4. Testing and Evaluating Formulated Hypotheses

Chapters 1, 2, and 3 in this report present the rationale for forming the expert panel, the major disputed issues between Eckstein & Associates, Inc. and the Division of Mineral Resources Management at the Ohio Department of Natural Resources, the panel's requests for additional data to further evaluate the disputed issues, and the analysis of those data by the expert panel. This chapter describes the application of those analyses to evaluating and testing the four sets of hypotheses formulated by the expert panel that embody the dissimilar views of the two groups. In doing these evaluations, we will apply the scientific method (pages 1-1 to 1-3) to the four sets of hypotheses. In concept, this is similar to what a judge would do in a Daubert hearing. As gatekeeper to expert opinions presented at the trial, the judge, prior to the trial, evaluates whether the reasoning and methodologies used in any expert testimony are scientifically valid and reliable. This is done as a way to screen out professional opinions based on conjecture and speculation (Blauvelt, 1999). This task of the expert panel is also similar to that of a jury in a civil trial that is charged with evaluating the evidence and determining liability.

Unlike a judge or a jury, the expert panel possesses technical expertise in the issues at dispute between E&A and DMRM. Unlike a judge or a jury, the expert panel had the ability to request additional field and laboratory testing, and the time to analyze and interpret those data. The applied research and professional experiences of the expert panel demonstrates that the power and the elegance of the scientific method lie in its requirement of hypothesis testing and in its capacity for hypothesis revision and retesting. If, after testing and evaluating a pair of hypotheses addressing one of the disputed issues between E&A and DMRM, we conceive a better, more discriminating hypothesis to test the disputed issue using the combined sets of new and old data, we did so. Those efforts are also presented in this section.

Disputed Issue No. 1

This issue deals with the subsurface migration of natural gas resulting from overpressuring the surface-production casing annulus of the English #1 gas well. The specific dissimilar statements made by E&A and by DMRM are given in Chapter 1. Based on those statements, the Expert Panel formulated the following two hypotheses, which are also presented in Chapter 1. (If appropriate, points that support or rebut an argument are listed more than once.)

E&A Formulated Hypothesis #1: Overpressurization of the annular space in the English #1 well caused the Ohio Shale to fracture creating a far-reaching, conical network of fractures extending throughout the Ohio Shale, downward through the "Big Lime," and upward through the Berea Sandstone into the Cuyahoga Shale.

Points Supporting E&A Hypothesis #1

1. 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 annular shut-in pressure in the English #1 well may have been sufficient to create a fracture of limited dimensions in the Ohio Shale (see page 2-18).

Points Challenging E&A Hypothesis #1

1. Pressures necessary to fracture the "Big Lime," as calculated from first principles exceed the maximum-recorded English #1 well shut-in surface-production casing annular pressure.

2. The lower limit of the "Big Lime" fracturing gradient, determined from drilling records from the English #1 well, exceeds the calculated upper limit of the imposed pressure gradient resulting from overpressurization of the English #1 well surface-production casing annulus.

3. Fracturing pressure calculated from published fracture gradients assuming the Ohio Shale behaves as a stiff rock, published field data, and anecdotal data place the fracture gradient for shallow Ohio Shale as nearly equal to the English #1 well surface-production casing shut-in annular pressure gradient.

4. Field experience from the use of gaseous nitrogen as a fracturing fluid in Appalachian Basin shales suggest the estimated gas rate communicating with the English #1 well surface-production casing annulus was not sufficient to cause the necessary fracture surface irregularities to hold open a fracture created in the Ohio Shale once the gas source was sealed off on December 17, 2007.

5. Calculations suggest that a fracture created in the Ohio Shale as a result of the over-pressurization of the English #1 well surface-production casing annulus would be limited in lateral extent and height, and therefore have a limited volume.

6. There is no evidence, direct or indirect, to support the creation of a spherical or conical radius of influence resulting from the overpressurization of the English #1 well surface-production casing annulus; nor are there any similar geometries of fractures reported in case studies of hydraulic fracturing or in theoretical analyses in the technical literature.

7. Well-established rock mechanics theory presented in textbooks states that new fractures will not propagate across existing open fractures because stress does not propagate across free space (Suppe, 1985). Consequently, the existing system of natural fractures would limit propagation of any fractures potentially created by overpressurization of the annular space in the surface-production casing of the English #1 well.

DMRM Formulated Hypothesis #1: 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.

Points Supporting DMRM Hypothesis #1

1. An inadequate primary cement job in the English #1 Gas Well apparently failed to maintain a hydraulic seal during fracture stimulation treatment, allowing the Clinton sandstone to communicate with the surface-production casing annulus. This provides a potential source of deep, high-pressure gas for accumulation and confinement in the annulus of the English #1 well surface-production casing. Additionally, the uncemented Newburg dolomite and a shallower, naturally-fractured zone in the "Big Lime," as well as the Ohio Shale, may have also contributed to this accumulation.

2. The results of the corrective remedial cementing taken by the operator of the English #1 well corroborate Point 1.

3. Based on several site-specific studies of groundwater contamination from subsurface migration of contaminants (brine and gas) from gas well drilling, of which one study is strikingly similar to the Bainbridge Township incident, Harrison (1983) concluded that in some extreme cases of overpressuring of oil- and gas-well annuli, where the pressure of fluids in the annulus below the surface casing becomes too great, propagation of existing fractures in some strata might occur.

4. 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 extensive fracturing of geologic formations exposed in the annulus.

5. Had an extensive, conical network of fractures delivered natural from deep sources, the effects of the invasive gas likely would have been detected in a much shorter period of time than the 31 days it took for the gas to surface in the Payne house via its well and in the Jordan well. The 31-day period that it took the gas to migrate into these wells in the Berea Sandstone is more consistent with the gas migrating along natural joints and bedding planes in the Ohio, Bedford shales, then in the intergranular pores in the Berea Sandstone and up along the top of Berea Sandstone surface.

Points Challenging DMRM Hypothesis #1

1. 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 English #1 well maximum recorded shut-in annular pressure may have been sufficient to fracture the Ohio Shale.

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.

Disputed Issue No. 2

This issue concerns the longevity of the subsurface gas invasion; whether the over-pressurization incident at the English #1 well created a one-time pulse of methane that will slowly pass through the shallow subsurface, after which conditions will return to normal, or whether the overpressurization incident connected a deep, continuous source of methane through propagation of deep fractures that transmit the methane gas to the shallow subsurface.

E&A and Markowitz Formulated Hypothesis #2: Overpressurization of the annulus of the English #1 well created a network of deep fractures enabling methane gas to migrate into residential wells and basements of homes that is a long-term condition that can last forever.

Points Supporting E&A and Markowitz Hypothesis #2

1. Wellhead LEL values measured in several residential wells in the investigation area did not decline over more than two years following the house explosion suggesting that a deep source of gas is may be connected via fractures to some of the residential wells in the investigation area.

2. Borehole videotapes taken in six residential wells in January and March 2008 indicate that methane gas was rising rapidly in the wellbores and churning at the water surface in several wells. Wellhead LEL readings made in several of these residential wells and in other residential wells in December 2007, 2008, and 2009 do not show a consistent pattern of decline suggesting a long-term, subsurface condition had formed.

Points Challenging E&A and Markowitz Hypothesis #2

1. The patterns of wellhead LELs indicate methane gas rose upward along fractures and bedding planes outside of the surface-production casing and the surface casing of the English #1 well. Upon rising into the Berea Sandstone, the gas rose through intergranular pores to the top Berea Sandstone and then migrated upslope beneath the poorly permeable Cuyahoga Shale to the high point in the top of the Berea Sandstone surface. Along this predominant flowpath, gas migration was strongly influenced by pumping of residential wells, which caused gas to migrate westward beneath Scotland Drive, and by upward leakage into the Cuyahoga Shale along naturally–occurring vertical joints (Figures 3–24, 25, 47, 48, 49. 50).

2. The differences in wellhead LEL patterns measured in residential wells can be explained based on well-established concepts of gas migration in single and double-porosity materials, without having to invoke the creation of tens of thousands of feet of fractures that extend a thousand feet or more downward to deep gas-production zones.

3. The borehole videotapes taken the 2009 and 2010 in the same six wells that were videotaped in 2008 show that the bottom of the fugitive gas zone rose 29 feet in the Jordan well, 33 feet in the de Gaetano well, and 124 feet in the Adams well (Figure 3–57, Table 3–5). This demonstrates that gas is dissipating upward. It also demonstrates that there is no gas rising from deeper sources to replenish the initial pulse of fugitive gas from the temporary overpressurization of the English #1 well.

4. Wellhead LEL measurements do not reveal the entire picture of subsurface conditions. LEL measurements only indicate the volume of methane gas within a volume of space. Although this is important information, it cannot be used alone to interpret subsurface conditions. The rising elevation of the fugitive gas zone in the Jordan, de Gaetano, and Adams wells also demonstrates that the pressure of the gas in these wells has decreased substantially, by 13, 14, and 54 psi, respectively (Table 3–4). The borehole videotapes do not record a single well in which the bottom of the gas zone has increased (deepened) over time. This indicates that the invasive gas is dissipating and is not being replaced by gas from a deeper, commercial gas-production zone. Wellhead LEL data do not provide this important information.

DMRM Formulated Hypothesis #2: The "Big Lime" and Clinton sandstone were not fractured by overpressurization of the English #1 well. Since December 17, the deeper sources of high-pressure gas in the Clinton sandstone and Newburg dolomite have been cemented behind casing. Overpressured gas escaped from the surface-production casing annulus in the English #1 well for 31 days beginning November 13, 2007.

Points Supporting DMRM Hypothesis #2

1. The borehole videotapes taken the 2009 and 2010 in the same six wells that were videotaped in 2008 show that the bottom of the fugitive gas zone rose 29 feet in the Jordan well, 33 feet in the de Gaetano well, and 124 feet in the Adams well (Figure 3–59, Table 3–4). This not only demonstrates that the invasive gas is dissipating, it also demonstrates that there is no gas

arising from deeper sources to replenish the initial pulse of fugitive gas from the temporary overpressurization of the English #1 well. Thus, the invasive methane gas detected in residential wells and homes is derived from a one-time event representing a pulse of overpressurized gas from the surface-production casing annulus in the English #1 well. It is not derived from a continuous source of deep gas transmitted upward along deep fractures.

Points Challenging DMRM Hypothesis #2

1. Wellhead LEL values measured in several residential wells in the investigation area did not decline over more than two years suggesting that a deep source of gas may be connected via fractures to these residential wells.

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.

Disputed Issue No. 3

This issue addresses use of measured wellhead LEL values and differences in their patterns to identify changes in deep subsurface geologic conditions. Although the content of this issue overlaps that of Disputed Issue No. 1, the main topic of this issue deals with the validity of using wellhead LEL measurements to define and delineate specific types of subsurface fractures that may have been created during the period of overpressurization in the annulus of the surface-production casing in the English #1 well.

E&A Formulated Hypothesis #3: Temporal changes in wellhead LELs demonstrate the creation of three types of fractures. A Type 1 wellhead LEL response, exemplified by six wells, occurs in residential wells located at fractures fed with gas directly from surface-production casing annulus of the English #1 well. A Type 2 wellhead LEL response, seen in four wells, occurs in residential wells located at fractures developed as a result of overpressuring of the deep gas-producing formation during the English #1 well annulus overpressuring. A Type 3 wellhead response, seen in nine wells, occurs in wells located at fractures developed as a result of deep fracturing of the bedrock during the English #1 well annulus overpressuring, down to gas-producing formation.

Points Supporting E&A Hypothesis #3

1. Temporal variations in wellhead LEL values measured in residential wells are not uniform or consistent. Immediately following the house explosion at 17975 English Drive, wellhead LEL values in some residential wells were 100 percent, whereas wellhead LEL values in other residential wells increased to 100 percent within a few days or weeks of the explosion. Wellhead LEL values in many wells decreased abruptly, whereas responses in others did not. Wellhead LEL values in some wells remain very high.

Points Challenging E&A Hypothesis #3

1. The first-order pattern of rising and declining wellhead LEL values measured in many residential wells (Figure 3-104, Appendix F) is caused by normal, seasonal fluctuations in water levels in shallow aquifers and confining beds (Figure 3-107), and not by periodic or sporadic rejuvenation of deep subsurface gas pressures.

2. The atypical wellhead LEL patterns in the de Gaetano (17971 Kingswood Drive), Prochazka (17927 Kingswood Drive), and Johnson (17926 Kingswood Drive) wells are caused by the "saddle" in the top of Berea Sandstone surface (Attachment 4) and not fractures connected directly or indirectly to the annular space in the surface-production casing of the English #1 well.

3. Wellhead LEL patterns in the Donaldson (17938 English Drive), Gaub (17939 English Drive), and Maguire (17925 English Drive) wells are caused by their proximity to the high point in the top of Berea Sandstone surface and, in the case of the Gaub and Donaldson wells, by being uncased through the lower section of the Sharon Sandstone that was locally overpressurized by gas entering the old, unplugged Payne well from the Berea Sandstone (Figure 3-29, pages 3-121, 122).

4. Wellhead LEL records document the success of intentionally overpumping residential wells as a means of dissipating invasive gas from the Berea Sandstone and Cuyahoga Shale during the first six months of 2008. The intentional overpumping of more than 16 residential wells caused wellhead LEL values measured in this period to be lower than measurements prior to and after this period. This caused the bottom of the gas zone, as seen in the sequence of three borehole videotapes taken in the Jordan well and two borehole videotapes taken in the de Gaetano well, to dissipate upward out of the Berea Sandstone and into the overlying Cuyahoga Shale. The wellhead LEL patterns from this period of intentional overpumping by shallow residential wells is not related to the creation of fractures or there orientation or depth.

5. Wellhead LEL records from several wells show that the thickness of accumulated gas in the Berea Sandstone and Cuyahoga Shale is slowly declining. As a result, wellhead LEL measurements in some wells categorized by E&A as belonging to fracture Types 1, 2, or 3 no longer conform to the criteria used to identify such fractures. Because E&A linked wellhead LEL responses to specific types of fractures created during overpressurization, the lack of temporal conformance in the wellhead LEL patterns in these wells indicates there must be causes other than fracturing that produce the patterns in the wellhead LEL data.

6. Wellhead LEL measurements in several of the nine wells assigned by E&A to Type 2 fractures are consistent with gas migration through the existing natural fracture system in the Ohio Shale, migration along the top of the Berea Sandstone, and then into natural fractures in the Cuyahoga Shale. These processes are well-documented in the technical literature and do not need to invoke thousands of linear feet of fracturing.

7. Neither creation of the shallow fractures, nor creation of the deep fractures proposed by E&A explain the lack of measureable wellhead LELs in the residential wells closest to the English #1 well where the density of created fractures would be greatest (e.g. wells at the Slacas, Newman, Wozniak, and MC properties at the south end of English Drive).

DMRM Formulated Hypothesis #3: Wellhead LEL values are a valuable diagnostic tool for determining the presence or absence of methane gas and for determining possible public safety responses to LELs measured in specific homes. Measurement of wellhead LELs, however, cannot determine the subsurface source of gas or the subsurface conditions that enabled the gas to enter the well. DMRM further concluded that variable LEL patterns resulted from multiple, complex variables related to the local geology, hydrogeology, and well construction.

Points Supporting DMRM Hypothesis #3

1. Wellhead LEL values do not measure changes in subsurface fluid or gas pressure and, therefore, are not a diagnostic means of evaluating the dissipation or accumulation of gas.

2. The patterns of wellhead LEL data measured in residential wells can be explained by well-documented petroleum engineering and petroleum geology concepts that do not invoke creation of thousands of linear feet of fractures encompassing a composite area of more than 10 million square feet (see Figures 4-1 through 4-4 on pages 4-11, 4-12, and 4-13), as postulated by E&A.

Points Challenging DMRM Hypothesis #3

1. Uncertainty in the precision of LEL values caused by use of multiple gas meters, sensitivity of different gas meters, calibration of gas meters, and variations in operator placement of gas meters.

2. Simply stating that variations in wellhead LEL values are related to a list of pertinent factors does not explain what factors control specific patterns. It is necessary to know what factors influence the wellhead LEL patterns in specific wells and what different factors influence wellhead LEL patterns in other wells.

Conclusions Reached by Expert Panel on Disputed Issue No. 3

E&A divided the patterns of wellhead LEL values measured in residential wells into three groups based on fractures created in the subsurface by overpressurization of the surface-production casing annulus in the English #1 well. The wellhead LEL pattern typical of each group, according to the E&A classification scheme, was caused by a different type of fracture geometry, as described below. Table 4–1 lists the specific residential wells typifying the wellhead LEL pattern for each type of fracture created by overpressurization of the annular space in the surface-production casing of the English #1 well. Table 4–1 also presents pertinent data collected at the request of the expert panel.

- **Type 1 fractures** occur at residential wells affected by the initial penetration of invasive gas. According to E&A, these wells are located at fractures fed with gas directly from the surface-production casing annulus in the English #1 well.

- **Type 2 fractures** occur at residential wells located at fractures created as a result of overpressuring the gas-producing formation. These wells continue to have moderate gas content (15% < LELs < 75%). The fractures, however, are not physically connected to the English #1 well.

- **Type 3 fractures** occur at residential wells located at fractures developed by deep fracturing of bedrock, down into a gas-producing formation. These wells continue to have high gas content (LELs > 75%) from fractures that are not physically connected to the English #1 well.

Table 4–1. Fracture Involvement in LEL Patterns in Residential Wells (after E&A, 2009)

Fracture Types Based on Wellhead LEL Patterns in Residential Wells (E&A, 2009)	Distance to English Well (feet)	Well Depth (feet)	Casing Length (feet)	Uncased Borehole (feet)	Uncased Geologic Units
Type 1 – Residential wells affected by initial penetration of gas, but improved with the squeeze job at the English #1 well. These wells are located at fractures fed with gas directly from the surface-production casing annulus in the English #1 well.					
17955 English (Cernicki well)	675	> 75	53	> 22	C
17971 Kingswood (de Gaetano well)	1027	245	95	95	C, B, Bd
17971 English (Gaub well)	1186	43	--	--	S, C
17938 English (Donaldson well)	1265	43	--	--	S, C
7950 Scotland (Komocki well)	1574	194	150	44	C, B
7867 Scotland (Abrams well)	2110	33	7	26	S
Type 2 – Residential wells located at fractures created as a result of overpressuring the gas-producing formation. Wells continue to have moderate content (15% < LEL < 75%). Fractures are not physically connected to the English #1 well.					
17969 Kingswood (Calo well)	833	151	56	95	S, C, B
17990 English (Jordan well)	943	160	72	88	C, B
7969 Scotland (Kukoleck well)	1266	140	36	108	C, B
7955 Scotland (Sanborn well)	1336	123	--	--	C, B
Type 3 – Residential wells located at fractures developed by deep fracturing of bedrock, down to the gas-producing formation. These wells continue to have high gas content (LEL > 75%) from fractures not physically connected to the English #1 well.					
7981 Scotland (Bastifell well)	1112	150	37	113	C, B
17925 English (Maguire well)	1380	76	41	35	C
7941 Scotland (Mason well)	1488	137	39	98	C
7915 Scotland (Hupp well)	1848	46	24	22	C
7897 Scotland (Buddenhagen well)	1869	180	57	123	C, B
7868 Scotland (Mesmer well)	2214	109	--	--	C
7859 Scotland (McGee well)	2294	142	59	83	C, B
7846 Scotland (Ohara well)	2438	134	64	70	C, B
17820 English (Adams well)	2791	300	97	203	C, B, Bd

S = Sharon Sandstone C = Cuyahoga Shale B = Berea Sandstone Bd = Bedford Shale

What is now known is that gas migration in the Berea Sandstone is not controlled by fractures either directly connected to the English #1 well (E&A fracture Type 1) or by fractures not physically connected to the English #1 well (E&A fracture Types 2 and 3). The borehole videotapes taken in 11 wells penetrating a total of 276 vertical feet of the Berea Sandstone show only 4 vertical joints (Appendix C). The predominant type of porosity in the Berea Sandstone is intergranular porosity. Secondary porosity along fractures is almost negligible. Gas migration in the Berea Sandstone is controlled by well-documented factors in the petroleum engineering and petroleum geology literature (e.g. Dahlberg, 1994; Levorsen, 1964). These classic, long-established factors include: (1) the buoyancy of the gas, (2) the intergranular porosity in the Berea Sandstone, (3) the altitude of the top of the Berea Sandstone surface, and (4) temporal and spatial changes in groundwater flow gradients within the Berea Sandstone.

Based on the six residential wells identified by E&A as being located at fractures fed by gas directly from the English #1 well annulus, the cumulative length of these fractures, based on the distance of the residential wells from the English #1 well, is nearly 16,000 linear feet. (It is actually 15,674 linear feet assuming the creation of two-wing fractures, which is consistent with established concepts and equations published in the technical literature and with field observations at experiment sites.) Figure 4–1 shows the length and orientation of the six fractures extending from the English #1 well to the residential wells exemplifying Type 1 fractures based on their wellhead LEL patterns, which can be seen in Appendix F.

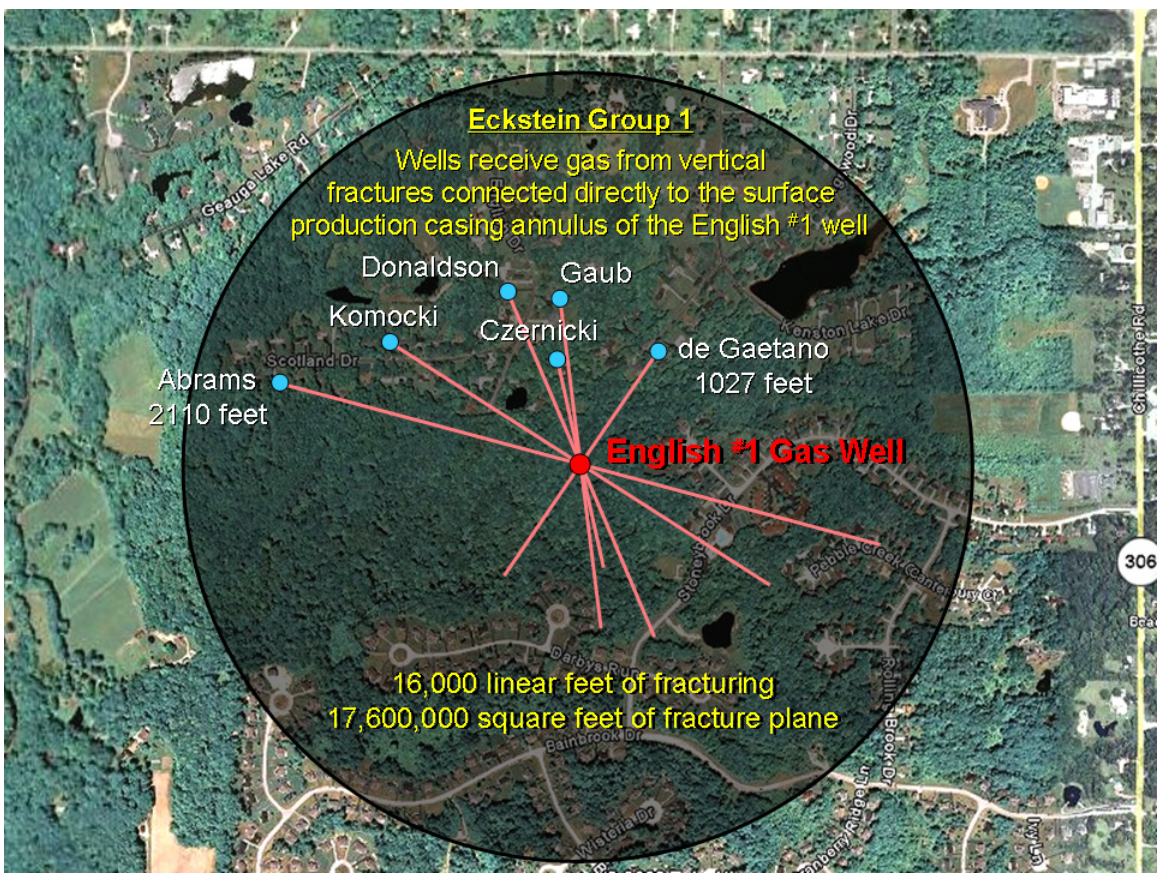

Figure 4-1. Minimum length of fractures connecting Group 1 wells directly to the surface-production casing annulus in the English #1 well (based on E&A, May 2009).

In all likelihood, 16,000 feet represents a minimum aggregate fracture length. It is unlikely the fractures terminate exactly at the locations of the residential wells. It is also unlikely that these

six residential wells intercept the only Type 1 fractures created in the manner proposed by E&A. If it is assumed that these Type 1 fractures extend from the Sharon Sandstone, the uppermost geologic unit penetrated by the six residential wells, down to the middle of the Ohio Shale, a distance of about 1,100 feet, then the minimum, composite surface area of these fractures would be approximately 1,100 feet x 16,000 feet, or about 17,600,000 square feet. By themselves, the six proposed Type 1 fractures that directly connect the six residential wells to the English #1 well would cover an area exceeding 0.6 square miles.

By comparison, state-of-the-profession engineering calculations made by the expert panel show that if the Ohio Shale fractured, the fracture would most likely be horizontally oriented, not vertically, and would cover an area of approximately 173,500 square feet based on a fracture radius of about 235 feet. The difference in areas between the six Type 1 fracture planes proposed by E&A and the and the single fracture plane computed using established petroleum engineering equations (Valkó and Economides, 1995; Economides and Martin, 2007) is a factor of 101 times. Figure 4–2 graphically shows this difference in terms of the areas of equivalent circles. The inner white circle represents the area computed using petroleum engineering equations based on values of physical properties pertinent to the Ohio Shale (pages 2–13 to 2–18). The outer yellow circle on represents the area equivalent to the sum of the Type 1 fracture planes that intersect residential wells exemplifying the wellhead LEL pattern of E&A's Type 1 fractures.

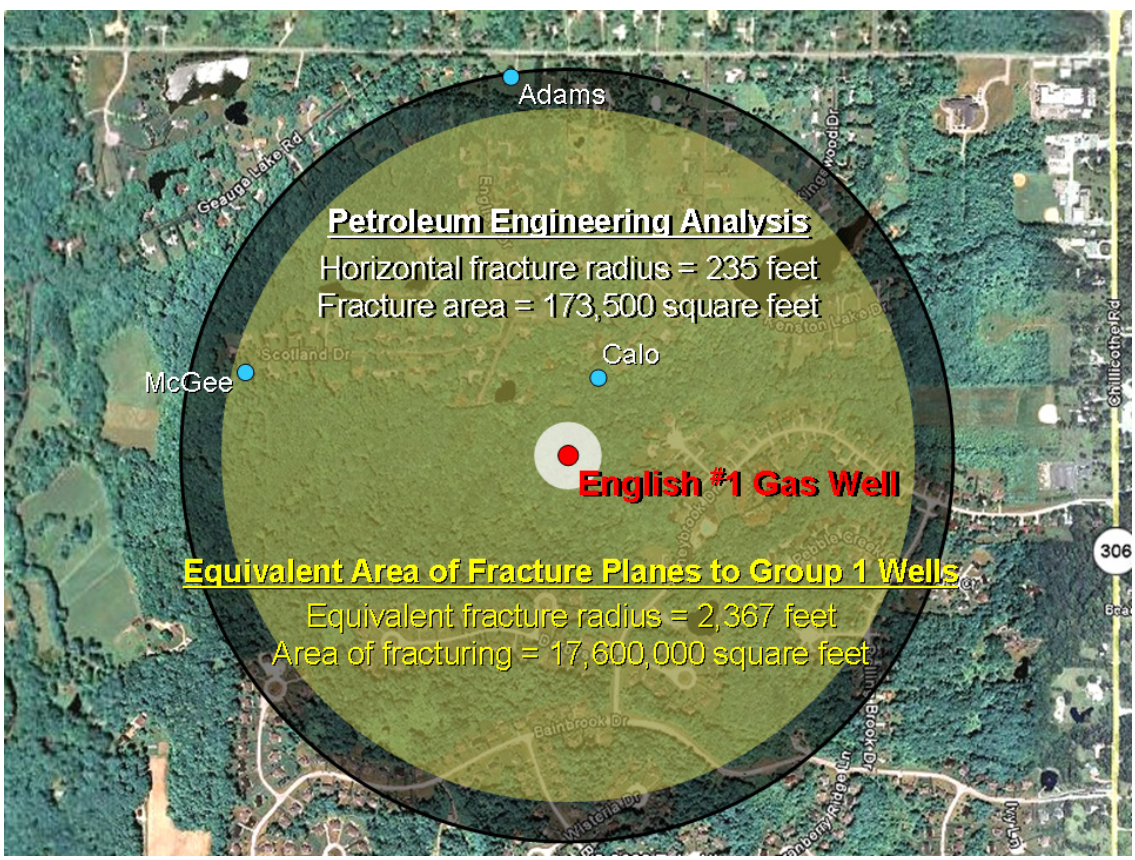

Figure 4-2. Comparison of fracture plane areas based on state-of-the profession computations for the Ohio Shale (white) and based on the area of a circle equivalent to the total area fracture planes proposed by E&A (2009) that intersect the six residential wells in Group 1 (yellow).

The composite equivalent area of fracture planes corresponding to the Type 1 fractures extending from the English #1 well to the six residential wells, shown on Figure 4-2, does not portray the additional areas of fracture planes in E&A's Type 2 and Type 3 fractures. These two types of fractures are also created due to overpressurization but extend from the deep gas-production zone upward to intersect at least 13 residential wells. Type 2 and Type 3 fractures, however, are not physically connected to the English #1 gas well (Table 4-1). E&A did not describe the orientation of these fractures, other than the fracture network created by overpressurization had the shape of an inverted cone. The wells that the Type 2 and Type 3 fractures penetrate, based on their wellhead LEL patterns, are portrayed on Figures 4-3 and 4-4. In these figures it is assumed that the orientations of the fractures, if in fact present, are consistent with established theory and field observations to be parallel to the axes of maximum stress in northeastern Ohio during the Appalachian Orogeny and at the present time (Engelder, 1982, 1993). Even assuming that the orientations of these fractures are aligned parallel to these axes, it is highly speculative and puzzling how deep fractures, such as Type 2 and Type 3, are created and propagate without being physically connected to a source of highly elevated fluid pressure, i.e. the English #1 well.

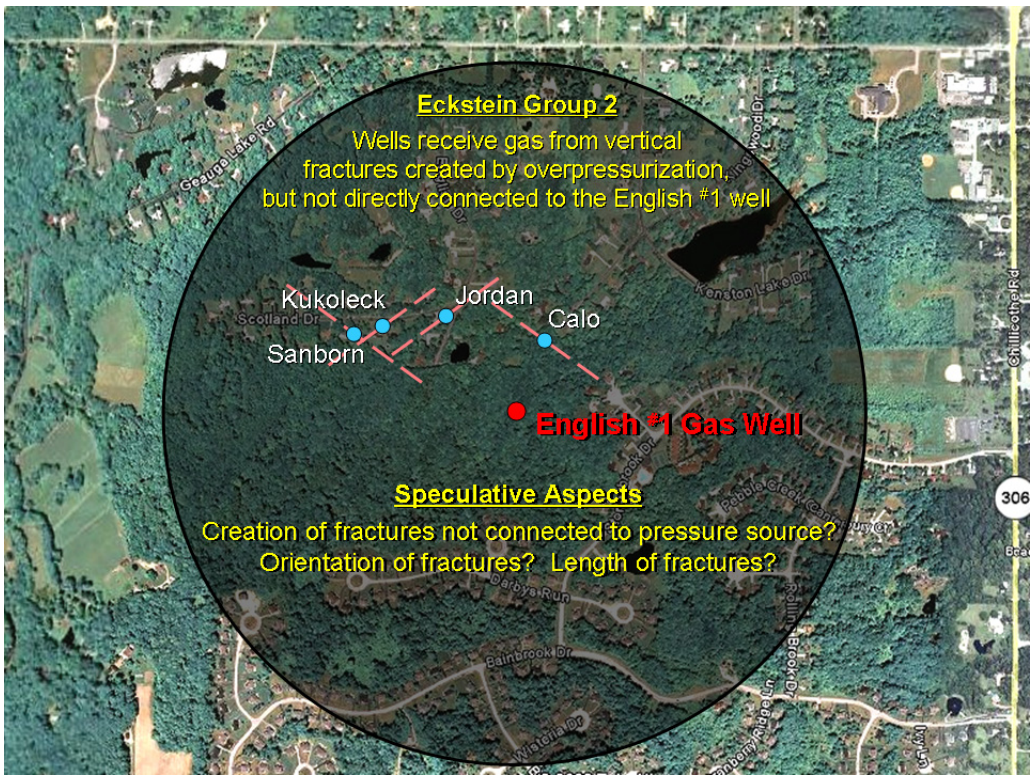

Figure 4-3. Hypothetical portrayal of Type 2 fractures created by overpressurization that connect residential wells to deep gas-producing zones but do not connect to the English #1 well (based on E&A, May 2009).

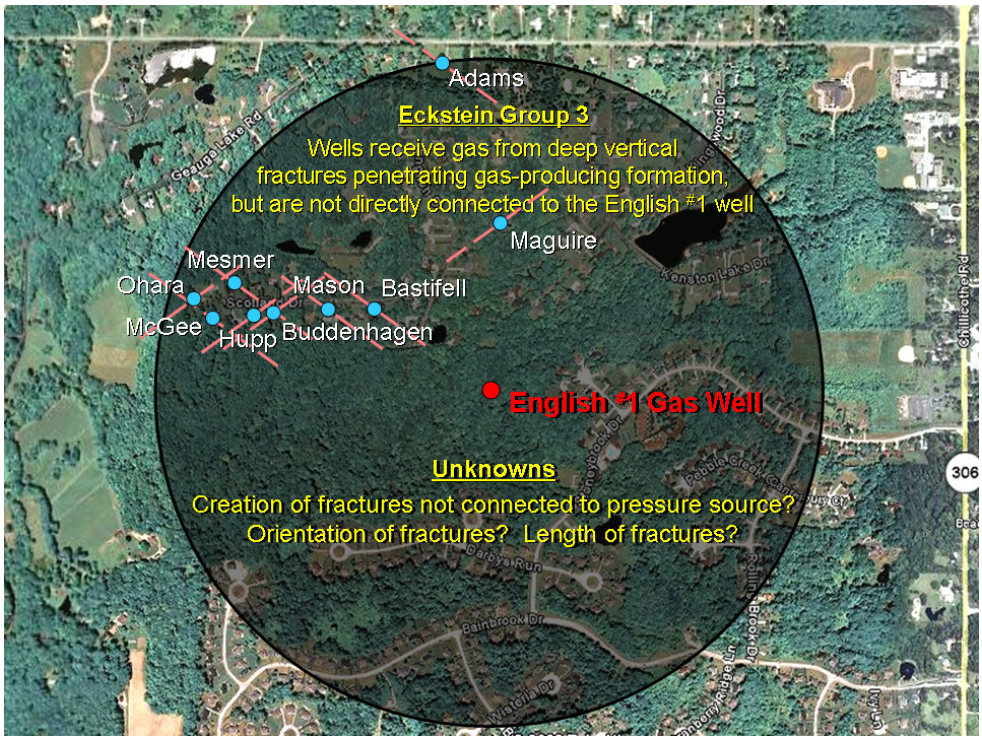

Figure 4-4. Hypothetical portrayal of Type 3 fractures created by overpressurization that connect residential wells to deep gas-producing zones but do not connect to the English #1 well (based on E&A, May 2009).

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.

Disputed Issue No. 4

This issue concerns the degradation of local groundwater supplies in terms of sediment content and water quality due to overpressurization of the annular space in the surface-production casing in the English #1 well.

E&A and Markowitz Formulated Hypothesis #4: Following the English #1 well incident, black sediment (a.k.a. black goo) consisting of toxic metals derived from asperities created during the fracturing of the Ohio Shale, continues to contaminate the water obtained from residential wells. The residential well waters also contain arsenic and other toxic metals that cause health risks.

Points Supporting E&A and Markowitz Hypothesis #4

1. Several homeowners reported an increase in sediment content (decrease in clarity) following the house explosion.

2. Sediment samples collected from water pumped from the Stover well (17860 English Drive) and scraped from the water filter show the presence of Cu, Zr, Ag, Y, Ce, C, and S.

3. Sediment samples collected from water pumped from the Rutana well (7982 Scotland Drive) show the presence of C, S, Zr, S, Ag, Cu, Ce, and Fe.

4. The presence of these elements in drinking water makes the water toxic regarding of their concentration or their rate of consumption.

Points Challenging E&A and Markowitz Hypothesis #4

1. The sediment samples collected from the Stover and Rutana wells were analyzed with ESEM-EDS, a technique that is not quantitative and does not determine accurate concentrations of metal ions.

2. The sampling protocol used to obtain the sediment samples from the Stover and Rutana wells did not require measurement of water volumes relative to sediment mass collected. As a result, concentrations of elements per liter of solution (concentrations) could not be estimated.

3. Wellhead LEL measurements in the Stover well never exceeded 1 percent and wellhead LEL measurements in the Rutana well never exceeded 5 percent, which is puzzling as to why these two wells were selected to demonstrate sulfate-reduction by methane as a possible cause of the black sediments.

4. Asperities are created by two surfaces sliding past one another. There is no evidence, either measured by seismometers in the OhioSeis seismic network or anecdotal from local residents, of any earthquake activity in November or December 2007. As a result, there is no evidence of differential movement along known deep basement faults in northeast Ohio or along unproven faults or fractures in the Bainbridge County area. At low earth surface temperatures (as opposed geothermal temperatures at depth), asperities undergo both fracture and plastic flow, making them less available to be entrained with natural gas bubbles.

5. Field experience with nitrogen fracturing in the 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. This, in turn, suggests that insufficient asperities would have been created to rise into the shallow aquifers tapped by residential wells.

6. The published research by Harrison (1983, 1985) indicates that sediment lying in the bottom of a residential well can be stirred up by fluid pressure increases transmitted through porous materials by overpressured annuli of oil- and gas-wells.

7. Calculation of hypothetical pressure changes in the Berea Sandstone caused by overpressurization indicate that pressure increases of several psi are transmitted several thousand feet in less than 30 days. Local values of pertinent geologic parameters were used in these calculations.

8. XRD analysis of sediment samples collected from five water wells in September 2009 were compared to XRD analyses of samples of the Berea Sandstone and Cuyahoga Shale. The sediments from well water samples that were analyzed by XRD can be divided into two broad groups: (1) particles derived from the aquifer material itself (17826 and 17926 Kingswood Dr, and 17975 English Dr), and (2) particles produced by geochemical reactions leading to the precipitation of different mineral phases (17954 English Dr and 7950 Scotland Dr). Wells drawing water from the Cuyahoga Shale contained sediment particles that closely matched that

of the Cuyahoga Shale sample. Wells drawing water from sandstone aquifers, either the Berea Sandstone (7950 Scotland Dr) or Sharon Sandstone (17954 English Dr) contain mineral precipitates that likely are derived from geochemical reactions occurring after the water is heated following its removal from the aquifer.

9. A statistical comparison of well water chemistry from samples taken near the English #1 Gas Well versus samples taken from background wells indicates there is little variability in water chemistry between the waters from the background public water-supply wells and the waters from wells near the English #1 well (Table 3-14 and Figure 3-121).

10. Sulfate-reducing bacteria were detected in water samples from the wells at 7859 Scotland Drive (McGee) and 8353 Bainbridge Road (Police station), but were not detected in groundwater from the well at 17860 English Drive (Stover) (Table 3-9). The wells at 7859 Scotland Drive and 8353 Bainbridge Road draw water from the Cuyahoga Shale and Berea Sandstone, whereas the well at 17860 English Drive draws water only from the Cuyahoga Shale. Neither sulfide nor sulfate reducing-bacteria were detected in groundwater from the well at 17860 English Drive indicating that little or no sulfate-reducing bacterial activity is present in the aquifer surrounding this well.

11. 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.

DMRM Formulated Hypothesis #4: Groundwater in the area of the English #1 well was not degraded, contaminated, or polluted by oilfield brine, crude oil, or hydraulic fracturing fluids; nor did invasion of gas into subsurface aquifers (Berea Sandstone, Cuyahoga Shale, Sharon Sandstone) cause local groundwater supplies to exceed Ohio EPA health-based PMCLs for arsenic or other heavy metals.

Points Supporting DMRM Hypothesis #4

1. XRD analysis of sediment samples collected from five water wells in September 2009 were compared to XRD analyses of samples of the Berea Sandstone and Cuyahoga Shale. The sediments from well water samples that were analyzed by XRD can be divided into two broad groups: (1) particles derived from the aquifer material itself (17826 and 17926 Kingswood Drive, and 17975 English Drive), and (2) particles produced by geochemical reactions leading to the precipitation of different mineral phases (17954 English Drive and 7950 Scotland Drive). Wells drawing water from the Cuyahoga Shale contained sediment particles that closely matched that of the Cuyahoga Shale sample. Wells drawing water from sandstone aquifers, either the Berea Sandstone (7950 Scotland Drive) or Sharon Sandstone (17954 English Drive) contained mineral precipitates that likely are derived from geochemical reactions occurring after the water is heated following its removal from the aquifer or occurring within the pore spaces of the aquifer with the matrix material.

2. A statistical comparison of well water chemistry from samples taken near the English #1 gas well versus samples taken from background wells indicates there is little variability in water chemistry between the waters from the background public water-supply wells and the waters from wells near the English #1 well (Table 3-147 and Figure 3-121).

3. Sulfate-reducing bacteria were detected in water samples from the wells at 7859 Scotland Drive (McGee) and 8353 Bainbridge Road (Police station), but were not detected in

groundwater from the well at 17860 English Drive (Stover) (Table 3-9). The wells at 7859 Scotland Drive and 8353 Bainbridge Road draw water from the Cuyahoga Shale and Berea Sandstone, whereas the well at 17860 English Drive draws water only from the Cuyahoga Shale. Neither sulfide nor sulfate reducing-bacteria were detected in groundwater from the well at 17860 English Drive indicating that little or no sulfate-reducing bacterial activity is present in the aquifer surrounding this well.

Points Challenging DMRM Hypothesis #4

1. The statistical analysis had an insufficient number of samples for use of robust tests based on a comparison of means, inside of a comparison of medians. More samples need to be collected and analyzed before the statistical evaluation is robust.

Conclusions Reached by Expert Panel on Disputed Issue No. 4

The sediment sampling protocol used by E&A did not facilitate taking diagnostic samples for analysis of toxic exposure to metals. Because the volume of water collected per mass of sediment was not measured, no exposure calculations could be made.

The expert panel rejects the hypothesis proposed by E&A that the particles found in the black goo and separately as sediment in several local water wells were formed as asperities in the Ohio Shale that became entrained in methane gas and rose a thousand or more feet upward in the Ohio and Bedford shales, through 50 feet or more of intergranular pores in the Berea Sandstone, and then into local water wells. There is no direct evidence that any of these processes occur; nor is it possible for methane gas with a density of 0.6 to 0.75 gm/cm^3 to entrain and lift particles with a density of 4 to 8 gm/cm^3 upward more than 1000 feet under the velocities that free gas migrates through water in shales and sandstones. Asperities are derived from differential movement along faults and the associated scraping of material on opposing surfaces on the fault plane. There is no evidence, anecdotal or scientific, of earthquakes triggering movement on faults in northeast Ohio in November and December 2007.

The expert panel accepts the hypothesis proposed by DMRM that the black particulates that occur in the black goo and as sediment in some well waters are from rock particles flaking off the uncased portions of shales, siltstones, and sandstone beds exposed in the wellbore and from particles of rust formed on the steel casing in the wells. The XRD analyses demonstrate the validity of this hypothesis. Based on XRD analyses of five sediment samples from wells within the investigation area, only one sample (Cooper well at 17954 English Dr) contained iron-sulfide minerals, which could be formed by sulfate reduction, although it is worth noting that the Cooper well never had an LEL value greater than 1.2 percent, which only occurred once. These findings suggest that if sulfate-reduction is occurring, it is not widespread as only 1 in 5 samples contained the black mineral precipitates characteristic of these reactions.

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 expert panel accepts the hypothesis proposed by DMRM that well waters in the area of Bainbridge Township impacted by the subsurface invasion of methane gas have not degraded in quality. The evidence indicates that (1) many wells in Geauga County contain naturally occurring bacteria, and (2) there are no differences in the chemistry of well waters sampled in the investigation area relative to well waters sampled in areas remote from the investigation area. The expert panel recognizes that methane gas commonly occurs in private residential wells and in public water-supply in Geauga County. For example, Ohio EPA detected methane gas in the public-water supply well at the Bainbridge Police Station at 8353 Bainbridge Road in 2004 several years before the overpressurization incident in the English #1 well. The Ohio EPA permitted the continued use of its public water supply well because there is no state or federal standard limiting the exposure of methane to humans. The panel also recognizes that if sulfate-reduction reactions are common across the Geauga County, the occurrence of black sediments in well waters cannot be unique to the Bainbridge investigation area.

Summary of Hypothesis Testing and Evaluation

The expert panel is not so much concerned with the final tally of which group E&A or DMRM had fewer rejected hypotheses or more accepted hypotheses, as it is with local residents and government officials learning through the hypothesis testing and evaluation process how the fugitive gas migrated and what might be the likely short-term and long-term consequences of the subsurface gas invasion, which is described in the next chapter.

Our analysis of the data, all the data, indicates that overpressurization of the English #1 well did not rupture the subsurface and create an extensive system of deep fractures that connected near-surface aquifers with a continuous deep source of methane gas. The borehole video data and the LEL data show that the fugitive gas migrated to different parts of the investigation area in different ways and arrived at different times. The borehole video data show that the gas has migrated upward out of the Berea Sandstone and up into the Cuyahoga Shale. Although the rates of upward dissipation vary, dissipation itself is an inevitable consequence of the fugitive gas being a one-time pulse source and the omnipresent buoyancy of gas in groundwater.

The panel identified five patterns were recognized 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 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.