in our western-most counties, from 1821 to at least 1993 (44 – 52). Among other possible health concerns, there is overwhelming evidence that industrial pollutants can cause or promote cancer in humans (128). As a preliminary approach to assessing potential human health effects from exposure to that environmental pollution, cancer mortality statistics were reviewed for Chautauqua, Cattaraugus and Allegany Counties. These three counties were selected because of their historically intensive gas industry activity, documented impairment of drinking water by industrial pollution sources, and distinctively rural character (to minimize influences from industries other than oil and gas). Based on nation-wide reports for 55 different cancer types from 1950 to 1994, women in this three-county area of New York were consistently in the top bracket for deaths caused by cancer of breast, cervix, colon, endocrine glands, larynx, ovary, rectum, uterus and vagina(129). Men from the same region were consistently in the highest statistical bracket for deaths caused by bladder, prostate, rectum, stomach, and thyroid cancers (129).

While it must be noted that county-wide cancer mortality statistics don't prove a connection between the elevated numbers of cancer deaths and gas industry pollution, the industry has also never been exonerated from a contribution to the unique profile of abnormally high cancer incidence and mortality in these counties. Clearly, much more investigative work needs to be done in this regard.

Conclusions:

As stated above, the working hypothesis for this risk assessment is that future impacts may be inferred from historical performance. Therefore, cumulative chemical and biological impacts from the gas industry in New York may be predicted for projects of any scope by combining incident statistics from Part 1 with related health and environmental impacts from Part 2. For example, from a development of 10,000 gas wells (a plausible estimate according to Anthony Ingraffea) (130), the sediment run-off into nearby waterways would amount to at least 80,000 tons per year. Such a development would reasonably be expected to generate about 1,200 citations for serious regulatory violations and at least 200 incidents of groundwater contamination in the short term. Over a century, about 1,600 more leaking gas wells should be anticipated. If this scale of development takes place in a 2-county area, then significant spikes in emergency room visits for respiratory complaints and other aspects of "down-winder's syndrome" in those counties should be anticipated as well. Changes in human chronic disease profiles and impacts on domestic, aquatic and forest ecosystems would be more insidious and difficult to measure – but not necessarily less significant.

The record of New York State officials in managing gas industry impacts has been no better than those of officials in neighboring states, and may be substantially worse. Documenting harm and penalizing those in the energy industry who caused it have historically done little to mitigate that harm or prevent its re-occurrence. New York State law regarding the gas industry clearly promotes production over environmental protection (35). Therefore, there is little evidence that changes to the regulatory process will be adequate to protect New York's environment and citizens from harm caused by this industry. These conclusions essentially agree with those made by Zoback, Kitasei and Copithorne (110), Hazen and Sawyer (131) and Fuller and Hetz (132). However, they disagree with the assessment of the Ground Water Protection Council (GWPC) (36); it is possible that the GWPC maintains lower standards for public safety and health than these other evaluators.

It is hoped that this instrument will be found useful to public servants at every level in New York State, whether they serve in executive, legislative, judicial, health, safety, planning, education, or advocacy roles. Decisions we make today regarding whether or how to proceed with shale gas development here will have ramifications for generations to come.

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