Executive Summary

This report is the product of a one-year study by an expert panel investigating the migration pathways and impacts of natural gas invasion into residential water wells and homes in Bainbridge Township, Geauga County, Ohio, resulting from the accidental overpressurization of the surface-production casing annulus in the English #1 gas well. In particular, the report addresses four disputed issues between the Division of Mineral Resource Management (DMRM) at the Ohio Department of Natural Resources (ODNR) and Eckstein & Associates (E&A), a geological engineering firm hired by Dale Markowitz, an attorney at Thrasher, Dinsmore & Dolan (TD&D), to assist in the lawsuit filed by 42 property owners against Ohio Valley Energy Systems Corp. (OVE) and six other parties involved in the leasing, drilling, and construction of the English #1 well.

The four main issues at dispute are described as:

1. **whether** overpressurization of the English #1 well created a conical network of far-reaching, shallow and deep fractures extending throughout the Ohio Shale and into overlying and underlying geologic units (E&A), **or whether** the amount of over-pressurization was insufficient to fracture the Ohio Shale and underlying geologic units (DMRM),

2. **whether** said network of fractures created a perpetual source of invasive gas in the residential water wells by connecting deep natural gas reservoirs below the Ohio Shale with the shallow aquifers tapped by the water wells (E&A), **or whether** overpressurization created a one-time, pulse of fugitive gas migrating along natural joints and bedding planes (DMRM),

3. **whether** measurement of methane gas concentrations at the wellhead of water wells can be used to characterize and delineate said network of fractures (E&A), **or whether** wellhead methane gas measurements are an important means to determine the presence or absence of methane gas and for determining possible public safety responses but cannot be used alone to interpret the size, shape, and depth of subsurface fractures (DMRM), and

4. **whether** subsurface fluid pressures were sufficient to force particles of Ohio Shale from creation of the conical fracture network upward into the overlying aquifers resulting in reports of "black goo" in some water wells (E&A), **or whether** the presence of black particulates in wells occurs as a result well construction materials and local maintenance practices, and recognizing that pressure perturbations can stir up sediment accumulating at the bottom of the well and can dislodge bacterial colonies attached to the casing and borehole walls (DMRM). **Furthermore, whether** the presence of methane gas in the subsurface environment altered the geochemistry of local groundwaters causing "black goo" and toxic metals to be pumped by some residential wells (E&A), **or whether** the geochemical data from residential wells and from wells outside the investigation area indicate that the quality of groundwater has remained unchanged (DMRM).

Background Information

None of the information presented in this section is at issue. The information is largely abstracted from the September 2008 document published by ODNR-DMRM titled "Report on the Investigation of the Natural Gas Invasion of Aquifers in Bainbridge Township, Geauga County Ohio," which contains a more detailed accounting of the materials, procedures, and sequence of events leading up to the overpressurization incident. The 2008 DMRM report can be downloaded at www.ohiodnr.com/mineral. To understand the text that follows, keep the following sequence of informally-named geologic units in mind. They are listed from shallowest to deepest:

- **Sharon Sandstone** – good aquifer, supplies residential wells
- **Cuyahoga Shale** – confining unit, poor aquifer, supplies residential wells
- **Berea Sandstone** – excellent aquifer, supplies residential wells
- **Bedford Shale –** confining layer
- **Ohio Shale** – confining layer, can locally contain natural gas
- **Big Lime** – thick sequence of tight limestone, dolomite, and evaporites, contains brine
- **Newburg zone** – thin, very porous limestone in the Big Lime, can contain gas
- **Packer Shell** – thin layer of very porous limestone
- **Clinton sandstone** – calcareous sandstone, target horizon for English #1 gas well

From October 20 to 26, 2007, the English #1 gas well was drilled to its target depth of 3926 feet into the Clinton sandstone, a common gas reservoir in northeast Ohio. While cementing the 4½-inch production casing, circulation was lost in the Packer Shell zone at a depth of 3640 feet. A cement-bond log run on November 1 indicated that the top of the cement was only 80 feet above the targeted production zone and 290 feet below the Newburg zone, a known producer of natural gas with a distinctive sulfur smell. The industry standard calls for 600 to 800 feet of cement to fill up the annular space above the Clinton sandstone production zone so that the Newburg zone is sealed off. On November 5, the Clinton sandstone was perforated from 3720 to 3740 feet, leaving only 80 feet of cement sealing off the Clinton production zone from the open annular space behind the surface-production casing. Despite the lack of cement above the uppermost perforations, the production zone in the Clinton sandstone was hydraulically fractured on November 13. Fracture stimulation was stopped immediately when fluid circulated out of the open valve on the surface-production casing annulus. For the next 31 days the well was shut-in, except when the valve on the annulus was periodically opened to release pressure, which had stabilized at 320 pounds per square inch (psi) but had been measured at pressures as high as 360 psi.

Early in the morning on December 15, 2007, an explosion occurred in the basement of the home at 17975 English Drive. Neither of the two residents was seriously injured but the home was severely damaged. The cause of the explosion was determined to be migration of natural gas from overpressurization of the surface-production casing annulus of the English #1 gas well, located less than 1000 feet away. The fire department, Geauga County Health Department, and DMRM responded immediately to the incident. Local emergency response officials evacuated residents from 19 homes. Neither the location nor the concentration of initial natural gas measurements was recorded. However, during the first day of the investigation, water wells were recognized as the points of pressure release and OVE began installing vents on all known basement water wells and DMRM established a schedule for ongoing monitoring of gas concentrations in basements and in the water well vents.

Measurement of methane gas concentrations in outside water wells and in basement water wells in several homes indicated natural gas levels exceeding the lower explosive limit (LEL) of 5 percent methane by volume. On the same morning as the home explosion, water spouted 15 to 18 feet above the land surface from the residential well at 17990 English Drive. Several hours later the well began blowing natural gas from the casing; this lasted several days.

On December 15 and 17, 2007, two cement squeeze jobs sealed off the annular space in the English #1 well, eliminating any additional natural gas from entering the subsurface environment. By December 24, all residents had returned to their homes, except the family living in the home damaged by the explosion. In the following months, 26 water wells were disconnected and temporary water tanks installed, natural gas warning devices were installed in homes, and routine measurements of natural gas concentrations were made in water wells and homes. Beginning in January and ending in July 2008, 16 of the temporarily disconnected water wells were turned on and intentionally overpumped in an attempt to purge fugitive gas from the shallow bedrock.

In January and March 2008, DMRM took borehole videotapes in six impacted water wells. The videos showed gas bubbles rising through the water column in the boreholes; in some wells the volume of gas was so large it caused the water surface in the borehole to churn. The videos also showed bacterial slimes, rusted casings, vertical joints, and bedding planes where the gas entered the borehole. The well at 17990 English Drive was videotaped in January and again in March. The latter video showed a marked decline in the volume of gas rising in the water column, indicating that the fugitive gas was beginning to dissipate at that location. In its September 2008 report, DMRM published its accounts of these events; causes of the overpressurization, natural gas invasions, and explosion; regional geologic and hydrogeologic information; background and site-specific water-quality information; corrective actions and recommendations.

In January 2009, TD&D, representing 42 property owners, filed suit in Geauga County Common Pleas Court against OVE and six other parties involved in the leasing, drilling, and construction of the English #1 well. The lawsuit claims that actions and inactions stemming from drilling the gas well caused the explosion at 17975 English Drive and contamination of the plaintiffs' properties and the groundwater aquifer, which serves as the drinking water supply for the plaintiffs' properties. TD&D hired E&A to evaluate the overpressurization of the English #1 gas well, the gas invasion incidents, and the severity and duration of health and safety issues. Following the assessment by E&A, disputes arose between DMRM and TD&D-E&A over interpretations of the data, designation of impacted and non-impacted residences, and predictions of long-term consequences.

Expert Panel

In April 2009, five experts in the fields of groundwater hydrology, petroleum engineering, petroleum geology, groundwater chemistry, and geomicrobiology were asked by DMRM to form an independent-style, expert panel to evaluate the disputed issues. The expert panel consisted of three professors (Scott Bair, Ohio State University; David Freeman, Marietta College; and John Senko, University of Akron) and two scientists at the U.S. Geological Survey Water Science Center in Columbus, Ohio (Martha Jagucki and Ralph Haefner).

The expert panel met for the first time on May 13, 2009. Prior to the meeting, panel members received a copy of the 2008 DMRM report. During the meeting, Dr. Yoram Eckstein, the principal scientist at E&A, made a PowerPoint presentation titled "Wellhead LEL Records in Bainbridge Residential Water Wells" that described his methods of analysis and conclusions concerning the consequences of the English #1 gas well overpressurization on local residential water wells. His interpretations were based on data in the 2008 DMRM report, records of wellhead LEL measurements posted on the DMRM website, and environmental scanning electron microscope energy dispersive x-ray spectroscopy (ESEM-EDS) analyses of sediment from several well water samples and plumbing fixtures. Throughout the meeting, it was obvious to the panel that Dr. Eckstein's analyses and interpretations were vastly different from those of DMRM (2008). The E&A PowerPoint presentation also can be downloaded at www.ohiodnr.com/mineral.

The tasks given to the expert panel by DMRM were (1) to evaluate the disputed issues, (2) determine what conclusions reached by E&A, DMRM, or by the panel itself best explain the irregular distribution of residential water wells impacted by invasive gas and best predict the long-term consequences of the gas invasions, and (3) to recommend any measures that could help remediate the impacted area.

To carry out these tasks, the expert panel was given the ability to request and supervise DMRM staff in the collection of additional field and lab data, and in the construction of geologic maps and cross sections based on those data. DMRM staff spent 15 days assisting panel members in measuring joints at local outcrops and quarries, sampling water and sediments from residential wells, measuring water levels, LEL concentrations, and water-quality parameters in residential wells, and taking additional borehole videotapes. Dr. Eckstein and Dwight Williams, a consulting geologist with KU Resources, hired by OVE, were present for parts of several days when borehole videotapes and water samples were taken. DMRM obtained homeowners' permission to run the borehole videos and to collect groundwater samples, and informed TD&D regarding scheduled field activities. As a matter of course, DMRM sent the homeowner a copy of the borehole video. Copies also were sent to TD&D and OVE. The panel had access to all the Bainbridge Investigation files compiled by DMRM and access to DMRM staff to answer any historic, procedural, or general questions. Dr. Eckstein and OVE staff also provided answers to panel members' questions. At the request of ODNR, OVE hired the outside contractors that assisted in the field work including well and pump services and routine measurement of LELs in the network of water wells. DMRM compensated the expert panel for its time.

Rather than approach its task to evaluate the disputed issues as would a jury, the expert panel chose to apply the scientific method to test the dissimilar conclusions reached by DMRM and E&A. In so doing, the panel focused on the four major issues at dispute. Using statements made by DMRM and E&A-TD&D, the panel formulated four pairs of opposing hypotheses, one pair for each disputed issue. This enabled the panel to request the additional data, if needed, to test and evaluate each pair of hypotheses.

Requests for Additional Data

No additional data were needed to address the differences of opinions between E&A-TD&D and DMRM in Disputed Issue No. 1. Calculations could be made using well-known petroleum engineering equations with regional and site-specific values for parameters. These calculations would be able to determine whether one or more fractures could be created in the Ohio Shale

or in the Big Lime and to estimate the approximate dimensions (height and length) of the fracture(s). The equations are based on the laws of physics and can be found in numerous articles published in the technical literature and in many petroleum engineering textbooks.

Additional data were needed to address Disputed Issues Nos. 2, 3, and 4. The additional data consisted of: (1) measurement of joint bearings at local outcrops and quarries, (2) construction of detailed geologic cross sections through the area of investigation, (3) measurement of intergranular porosity and permeability from core and outcrop samples, (4) examination of petrographic thin sections using a scanning electron microscope, (5) taking borehole videotapes in a wider distribution of water wells and retaking videos in the six wells videotaped in early 2008, (6) sampling selected residential water wells and public water-supply wells inside and outside the area of investigation and analyzing these samples for a variety of geochemical and bacterial parameters, and (7) scanning samples of Cuyahoga Shale and Berea Sandstone using x-ray diffraction and comparing the signatures to those from sediments (particles) collected from water produced at several residential wells.

None of the additional data were available to DMRM (2008) or E&A (2009) when they were developing their interpretations and composing their documents assessing the problems from overpressurization of the English #1 gas well. The panel used the additional data to test the formulated hypotheses and to develop and test its own hypotheses.

Analysis and Interpretation of Additional Data

Hydraulic Fracturing

The expert panel used standard petroleum industry equations with site-specific and local values for relevant parameters to determine whether or not the Ohio Shale and the Big Lime could be fractured by the shut-in pressures recorded in the annulus of the surface-production casing in the English #1 well. The calculations and field observations suggest, to a reasonable degree of engineering certainty, that any fracture created in the Ohio Shale was likely shallow and oriented horizontally. However, it is not clear if the shut-in pressure was in fact sufficient to fracture the formation. The most compelling evidence (published fracture gradients corroborated by published field as well as anecdotal data) place the shallow Ohio Shale fracture gradient as nearly equal to the English #1 well surface-production casing shut in annular pressure gradient. However, field experience with nitrogen fracturing in the Devonian (Ohio) shale is suggestive of a gas rate flowing into the English #1 well surface-production casing annulus that was insufficient to create the necessary irregularities on a created fracture surface to hold the fracture open once the gas source was sealed off. The calculations also suggest that a created fracture would have been of limited length if the fracture was oriented vertically or of limited radius if the fracture was horizontal.

Additional calculations and field observations pertaining to Big Lime demonstrate, to a reasonable degree of engineering certainty, that it was not fractured by the overpressurization in the English #1 well. Additionally, had any fractures been created, no propping material was introduced to prevent them from healing once the fracturing (i.e., annular) pressure dissipated. As a result, it is unlikely a created fracture allowing deep gas migration to the overlying aquifers exists, let alone a network of conical-shaped fractures.

Measurements of the surface-production casing annulus pressure data collected on the English #1 well during the mostly shut-in period following the hydraulic fracturing treatment are more reflective of gas migration beginning once a sufficient annular pressure was achieved as opposed to fracturing of the formations exposed to the annulus.

Natural Fractures

The orientations (bearings) of 95 rock joints measured at local rock outcrops and quarries showed that these natural features are consistent with joint bearings measured by researchers making detailed studies in eastern Ohio, western Pennsylvania, and southwestern New York. The dominant joint bearings are N 55° E and N 55° W. Data from oil and gas fields in these same areas indicate that these joints can extend several thousand feet below land surface and provide the porosity and permeability permitting oil and gas production from the Ohio Shale since the 1880s. Based on the occurrence and bearings of these natural fractures in and around the investigation area, the expert panel concludes that similar fracture patterns and depths are present within the area of investigation.

Borehole Videotapes

In the summer and autumn of 2009 and the winter of 2010, 24 additional borehole videotapes were taken in 21 water wells in the investigation area and in two water wells more than 10 miles outside of it. These videos were made with a newer, smaller diameter camera than the one used to make the videos in early 2008. This enabled the new camera to slip past centralizers and pumps that the older camera could not, resulting in a deeper visual record of borehole features than recorded by the older camera. Each of the old and new borehole videos was examined by Dr. Bair, who made detailed logs of the depths to prominent bedding planes, vertical joints, gas bubbles, gas source openings and gas zones, changes in lithology and geologic units, bacterial colonies, the degree of corrosion (rust) of the steel casing, and any holes in the casing allowing surface water to enter the wellbore. This facilitated construction of detailed cross sections through the investigation area showing tops and bottoms of geologic units, water levels, and depths and lengths of well casings. Multiple borehole videotapes, separated by 6 to 21 months, were successfully made in five wells. These videotapes were particularly useful because they enabled the panel to directly observe changes in the depths of gas source openings and gas zones and changes in gas pressures over time. The videotapes clearly showed that the depths to the lowermost gas source zones were moving upward over time, by 124, 33, and 29 feet in three of the wells, and from the Berea Sandstone up into the Cuyahoga Shale.

The videotapes taken in the two residential wells 10 miles away in Chester Township show all of the same geologic features as seen in the borehole videos from residential wells in the investigation. One of the wells also contained natural gas that could be seen emanating from a small bedding plane opening in the Berea Sandstone. It has long been known that water wells in Geauga County commonly produce small amounts of natural gas.

Based on examination of this new information and comparison of it to the information from the older borehole videotapes, the expert panel concluded that fugitive gas in the investigation area was migrating upward from the Berea Sandstone into shallower geologic units, that fluid pressure of the fugitive gas was diminishing, and that the gas was not being replaced by

natural gas from deeper sources. Hence, the fugitive gas is a one-time pulse of gas that rose in concentration and pressure, which then dissipated with time. There is no evidence supporting the contention that the fugitive gas comes from a deep, continuous source of natural gas. If this were so, the bottom of the gas zone would not be rising into shallower geologic units and the fluid pressure of the gas would not be decreasing.

Top of Berea Sandstone

A map of the top of Berea Sandstone surface was constructed using existing oil- and gas-well logs, water-well logs, and data from the borehole videotapes. This is a signification addition to the information needed to analyze the patterns of fugitive gas migration. The Berea Sandstone serves as the reservoir supplying water to several of the wells investigation area and hundreds of wells in Geauga County. It is the first major porous and permeable unit above the Ohio Shale. As such, it acts as a reservoir to the fugitive gas rising around the English #1 gas well. Due to the buoyancy of gas in water, the fugitive gas rises within the Berea Sandstone until it reaches the very top of the sandstone, which is overlain by the highly jointed, poorly porous Cuyahoga Shale. The gas accumulates under the interface between these to geologic units because it does not easily migrate upward into shale. If the top of the Berea Sandstone surface has a gradient (undulates), the buoyancy of the fugitive gas will cause it to migrate up the steepest slope toward the highest point in the Berea Sandstone surface and directly beneath the Cuyahoga Shale.

One way to visualize this is to imagine a baseball cap, which has a brim and a dome. The ball cap itself represents the Cuyahoga Shale. The space beneath the ball cap is the Berea Sandstone. If fugitive gas rises up at a location directly beneath the poorly permeable brim, the gas will continue to rise up the slope of the brim into the dome. Fugitive gas will accumulate under the dome until it fills it up; then the gas will spill out at the lowest point around the perimeter of the dome, which in an adjustable ball cap would be at the cutout in the back where the Velcro straps connect. This is exactly what the fugitive gas in the investigation area did. The map of the top of the Berea Sandstone surface shows that a dome-like structure with a brim-like extension exists in the top of the Berea Sandstone surface. The brim overlies the English #1 gas well and the apex of the dome lies just north of the Payne home (17975 English Dr) that exploded. It is not coincidence that the Payne's house had an improperly abandoned (unplugged) well completed into the Berea Sandstone that was connected to the house through the basement wall and that the well lies directly along the steepest gradient between the English #1 gas well and the high point under the dome in the top of Berea Sandstone surface. A large portion of the gas migrating in the Berea Sandstone from the English #1 well to the apex of the dome passed by this water well. Nor is it coincidence that no fugitive gas was reported in wells or homes, which are few, south of the English #1 well because the slope on the top of Berea Sandstone surface is to the north, away from this area. Using the terminology of petroleum geologists and engineers, the Berea Sandstone is a gas reservoir, the dome within its top surface is the trap that enables gas to accumulate, and the Cuyahoga Shale is the caprock that impedes the further vertical migration of the gas (albeit only temporarily).

The contour lines depicting the undulations in the top of the Berea Sandstone surface also can be used to delineate areas where fugitive gas emanating from the English #1 well cannot reach. For example, Ohio EPA records and homeowner conversations with DMRM staff indicate that natural gas was known to occur in the water wells at 8139 Bainbridge Road (Police station) and 7780 Bainbridge Road (Cloninger) several years before the English #1 well incident. Although

both of these wells are within 4,000 feet of the English #1 well, they are located outside the domal structure that trapped the fugitive gas from the English #1 well. Hence, the gas in these two wells is natural gas unrelated to the English #1 well incident. What is also diagnostic about natural gas in wells outside the domal structure is that it occurs in the Berea Sandstone. By the autumn of 2009, when videotapes were made in the Police station well and in the Cloninger well, fugitive gas in wells inside the dome had migrated vertical into the Cuyahoga Shale.

The expert panel found that a map of the top of Berea Sandstone surface was crucial to understanding the migration patterns of gas in the Berea Sandstone, which is important because the Berea Sandstone redistributes the fugitive gas upslope and away from the English #1 well and because all the fugitive gas from the English #1 well has to migrate vertically completely through the Berea Sandstone or within the Berea Sandstone before reaching any residential water wells. The redistribution of natural gas by a laterally extensive permeable unit, like the Berea Sandstone, that overlies the area where natural gas escaped from the overpressurized annulus of a gas well, was described in detail by Dr. Samuel Harrison, a professor at Allegheny College in Meadville, Pennsylvania, in technical papers he published in 1983 and 1985.

Lacking a detailed, site-specific map of the top of the Berea Sandstone surface, as did DMRM and E&A prior to the panel's request for taking borehole videotapes in many more residential wells, only general or speculative statements could be made about how fugitive gas reached some wells and not others, and why fugitive gas reached some wells faster than others.

Pressure Buildup

During the 31 days that the annular space in the surface-production casing in the English #1 well was largely shut in, fluid pressures also increased in the Ohio and Bedford shale and in the overlying Berea Sandstone. Fluid-pressure increases in these rocks extend outward from the English #1 well in a radial pattern such that the largest pressure increase is closest to the gas well and the smallest pressure increase is at a distance away from the gas well. The radial distance from the gas well where the pressure change equals zero is a function of the porosity and permeability of the rock. Given all other factors being equal (fluid viscosity, reservoir thickness, reservoir compressibility, pressure change at the gas well, and time), pressure increases in a poorly porous and permeable rock like the Ohio and Bedford shales do not travel far from the gas well, whereas pressure changes in a highly porous and permeable rock like the Berea Sandstone can travel large distances from the gas well. It is important to recognize that these statements do not refer to the physical movement of molecules of fluid or gas. Rather, they refer to the propagation of a pressure wave or pulse much like that produced by a tsunami or an earthquake, where water molecules solely move up and down, not laterally, as the tsunami wave passes and then return to their original positions, or where molecules of rock move up and down or laterally during the passage of an earthquake (shock) wave but return their original positions after the wave passes.

Evidence of the magnitude and distance of the pressure increase in the Berea Sandstone caused by large pressure increase in the English #1 well occurred in the Jordan well (17990 English Dr) on the same morning as the explosion in the Payne house across the street (17975 English Dr). So much pressure had built up in the Berea Sandstone beneath the Jordan property that groundwater spouted out of the well 15 to 18 feet above land surface and when the water in that portion of the Berea Sandstone was being replaced by fugitive gas migrating

upslope toward the dome in the top of the Berea Sandstone surface, the spouting water was supplanted by spouting gas, which lasted several days until the effects of two cement-squeeze jobs sealing off the source of the elevated pressures in the English #1 gas well caused the elevated pressures near the gas well in decline.

Harrison (1983; 1985) describes other evidence of pressure increases in water wells due to overpressurization of a nearby gas well. In his studies in northwestern Pennsylvania he commonly found that residents noticed changes in the turbidity (i.e., cloudiness) in the water coming from their faucets. His work showed that the cloudiness was caused by pressure waves kicking up the sediment that naturally accumulates at the bottom of a well and by loosening rust particles that spalled off corroded steel casing and landed on the small ledges cut by the drill bit into the sides of the wellbore. These same observations were made by residents along English Drive in the days preceding and immediately following the temporary "geyser" in the Jordan well, as reported at the Payne, Weber, Mesmer, Gaub, and Ohara wells on English and Scotland drives. Harrison (1983, 1985) also describes instances where increases in the amount of gas coming out of residential water wells are caused by pressure waves created by a nearby overpressurized gas well. In the Bainbridge investigation area, this occurred in the Police station well several days before the Jordan well became a "geyser."

Gas Migration Patterns

The expert panel noted that there were three stages to the period of fugitive gas migration, such that the factors controlling gas movement in one stage were different than the factors controlling gas movement in the other stages. The common factors among all three stages are the buoyancy of gas in water and the shape of the top of Berea Sandstone surface.

- **Stage 1 – Pressure Buildup** begins with the construction of the English #1 well and ends in the middle of December 2007 with the cement-squeeze jobs that sealed off sources of deep gas in the annular space in the surface-production casing. During Stage 1 gas migration is controlled by the buildup of subsurface fluid pressures around the English #1 well and upward migration of gas in the Ohio and Bedford shales along natural joints and bedding planes proximal to the gas well. When the gas reaches the Berea Sandstone it migrates upward until it reaches the top of the Berea Sandstone surface, which directly underlies the poorly permeable Cuyahoga Shale, and then migrates up the slope of the top of the Berea Sandstone surface toward the high point under the domal structure just north of the house that exploded at 17975 English Drive.

  The evidence of this pattern of gas migration is **(1)** the high methane gas concentrations (LELs) measured in residential wells at the south end of English Drive immediately after the house explosion (Czernicki at 17995; Jordan at 17990; Donaldson at 17938; Gaub at 17939), **(2)** a report of turbid water produced by the Payne well at 17975 English Drive, **(3)** a report of greater amounts of methane gas than normal at the Police station well at 8153 Bainbridge Road, and **(4)** the spouting of water out of the Jordan well (17990 English Dr).

- **Stage 2 – Intentional Pressure Dissipation** extends from completion of the two squeeze jobs in mid-December 2007 to July 2008. During Stage 2 gas migration is controlled by the slow dissipation of elevated fluid pressures around the English #1 well subsequent to the cement-squeeze jobs, the slowing of upward migration of gas in the

Ohio and Bedford shales along natural joints and bedding planes near the gas well, and the influence of overpumping as many as 16 residential wells in a successful attempt to purge fugitive gas from the Berea Sandstone and Cuyahoga Shale.

This pattern of gas migration is evidenced by **(1)** the spread of fugitive gas to the east and west of English Drive to residential wells along Scotland and Kingswood drives, as seen in wellhead LEL measurements (e.g., Bastifell, Kukoleck, Mason, and McGee on Scotland Dr; Calo, de Gaetano, Johnson, and Prochazka on Kingswood Dr), **(2)** the diminution or absence of positive wellhead LEL values in wells around the areas of intentional overpumping (e.g., Czernicki, Donaldson, Gaub, Jordan on English Dr; Calo, de Gaetano, Prochazka on Kingswood Dr; Bastifell, Buddenhagen, Komocki, Mowery, Ohara, and Sanborn on Scotland Dr), and **(3)** the borehole videotapes taken in the Jordan and de Gaetano wells, which show the lowermost gas source zone to be in the Berea Sandstone in Stage 1, whereas in Stage 2 the lowermost gas source zone has risen up into the Cuyahoga Shale.

- **Stage 3 – Passive Pressure Dissipation** covers the period from August 2008 to the present. For some reason during the summer of 2008, the intentional overpumping of selected residential wells ceased, which was unfortunate. The cessation of overpumping resulted in a second change in the factors controlling fugitive gas migration. By this time the fluid pressure increases around the English #1 well had dissipated and very little fugitive gas was migrating upward out of the Ohio and Bedford shales into the Berea Sandstone near the gas well. The large area of the Berea Sandstone underlain by fugitive gas in Stage 2 became smaller and smaller as more and more fugitive gas migrated up into the Cuyahoga Shale (without being replenished by additional gas from deeper sources). As a result, the once large, contiguous zone of fugitive gas in the Berea Sandstone in Stage 2 was now divided into four separate, small gas zones. The locations where the contiguous gas zone divided are controlled by the undulations in the top of the Berea Sandstone surface and by the intentional overpumping of selected wells throughout Stage 2.

  This pattern of fugitive gas migration is supported by **(1)** a reduction in the number of wells with positive or large LEL readings including Prochazka, Johnson, and de Gaetano on Kingswood Drive; Dickerson on Kenston Lake Drive; Komocki, Mesmer, Mowery and Sanborn on Scotland Drive, and **(2)** borehole videotapes showing the absence of gas source zones in the Berea Sandstone in wells including Buddenhagen, Kukoleck, Bastifell, McGee on Scotland Drive; Adams, Jordan, (old) Payne on English Drive; and de Gaetano and Johnson on Kingswood Drive.

The expert panel recognizes that the strength in identifying these gas migration patterns based on the specific factors controlling gas migration during each of the three stages lies in the integration and correspondence of so many facts and observations with long-established concepts and of gas movement, groundwater flow, and geologic mapping. No previous explanation of gas migration patterns is supported by so much diverse evidence.

LEL Measurements and Patterns

Natural gas is a mixture of methane, ethane, propane, and butane, although methane normally represents 70 to 98 percent of the mixture. The lower explosive limit (LEL) of methane gas is 5

percent by volume or 50,000 parts per million. On the standardized LEL scale used by fire departments and safety officials across the country, the lower limit of explosivity, 5 percent natural gas by volume, is re-defined as 100 percent of the LEL.

Wellhead LEL measurements first were taken in the Bainbridge investigation area on December 16, 2007. Although the network of wells in which LELs are measured has changed, measurements of wellhead LELs continue to be taken today in 2010. The measurements are taken with a handheld meter that can be inserted down into the open space at the top of the well casing. The meters used to make these measurements must be routinely re-calibrated to ensure reliability. Since the first LEL measurements were taken in the impacted area on, five different meters have been used by seven different field personnel. The accuracy and precision of the LEL measurements is uncertain because of the different field conditions at each well and because of instrument and operator variability. Consequently, interpretation of LEL data should be based on trends in values over time, not on individual values at any one point in time.

Following the explosion at the Payne home on December 15, 2007, field inspectors measured LEL values in wells and in homes at 78 locations. During 2009, a contractor hired by OVE measured LELs at 71 residences on a routine basis. These records are on file at DMRM and are posted on its website. Based on these data, 56 residential wells (72 percent of the total) never had a wellhead LEL measurement above one percent or 20 parts per million. Consequently, wellhead LEL patterns could not be discerned for them.

The focus of expert panel's interpretations of the wellhead LEL data is on the migration of the fugitive gas from the Berea Sandstone into residential wells completed in the Berea Sandstone, Cuyahoga Shale, and Sharon Sandstone. From this perspective, wellhead LEL measurements are the final point that fugitive gas molecules can be detected along their migration paths from the overpressurized surface-production casing annulus in the English #1 well, vertically upward through the Ohio and Bedford shales, upward in the Berea Sandstone where the molecules are redistributed laterally because of the overlying poorly permeable, but well-jointed Cuyahoga Shale, and finally upward into the Cuyahoga Shale and Sharon Sandstone where the gas molecules can be detected in a water well using an LEL meter. The panel recognized that the differences in the fugitive gas migration patterns should be reflected in the trends and patterns in wellhead LEL values measured in the network of wells. The expert panel identified five major patterns in graphs of the wellhead LEL data. No single well displays all five patterns. Many wells display two or three patterns. Some wells, because of their location relative to geologic features in the Berea Sandstone or because of their construction display but one pattern.

- **Wellhead LEL Pattern #1 – Delay in Arrival of Fugitive Gas**
  Many wellhead LEL graphs display a delay in the arrival of fugitive gas relative to the first detection of natural gas in wells on December 16. The delay is caused by the location of the well relative to undulations in the top of Berea Sandstone surface and by the geologic units exposed in the uncased portion of the well. This delay can be seen in the wellhead LEL graphs from the Mason, McGee, Ohara, Komocki, Kukoleck, and Bastifell wells along Scotland Drive. All of these wells are offset from the steepest slope in the top of Berea Sandstone surface between the English #1 well and the apex of the dome just north of the Payne well. The wellhead LEL graphs from the Czernicki and Jordan wells along English Drive and from the Calo well on Kingswood Drive lie along the steepest slope and do not show this delay.

- **Wellhead LEL Pattern #2 – Dissipation by Intentional Overpumping**
  Many wellhead LEL graphs show a diminution in LEL values or values of zero (i.e., no methane is detected) during the seven-month period that selected residential wells were intentionally overpumped to purge fugitive gas from the geologic units supplying water to wells. The effectiveness in lowering wellhead LEL values or in eliminating fugitive gas completely by overpumping selected wells is seen the wellhead LEL values during this period of time. This pattern can be seen in wellhead LEL graphs from the Czernicki and Jordan wells on English Drive; Calo and de Gaetano on Kingswood Drive; Bastifell, Buddenhagen, Komocki, Mowery, and Sanford on Scotland Drive.

- **Wellhead LEL Pattern #3 – Seasonal Variations in Fluid Pressures**
  The most common pattern seen in the wellhead LEL graphs is produced by seasonal variations in the depth to the water table in the Sharon Sandstone and to the potentiometric surface of the Berea Sandstone. Seasonal changes in water levels are related to the annual hydrologic cycle of precipitation, infiltration, runoff, evaporation, and transpiration. In Ohio, water levels are usually highest in April-May and lowest in October-November. As water levels rise and fall seasonally in response to the annual hydrologic cycle, changes also occur to fluid pressures in near surface aquifers, which in turn cause changes in wellhead LEL values. This pattern is seen in all of the wellhead LEL graphs except those with values too small to discern seasonal variations. The annual water-level fluctuations can be looked at as a (sine) wave with a peak, a trough, and two times per cycle when the wave passes through its mid-point. The two times a year when water levels pass through the mid-point of their annual wave are around August, as water levels decline from May to November, and again around February, as water levels rise from November to May.

  The next several sentences apply to the view of this process from a single, <u>stationary</u> pore. In August the water table is at the exact depth of the stationary pore and the pressure of the fluid (water or gas) in the pore in equal to atmospheric pressure, which is defined as $P=0$. As the water table declines below the pore, the fluid pressure in the pore also declines because the stationary pore is now in the vadose zone above the water table where pore fluids are under tensional forces $(P<0)$. During this period of the annual hydrologic cycle, fugitive gas preferentially remains in the pores in the vadose zone constrained from moving upward or downward by its lower fluid pressure. Thus, when the water table declines, fugitive gas gets seasonally stranded because it experiences lower pressures (without physically moving up or down). As a result, wellhead LELs values decline in late summer and early autumn as water levels decline and fugitive gas becomes stranded above the declining water table. The stranded gas cannot migrate to residential wells via groundwater flow (even if wells are pumping) because the water table is now beneath the stationary pore space. During the early winter the water table slowly begins to rise and in February the water table is again at the same depth as the stationary pore and the fluid pressure in the pore is again zero $(P=0)$. As the water table continues to rise above the stationary pore, the fluid pressure in the pore is increases to values greater than zero $(P>0)$. The fugitive gas in the stationary pore is no longer stranded and is able to move higher up into the saturated zone below the overlying water table via its buoyancy or to move via groundwater flow toward pumping wells.

  Thus, wellhead LELs generally rise in winter and spring and decline in summer and autumn, which is directly related to seasonal changes in fluid pressures in pore spaces,

which are directly related to seasonal variations in water levels. These fluctuations in wellhead LEL values are seen routinely at the same times of the year in 2007, 2008, and 2009. True to form, wellhead LEL values measured during February, March, and April 2010 are increasing relative to values measured in the winter, as the pattern of seasonal variations in wellhead LELs continues season after season, year after year.

Most deep residential wells in the investigation area are uncased in the Cuyahoga Shale and the Berea Sandstone, whereas most shallow residential wells are uncased in the Sharon Sandstone and the Cuyahoga Shale. Water levels in wells open in two or more geologic units are called "comingled" because the composite water level in the well is an average of the water levels in each geologic unit. Water-level measurements taken in shallow comingled wells or in deep comingled wells in the investigation area rise to a position somewhere in the Cuyahoga Shale and seasonal fluctuations in water levels occur within the thickness of Cuyahoga Shale. Although on a much shorter time scale than the seasonal fluctuations described above, when a comingled residential well is pumped, the water level in the well declines and forms a cone of depression surrounding the well. As the cone of depression spreads outward with continuing pumping, pores in the Cuyahoga Shale, and in Sharon Sandstone if the well is shallow, drain water and fugitive gas gets stranded until the water level rises again when the well shuts off.

- **Wellhead LEL Pattern #4 – Cutoff of Fugitive Gas East of Saddle**
  There is a low, elongated trough in the top of the Berea Sandstone surface to the right of the dome underlying the middle segment of English Drive. This trough extends from north to south and is defined by the elevation of the contact between the Berea Sandstone and the overlying Cuyahoga Shale measured in eight wells. The trough is a local low feature in the top of the Berea Sandstone surface and is the spill point for fugitive gas migrating up the east side of the slope leading from the English #1 gas well to the dome. Geologists call a low trough a "saddle." Wells in the area east of the saddle have a unique wellhead LEL pattern. These wells are only able to receive fugitive gas after gas begins to fill the main closed structure forming the dome in the top of Berea Sandstone surface. The dome must fill with enough fugitive gas to enable the increasing thickness of accumulated gas to spill under the saddle and migrate to the wells on the east flank of the saddle. As a result, the arrival of fugitive gas in wells east of the saddle is delayed. This is seen in the wellhead LEL graphs from the de Gaetano, Prochazka, and Johnson wells along Kingswood Drive.

  The continued replenishment of fugitive gas to the wells east of the saddle depends on the thickness of the (main) gas cap accumulating under the dome. As the thickness of the main gas cap increases, more fugitive gas is able to spill under the saddle to the east gas cap. Because the source of fugitive gas was sealed off by the two cement-squeeze jobs in the English #1 well, over time the thickness of the main gas cap decreases as gas migrates upward out of the Berea Sandstone and into the joints in the overlying Cuyahoga Shale. As a result of this and the intentional overpumping of selected wells east of the saddle, the amount of fugitive gas spilling under the saddle decreases. Eventually, the main gas cap becomes so thin that no fugitive gas spills under the saddle and a separate, isolated gas cap forms on the east side of the saddle.

  The relatively instantaneous cut off of fugitive gas spilling under the saddle is seen in the wellhead LEL graphs from the de Gaetano, Prochazka, and Johnson wells, which are all uncased in the Berea Sandstone and the Cuyahoga Shale. Because of the relatively

instantaneous cut off of fugitive gas spilling under the saddle, these wells have a have a unique wellhead pattern not seen in wells west of the saddle.

- **Wellhead LEL Pattern #5 – Sharon Sandstone Wells Near Old Payne Well**
  This wellhead LEL pattern pertains to the migration of fugitive gas before the explosion at the Payne house (17975 English Dr). The evidence for this pattern is largely inferred from the sequence of events leading up to the explosion, construction details of the old Payne well, and wellhead LEL measurements taken in shallow wells at properties adjacent to the Payne house that are uncased in the lower part of the Sharon Sandstone.

  There were two wells at the Payne property. The old well was constructed in a shallow pit about five feet from the back the house in 1956 and was not used after 1973 when the new well was constructed. The old well was improperly abandoned; the casing and open wellbore were not filled with cement and the pit was simply covered with a concrete slab and buried under several inches of soil. Because the wellhead was not sealed, fugitive gas could still enter the pipe extending from the buried well pit into the basement. The borehole videotape crew relocated the old well on December 1, 2009, with the aid of a metal detector. The borehole videotape taken that day showed that the old well is 165 feet deep and has 35 feet of corroded steel casing that does not extend completely through the Sharon Sandstone. As a result, 5 to 6 feet of permeable Sharon Sandstone is open and uncased in the borehole, which extends completely through the Cuyahoga Shale and 20 feet into the Berea Sandstone.

  The new well is located more than 100 feet from the house, is 40 feet deep, and terminates in the upper part of the Cuyahoga Shale. Consequently, it could not have been the conduit for fugitive gas to enter the Payne house and cause the explosion on December 15, 2007. The most likely path for fugitive gas to enter the basement of the Payne house was through the uncemented old well that extended into the Berea Sandstone. Under the highly elevated fluid and gas pressures at that time, remember the "geyser" in the Jordan well occurred the same morning, fugitive gas was able to be forced into the basement. The gas likely was ignited by the pilot-light in the hot water heater.

  The pressure that built up in the wellbore of the old Payne well likely was large enough to force the fugitive gas from the Berea Sandstone into the uncased section of Sharon Sandstone in the well. Under the steadily increasing gas pressure in the old Payne well, the fugitive gas in the Sharon Sandstone could have spread laterally away from the old Payne well. As a result, the Sharon Sandstone also could have redistributed the fugitive gas as early as late November. In the highly permeable Sharon Sandstone, this gas could travel to adjacent properties and enter wells on those properties that are also uncased in a portion of the Sharon Sandstone. A similar scenario is described by Harrison (1983, 1985). The Gaub, Donaldson, and Weber wells along English Drive were between 41 to 43 feet deep, based on the cement plugging reports submitted to the state in early 2010, and tapped the Sharon Sandstone for water.

  The pattern of wellhead LEL values in these three wells also is unique. The pattern is characterized by the very high LEL values immediately after and likely well before the explosion at the adjacent Payne house. Within a week after the explosion, the wellhead LEL values drop to almost zero, which continues to the present day. The seemingly

mysterious decrease in wellhead LEL values in these three wells was caused by the instantaneous decrease in gas pressure in the old Payne well during the explosion. In essence, the explosion cut off the supply of gas to the Sharon Sandstone and therefore to these shallow wells.

The expert panel recognizes that the various pieces of geologic and well construction information needed to delineate the five wellhead LEL patterns and to identify what patterns occur in specific residential wells were not available for previous investigations. The panel also recognizes that the identification of the LEL patterns in the residential wells integrates and confirms several concepts presented in this executive summary and detailed in our report including the limited time that overpressurized gas entered the subsurface environment from the English #1 well, the upward migration of fugitive gas along natural joints and bedding planes in the Ohio and Bedford shales and its redistribution in the Berea Sandstone due to the undulating surface of the top of the Berea Sandstone, and vertical leakage of fugitive gas into the overlying Cuyahoga Shale along vertical joints and bedding planes.

No doubt, this all seems complicated, especially to readers lacking backgrounds in geology and petroleum engineering. Despite its complexity, it is based on well-established laws of physics and standard concepts in geologic mapping and petroleum geology, direct and indirect observations of tops and bottoms of geologic units, direct observation of fugitive gas source zones and their upward migration as gas dissipates without being replaced from below, and direct measurement of wellhead LEL values. What the expert panel presents is a very tightly constrained chronicle of how, why and when overpressurized gas from the English #1 well reached local residential wells. The famous Canadian hydrogeologist, Professor R. Allan Freeze, stated at an international conference that "a complex, arcane truth is always preferable to a simple, easily understood falsehood." Although he was describing the causes of groundwater contamination at a Superfund site, the panel recognizes that the same maxim applies to understanding the subsurface gas invasions in Bainbridge Township.

Black Sediments

More than a year after the English #1 well incident several residents began to complain about the occurrence of black sediments and black goo in their household water and on their water filters. As with other aspects of the subsurface gas invasion incident, E&A and DMRM reached dissimilar conclusions regarding the origin of the black sediments, which became the final disputed issue. Unfortunately, the sampling plan executed by E&A contained some oversights and the results of some of the sediment sampling and lab analyses did not allow robust conclusions to be made. The sampling plan executed by DMRM focused on collection of residential water-well samples within the investigation area. To answer the pertinent questions about possible water-quality degradation and health risk from the presence of the methane gas and from the presence of asperities derived from the Ohio Shale, would have required the skills of a clairvoyant to anticipate the accident and to have already collected samples in residential wells before the accident in the future area of investigation as well as to have collected samples outside the area that would be impacted by the accident.

As a consequence of non-clairvoyance, the sampling and analysis plan adopted by the expert panel is not without deficiencies, the most significant of which is the need for datasets that contain the same dissolved species (cations, anions, physical properties) in the same form as dissolved species and/or total (dissolved plus suspended). The big biggest difficulty in analyzing the combined DMRM and Ohio EPA datasets was a lack species common to both

datasets. The second major problem encountered in analyzing the water-quality data was the lack of data prior to the accident from inside the investigation area and outside the investigation area, but this could not be helped.

The expert panel used XRD analysis to determine if sediments collected from five well-water samples had XRD spectra similar to the bedrock units in which the wells were completed, or with the rusting steel casing materials, or with iron-sulfide minerals suggesting sulfate reduction by bacteria stimulated by methane gas, or with amorphous precipitates formed as a result of water softening or water heating. The XRD results from the five sediment samples indicate that the spectra from the Johnson, Davidson, and (new) Payne samples were consistent with that of the Cuyahoga Shale. All three of these wells are open and uncased through portions of the Cuyahoga Shale. The sediment sample from the Komocki well had an XRD spectrum indicating the presence of calcium and magnesium carbonate minerals, which are likely to form in a residential water well system after the water passes through a water heater. The Komocki well draws water solely from the Berea Sandstone. The sediment sample from the Cooper well was the only one with an XRD spectrum suggesting the presence of iron-sulfide and iron-hydroxide minerals such as pyrite or lepidocrosite. These minerals are black, form under reducing conditions, could be a source of some the black sediment found in local wells. The odd aspect of finding these minerals in sediments from the water sample collected from the Cooper well is that the Cooper well has consistently had some of the lowest wellhead LEL readings in the entire investigation area. Only once has the wellhead LEL in the Cooper well exceeded 1 percent, which is close to the detection limit on most of the hand held meters.

According to analysis of countywide water samples taken in several different geologic units, sulfate-reducing conditions are common in Geauga County, which could stimulate sulfate-reduction reactions producing black particles throughout the county. As a result, it is difficult to identify the Bainbridge investigation area as uniquely home to black particles resulting from the overpressurization of the English #1 gas well.

To determine if detrimental changes in groundwater quality occurred as a result of natural gas invading the shallow aquifers tapped by residential water wells, a suite of dissolved chemical species was measured in water samples taken in eight wells <u>inside</u> the area of investigation. These data were then statistically compared to water-quality data from wells completed in the same geologic units <u>outside</u> the area of investigation but in Bainbridge Township. The two datasets did not have many water-quality parameters in common, nor were there enough samples to use robust statistical tests. The statistical comparisons were based on dissolved concentrations of sulfate, barium, iron, manganese, chloride, calcium, magnesium, and sodium. These data were compared statistically using the Wilcoxan Rank Sum (WRS) test and visually using boxplots. The statistical analysis indicates that at a 95 percent confidence limit there is little difference in water chemistry between the <u>outside</u> well-water samples and the <u>inside</u> well-water samples taken at residential wells in the investigation area.

Asperities were another idea broached in the May 2009 meeting with E&A as a possible source for the black particulates found in the well waters in the investigation area. Asperities are very small particles of rock or metal that can be sheared off when two surfaces slide across one another. The asperities are the tiny protuberances in one surface that contact the other surface. Hence, the conjecture is that the black particles in the well waters in the investigation area are derived from the shearing of asperities from fracture surfaces in the Ohio Shale that become entrained with gas bubbles rising up into the Berea Sandstone and Cuyahoga Shale where they collect in residential wells. This difficulty with this idea is that it requires there to be

faulting in the Ohio Shale to produce the frictional shearing that dislodges the asperities. A check of earthquakes recorded by the OhioSeis seismic network show that there were no earthquakes in November or December of 2007. It is also difficult to envision black, heavy metal particles with a density of 4 to 8 gm/cm^3 being entrained by natural gas bubbles with a density of 0.65 gm/cm^3. Although sand blasters accomplish this under very high compressed air velocities, it is difficult to fathom the necessary velocities to entrain and carry heavy metal particles under water through 2,000 or more feet of discontinuous joints and bedding planes in shale.

The expert panel evaluated all the various ideas proposed for the unique presence of black particles in the well waters in the investigation area and found sulfate-reduction reactions to be the only viable possibility, but it is equally viable throughout the Geauga County, not solely in the Bainbridge investigation area, because sulfate reducing conditions are known to occur across the county in the same geologic units as those in the investigation area. All the evidence available to the expert panel indicates that the presence of black particles is not unique to the water wells in the Bainbridge investigation area.

Hypothesis Testing

Conclusions Reached by Expert Panel on Disputed Issue No. 1

There are several significant points challenging E&A's hypothesis, whereas only one point challenges the DMRM hypothesis. As shown in Chapter 3 of this report, calculations and field observations suggest, to a reasonable degree of engineering certainty, that any fracture created in the Ohio Shale by overpressurization of the English #1 well surface-production casing annulus would likely be shallow, oriented horizontally, and of very limited extent. Fracturing pressure calculated from first principles, published in-situ stresses, and published fracture gradients assuming the Ohio Shale behaves as a less stiff rock suggest the maximum-recorded shut in annular pressure in the English #1 well may have been sufficient to fracture the Ohio Shale. However, the most compelling evidence (published fracture gradients assuming the Ohio Shale behaves as a stiff rock, which is corroborated by published field data and anecdotal information) place the fracture gradient for shallow depths of the Ohio Shale as nearly equal to the English #1 well surface-production casing shut-in annular pressure gradient, making it less clear whether or not the shale was fractured.

Actual field data, in the form of surface-production casing annulus pressure data collected at the English #1 well during the mostly shut-in period following the hydraulic fracturing treatment, are more reflective of gas migration occurring once a sufficient annular pressure was achieved, as opposed to fracturing the geologic formations exposed in the annulus. In addition, field experience with nitrogen fracturing in Devonian shale is suggestive of a gas rate flowing into the English #1 well surface-production casing annulus that was insufficient to create the necessary irregularities on a created fracture surface to hold a fracture open once the gas source was sealed off. Calculations further suggest that any created fracture would have been of limited length (≤ 300 feet) if the fracture was oriented vertically or of limited radius (≤ 250 feet) if the fracture was oriented horizontally. Accordingly, it could be argued that if any shallow fractures were created in the Ohio Shale by overpressurization of the English #1 well surface-production casing annulus, the fractures did little more than temporarily augment gas migration through the natural fracture system.

The expert panel is troubled by the lack of direct evidence demonstrating the existence or likelihood of fractures created by overpressurization of the surface-production casing annulus in the English #1 well. With double-wing fractures emanating directly from the English #1 well to the six residential wells intercepted by Type 1 fractures, as identified by E&A, one would expect to see gas seeping from ground surface near the English #1 well where the Type 1 fractures all converge toward the wellbore. The inference that these fractures exist is based solely on wellhead LEL information, which is not, in and of itself, diagnostic or conclusive. The expert panel also is troubled by the facts that (1) the size, shape, and orientation of the inferred fractures do not adhere to well-documented field observations of hydraulic fractures in the technical literature, (2) that the size, shape, and orientation of the inferred fractures are not consistent with state-of-the-profession equations routinely used by petroleum engineers, and (3) that the planar dimensions of the inferred fractures grossly exceed mass balance constraints on propagation of hydraulic fractures. For these reasons, the expert panel rejects the E&A hypothesis that overpressurization of the annular space in the English #1 well caused a far-reaching, deep, network of conical fractures to develop.

The expert panel is in agreement with statements made by DMRM that the overpressurization of the annular space in the English #1 well caused gas to migrate upward along natural vertical joints and horizontal bedding planes in the bedrock surrounding the base of the cemented surface casing. This explanation is consistent with the rate of gas propagation and the distribution of gas across the investigation area in December and January, as based on wellhead LEL measurements.

Conclusions Reached by Expert Panel on Disputed Issue No. 2

The direct, visual evidence of the gas zone rising in the Jordan, de Gaetano, and Adams wells demonstrates that the fugitive gas is slowly dissipating and is not being replenished by the migration of additional gas from any source. This is corroborated by the decrease in gas pressure in these wells. These observations and calculations demonstrate that the fugitive gas is from a one-time pulse and not from a deeper, long-term gas source. For these reasons the expert panel accepts the hypothesis of DMRM that overpressurized gas escaped from the English #1 well for a limited time and, therefore, represents a one-time, pulse source of gas that will slowly dissipate. The hypothesis proposed by E&A is not accepted because of the direct, visual evidence demonstrating that the gas zone is dissipating upward, gas pressures in wells are decreasing, and therefore gas is not being replaced by high-pressure gas from a deeper source.

Conclusions Reached by Expert Panel on Disputed Issue No. 3

Five patterns were recognized by the expert panel in the wellhead LEL graphs. Each pattern is related to the fluid mechanics and manner in which the fugitive gas moved through the geologic media, either by its buoyancy along discontinuous fractures and bedding planes in the Cuyahoga Shale or by groundwater flow and buoyancy in the intergranular porosity in the Berea and Sharon sandstones. The patterns are also related to the structure on the top of the Berea Sandstone, intentional overpumping of selected water wells, seasonal variations in water levels, and well construction details. No wellhead LEL trends were measured that could not be explained by the processes defining the five wellhead LEL patterns described in this report.

The expert panel rejects the hypothesis proposed by E&A that temporal patterns in wellhead LELs demonstrate the creation of three different types of fractures. There is no direct subsurface geologic evidence that these fractures exist. The temporal patterns in wellhead LEL values can be explained by applying well-documented, well-established concepts published in textbooks to the specific geologic conditions in the area. The expert panel accepts the DMRM hypothesis that wellhead LEL measurements are non-diagnostic in terms of characterizing subsurface geologic conditions.

Conclusions Reached by Expert Panel on Disputed Issue No. 4

The XRD analyses indicated that the precipitation of black sediment is not widespread. The geochemical reactions creating black, iron sulfide particulates were identified in only one of five wells analyzed from the investigation area. Because this study was actuated by the accidental release of methane gas to the subsurface environment, any water well sampling strategy had to be compromised because of a paucity of water-quality data both inside and outside the investigation area prior to the gas invasion incident. Analysis of the available water-quality data suggest that the low dissolved methane concentrations in wells in the investigation area may limit sulfate-reduction reaction products in the geologic units tapped by residential wells, which with the available data cannot be distinguished from sulfate-reduction reactions known to be occurring naturally in Geauga County in the same geologic units.

The non-parametric statistical analysis of the well waters samples collected "inside" the investigation area and "outside" the investigation area indicate that at a 95 percent confidence level there is little difference in water chemistry between the "outside" well water samples taken at public water-supply wells and the "inside" well water samples taken at residential wells in the investigation area that may have been exposed to methane. The only parameter with a statistically significant difference is barium, which has lower values in the "inside" well water samples than in the "outside" well water samples. All of the other water-quality parameters, pH, alkalinity, sulfate, nitrate, chloride, arsenic, calcium, total iron, total manganese, and sodium, demonstrate that there is no statistical difference at a 95 percent confidence level between the "inside" and the "outside" water well samples.

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