A White Paper Summarizing the Stray Gas Incidence & Response Forum

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Cleveland, Ohio

STRAY GAS
Incidence & Response Forum

GROUNDWATER PROTECTION COUNCIL

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Chapter 1 - Introduction

The Ground Water Protection Council (GWPC), with funding support from the U.S. Department of Energy, held the Stray Gas Incidence & Response Forum (the Forum) from July 24-26, 2012 in Cleveland, Ohio. The Forum focused on stray gas in areas where shale gas or other unconventional natural gas is being developed.

1.1 The Forum

The purpose of the Forum was to explore the technical and scientific basis for stray gas investigations including the fundamentals of the physical and chemical properties of methane, and factors that influence the occurrence, migration, and fate of methane in the shallow subsurface environment. The conference agenda was structured to address the diverse topics and issues that should be considered during the course of an emergency stray gas incident response including:

- Emergency response priorities,
- Science-based action levels,
- Identification of potential sources,
- Defining migration pathways and driving mechanisms,
- Assessment of the integrity of wellbores in nearby oil and gas wells,
- Mitigation measures,
- Methods to aid in determining the source of methane (forensics), and
- Data management and interpretation.

The idea for the Forum was conceived following the GWPC's annual UIC Conference in January 2012. During that meeting, several presentations described stray methane gas found in water supplies in Pennsylvania. Initially, the methane was thought to result from new Marcellus Shale exploration and development activities. But upon more careful geochemical investigation using various analytical tools (described in more detail later in the white paper), the gas found in the water supplies was found not to have the same geochemical characteristics as the gas produced from the Marcellus. This suggested that the gas originated from other locations.

[1] The white paper was prepared for GWPC by John Veil of Veil Environmental, LLC.

Other presentations pertaining to stray gas at the GWPC UIC Conference included case histories of investigations in Ohio (Bainbridge Township) and Texas (Parker County). These presentations illustrated the technical complexities involved in some stray gas investigations and the importance of thorough assessments of site geology, the need to evaluate the full range of potential methane sources, and the value of using compositional gas analysis to complement isotopic analyses. Incidents of alleged stray gas often require evaluation of multiple potential sources. The source of stray gas may be the result of a natural condition or due to a variety of anthropogenic activities, or a combination of both. Incidents can manifest as non-threatening or as a significant threat to public safety.

Those presenters and GWPC staff realized the importance of this type of information in the context of shale gas production that has expanded rapidly in many parts of the United States. They decided to work on organizing a new conference dedicated to discussion of stray gas. This idea led directly to the Forum. Through the hard work of GWPC staff (particularly Ben Grunewald and Paul Jehn), Scott Kell (a consulting geologist with many years of state regulatory experience), and Fred Baldassare (a geochemical consultant who also has state regulatory experience), and others the Forum was planned and organized. The Forum was supported by the State of Ohio, which led to holding the event in Cleveland. Much of the information presented at the Forum was associated with studies conducted in the Marcellus Shale region, although a few presentations provided data and investigation case histories from other locations. Nevertheless, the Forum attracted nearly 200 attendees, including many who had never before attended a GWPC event.

The presentations included three short courses that allowed for a detailed review of specific topics and about 30 other technical talks over more than two and a half days.

1.2 The White Paper

This white paper summarizes the information that was discussed at the Forum. Much of the material is highly technical and esoteric. That information is very useful to specialists and practitioners. But in order to explain the importance of stray gas and the issues surrounding it to a wider audience, this white paper is written in a style and at a level for a broader non-technical audience.

Rather than summarizing each presentation in the order in which speakers actually made their presentations, the white paper pulls material from different presentations into a more thematic narrative that covers the key topics in a coordinated way.

Most of the speakers at the Forum agreed to let the GWPC post copies of their presentations on the GWPC website. Where those presentations are available, they are directly linked to references in this white paper. For example, the opening remarks and welcome from GWPC president, Stan Belieu of the Nebraska Oil and Gas Conservation Commission, are linked here. For those other presentations whose authors did not authorize the GWPC to post the slides, relevant information is summarized, and reference is made to their names – readers can contact those authors directly for additional information.

The white paper also includes three appendices. Appendix A shows the agenda for the Forum. Appendix B provides contact information for each of the speakers. Appendix C shows the companies and organizations that supported and contributed to the Forum.

Chapter 2 - Stray Gas

2.1 What Is Stray Gas?

Stray gas can be defined as gas that migrates from its usual geological location into aquifers or the vadose zone (the zone between the groundwater and the surface) within the shallow subsurface. When stray gas migrates into a drinking water well or into a building, there are potential risks. Although the Forum focused its attention on stray methane gas, a broader definition of stray gas could include other gases that are found in the subsurface. For example, the presentation made by Kevin McCray of the National Ground Water Association (NGWA) described a Best Suggested Practice guidance document prepared by the NGWA for water well drillers. It evaluates risks and safety practices relating to carbon dioxide, carbon monoxide, dissolved oxygen, hydrogen sulfide, radon, and sulfur dioxide, in addition to methane, that may be found in potable water aquifers.

Since the Forum focused on stray methane gas, this white paper also limits its scope of stray gas to just methane.

2.2 Methane

Methane is the simplest hydrocarbon molecule, containing only a single carbon atom. It has the chemical formula CH_4. According to a Material Safety Data Sheet[2]:

- Methane is a flammable, colorless, and odorless gas.
- Its specific gravity is 0.55.
- Its solubility at atmospheric pressure is 33 ml/l (~28 mg/l).
- It poses an immediate fire and explosion hazard when mixed with air at concentrations 5% to 15%.
- Methane is nontoxic when ingested. It can, however, reduce the amount of oxygen in the air necessary to support life. Exposure to oxygen-deficient atmospheres (less than 19.5% oxygen) may produce dizziness, nausea, vomiting, loss of consciousness, and death. At very low oxygen concentrations (less than 12%) unconsciousness and death may occur without warning.

The third bullet above talks about the solubility of methane at atmospheric pressure. However, the solubility of methane increases for each foot of depth below the ground surface. The importance of this to the stray gas issue is that water lifted by a well pump from an underground aquifer may contain dissolved methane at a concentration much higher than 28 mg/l. When that water encounters atmospheric pressure, any dissolved methane above 28

[2] See http://avogadro.chem.iastate.edu/MSDS/methane.pdf.

mg/l will come out of solution and will enter the air. If this happens in a confined space, the potential for elevated methane concentrations can occur.

2.3 Sources of Stray Gas

Stray gas found in a water well or in a home may originate from various sources. The primary source is pre-existing, shallow deposits of natural gas, which is described in section 2.2.1. Other sources include:

- Underground activities unrelated to shale gas production (e.g., coal mining, landfills),
- Leaks from abandoned, recently drilled, or operating gas wells, or
- Leaks from natural gas pipelines or natural gas storage fields or caverns.

In any investigation of stray gas, it is important to evaluate and identify the actual source of the methane so the appropriate remedial actions can be taken.

2.3.1 Pre-existing Natural Gas

Much of the region underlain by the Marcellus Shale has shallower geologic layers formations that are oil and natural gas sources. The earliest U.S. gas well was drilled in the 1820s in Fredonia, New York (very southwestern corner of the state). The earliest U.S. oil well was drilled less than 100 miles away in Titusville, Pennsylvania in the 1850s. Hundreds of thousands of wells were drilled to shallow formations throughout the region in New York, Pennsylvania, Ohio, and West Virginia.

Brent Wilson of Chesapeake Energy presented a review of the geology in northeastern Pennsylvania. He cited evidence of gas shows (the presence of gas found in the circulating drilling fluids used to drill the well – this can be linked to a precise depth and geologic formation) in the shallow Upper Devonian layers known as the Catskill and Lock Haven formations. Additional information was gained from monitoring the drill cuttings that showed coal and pyrite fragments at depths associated with those formations. Wilson showed quotes from old publications dating back to the mid-1800s that corroborated the presence of plant materials later converted to thin coal layers. He showed photographs of four surficial outcrop locations of the Catskill and Lock Haven formations with deposits of material having high organic content (this suggests they are sources of natural gas). Wilson concluded:

- Methane is naturally occurring in Upper Devonian formations and predates modern and historic drilling, and
- Water wells drilled into Upper Devonian bedrock have high potential of containing naturally occurring methane.

Damian Zampogna of ALL Consulting presented a fascinating look back into the history of petroleum discovery and production in the same region (Bradford and Wyoming Counties). He visited historical societies and libraries in those counties and searched through old newspaper records. He documented several boom and bust cycles starting as early as 1865. He also found evidence describing drilling, well construction, and closure practices from the past eras. Zampogna concluded:

- During the late 1800s and early 1900s there were several reports of people encountering shallow pockets of gas either while drilling water supply wells or while drilling deep oil or gas wells.
    - The presence of naturally occurring shallow gas in the potable aquifers or discharging to surface water features is not a new occurrence.
- Early oil well drilling and completion practices employed during the mid-1850s to the 1930s did not completely isolate groundwater aquifers from oil and gas bearing strata.
    - The well drilling and abandonment techniques used in early oil and gas development could have further contributed to the presence of natural gas in shallow aquifers by serving as preferential conduits for vertical migration of the gas.
- Observations of natural gas, which on occasion were reported to be flammable, elevated sodium chloride and hydrogen sulfide in groundwater were documented in the 1930s and commented on in the 1980s.
    - The 1930s groundwater quality data was gathered during a period following the resurgence of oil and gas activity and the 1980s groundwater quality data was gathered during a period of relatively little oil and gas activity.

In his welcoming remarks, Rick Simmers, Ohio's oil and gas director, stated that stray gas is common in Ohio. He noted that the Devonian-aged shales that outcrop in northeastern Ohio along Lake Erie were subject to fracturing following glaciation in the area –- this provided natural pathways for methane movement. Simmers shared a story about construction of the Rock and Roll Hall of Fame (located less than a mile from the hotel where the meeting was held). Seeps of gas were found in test core-holes drilled in preparation for constructing the foundation for the building in downtown Cleveland. The Division of Oil and Gas was called in to advise contractors regarding methods to properly plug the core-holes.

Debby McElreath noted that Chesapeake Energy has collected more than 31,000 water well samples in areas where shale gas drilling was planned. These spanned the states of Arkansas, Colorado, Kansas, Louisiana, New York, North Dakota, Ohio, Pennsylvania, Texas, West Virginia, and Wyoming. About 25% of all the samples had detectable methane concentrations. The highest concentrations of dissolved methane have been found in Louisiana, Ohio, and Pennsylvania.

2.4 Potential Risks from Stray Gas

Methane dissolved in water is not toxic when ingested by humans. However, a greater risk is posed by gaseous methane that moves from a subsurface location into a dwelling or other closed building or into headspace at the top of a water well, especially when a water well is located inside a dwelling or enclosed structure. If the concentrations of methane in air reach critical levels, and an ignition source is present, there is a risk of fire or explosion. The term lowest explosive limit (LEL) is used to express a threshold beyond which explosion risks are significant. For methane, the LEL is 5% methane by volume. Regulatory standards for ventilating or evacuating structures are typically established at some fraction of the LEL.

Pennsylvania uses a three-tiered system to evaluate methane risk. Their protocol (shown below) was described by Fred Baldassare and later by Joe Lee of the Pennsylvania Department of Environmental Protection:

> ***Category 1*** - ***Immediate threat***: *detectable concentrations equal to or greater than 10% of the lower explosive limit (LEL) of combustible gas in a building or structure(s).*
>
> ***Category 2*** - ***Potential threat***: *detectable concentrations less than 10% of the LEL of combustible gas in a building or structure(s), and/or combustible gas greater than 50% of the LEL in the head space of a water well, and/or visual or audible evidence of stray gas bubbling through a water well column or surface water body, and/or detectable concentrations of stray gas in the soils, and/or concentrations of dissolved methane in water at or above 25% of the lower solubility limit for methane (7 mg/l).*
>
> ***Category 3*** - ***No apparent threat***: *none of the above conditions were met. If conditions indicate methane in groundwater at concentrations above 0.5 mg/l, but below 7mg/l, continued monitoring is necessary to ensure that concentrations do not trend to a Category 2 potential threat.*

Scott Kell presented a table showing recommended action levels when mitigative actions may be prudent to ensure the safety of structures and the public. The table was originally published as part of a 2001 U.S. Department of the Interior, Office of Surface Mining Reclamation and Enforcement report.[3] It is included below as Table 1.

[3] "Technical Measures for Investigation and Mitigation of Fugitive Methane Hazards in Areas of Coal Mining," Office of Surface Mining Reclamation and Enforcement, September 2001. Available at: http://arblast.osmre.gov/downloads/Mine%20Gases%20and%20Dust/FINAL-Methane.pdf.

Rebecca Fugitt of the Ohio Department of Health noted that her agency was proposing to use the same action levels for detections of methane gas in homes as shown in Table 1.

Table 1 – Recommended Action Levels for Methane

Action Level	Atmospheric (Percent by Volume)		Dissolved in Water (mg/L)	Soil Gas (Percent by Volume)
	Occupiable Spaces (homes)	Un-Occupiable Spaces		
Immediate Action	>1.0%	>3.0%	>28 mg/L	>1.0%
Warning, Investigate	0.5% but <1.0%	>1.0% but <3.0%	>10 mg/L but <28 mg/L	>3.0% but <5.0%
Monitor to Determine Concentration Trends	>0.25% but <0.5%			<3.0% but >1.0%
No Immediate Action	<0.25%	<1.0%	<10 mg/L	

Source: OSMRE (2001)

2.4.1 Case Example - Bainbridge Township Incident

One of the most carefully studied cases of a stray gas problem was an incident in Bainbridge Township, Ohio in October 2007. Scott Kell gave an overview of the case, and in a short course format, Scott Bair of Ohio State University presented a much more detailed description of the cause, the geologic (stratigraphic and structural) controls that influenced the accumulation and migration of stray gas in multiple aquifers, and the eventual dissipation of the gas. Bair also described how the problem was remediated, and the extensive monitoring and investigation that took place.

In November 2007, a gas well (English #1) was drilled to a total depth of 3,926 ft near a neighborhood where residents were dependent on domestic water wells. The top of the target reservoir was approximately 3,720 ft below surface. The production casing of the English well was cemented to a depth of 3,640 ft, only 80 ft above that uppermost perforation in the target zone (the Clinton sandstone). It is standard industry practice in Ohio to cement production casing approximately 500 ft above the Clinton sandstone in order to isolate the overlying brine-bearing Newburg zone that can contain sour gas in some locations. The owner planned the cementing job to isolate the Newburg; however, the wellbore encountered a fault zone 80 feet above the Clinton sandstone that caused some loss of cement leading to an incomplete cement job. The owner elected to complete the well without additional measures to isolate the Newburg, and with limited isolation of the Clinton sandstone.

The well was completed (i.e., perforated and fractured) in November 2007. The well was shut in on November 16. While shut in, gas from the Newburg formation, through which the well had not been adequately cemented, entered the well into the annular space between the surface casing and the production casing. Over several days, pressure within that annulus rose to 320 psi creating over-pressurized conditions that allowed gas from the Newburg formation to migrate outward and upward into the overlying Berea sandstone aquifer.

On December 11, a nearby residence experienced cloudy water from their tap. On December 13 and 14, other homes in the neighborhood experienced gas in their water, including one water well that flowed to a height approximately 18 feet above ground surface. These conditions were not reported to the Ohio Department of Natural Resources (ODNR). On December 15, gas entered the basement of a home through an unplugged, abandoned water well in a vault adjacent to the foundation. Gas leaked from the vault into the basement, accumulated at explosive levels, and ignited, causing an explosion that damaged the foundation.

The fire department's initial response was to evacuate 19 homes. However, the location and concentration of gas measurements were never recorded; therefore, the basis of the evacuation decisions could never be established. Over the next few days, the owner of the gas well installed vents on indoor water wells, installed 26 temporary water systems and 49 in-home methane detectors, and began to provide bottled water to 48 residences upon request.

On December 15, the gas well owner completed a remedial cementing job that effectively sealed and isolated the well from the Newburg formation, thereby eliminating the source of the gas.

In January 2008, some of the homeowners in the area filed a lawsuit against the owner of the English well. The supporting evidence in their suit followed a different interpretation than the ODNR had made. To resolve the differences, the parties agreed to form a panel of experts to evaluate opposing hypotheses (Dr. Bair was one of the three experts on the panel). Using historical data, new data collected during their studies, and additional downhole video examinations of the water wells, the panel concluded that the ODNR had properly identified the cause of stray gas, and the owner terminated the source by performing the cement squeeze job:

- The Newburg gas released from the improperly cemented well migrated upward through the surface casing/production casing annulus and entered the shallow aquifer supplying water to the homes. It eventually moved into the basement of one house, where it exploded. The remedial actions to improve the cement job stopped any new flow of gas. The gas pocket that accumulated in the Berea Sandstone aquifer began to diminish due to intentional strategic over pumping of local water wells to purge the systems. By 2009, the methane had disappeared from the well water.
- The hydraulic fracturing job in the gas well did not cause fractures that extended from the target formation upward to the deepest aquifer. The observed gas was caused by an inadequate cement job that allowed gas to release and migrate upward in the annulus, not by permanent new conduits caused by the fracturing.
- The elevated and fluctuating concentrations of methane in other wells were not caused by fractures. They resulted from a combination of factors, including:
    - Their distance from the gas well,
    - Their location in relation to the top of the Berea sandstone formation,
    - Domestic water well usage,
    - Intentional over pumping of selected residential wells,
    - Seasonal variations of static ground water levels,
    - Fractured nature of the Cuyahoga Shale caprock, and
    - Elimination of gas source following the remedial cement job.
- The metals and "black goo" that were observed in some water wells were not caused by the gas leak. They were naturally-occurring scale and bacterial films typical of older water wells in the area that were not cleaned on a regular basis.

The findings of the panel were used by an arbitrator to settle the lawsuit.

Chapter 3 – Water Well Sampling for Stray Gas

Many of the presentations at the Forum discussed different types of monitoring programs, with an emphasis on samples collected from water wells prior to drilling shale gas wells in the area. This chapter describes sampling of water wells to detect methane. When methane is detected, various forensic tests can help determine the source of the methane that has migrated into drinking water.

3.1 Pre-Drill Sampling Programs

As shale gas development began in the Marcellus region less than a decade ago, the Pennsylvania DEP and oil and gas well owners began to respond to stray gas reported by local citizens. Property owners generally assumed that the methane had been caused by the gas companies. As a defense, the gas companies began collecting samples in local water wells before they started drilling in an area in order to characterize the existing quality of well water and the presence of methane. Later state agencies recommended this type of pre-drill sampling and provided basic guidelines on which parameters to test. In addition, citizens have expressed interest in sampling and testing their own water supplies prior to local site development or drilling activities

3.1.1 Ohio

Rebecca Fugitt described guidelines developed in Ohio for pre-drill sampling by citizens.[4] The guidelines recommend sampling different parameter sets based on the cost and importance of the results. The three-tiered system is shown below in Figure 1.

Figure 1 – Ohio Pre-Drill Sampling Recommendations

Recommended Water Quality Sampling Parameters		
Tier 1 Parameters	**Tier 2 Parameters**	**Tier 3 Parameters**
Barium Chloride Magnesium Potassium Sodium Strontium Sulfate Total dissolved solids Specific Conductivity	**Tier 1 sample parameters +** Calcium Hardness Total Alkalinity pH Iron Manganese Total suspended solids Bromide	**Tier 1 and 2 sample parameters +** BTEX (benzene, toluene, xylene, ethylbenzene) Methane (dissolved)*

*Include with Tier 1 if laboratory can analyze for methane.

Source: Recommendations for Water Well Sampling Before Oil and Gas Drilling Fact Sheet

[4] Two pre-drill sampling documents are available on the Ohio Department of Natural Resources website at http://www.ohiodnr.com/oil/watersampling_bmp/tabid/23361/Default.aspx.

Tier 1 – lowest cost, most critical parameters
Tier 2 – moderate cost
Tier 3 – most comprehensive list

3.1.2 Chesapeake Energy

Debby McElreath described the ongoing multi-state pre-drill sampling program followed by Chesapeake Energy. She indicated that Chesapeake had collected more than 31,000 samples to date. Samples are taken from water wells within a 1,000-ft radius from the surface location of the proposed gas wellhead or reflect the state regulatory requirement, whichever is greater. The program relies on several independent consultants to collect samples and several certified analytical laboratories to make the measurements. Chesapeake's standard parameters for baseline sampling include field screening, general chemical parameters, heavy metals, organics, and isotopic methane (see slide 7 of McElreath's presentation for the details).

The landowners are provided with a copy of the results. McElreath's presentation offers many useful suggestions for a sampling program. Some of the key points are:

- The gas company's sampling program document should be written.
- Photo documentation of the well and the sampling location is critical.
- All attempts to provide testing at a landowner's well should be documented.
- Dissolved methane sampling and analyses require careful consideration.
- Multiple lines of evidence are necessary due to the complexity of the issue – isotopic analysis[5] is useful but is not sufficient by itself.

Some of the detailed results from selected Chesapeake Energy sampling programs are described in the next section.

3.2 Detailed Sampling Results from Northeastern Pennsylvania

Speakers from three separate consulting organizations that supported Chesapeake Energy in its sampling programs in Pennsylvania described the trends in data and the high degree of variability that was found when the same water well was sampled repeatedly over time.

3.2.1 Overview of Chesapeake Data from Pennsylvania

Elizabeth Perry of AECOM presented the results of more than 14,000 samples taken during 2009 through 2012 at water wells in Pennsylvania, Ohio, and West Virginia. The samples were collected six to nine months prior to gas well pad construction. The samples were analyzed for methane, metals, inorganics, and organics. Methane was detected in about 25% of those

[5] Isotopic analysis is an advanced geochemical technique. It is described in more detail later in this chapter.

samples. Methane was measured at levels higher the Pennsylvania Action Level of 7 mg/L in 3.5% of the samples.

Perry's findings show that higher methane concentrations appear to be associated with:

- Certain geologic units (particularly the Lock Haven and Catskill formations),
- Water that has lower sulfate concentrations,
- Certain water types (particularly those dominated by sodium bicarbonate and sodium chloride water – [note: waters are often characterized by their primary chemical ions]),
- Waters having higher concentrations of total dissolved solids, sodium, chloride, barium, and strontium), and
- Topographic position – in northeastern Pennsylvania, higher methane is found at wells in lower topographical locations (in valley groundwater discharge areas).

3.2.2 Long-Term Monitoring of Selected Wells

Charles Whisman of Groundwater & Environmental Services presented data from a year-long study of 12 water wells. Sampling was done on a weekly or monthly basis for dissolved gases and Chesapeake's baseline parameters. Samples were collected for isotopic analysis where applicable. In addition, real-time monitoring was conducted downhole and in the head space of the well. Data were logged every minute and transferred remotely to a secure management system.

Dissolved methane measured in the same well varied substantially over time as shown in Figure 2 for a well identified as "EH". Over the course of four months, dissolved methane ranged from nearly zero to more than 15 mg/L. A visual evaluation of Figure 2 suggests that the "average" methane concentration was approximately 7 mg/L. Data presented from other wells also showed a high degree of variability.

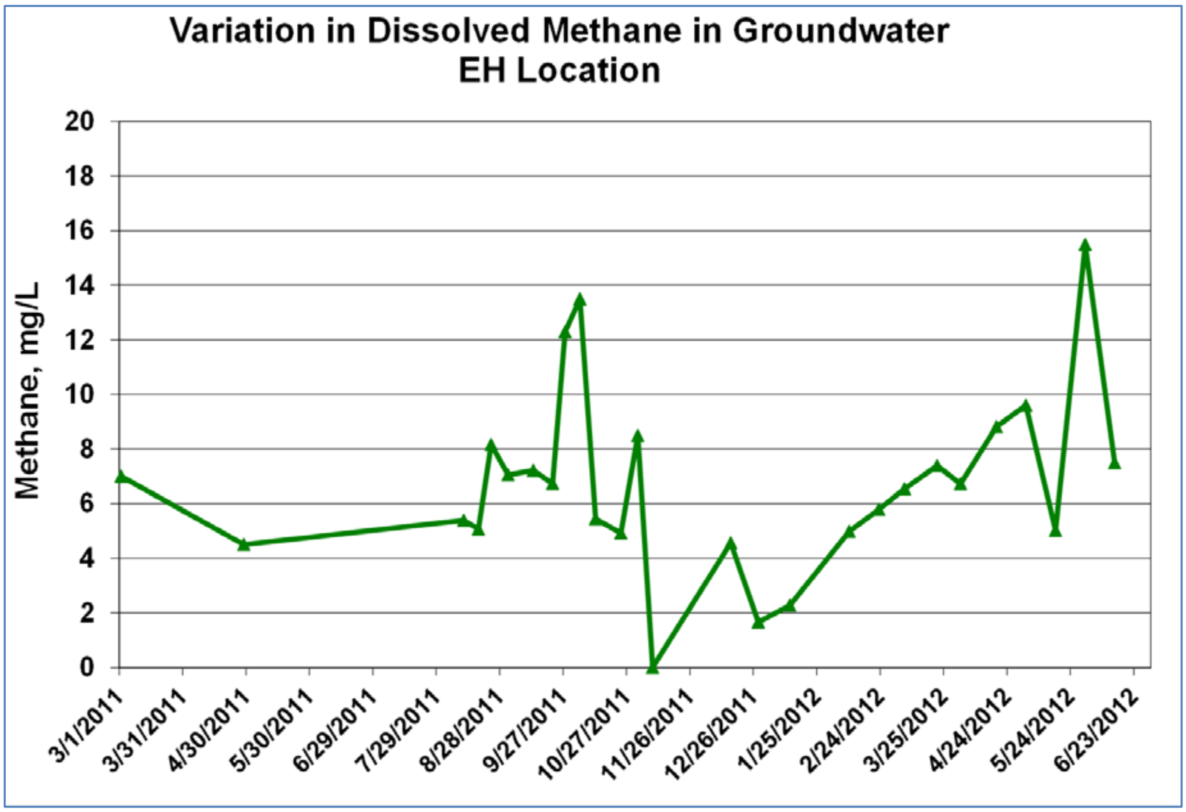
Methane measured in the headspace of the well (i.e., the layer of air found above the water column inside a well) also varied quite a bit. An inverse correlation was observed between water level and headspace methane concentration. As the well pump turns on and lowers the water level, the headspace methane increases. Many other graphs are shown in Whisman's slides.

Whisman offers several preliminary findings:

- Methane occurs naturally and is highly variable:
    - Spatially and temporally,
    - With temperature, barometric pressure, seasonal variability, and drought.

- With human-induced changes (well pumping). A single pre-drill baseline methane sample may not be representative of natural variability.
- Methane levels (headspace and dissolved) may be influenced by pumping and/or water level fluctuations.
- Water level declines (pumping or natural) may result in increased methane headspace concentrations.
- Sample collectors should document variables that could influence methane concentrations.

Figure 2 – Weekly Dissolved Methane Results from a Water Well



Source: C. Whisman presentation.

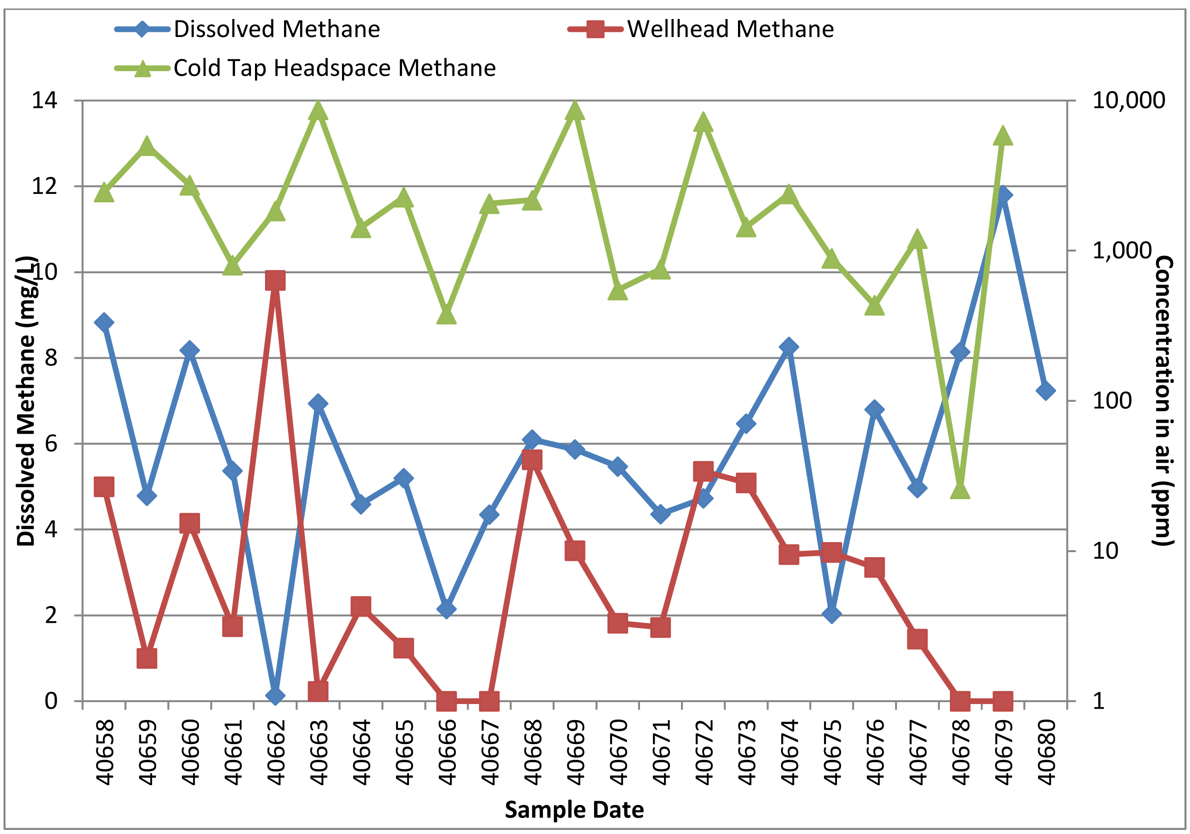
- Methane levels in well headspace may correlate with:
  - Changes in air temperature,
  - Changes in carbon dioxide content,
  - Changes in barometric pressure.
- A correlation of headspace methane levels across multiple well locations (influenced by weather and/or pumping) was observed, including wells located 5-40 miles apart.
- Methane concentrations may vary seasonally.

3.2.3 Short-Term Variability in Methane Concentrations

Nancy Coleman of Environmental Consultants described a project involving 30 domestic wells that were sampled on a daily and/or weekly basis in April and May 2011. The project began following a surface release of produced fluid (mixture of hydraulic fracture fluid and produced formation water) at a well pad in northeastern Pennsylvania in April 2011. The 7 water wells located closest to the wellpad were sampled daily for 24 days then weekly for another 4 weeks. An additional 23 wells within 4,000 ft of the well pad were sampled weekly for 4 weeks.

The range of measured dissolved methane concentrations for the nearer wells was <0.026 – 11.8 mg/L. For the other wells within the 4,000-ft radius, the range of dissolved methane was <0.026 – 17.4 mg/L. Coleman also presented a comparison of methane measured as dissolved methane in water, wellhead methane (in air), and a third measurement called cold tap head space methane (in air). These are shown in Figure 3. The measured values fluctuated a great deal from day to day. However, there was no observed correlation between the three types of measurements. But Coleman did find a direct relationship between dissolved methane and both chlorides and sodium, and an indirect relationship with sulfate.

Figure 3 – Comparison of Methane Measurements for a Single Well



Source: N. Coleman and D. McElreath presentation.

Coleman concluded that there are short-term variations in groundwater methane concentrations. She noted:

- Some dissolved methane concentrations may change by several mg/L on a day-to-day basis.
- Variability is not consistent and is not the same for all domestic wells.
- Wells with stratified water quality (those completed in restricted flow zones typically associated with water wells developed in groundwater discharge areas such as valleys with longer groundwater residence times) show the greatest degree of variability.
- Some of the variation may be due to differences in sample techniques and laboratory analysis.
- Some of the variation is due to the pumping action in the well, well construction, and well completion in fracture-based geology.
- Additional variation is associated with differences in domestic use on a daily basis, particularly in marginal yield wells.
- Cold tap headspace and wellhead measurements may not be predictive of low dissolved methane concentrations.
- Recognition of natural variability is important in interpretation of water-quality data.

3.2.4 Additional Marcellus Data

Lisa Molofsky of GSI Environmental presented data collected by Cabot Oil & Gas, another large gas operator in the Marcellus. Cabot collected pre-drill methane samples in more than 1,700 water wells in northeastern Pennsylvania between 2008 and 2011. From those samples, more than 78% of the water wells showed some methane. Higher methane concentrations were found from wells in low-lying areas like valleys as compared to wells situated at higher elevations.

3.3 Sampling Techniques

Several presenters noted that some of the variability in the methane results was likely caused by variation in the sampling techniques used. Large-scale and ongoing sampling programs can benefit from consistency in sampling techniques, containers, and the personnel who do the work.

Rebecca Fugitt offered the following guidelines for sampling:

- The water sample should be collected prior to any treatment devices (water softener, disinfection) near the point of entry into the home.

- A representative sample should be collected by flushing the system at least 5-10 minutes to ensure water collected is coming from the aquifer and not water stored in the well bore.
- Sample location, date/time, site ID information should be properly documented.
- Water should be collected in proper containers for analysis method, and preservatives should be used where appropriate.
- On-site measurements of pH and conductivity may be collected.

Keith Hackley of Isotech Laboratories talked about sampling methods. He noted that good sampling techniques and appropriate sample containers are required for good data and accurate interpretations. For conditions where gas is below the saturation limit (i.e., the gas remains in solution), bubbles will not form and gas will leave solution only by diffusion. Water can be collected in a non-permeable bottle by minimizing contact with air. The sample bottle is immersed in a bucket filled with formation water and filled. The resulting sample is chilled and may be treated with a preservative to prevent bacterial activity prior to laboratory analysis. At the laboratory, a head space equilibration method is used to collect and accurate sample that can then be analyzed.

When gas is above saturation pressure (such as when saturated water is brought up from a depth), different sampling methods are required. A water displacement method that collects gas samples without air contact can be used. Hackley's company also uses an evacuated bag (the IsoBag™) and is developing a new sampling container (the IsoFlask™).

3.4 Stable Isotope Analysis and Interpretation

Many of the presenters showed data that used stable isotopes (or isotopic analysis) to help characterize and distinguish methane from different sources through "fingerprinting". The next few sections provide a brief introduction to the subject.

3.4.1 What Are Isotopes?

Isotopes are different forms of an atom that have slightly different atomic mass due to the presence of one or more extra neutron particles. To use hydrogen as an example, the most common form of the atom is referred to as hydrogen or ^{1}H. It has an atomic number of 1 and has one proton and no neutrons. Other forms of hydrogen occur with one neutron (deuterium or ^{2}H) and two neutrons (tritium or ^{3}H). The carbon atom in methane also has alternate isotopic forms. The common carbon is ^{12}C, but isotopic forms ^{13}C and ^{14}C are also found.

Other atoms also have isotopes that have been used in geochemical analyses. For example, strontium, and oxygen isotopes can help distinguish samples when the carbon and hydrogen information is inconclusive.

3.4.2 How Isotopic Ratios Are Used

Isotopic ratio measurements of an element can give information about the production of the compound, and the possible secondary reaction of the compound. Using the carbon in methane as an example, the ratio of $^{13}C/^{12}C$ changes during compound production or reactions because the two isotopically different atoms react at different rates.

Kinga Revesz of the U.S. Geological Survey provided two equations to show how the ratios of isotopes are compared to reference standards (Figure 4). The ratio is referred to as the letter δ or delta.

Figure 4 – Equations to Calculate Deltas

$$\delta^{13}C = \frac{R_{sample} - R_{reference}}{R_{reference}}$$

Where $R = {}^{13}C/{}^{12}C$,
$R_{reference}$= VPDB (Vienna PeeDee Belemnite)

$$\delta^{2}H = \frac{R_{sample} - R_{reference}}{R_{reference}}$$

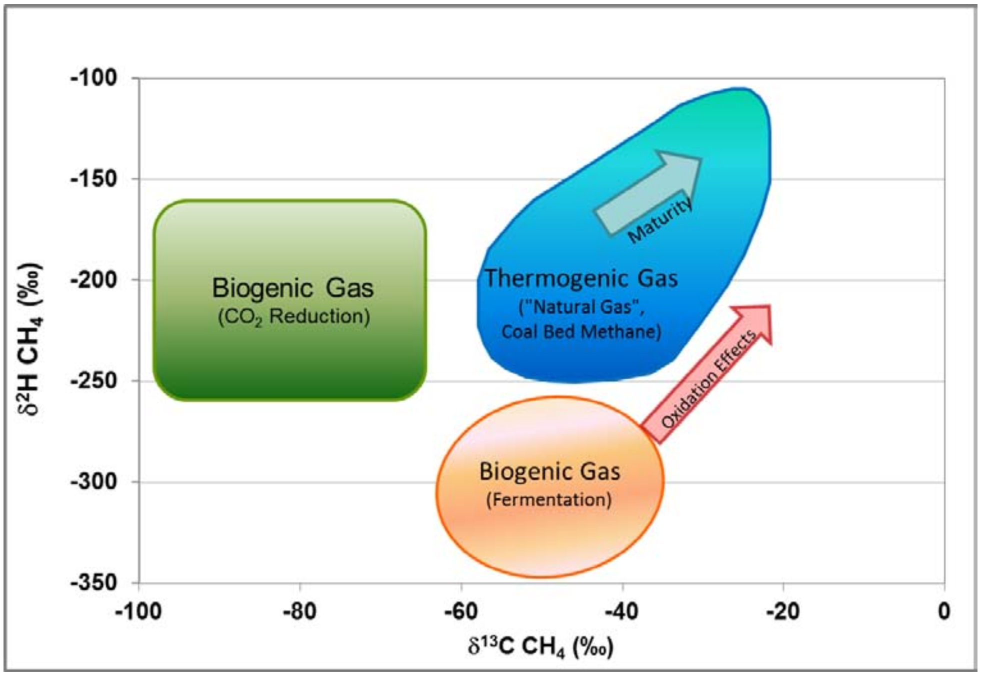
Where $R = {}^{2}H/{}^{1}H$,
$R_{reference}$= VSMOW (Vienna South Mean Ocean Water)

Source: K. Revesz presentation

When the isotopic signatures of different samples are plotted on a graph, their relative positions, when used in conjunction with other analytical methods, may help investigators or researchers to differentiate gas that originated from different sources. Various presenters showed many different combinations of comparisons using different ratios on the horizontal and vertical axes of graphs. The most common comparison was plotting the $\delta^{2}H$ of methane on the vertical axis and the $\delta^{13}C$ of methane on the horizontal axis. Figure 5 shows how those deltas are plotted, as well as how the results can be used to delineate the three groupings of methane samples based on the process by which the methane was formed.

More graphs showing additional comparisons of ratios are not included here but are available in many of the linked presentation (in particular, see the presentations by Kinga Revesz, Julie Sueker, Lisa Molofsky, Anthony Gorody, and Peter Pope).

Figure 5 – Plot of Isotopic Ratios of Carbon and Hydrogen in Methane



Source: J. Sueker presentation

The presentations by Fred Baldassare, Avner Vengosh, and Thomas Darrah, also included graphs showing different uses of isotopic comparisons. However, those presentations are not available on the GWPC website. Darrah's presentation described the use of isotopes of noble gases (e.g., argon, helium, neon) as indicators to help distinguish gas samples. When used in conjunction with other types of isotopic analysis, the noble gases can provide additional discriminating power.

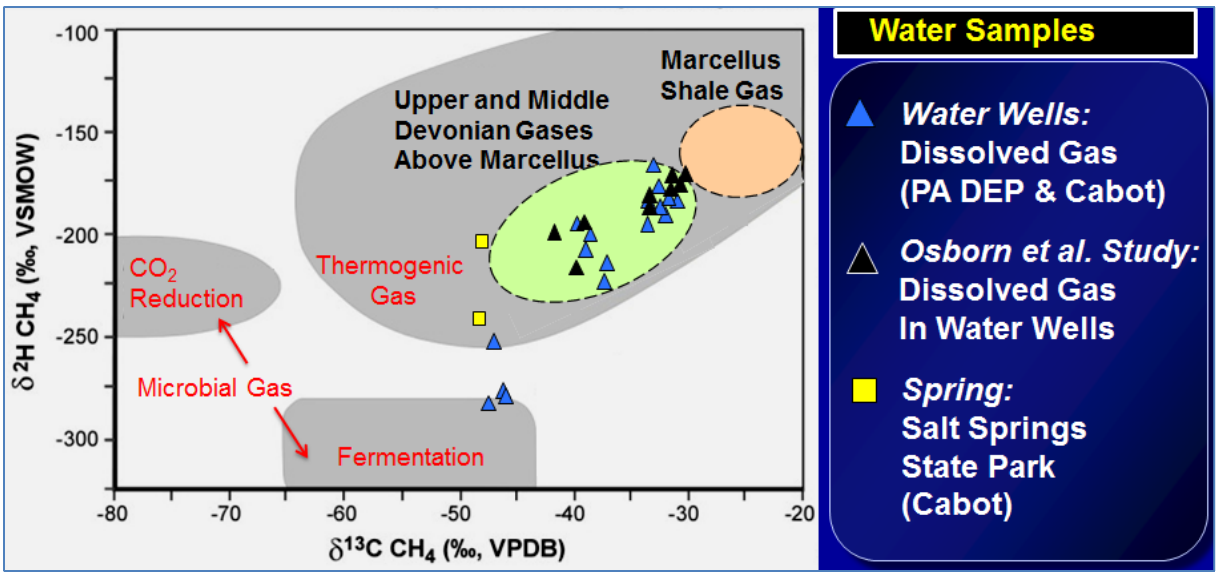
3.4.2 Different Types of Methane Distinguishable by Isotopic Ratios

Fred Baldassare explained that the isotopic and compositional variations in methane can be described for the most part by the processes under which the methane was originally formed. The two primary methane pathways involve biogenic or thermogenic origins. Biogenic gas typically arises from bacterial decomposition of shallow organic material like marshes or landfills. Or it can arise from reduction of carbon dioxide. Thermogenic gas is formed by the thermal breakdown of organic material. Variations in the isotopic ratios result from other processes that occur during secondary migration, such as mixing, microbial oxidation, and fractionation. Baldassare indicated that methane of different origins can be segregated by their carbon and hydrogen isotopic ratios.

These procedures, when used in concert with compositional analyses and other investigative tools, can be used in a forensic capacity to identify the origins of specific stray gas in water well samples. Several presenters showed graphs similar to Figure 5 but with individual water well samples superimposed on the same graph. The location of those water well samples on the graph give a clue as to which type of gas (and therefore whether it came from shallow sources or deeper Marcellus sources) was present.

Figure 6 shows an example of one of these graphs. The data points for dissolved methane in water wells cluster in an area that suggests the gas arises from formations above the Marcellus shale, rather than from the Marcellus shale itself.

Figure 6 – Plot of Isotopic Ratios with Water Well Data



Source: L. Molofsky presentation

3.5 A Theory for Widespread Stray Gas in Northeastern Pennsylvania

Dan Soeder of the U.S. Department of Energy's National Energy Technology Laboratory (NETL) offered a theory on how data sets that might not appear compatible can be linked together. He cited two sets of data. The first is data published by several Duke University authors in 2011 (one of the co-authors, Avner Vengosh, presented portions of this information during the Forum, but his presentation is not available through the GWPC website). They measured methane content in groundwater in wells in northeastern Pennsylvania. They found that dissolved methane was considerably higher in water wells located near gas wells. The authors concluded that the elevated methane was related to some aspect of the shale gas wells. However, they found no evidence that the hydraulic fracturing stage caused any of the elevated methane.

The second set of data (previously described in section 3.2.4) is the result of more than 1,700 pre-drill samples collected by Cabot Oil and Gas. Lisa Molofsky and her colleagues published those data a few months after the Duke University paper. Molofsky's Forum presentation describes this data set. They concluded that methane is common in the regional groundwater. Further, it varies with topography (it is highest in stream valleys). The authors believed that methane is migrating along fracture systems that control stream locations.

Soeder postulates that if the methane source is natural upward migration of thermogenic gas, and the gas is more concentrated near wells, the well drilling process itself may be affecting gas accumulation. He assumes:

- Gas from the Marcellus Shale is generally not migrating upward to shallow aquifers.
- Gas in shallow aquifers is ubiquitous and sourced from higher in the geologic column.
- Some gas migration may be via the annulus from openhole completions, bad cement or defective casing, but not all wells are bad completions.

Many Marcellus wells are drilled using air drilling techniques for the upper, vertical portions of the well. If high pressure drilling air gets trapped in the fracture system, it could push groundwater in a radial surge away from the well. Trapped, high pressure drilling air in fractured aquifer causes groundwater surge, entraining and mobilizing pre-existing methane. The surge is stronger closer to well, entraining more gas. The surge also entrains minerals and sediment. Soeder reported that NETL is collaborating with industry and other researchers to obtain field data to evaluate this conceptual hypothesis.

3.6 Estimating Background Methane in the Absence of Pre-Drill Sampling

Seth Pelepko of the Pennsylvania Department of Environmental Protection described efforts that his agency had made to estimate pre-existing background concentrations of methane in groundwater when no pre-drill sampling had been done. He developed a multiple regression model using the following variables:

- Surface Elevation,
- Bottomhole elevation,
- Topographic Position Index (TPI),
- Gas well distribution,
- Gas show density (0 to 500 feet and 0 to 1,000 feet),
- Depth to Tully formation,
- Longitude,
- Latitude,
- % Sand (0 to 500 feet and 0 to 1000 feet),

- Sample date, and
- Gas well production for first period of reporting.

They evaluated each of the variables separately but found poor individual correlations with methane concentration. However, when combining the variables into a multiple regression model, they had somewhat better success. The three most important variables for predicting dissolved methane are TPI, latitude, and bottomhole elevation. However, the goodness-of-fit was less than desirable – only 36% of variance was explained.

As result, Pelepko's office is considering a more advanced analysis that would integrate gas well construction and mechanical integrity test data with subsurface structure, water quality trends, and the time dimension. He also discussed the use of other affordable and accessible geospatial tools such as:

- Topographic Position Index (TPI)
- Interpolation and extrapolation techniques
    - Natural Neighbor
    - Kriging
- 3D Modeling and ArcScene.

Chapter 4 – Other Types of Monitoring Programs

Chapter 3 described studies that sampled for methane in water wells. This is the most common place to look for stray gas. But stray gas can be found in other places too. Several examples are described in this chapter.

4.1 Broad Area Monitoring Techniques

This section covers techniques that can be used to monitor large geographic areas as a first cut in identifying potential locations for stray gas.

4.1.1 Screening Techniques to look for Fractures

Tim Erikson of Moody and Associates described a technique called fracture trace analysis, in which stereo-pair aerial photographs are examined to identify natural linear features that are geologic in origin (fractures or faults). The technique can be done in an office setting. The technique does have limitations, however, when there is a significant thickness of unconsolidated overburden in the area. The technique's utility is limited to the identification of vertical or near vertical fractures. Moody and Associates has used the technique to identify locations for high-yield water wells.

Erikson suggested that fracture trace analysis can be augmented by VLF (very low frequency) surveys, in which a technician walks through an area in a defined pattern with a VLF meter that can measure several hundred ft underground. A companion GPS (global positioning satellite) unit allows for accurate geographic tracking of the resulting readings. Advantages of VLF surveys include ease of use, rapid deployment, simple data processing and relatively low cost.

4.1.2 Remote Sensing Techniques

Bryce McKee of Shell described the neoPROSPECTOR program that Shell and its partner NEOS GeoSolutions are using in Tioga County in northern Pennsylvania to detect old abandoned wells, find surface lineaments and hydrocarbon seeps, and identify surface structural features that control aquifer distribution and occurrence of hydrocarbon seeps. They used a variety of sensors mounted on a helicopters and fixed–wing aircraft to fly grids over a target area, followed by additional monitoring on the ground for confirmation.

McKee indicated that the project had been successful. His findings include:

- Well Detection
    - The project used remote magnetic sensing to identify 67% of the documented wells in the test area, and has identified 43 additional "potential" abandoned buried well heads.

- Surface Lineament Mapping and Hydrocarbon Seep Detection
    - The project has been able to interpret faults/fractures at or near the surface. These interpreted surface and near-surface structural features were integrated with hydrocarbon indicator analyses to identify locations of surface hydrocarbon seeps. The project has identified potential surface hydrocarbon seeps based on hyperspectral, spectroradiometer, FTIR (infrared), and resistivity data.
- Near-Surface Shallow Gas Sand Detection
    - The project has been able to interpret shallow gas occurrence at a range of depths (using depth-matched filtering) with magnetic and electromagnetic resistivity data.

4.2 Other Case Examples from the Forum

This section describes several case examples that were presented by different speakers.

4.2.1 – Mamm Creek, Colorado

The Mamm Creek field is part of the Piceance Basin in western Colorado. Operators are producing gas from tight gas sands in the Williams Fork formation from 3,000 to 7,000 ft depth. Shallow gas is often seen in the overlying Wasatch formation at less than 1,000 ft. Claims of methane contamination in groundwater have been made. Pete Penoyer of the National Park Service and Anthony Gorody of Universal Geoscience Consulting presented information about studies conducted to determine the source of the stray methane.

Penoyer's investigation focused on the Swartz 2-15B well. The initial cement job was inadequate. This allowed methane and gas condensate to migrate to shallow groundwater through naturally fractures or a fault that intersected the well. The leakage was controlled by performing a remedial cement job that stopped the leakage.

Penoyer noted that "nuisance" gas in the Wasatch formation is unrelated to the cement job problem in the Swartz well. Rather it is an independent issue in the greater Mamm Creek area that leads to positive bradenhead[6] pressures on a significant percentage of wells. Bradenhead monitoring and venting is effective mitigation method for potential impacts (evaluate wells for remediation when pressure exceeds 150 psi) but it is unclear to what degree any sustained

[6] "Bradenhead refers to a surface casing head. The bradenhead seals the annular space between the production casing, intermediate casing (if present) and the surface casing. It enables the use of one size pipe inside another and allows flow into or out of each pipe separately. Bradenhead gas enters the well from sources different from the target gas that enters the production casing or tubing.

pressure poses a threat of methane migration to drinking water aquifers/supplies over the long term should an open fracture system intersect the open annular borehole wall.

Gorody noted that the shallow Wasatch formation contains a complex mix of methane from thermogenic, altered thermogenic, and biogenic origins. He described pressure test studies that were undertaken in order to identify whether pressure linkage occurred between the deeper Williams Fork formation and the bradenhead pressure in the well. Analysis of pressure data shows that there was no pressure communication between bradenheads and the Williams Fork completion interval. Pressure cycling at the bradenheads was not observed in downhole pressure data and the gradual increase in downhole pressure buildup was not observed to affect maximum buildup pressures in bradenheads.

In addition, methane samples were collected. Gas composition data supported the conclusions reached from pressure transient and bradenhead pressure cycling analysis. At least four shallow geologic intervals, each with distinctly different gas composition, variably contribute their share of non-associated pressurized gas to bradenheads at the pad; none of those sources contain gas similar in composition to Williams Fork formation gases. Gorody's presentation contains many graphs that show the types of data that were collected. Among Gorody's conclusions are that the highest risks [to stray gas showing up in groundwater] are poor cement integrity and abandoned wells.

4.2.2 Parker County, Texas

Another stray gas case that received a great deal of attention was found in the Barnett Shale area in Parker County, Texas. Peter Pope of the Railroad Commission of Texas (RRC – this is the state oil and gas regulatory agency in Texas) presented a detailed review of the case, which featured a significant difference of opinion between the RRC and the U.S. Environmental Protection Agency (EPA) on the source of the stray gas and the necessary follow-up measures. An abbreviated summary of his presentation follows here.

In August 2010, a landowner filed complaint of natural gas in a domestic water well. A nearby gas well operated by Range Resources was considered a possible source for the stray gas. The RRC investigated and collected samples from the water well. Additional samples of methane were collected from the gas well that was developed in the Barnett Shale. Both agencies agreed that the gas in the water wells and the Barnett Shale were thermogenic in origin. Based upon isotopic analyses, EPA issued a controversial endangerment order, requiring installation of alternative water supplies for several local residents. The RRC staff proceeded to conduct a more thorough investigation by requiring Range Resources to perform mechanical integrity tests, interviewing local water well drillers and residents about the historic occurrence of natural gas in area water wells, assessing stratigraphy and structure on the local aquifers, and collecting gas samples for compositional analysis. Based upon broader lines of evidence, the RRC concluded that there was no pathway or driving mechanism to explain how gas could migrate from wells developed by Range Resources.

Pope's presentation as well as a portion of Lisa Molofsky's presentation reported that the isotopic methane data were not conclusive in showing that gas in the water wells was different from the deeper Barnett Shale gas. However, additional comparisons using nitrogen and carbon dioxide content and nitrogen isotopic signatures did provide clear geochemical evidence of different origins. There was sufficient evidence to show that gas occurred naturally in the aquifer prior to the completion of the Range Resources wells. As a result of the evidence, the RRC hearing examiner found in March 2011 that Range Resources' natural gas wells should be allowed to continue to produce as the wells were not causing or contributing to contamination of any Parker County domestic water wells. EPA has since withdrawn its endangerment order. The case illustrated the importance of conducting thorough investigations before reaching conclusions in support of enforcement actions.

4.2.3 Mississippi Gas Storage Caverns

Julie Sueker of ARCADIS described investigations at a salt dome on the Gulf coast of Mississippi. Several large natural gas storage caverns had been created in the same salt dome. They were used as seasonal storage facilities for natural gas. The well leading from the surface to one of the caverns had several leaks that allowed natural gas to escape from the cavern and migrate upward to reach the surface as bubbles in nearby water bodies. The leaks were subsequently repaired, and a series of vent wells were drilled into the salt dome to collect the escaped gas.

The company collected many samples and performed isotopic analysis to identify the likely origin of the gas observed at the surface and in water wells. The results showed that much of the stray gas found in the area originated from shallow sources rather than from gas that had escaped from the cavern. This helped to delineate a smaller zone for which the gas company had responsibility.

When stray gas is found to be bubbling through the water in a river or other water body, creative sampling techniques may be required. Sueker's presentation reported on the innovative use of a child's plastic swimming pool that was inverted, held in place by ropes, and attached to a sample tube. The pool (see Figure 7) served as a capture dome.

Figure 7 – Methane Sampling Device Using a Swimming Pool and Tubing

Source: J. Sueker presentation

4.3 Other Federal Research Relating to Hydraulic Fracturing

4.3.1 Well Data Related to EPA's Hydraulic Fracturing Study

This section describes data collected for Chesapeake Energy related to EPA's ongoing study of hydraulic fracturing impacts on drinking water. Deborah Watkins and Thomas Cornuet of Weston Solutions are contractors to Chesapeake that took split samples during the retrospective case study in Bradford County, Pennsylvania. The presentation described sampling results from 15 groundwater locations as well as a review of three existing databases of groundwater data from the same region. The 15 samples were a subset of the 37 locations sampled independently by the EPA. Weston presented the results of their work to date.

Their presentation concluded:

- The 15 groundwater sample locations do not appear to be impacted by natural gas drilling or production activities.
    - For all 15 groundwater sample locations, water quality data were typical of water quality concentrations in historical USGS databases and regional baseline data.
    - There are no significant increases in inorganic and other water quality parameters when comparing data from each of the 12 study wells with available baseline data.

- o There are no significant increases in dissolved methane when comparing data from each of the 12 study wells with available baseline data.
- o Few organics were detected - None of these are attributable to natural gas production activities or exceeded applicable drinking water standards.

Similar to the historical/baseline databases, the15 sample locations contained aluminum, arsenic, barium, chloride, iron, lead, lithium, manganese, pH, sodium, strontium, and turbidity; in several instances, these naturally occurring concentrations exceeded EPA and/or PADEP screening criteria.

4.3.2 Multi-Agency Collaboration on Unconventional Oil and Gas Research

Representatives from EPA, DOE, and USGS described some of their research activities that relate to unconventional oil and gas. Kevin Teichman of EPA described a multi-agency research plan to address the highest priority research questions associated with safely and prudently developing unconventional shale gas and tight oil resources. The program is intended to generate timely, policy-relevant science directed to research topics where collaboration among the three agencies can be most effectively and efficiently conducted. The research is intended to provide results and identify technologies that support sound policy decisions to ensure the prudent development of energy sources while protecting human health and the environment.

The potential research areas envisioned in the plan include:

- Enabling prudent development,
- Water quality,
- Water quantity,
- Air quality and greenhouse gas emissions,
- Ecological effects,
- Human effects, and
- Induced seismicity.

Teichman asked the Forum attendees to offer suggestions and feedback on the research plan. Comments should be sent to unconventional@hq.doe.gov.

David Russ of the USGS described an integrated study plan on the effects of Marcellus Shale gas production on the environment that the USGS is undertaking. It covers three major river basins (Delaware, Ohio, and Susquehanna) that make up nearly all the Marcellus region. It considers the observed/potential environmental effects on key thematic science issues, including a list that is similar to the national research plan described by Teichman:

- Hydrogeologic framework,
- Water availability,
- Water quality,
- Air quality,
- Induced seismicity,
- Landscape changes, and
- Biological resources.

George Guthrie of DOE described NETL's intramural (in-house) research efforts. Those efforts are focused on:

- Fugitive air emissions and greenhouse gases
  - Collection of field-based data tied to key uncertainties identified in NETL's Life Cycle Assessment Model.
- Produced water management
  - Develop a science base to predict volume and composition of flowback water (as a function of reservoir variability, stimulation method, and frac fluid properties) and composition and fate of other solid/liquid waste products.
- Subsurface migration of gas and fluids
  - Conservative analytical modeling demonstrates that hydraulically-generated fractures in Marcellus will not extend to drinking water aquifers under normal operations.
  - Wellbore integrity is essential.
- Induced seismicity

Guthrie also described several other related projects.

Chapter 5 – Mitigation and Remediation when Stray Gas is Observed

When an indication of stray gas is observed in places where it is not wanted, various steps should be taken. Fred Baldassare's short course provided a list of general steps that should be followed:

- Determine the threat level,
- Implement measures to ensure public health and safety,
- Define the origin of the stray gas,
- Delineate the extent of the stray gas plume,
- Conduct periodic monitoring to define trends,
- Identify potential sources of the stray gas,
- Focus the investigation on those sources,
- Evaluate potential source(s) individually for mechanism of migration, and
- Monitor to confirm a remedy.

Several of these steps have been described in the previous chapter. Once the source of the stray gas has been determined, the responsible party can take steps to mitigate the effects of the gas. This chapter describes some of the investigations that are used to find leak points and how those leaks are repaired. In addition it explains various techniques to remove the stray gas from water or dwellings to make them safe.

5.1 Tests to Delineate the Extent of Stray Gas Migration

Various procedures can be used to delineate the extent of stray gas migration. Baldassare recommends conducting soil gas surveys and collecting wellhead samples and other samples of gas bubbling through a water body. If necessary, additional Very Low Frequency (VLF), electromagnetic imaging, and seismic sampling can be used. He also mentioned the possible use of monitoring wells.

If the source of the stray gas is potentially from a leaking gas well, Baldassare recommends evaluating records relating to the well construction and completion, such as (among others):

- The depths at which the casing were set,
- The type and amount of cement used,
- The types of casing and hardware used,
- Cementing, logging, perforating, and hydraulic fracturing service records,
- Downhole video or camera surveys,
- Mud logging surveys, and
- Annular pressure measurements.

5.2 Evaluating Wellbore Integrity

Oil and gas wells are designed with multiple strings of casing that are cemented into a drilled hole. In theory, this provides several barriers of protection to keep fluids in the well isolated from the surrounding formation. However, if the well construction practices are not done correctly, opportunities can arise for materials to leave the well and move into areas where they are not expected. This section talks about methods used to evaluate the integrity of a well.

Dan Arthur of ALL Consulting presented a short course on evaluating well integrity. He recommends following a holistic well evaluation process that encompasses multiple types of investigations looking at both internal (e.g., tubing, casing, packers, plugs, perforations) and external (e.g., cement, drilling fluids, annular fluids, the presence of microannuli, cement channels, or pores) well integrity. In addition the holistic analysis should include an understanding of regional geology and hydrogeology, drilling and completion practices, well integrity practices, historic area issues, among other topics.

Arthur described several types of pressure tests that can help evaluate internal integrity.

- Shut-in surface casing pressure testing,
- Production casing build-up/leak-off testing, and
- Pressure differential testing.

For wells having more than one exterior annulus (e.g., 3-string well), all annular spaces should be tested. He suggests that continuous pressure testing is important. This allows specialists to develop a pressure curve analysis that can give clues about the well's behavior. Arthur's presentation includes a variety of pressure curves that show different patterns and trends.

Arthur discussed various tools and techniques for monitoring external well integrity:

- Visual analysis and inspection,
- Sampling for methane in air concentrations to evaluate explosion risks,
- Well drilling and completion analysis,
- Casing and cementing records review,
- Vent rate testing,
- Geology review,
- Cement bond logs,
- Temperature logs,
- Noise logs, and
- Pressure build-up testing.

These testing methods target assessment of significant gas or two-phase fluid movement external to the production casing. Arthur's slides provide many examples of well log results. The conclusions in his presentation offer valuable insights into evaluating integrity:

- A combination of testing methods and analyses can be used effectively to assess well integrity.
- Regulatory agencies tend to seek tests and analysis methods that provide a black and white answer, but tend to recognize the complexities.
- Most testing methods do not offer an absolute and definitive answer regarding well integrity.
- Sometimes, achieving an absolute finding is difficult or impossible. This is why EPA allows some leak-off on the standard annular pressure test – achieving a zero leak-off is generally impossible considering all the factors involved.
- Some issues are simply a nuisance and not a significant environmental or safety concern.

5.3 Remedial Actions

Remedial actions can take several forms. Some activities should be conducted as soon as possible to remove an immediate threat to human safety through explosion or inhalation. Once those immediate threats are reduced, other actions can be undertaken to stop the source of stray gas (particularly if it is from defined leak) or to mitigate the effect of methane. If stray gas has been detected in a building, methane alarms should be installed.

Baldassare described several methods for keeping methane from entering dwellings. Well vents should be installed on the wellheads when detectable concentrations of stray gas are found in the head space of water wells. The well vents should extend above building roof lines, or other areas of exposure. Sub-slab positive air pressure ventilation units can push clean air beneath the foundations of dwellings at low pressure. This serves as a pressure barrier that keeps methane from seeping into a dwelling. Ventilation trenches can be installed to intercept, control, and vent stray gas before it migrates to structures and other areas of concern.

John Sepich of Brownfield Subslab described a variety of approaches for preventing methane from entering dwellings. Some of his examples were the same as the ones mentioned by Baldassare, but Sepich had some different techniques too. He mentioned active ventilation systems that operate in a reverse direction from the positive pressure ventilation described by Baldassare. These are similar to the radon ventilation devices used in many homes to capture gas from beneath the concrete slab or basement floor and ventilate it above the roof line of the house. Sepich also showed examples of several ways to block or plug the pathways that would allow for methane intrusion into a dwelling.

Rebecca Fugitt discussed some possible mitigation steps that could be used to remove methane from a water supply. She noted that Ohio rules require a permit from the local health district to install water quality treatment equipment (for contaminants) or alter a private water system. Installation must be performed by a registered private water systems contractor.

Chapter 6 – Other Presentations from the Forum

The previous chapters cover many of the technical issues associated with stray gas. The Forum had several other informative presentations that do not fit into the themes of the earlier chapters. They are included here.

6.1 Legal and Regulatory Issues

Natural gas development is a regulated activity. Drinking water is protected by other regulations. When stray gas moves into drinking water, conflict is likely to happen. It is not uncommon for property owners whose wells contain methane to look toward the gas developers as the perceived source of the methane. This section summarizes two presentations made by attorneys.

David Overstreet of K&L Gates explained the types of lawsuit claims that gas companies might face when property owner lawsuits are filed. The claims most frequently asserted include:

- Negligence – duty and breach
  - The company failed to use reasonable care and failed to comply with regulations and industry standards.
  - Some injury (physical or otherwise) occurred.
- Nuisance – unreasonable invasion vs. trespass – intentional invasion
- Strict liability – abnormally dangerous activities
  - The company knew its activities were dangerous but still proceeded.
- Contract – water supply replacement clause.

Overstreet provided discussion of the responsibilities of the plaintiff and defendant to provide sufficient evidence to make a compelling case. He talked about the burden of proof, the reality of circumstantial evidence, and the material facts that must be part of the suit:

- Geochemistry,
- Manifestation,
- Mechanism,
- Pathways, and
- Regulatory findings and alternative explanations.

Jean Mosites of Babst Calland talked about the regulations in Pennsylvania, Ohio, and West Virginia that deal with stray gas. The Pennsylvania legislature passed Act 13 in 2012. Some of the relevant provisions include:

- Gas companies needed to provide an alternate water supply when pollution or diminution damages a water supply.
- There are new ways to defend against a presumption of liability. A pre-drill survey was needed in order to preserve this type of defense.
- Civil penalties were increased.

The Department of Environmental Protection passed new regulations in Chapter 78 in 2011. The purpose of the new regulations is to improve drilling, casing, cement, testing, monitoring and plugging requirements for oil and gas wells to minimize gas migration and protect water supplies. Some of the new requirements included:

- Pressure barriers were needed to minimize well control events,
- A list of emergency contacts must be kept at the well site,
- Blow-out prevention equipment was required,
- Operators needed to show an adequate bond between cement, casing, and wellbore,
- Centralizers must be used to position casings,
- The actions in the event of a gas migration incident were identified,
- Reporting requirements were revised,
- Increased mechanical integrity testing, and
- An enhanced response to gas migration events was required.

The Pennsylvania Clean Streams Law also plays a role in regulating activities at gas wells sites that might affect surface water bodies. The Department of Environment Protection updated many of its forms, guidance documents, and applications.

Ohio adopted a new law effective September 2012 that requires pre-drill sampling, improves well construction standards and plugging requirements, and ensures water supply replacement when a supply has been damaged or diminished by oil and gas activities. New regulations are effective in August 2012. These deal with casing, cementing, and plugging of wells, as well as pre-drill sampling programs.

Mosites also gave a brief outline of the West Virginia statutes and regulations but did not identify any recent revisions.

Several of the other speakers mentioned regulatory requirements in their presentations too. Dan Arthur had several slides on regulations in Texas and Pennsylvania. Joe Lee reviewed Pennsylvania new regulations for well construction and mechanical integrity monitoring designed to prevent gas migration. Rebecca Fugitt discussed some requirements in Ohio's water well regulations related to venting water wells. Scott Kell described new oil and gas regulations in Ohio designed to prevent stray gas migration. Those regulations:

- Mandate isolation of natural gas "flow zones" behind intermediate or production casing with at least 500 feet of cement, consistent with API recommended practice,
- Require cement design consistent with methods recommended in API RP 65-2 to effectively seal and isolate gas-bearing zones based upon assessment of well-specific conditions,
- Require continuous annular pressure monitoring on the surface-production casing annulus,
- Require a properly functioning pressure relief valve set to release to atmosphere if annular pressure exceed hydrostatic pressure at the surface casing seat,
- Mandate notification if annular pressure cause release at the pressure valve,
- Describe the requirements for testing and/or logging to diagnose conditions, and
- Outline the authority to require corrective actions necessary to prevent migration of gas into protected groundwater.

6.2 Migration of Marcellus Brine to Shallow Aquifers

As part of his presentation, Avner Vengosh of Duke University talked about a new study that he and his Duke co-authors published in July[7]. The authors sampled numerous wells in northeastern Pennsylvania. They found saline groundwater enriched in barium in shallow aquifers. According to the published article:

> *"Geochemical evidence from northeastern Pennsylvania showing that pathways, unrelated to recent drilling activities, exist in some locations between deep underlying formations and shallow drinking water aquifers. Integration of chemical data and isotopic ratios from this and previous studies in 426 shallow groundwater samples and 83 northern Appalachian brine samples suggest that mixing relationships between shallow ground water and a deep formation brine causes groundwater salinization in some locations."* *and*
>
> *"The occurrences of saline water do not correlate with the location of shale-gas wells and are consistent with reported data before rapid shale-gas development in the region; however, the presence of these fluids suggests conductive pathways and specific geostructural and/or hydrodynamic regimes in northeastern Pennsylvania that are at increased risk for contamination of shallow drinking water resources, particularly by fugitive gases, because of natural hydraulic connections to deeper formations."*

Vengosh noted that no evidence has been identified so far showing direct groundwater contamination from brine/flowback water or any indication that the saline water is linked to

[7] Available at http://www.pnas.org/content/early/2012/07/03/1121181109.full.pdf+html.

shale gas exploration. However new data show the possibility of hydraulic connectivity between the Marcellus and shallow aquifers in PA.

This portion of Vengosh's presentation was the most controversial event in the Forum. Several commenters immediately challenged Vengosh's conclusion. In particular, one commenter noted that the Marcellus Shale does not contain much natural moisture. Rather, it tends to imbibe water from injected fracture fluids. The commenter questioned how such a dry and deep formation could contribute sufficient moisture to the shallow groundwater. The resulting debate was inconclusive, with neither party conceding.

6.3 API Standards

Glen Benge (retired) made two presentations on the comprehensive standards program coordinated by the American Petroleum Institute (API). API began publishing standards for the oil and gas industry in 1924 and now has more than 600 technical standards. Their standards program is accredited by the American National Standards Institute (ANSI). The standards must include:

- Openness, balance, consensus, due process
  - Standards undergo regular review
- Regular program audits (conducted by ANSI)
- Transparent process
  - Anyone can comment on any document – www.api.org/standards
  - All comments must be considered.

Benge specifically mentioned three separate standards for hydraulic fracturing operations, other standards for environmental protection at onshore wells, and isolating potential flow zones during well construction. All API HF standards are available for free on-line at http://publications.api.org.

In his second presentation, Benge provided some of the details on Standard 65-2 – Isolating Potential Flow Zones during Well Construction. The standard covers:

- The need for defined mechanical barriers,
- Cement as a barrier,
- Cementing practices,
- Post cement job analysis, and
- Process summary.

The standard can be viewed and downloaded at http://www.shalegas.energy.gov/resources/65-2_e2.pdf.

6.4 Data Management Using RBDMS

Paul Jehn, GWPC's technical director, gave a presentation on the highly acclaimed Risk-Based Data Management System (RBDMS) that GWPC developed nearly 20 years ago. Different versions of RBDMS are used by more than 20 states and one Indian tribe to manage large amounts of data from oil and gas programs. Some of the RBDMS modules include:

- Regulatory data management,
- Field inspection,
- Data mining,
- Well schematics,
- Electronic permitting and reporting, and
- National Data Exchange.

In recent years, RBDMS was expanded and adapted to provide data management capabilities for other types of environmental data associated with the oil and gas program. Stray gas investigations can be data-intensive and require usage of data-management systems that allow storage, retrieval, and analysis of large quantities of diverse data. Jehn described RBDMS Environmental, which can manage data collected from surface water, ground water, sediment, soil, and air. It can accommodate qualitative and measured field observations and analytical water quality and chemical data reporting from industry operators and their third-party laboratories.

Some of the functions in RBDMS Environmental include:

- Facility name and location,
- Sample name, date, and location,
- Quality Control screening, including
    - Cation-to-anion ratio
    - MCL exceedance tracking
    - Holding time evaluation
    - Missing analysis evaluation
    - Dissolved vs. total metals
    - Percent difference from baseline analysis
    - Other user defined features and calculations,
- Industry operator or laboratory representatives can log in to RBDMS Environmental and upload data using online forms.

Chapter 7 – Review of Major Findings and Issues

The Forum provided an important opportunity for experts and other interested parties to gather and share information. The amount of information presented over three days was staggering – yet most participants remained in their seats until the end of each day. This chapter lists a few of the major findings and issues discussed during the Forum.

1. Stray gas in the form of methane is prevalent in many shallow formations around the country. It is particularly prevalent and well-documented in Pennsylvania where Marcellus Shale gas well drilling has focused attention on water quality.

2. Methane does not pose any known health risk from ingestion, but can cause serious safety risks when trapped in confined spaces at sufficient concentrations. The lowest explosive level (LEL) for methane is 5% by volume. A common regulatory standard for initiating mitigation measures is 10% of the LEL (0.5% by volume).

3. Large numbers of water well samples have been collected throughout the Marcellus region. Chesapeake Energy's massive pre-drill data set shows that approximately one quarter of the sampled wells show some detectable methane concentration. Another large set of pre-drill samples collected by Cabot Oil & Gas shows an even higher percentage of methane detection.

4. There are multiple potential sources of stray gas. The Pennsylvania DEP has documented cases where stray gas has been caused by deficient gas well construction practices. However, detailed geologic and geochemical investigations using chemical data and isotopic analysis show strong evidence that most of the methane observed in water wells has origins in shallower geological formations, rather than the Marcellus Shale.

5. Chesapeake Energy has not only collected samples from many water wells, but also has conducted several focused data collection efforts over time on the same set of wells. The evidence from those studies shows a wide range of variability in dissolved methane over time (seasonal, monthly, and even daily). Correlations can be drawn to atmospheric conditions, well pumping rates, and other factors. This suggests the importance of carefully documenting conditions such as air temperature, barometric pressure, pre-sampling pumping rates and volumes, static water level prior to pumping, and static water level at the time of sample collection.

6. When elevated methane is observed in a water well or in a building, a prompt investigation of the health and safety risks is warranted. Depending on the concentration of the methane, various venting, plugging, and treatment methods can be used to mitigate the safety risk associated with continued use of the water well. When the source of the stray

gas is clearly linked to a natural gas well, repairs, co-production of annular gas, or permanent plugging of the well may be appropriate to stop additional gas migration.

7. Many of the speakers spoke of using multiple lines of evidence or a "holistic" approach when investigating stray gas issues. Several speakers gave detailed case examples from Ohio, Colorado, and Texas that gave the audience a perspective on the types of real-world challenges that must be managed during stray gas investigations.

8. State laws and regulations continue to evolve to include more protective well construction and monitoring standards and other requirements to further reduce the risk of stray gas caused by mechanical integrity failures and improve protection of groundwater resources.

Appendix A – Forum Agenda

Tuesday	– July 24
8:00-10:00	*Introductions – **Mike Paque**, GWPC Executive Director and **Stan Belieu**, Nebraska O&G and GWPC President* *Welcome - **Rick Simmers**, OH Oil & Gas Director* *Panel: **Federal Agency Perspectives Regarding Stray Gas and Related Research Initiatives*** With the recent Executive Order that led to the establishment of an EPA, DOE, & DOI memorandum of understanding to coordinate research on natural gas development, we will have a panel of agency representatives to discuss individual agency and coordination of initiatives related to stray gas issues. *Panelists include:* *- **David Russ**, Northeast Region U.S. Geological Survey ;* *- **George Guthrie**, National Energy Technology Laboratory; and* *- **Kevin Teichman**, US Environmental Protection Agency.* *Charge to Participants - **Scott Kell**, OH Oil & Gas and former GWPC President*
20 min.	BREAK:
10:20-11:20	*Introduction to Stray Gas* - What is stray gas? - Properties and potential hazards of methane *Stray Gas Incident Response Short Course* *Instructor – **Fred Baldassare**, ECHELON Applied Geosciences Consulting* • Interviews, Reconnaissance surveys and Determination of threat level • Establishing a Timeline and Defining the preliminary area of investigation • Stray Gas forensics & secondary effects • Combustible gas field screening-gas and monitoring protocols • Protocol for active soil gas surveys • Mitigation Strategies
11:20-12:20	*Response Framework & Action Levels for Methane Concentrations* - Development of State Regulations to Include Emergency Response Procedures *Presenter – **Joe Lee**, Pennsylvania DEP Bureau of Oil & Gas Management* - Working Toward Rational, Consistent, Science-based, Risk-assessment Protocols • Gas in confined inhabited spaces • Gas in confined, non-inhabited spaces • Gas emitted from water well head space • Dissolved gas in groundwater • Soil gas *Presenter – **Scott Kell**, OH Oil & Gas*
60 min.	LUNCH BREAK (on your own)
1:30-2:00	*Measures to Protect Public Health and Safety* - Best Suggested Practices to Reduce and Mitigate Problematic Concentrations of Stray Gases in Water Well Systems – ***Kevin McCray**, National Ground Water Association*
2:00-2:30	*Tools for Preliminary Communications with the Public* - Communication of Methane Analysis Results and Mitigation Information to Private Well Owners in Ohio – ***Rebecca Fugitt**, Residential Water and Sewage Program, Ohio Department of Health*
2:30-4:30	*Pre-Drill Sampling and Variability* - Real-Time Monitoring System for Evaluating Long-Term Variability in Methane in Domestic Water Wells in Northeast Pennsylvania – ***Charles Whisman**, Groundwater & Environmental Services, Inc.* - Short-Term Intra-well Variations in Methane Concentrations in Groundwater from Domestic Water Wells in

	Northeastern Pennsylvania – *Nancy Coleman, Environmental Consultants* - The Occurrence of Methane in Shallow Groundwater from Extensive Pre-Drill Sampling – ***Elizabeth Perry**, AECOM* - Evaluation Water Well Analytical Data Associated with EPA's Hydraulic Fracturing Retrospective Case Study - ***Deborah Watkins**, and **Thomas Cornuet**, Weston Solutions, Inc.*
20 min.	BREAK:
4:50 5:50	*Characterizing Gas Composition: Stray Gas Forensics* - Lines-of-Evidence Approach to the Evaluation of Stray Gas Incidents **-** ***Lisa J. Molofsky**, GSI Environmental* - A Geochemical Context for Stray Gas Investigations in the Northern Appalachian Basin: Implications of Analyses of Natural Gases from Quaternary-through-Devonian-Age Strata – ***Fred Baldassare**, ECHELON Applied Geosciences Consulting*

Wednesday – July 25	
8:00- 10:00	*Oil and Gas Well Integrity Evaluations When Oilfield Activities are Considered a Possible Source of Stray Gas* - Summary of Water Quality Impacts from Historical Oil and Gas Well and Industrial Development in Northeast Pennsylvania Counties - ***Damian M. Zampogna**, ALL Consulting* *Well Integrity Evaluation Short Course* *Instructor – **Dan Arthur**, ALL Consulting* Oil and gas drilling operations • Shallow System Gas Intrusion • Subsurface blowouts Completed oil and gas wells • Assessing Annular Pressure and Pressure Trends • Assessing Annular Gas Vent Rates • Cement Evaluation Relevant to Stray Gas • Planning and Evaluating Cement Adequacy • Surface Casing Adequacy and Testing • Intermediate and Production Casing Considerations • Testing and evaluating Internal & External mechanical integrity • Designing for Remedial Action • Products Used in Remedial Stray Gas Operations • Considerations for Effectively Sealing Perforations • Holistic Well Evaluation Process
20 min.	BREAK
10:20- 11:00	*Physical and Inorganic Water Quality Changes in Groundwater Associated with Stray Gas* - Water Quality Changes Associated with Stray Gas Incidents - ***Anthony Gorody**, Universal Geoscience Consulting*
11:00- 11:30	*Stray Gas Information Management* - RBDMS Environmental: Online Reporting and Tracking of Environmental Data Associated with Oil and Gas Operations – ***Paul Jehn**, Ground Water Protection Council*
60 min.	LUNCH BREAK (on your own)

12:30-2:00	*Subsurface Gas Migration: Defining Migration Pathways Short Course* *Instructor – **Dr. Scott Bair**, Ohio State University* • Importance of understanding the three-dimensional geologic framework • Factors affecting subsurface gas migration (dissolved gas; free gas) • Identifying migration pathways • Identifying driving mechanisms • Distribution of gas in aquifer systems • Down-hole videography • Evaluating potential contributing factors - Drought - Seasonal water table fluctuation - De-watering - Seismic activity - Barometric pressure changes
2:00-3:00	*Long-Term Monitoring and Mitigation* - The Application & Case Studies of Geophysical, Remote Sensing & Earth Fracture Analysis Techniques to Identify Methane Gas Migration Pathways in the Subsurface - ***Tim Eriksen**, Moody & Associates* - Engineering Design of Methane Mitigation Systems - ***John Sepich**, P.E., Brownfield Subslab* - Collection and Analysis of Gas Samples from Probes and Groundwater - ***Keith C. Hackley**, Isotech Laboratories*
20 min.	BREAK:
3:20-6:20	*Stray Gas Incidence Case Histories:* Lessons Learned - Tools for Assessing Stray Gas Migration: A Case Study in Pennsylvania - ***Seth Pelepko**, Pennsylvania Department of Environmental Protection's Bureau of Oil & Gas Planning and Program Management* - Carbon and Hydrogen Isotopic Evidence for the Origin of Combustible Gases in Water-Supply Wells in North-Central Pennsylvania – Implications for Hydraulic Fracturing – ***Kinga Revesz**, USGS* - Geologic and Baseline Groundwater Evidence for Naturally Occurring, Shallow Source, Thermogenic Methane Gas in Northeastern Pennsylvania - ***Brent Wilson**, Chesapeake* - Mamm Creek Field Colorado: A Case Study in Potential Stray Gas Migration in an Unconventional Resource Development Context - **Pete Penoyer**, National Park Service - The Parker County, Texas Study- ***Peter Pope**, Railroad Commission of Texas*

Thursday – July 26	
8:00-10:00	*Stray Gas Incidence Related Studies* - Isotope Forensic Techniques for Differentiating Fugitive Gases in Complex Geological Settings – ***Thomas Darrah**, and Avner Vengosh, Division of Earth and Ocean Sciences, Duke University* - Geochemical and Isotopic Evidences for Possible Natural Migration of Marcellus Formation Brine to Shallow Aquifers in Pennsylvania - ***Avner Vengosh**, Division of Earth and Ocean Sciences, Duke University* - Isotopic Forensic Techniques for Methane Source Discrimination – ***Julie Sueker**, ARCADIS* - Field Test of an Alternative Hypothesis for Stray Gas Migration from Shale Gas Development - ***Daniel J. Soeder**, National Energy Technology Laboratory*
20 min.	BREAK
10:20-11:20	*Potential Legal Implications of Stray Gas Migration* - The Law as it Pertains to Alleged Gas Migration Incidents - ***David Overstreet**, K&L Gates* - Where Do the Liabilities Lie? - ***Jean Mosites**, Babst Calland*
11:20-12:00	*Industry Stray Gas Incident Prevention Initiatives* - Overview of API Responsible Practices and Guidance - ***Glen Benge**, ExxonMobil (retired)*
60 min.	LUNCH BREAK

1:00-3:00	- Baseline Water Quality Sampling in Shale Gas Exploration and Production Areas – *Debby McElreath, Chesapeake* - The Shell-NEOS neoPROSPECTOR Project in Tioga County, North-Eastern Pennsylvania: Use of Remote Sensing Technologies to Detect Surface and Near-Surface Stray Gas Occurrence and Potential Migration Pathways - Bryce McKee, Shell E&P - Isolating Potential Flow Zones during Wellbore Construction: API Standard 65-2 - *Glen Benge, ExxonMobil (retired)*

Appendix B – Contact Information for Speakers

First_Name	Last_Name	Email Address	Organization
Dan	Arthur	darthur@all-llc.com	ALL Consulting
Scott	Bair	bair.1@osu.edu	Ohio State University
Fred	Baldassare	fbaldassare@echelonagc.com	Echelon Applied Geosciences Consulting
Stan	Belieu	sbelieu@nogcc.ne.gov	Nebraska Oil & Gas Conservation Commission
Glen	Benge	gbenge@sbcglobal.net	ExxonMobil (Retired)
Nancy	Coleman	nancy.coleman@chk.com	Environmental Consultants
Thomas	Cornuet	tom.cornuet@westonsolutions.com	Weston Solutions, Inc.
Thomas	Darrah	thomas.darrah@duke.edu	Duke University
Timothy	Eriksen	teriksen@moody-s.com	Moody and Associates, Inc.
Rebecca	Fugitt	rebecca.fugitt@odh.ohio.gov	Ohio Department of Health
Anthony	Gorody	awgorody@gmail.com	Universal Geoscience Consulting, Inc.
George	Guthrie	george.guthrie@netl.doe.gov	U.S. Dept of Energy -NETL
Keith	Hackley	khackley@illinois.edu	Isotech Laboratories
Paul	Jehn	pauljehn@gmail.com	Ground Water Protection Council
Scott	Kell	scott.kell@yahoo.com	Consulting Geologist
Joseph	Lee	joslee@pa.gov	PA DEP, Bureau of Oil and Gas Planning & Program
Kevin	McCray	kmccray@ngwa.org	National Ground Water Association
Debby	McElreath	debby.mcelreath@chk.com	Chesapeake Energy
Bryce	McKee	bryce.mckee@shell.com	Shell E & P Company (Shell Appalachia)
Lisa	Molofsky	ljmolofsky@gsi-net.com	GSI Environmental Inc.
Jean	Mosites	jmosites@babstcalland.com	Babst, Calland, Clements and Zomnir, P.C.
David	Overstreet	david.overstreet@klgates.com	K&L Gates LLP
Mike	Paque	mpaque@gwpc.org	Ground Water Protection Council
Seth	Pelepko	mpelepko@pa.gov	PA Dept of Environmental Protection
Pete	Penoyer	pete_penoyer@nps.gov	National Park Service
Elizabeth	Perry	elizabeth.perry@aecom.com	AECOM
Peter	Pope	peter.pope@rrc.state.tx.us	Railroad Commission of Texas
Kinga	Revesz	krevesz@usgs.gov	U.S. Geological Survey
David	Russ	druss@usgs.gov	US Geological Survey
John	Sepich	jesepich@gmail.com	Brownfield Subslab
Rick	Simmers	rick.simmers@dnr.state.oh.us	Ohio Dept of Natural Resources

First_Name	Last_Name	Email Address	Organization
Daniel	Soeder	Daniel.Soeder@netl.doe.gov	U.S. Dept of Energy - NETL
Julie	Sueker	Julie.Sueker@arcadis-us.com	ARCADIS U.S.
Kevin	Teichman	teichman.kevin@epamail.epa.gov	U.S. Environmental Protection Agency
Avner	Vengosh	vengosh@duke.edu	Duke University
Deborah	Watkins	deb.watkins@westonsolutions.com	Weston Solutions, Inc.
Chuck	Whisman	cwhisman@gesonline.com	GES
Brent	Wilson	brent.wilson@chk.com	Chesapeake Energy
Damian	Zampogna	dzampogna@all-llc.com	ALL Consulting

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