GAS WELL PILLAR STUDY UPDATE
PO 4300311202 AND 4300400813

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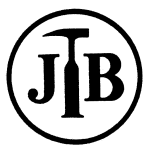
PENNSYLVANIA DEPARTMENT
OF ENVIRONMENTAL PROTECTION
BUREAU OF OIL AND GAS MANAGEMENT

By

John T. Boyd Company

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Pittsburgh, Pennsylvania

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Attention: Mr. Rodney Emlet
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               Office of Oil and Gas Management

Subject: Gas Well Pillar Study Update
               PO 4300311202 and 4300400813

Ladies and Gentlemen:

As authorized by the Pennsylvania Department of Environmental Protection (PADEP), Bureau of Oil and Gas Management (BOGM), this report presents John T. Boyd Company's (BOYD) findings and recommendations relative to the update of the Joint Coal and Gas Committee's Gas Well Pillar Study[1] that was commissioned in 1956 and published in 1957.

We wish to acknowledge the cooperation and participation of Pennsylvania's coal and gas industries during the conduct of this study. Over the course of this investigation meetings were held with industry participants to solicit input and recommendations from industry representatives and to obtain relevant technical data. Particular recognition is due to the Pennsylvania Coal Alliance and Marcellus Shale Coalition for their assistance in coordinating contacts with member companies and to CONSOL Energy (CONSOL), Alpha Natural Resources Inc. (Alpha), EQT Production, and Range Resources for providing prior research results and technical information useful toward our conclusions.

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[1] Joint Coal and Gas Committee, updated, "Gas Well Study," Commonwealth of Pennsylvania, Department of Mines and Mineral Industries, Oil and Gas Division.

Table of Contents

Table of Contents – Continued

1.0   Objective and Purpose

This report is prepared at the request of the BOGM of PADEP, to provide professional consulting services to update the Joint Coal and Gas Committee Gas Well Pillar Study commissioned by the Department of Mines and Mineral Industries in 1956 and published in 1957. The objective is to assess and provide criteria, standards, and guidelines that can be considered by PADEP toward the approval of coal pillars to be constructed around an oil or gas well that penetrates a workable coal seam.

This update is considered necessary because the techniques and processes common to the Pennsylvania gas and coal industries have changed considerably since the time of the 1956 study.

Unconventional gas resource development and modern techniques allowing multiple wells to be drilled from a single site has led to a significant increase in the number of wells located in coal bearing areas within the Commonwealth. The design of well installations and the materials used in their construction are more advanced than those studied earlier.

Mining practices have changed since 1956 with modern longwall mining representing most of the coal production in the Commonwealth as compared to the room-and-pillar method that dominated production at the time of the study. The longwall operations today produce more coal over larger areas and at much faster rates. Mines have since advanced to deeper coal and operations have progressed to counties beyond the original study area where thinner seams exist. Analytical methods for the design of underground structures have advanced and more fully consider the stress distributions and abutment pressures associated with retreat mining.

This project was completed in two phases; the initial work was conducted under PO 4300311202 in 2012 and focused solely on the recommendations for protective pillar sizes using a formula or reference table. During the course of the first phase review by industry, concern was expressed as to the feasibility of the recommended pillar sizes in light of current longwall design configurations even though these endorsed pillars were smaller than those suggested by Joint Coal and Gas Committee in 1957.

It was readily acknowledged by the study participants that field testing would provide the best means to:

- Measure actual ground movements in the subsurface.
- Measure actual mining impacts on typically constructed shale gas wells.
- Develop a modelling approach to predict the impacts on wells under varying geologic conditions.
- Predict the post-mining integrity of wells constructed using alternate designs.

CONSOL agreed to lead this experiment noting that their Enlow Fork Mine could provide a suitable test site on both the surface and at mine level where a longwall system would retreat both sides of a gate road where the abutment pillar can host test wells and monitoring stations. The field testing was conducted in 2013 and 2014. BOYD's review

of this experiment and incorporation into the overall pillar study was completed under PO 4300400813.

2.0　Summary

This report presents the findings and recommendations for the update of the 1957 Joint Coal and Gas Committee report, which provide pillar sizes for the protection of gas wells to assure the safety of coal miners in Pennsylvania.

It was initially envisioned that an update would involve a similar empirical study that formed the basis of the 1957 report. Empirical studies rely on past observations and experiences to establish design equations or tables through statistical analysis of at least one contributing factor. In the case of the 1957 recommendations, which were based on 66 well failures, the contributing factor studied was the depth of the coal mine.

However, the initial work on this study's update quickly revealed that there is only one reported gas or oil well disturbance related to coal mining since 1957. This excellent record was achieved even though the 1957 recommendations were not always strictly followed in such areas as centering the well within the protection pillar and in restricting mine opening widths. This absence of an oil or gas well failure related to coal mining post 1957 makes a similar empirical study impossible because failed cases are needed for the statistical analysis. Therefore, a rather more rigorous and more time consuming analytical study is required to update the 1957 recommendations.

The analytical approach, unlike the original study, provides benefits from an improved understanding of the conditions pertinent to the relationship between mines and wells. The analytical approach allows for:

- A more in-depth investigation on how coal mining adversely affects oil and gas wells. The investigation revealed that the horizontal shear due to subsidence or failure of the protection pillar (or its foundation) as the overriding conditions.

- Consideration of various Pennsylvania conditions and mine settings since the 1956 study, because in 1956:

    - Only room-and-pillar methods were practiced and now longwall mining is common.

    - Primarily only two seams were mined underground and since then more than six seams have been mined extensively.

- Five counties supported underground mining and now nine counties have underground coal mines.
- The deepest mines approached 800 ft but will approach 2,000 ft in the future.
- Typically, only coal seams thicker than 5 ft were underground mined but now mining of much thinner seams is common.

BOYD's analyses resulted in recommended procedures to design the minimum width of the protection pillar. In these procedures, the protection pillar size is calculated based on both the adverse effects of subsidence and the required pillar strength. The larger of the calculated pillars is then chosen as the recommended protection pillar size.

The recommended procedures presented herein, and resulting protection pillar sizes, are intended for use where a more rigorous site-specific design approach, perhaps incorporating alternate techniques, methods, or equipment, has not been conducted.

In general, subsidence will control the width of the protection pillar up to a depth that will vary within an approximate range between 650 ft to 1,470 ft, depending on mine configuration and extraction thickness. A formula (Equation 30) has been developed to determine the minimum distance ("the safeguard distance") from any single well (isolated or in a cluster) to the mine opening susceptible to future caving. From this safeguard distance, the minimum pillar width can be calculated.

Pillar strength is more important for well protection at depths exceeding 650 ft to 1,470 ft. Appropriately sized pillars with sufficient strength can be determined using the National Institute for Occupational Safety and Health (NIOSH) methodology that applies the Mark-Bieniawski pillar equation. Two computer programs are readily available for this task; Analysis of Longwall Pillar Stability (ALPS) for longwall mining and Analysis of Retreat Mining Pillar Stability (ARMPS) for room-and-pillar techniques.

A field experiment conducted in 2013 and 2014 under active mining conditions with test wells of various designs provided results that supported the appropriateness of the pillar sizes recommended in the initial phase of this study.

The experiment also showed that 3D finite element modelling provides a reliable approach to evaluate well displacement and casing deformation from nearby mining. Simulations from the modelling showed that alternate casing and cementing designs that accommodate the anticipated movement can maintain well integrity with little deformation and no inelastic strain.

Wells planned or constructed in existing or planned gate road pillars that do not adhere to the recommended protective size should be otherwise isolated from the effects of mining. This can be conclusively accomplished by plugging the well below the level of the coal for the duration of subsidence movement. Post-mining integrity testing and remedial work can then be conducted to return the well to operation.

3.0   1956 Gas Well Pillar Study

3.1   Summary of 1956 Gas Well Pillar Study

The Joint Coal and Gas Committee completed a study in 1956 on gas well failures caused by coal mining in the Commonwealth of Pennsylvania. The study, provided as Appendix A of this report, included 72 well failures that occurred over a 25-year span. The study addressed 66 of these failures and was limited to:

- Mines in the Pittsburgh and Double Freeport[2] coal seams, which were the principal producing underground operations at that time in Pennsylvania.

- Underground coal mines located in the southwestern Pennsylvania counties of Allegheny, Fayette, Greene, Washington, and Westmoreland. All of these counties experienced well failures.

- Mining depths ranging from 55 ft to 771 ft.

- Well failures that occurred in seam thicknesses of 5.2 ft to 8.1 ft. No failures were reported as associated with thinner seams. Mining, at that time, was rarely conducted in seams less than 5 ft thick.

- Room-and-pillar mining was the only underground technique used. Longwall mining as known today was not practiced at that time.

Prior to the 1956 study, Section 203 of the Pennsylvania Gas Operations, Well-Drilling, Petroleum, and Coal Mining Act of 1955 required a coal pillar up to 100 ft in radius to be left around oil and gas wells unless unusual conditions existed that required a larger pillar up to, but not exceeding, 150 ft in radius. Engineers involved apparently objected

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[2] Double Freeport and Thick Freeport are out-of-date terms for the Upper Freeport Coal Seam and specifically refers to a +4 ft thick south-southwestward trend of Upper Freeport that occurs in eastern Greene and Washington counties as well as southeastern Allegheny, and western Westmoreland counties. This trend is characterized by a series of large coal pods with centers exceeding 8 ft thick.

to defining only a maximum size and the following dimensions were agreed to as a minimum requirement until further study:

Depth (ft)	Pillar Radius (ft)
0-500	50
500-700	75
Over 700	100

The coal operators suggested the following on May 24, 1956, for active and inadequately plugged wells:

Depth (ft)	Pillar Radius (ft)
0-500	50
Over 500	75

Adequately plugged wells at any depth would require a 50 ft radius pillar.

On May 31, 1956, the oil and gas associations called for a detailed study and the Joint Coal and Gas Committee was formed and convened on June 25, 1956. Procedures were developed to collect data on damaged wells where the oil and gas companies supplied information on the damaged well and the coal companies supplied information on the mining and geologic setting. Data gathered included:

- Location: tract, township, and county.
- Geology: coal seam, seam thickness, strike and dip, overburden, and surface elevation and bottom of coal elevation. Also, mine floor rock type and if the floor was wet or dry and hard or soft.
- Failure: date, depth of failure.
- Mine setting: mine type—partial or full extraction, percent extraction around protection pillar, size of pillar as minimum radius.
- Dates of first and retreat mining.

The study quickly established that damage to the well was at, or close to, the mine horizon indicating that pillar failure, not subsidence, was causing the well damage. Thus, the study focused on pillar size recommendations in the form of a minimum pillar radius according to mine depth.

The well data was plotted to compare mine depth with minimum pillar radius to empirically derive a recommendation. This plot was used to calculate the angle between a vertical line drawn at the well with a line that originated at the surface location of the

well down to the closest edge (the minimum radius) of the coal pillar surrounding the well.

The resulting graph showed that the highest frequency of failure occurred at an angle of 5 degrees to 6 degrees with only one damaged well occurring at 8 degrees. Well failures at angles greater than 8 degrees were determined not to be caused by pillar failure, but instead were due to:

- The well not being centrally located within the pillar.
- Pillar stumps left around the protective pillar were too small and thus inadequately supported the overburden.
- Surface slope movement.

Other conclusions included:

- Terrain was not a contributing factor, with the possibility of two exceptions.
- Strike and dip had no bearing on pillar failure.

The following recommendations were made to the committee on January 22, 1957:

- Protective pillars should be square.
- The well should be centrally located within the pillar.
- Pillar size to be based on an 8-degree angle of draw.
- Required pillar sizes (as subsequently revised on February 15, 1957, by the Commission of State Mine Inspectors) are:

| | Pillar Area (ft^2) | | |
Cover (ft)	Protective Pillar	Additional Pillar (Solid or Split)	Total Pillar Bearing Surface
0 – 149	3,600	-	3,600
150 – 249	5,625	-	5,625
250 – 349	10,000	-	10,000
350 – 449	10,000	5,600	15,600
450 – 549	10,000	13,000	23,000
550 – 649	10,000	22,000	32,000
Over 650	10,000	30,000	40,000

* Opening not to exceed 15 ft and least width of pillar not less than twice the opening width for Pittsburgh and Double Freeport Seam pillars.

Finally, the committee noted that "It may be necessary to revise this information periodically."

3.2   Need for Study Update

The 1956 study was limited to five Pennsylvania counties with underground bituminous coal production. However, in 2010[3], 36 underground mines in Pennsylvania produced bituminous coal in nine counties: Greene, Somerset, Clearfield, Armstrong, Indiana, Cambria, Jefferson, Elk, and Beaver. Coal was also produced by surface and highwall operations in 14 other counties: Westmoreland, Allegheny, Clarion, Butler, Washington, Lycoming, Fayette, Mercer, Centre, Bedford, Blair, Cameron, Venango, and Huntingdon. Underground operations could potentially exist there in the future.

Underground production in 1956 was principally from the Pittsburgh and Upper Freeport coal seams, which still produce today[4]. In addition to those the Lower Freeport, Upper Kittanning, Lower Kittanning, and Sewickley coal seams are now mined by underground methods. Several other seams were produced in the past and there is potential for other seams to be developed in the future.

Most coal in 1956 was produced from seams thicker than 5 ft and the seam thickness was typically the extraction height. Today, production can be in significantly thinner seams with extraction height commonly occurring down to 3.5 ft. Additionally, roof and floor rock are often removed to attain better operating efficiencies, or unstable roof rock is removed to provide a stable opening. Thus, extraction height and seam thickness today are not equivalent.

Room-and-pillar mining configurations were predominant in 1956 but today longwall mining is common place. Additionally, multiple seam operations are now common and will increase in frequency.

The 55-year-old study is considered to be out-of-date and the committee correctly noted at the time of the study that revisions may be necessary.

4.0   Mining Effects on Oil and Gas Wells

Underground mining can affect oil and gas wells by changing the stress and strain environment. These changes are due to ground movement and load transfer resulting from the removal of coal. These effects can manifest by decreasing the stability of

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[3] Pennsylvania Coal Association, 2011, "Pennsylvania, Coal Data 2011," Harrisburg, Pennsylvania.

[4] Bureau of Mining Programs, 2010, "Bituminous Underground Mines Reporting Production - Listed by County," Commonwealth of Pennsylvania, Department of Environmental Protection.

surrounding slopes and by impacting the well's structural integrity and function. These effects are caused by either the formation of the mine pillar or mine subsidence.

There are two types of mine subsidence: sinkhole and trough, and it is the width of the extraction (and to a lesser degree the extraction thickness and depth) that determines what type of subsidence will be experienced.

4.1   Pillar Formation

When openings are made around a coal block forming a pillar, the load of the overlying rock (overburden) once carried by the extracted coal is transferred to the surrounding pillars. This load dramatically increases as more coal is extracted. These transfer loads are greatest when full extraction mining is employed such as full retreat room-and-pillar and longwall systems.

This increase in load could result in:

- Squeezing out weak rock from above, within, or below the pillar.
- The pillar material, coal and rock, moving toward the mine openings.
- As related to oil and gas wells, increasing the crushing load on the borehole, casing, and piping above, within, and below the pillar.

As weak rock, typically claystone, mudstone, or clayey shale, is squeezed toward the mine opening, lateral shear stress and movement is added to the well system comprised of the borehole, casing, and pipe. The increased load on the pillar is primarily vertical, but due to Poisson's effect (i.e., expansion perpendicular to compression), a horizontal compressive stress is created that provides a crushing load to the well.

As load is transferred to the pillar, the pillar reacts to accommodate the load by a process of strength mobilization. This is accomplished by confining the center (core) of the pillar with the pillar material (coal) that surrounds the core. To create this confinement requires some movement of the coal in the pillar outward toward the mine openings. This generates shear stress and strain which, in part, is added to the well borehole, casing, and pipe, and tend to be concentrated at the top and bottom of the pillar. The effects upon the well system due to pillar formation are at a minimum at the center of the pillar and increase outward.

4.2   Sinkholes

When the extraction area is relatively small and the mine workings are close to the surface (normally 100 ft or less but sometimes greater than 150 ft), subsidence can manifest in the form of a sinkhole. Sinkholes occur as the result of mine opening collapse, typically, from an opening less than 200 ft wide. If the collapse reaches the ground surface, a sinkhole is formed. This event occurs directly over the mine opening and, therefore, naturally has no significant effect on an oil or gas well located over a pillar or other coal block.

4.3   Trough Subsidence

Trough subsidence results from longwall and retreat room-and-pillar systems but can also occur when several pillars, or their foundations, fail. The potential impact of trough subsidence on an oil or gas well should be evaluated whenever a well is to be located in the vicinity of an existing or planned underground mine. Trough subsidence generally entails both vertical and horizontal movement, stress and strain, tilt, and curvature of the ground and manifests itself at the surface as a shallow basin. Surface cracks may result and reflect the location of tensile stress.

Tensile and compressive stress and strain zones extend from the mine to the ground surface. The ground surface area affected by trough subsidence is larger than the extracted area and the extent of subsidence in the overburden and at the surface is determined using the angle of draw. The angle of draw is the inclination between the edge of the opening at mine depth which caused subsidence and the point on the surface where no subsidence effects occur.

The draw angle varies with location, the coal seam, surface topography, overburden geology, and mining method. The angle of draw varies due to the dip of the coal seam and the slope of the ground surface and these effects decrease as the percentage of hard rock (sandstone and limestone) in the overburden increases. The angle of draw, in Pennsylvania, typically ranges from 10 degrees to 25 degrees.

The factors that affect the amount of movement and stress and strain due to trough subsidence include extraction thickness and depth, seam dip, the rock types and discontinuities, in situ stresses, surface topography, and extraction ratio.

Mining should be limited before reaching a point where ground deformations will adversely affect an active well, unplugged well, or plugged well not approved for mining through. As the depth of the mine increases, the subsidence effects are felt further afield

as defined by the angle of draw, but the magnitude of the effects decrease. The effects extend further and further out from the excavation the deeper the extraction occurs, and extends out and over the pillars and coal blocks that are adjacent to the extraction area. Surface and subsurface movement are greatest, and have the highest potential for adverse impact, near the edges of the total extraction area. This includes the maximum horizontal movement, tilt, curvature, and stress and strain.

The adverse effects from subsidence decrease away from the extraction area until the angle of draw is reached, at which point there is no measureable movement. However, prior to reaching the angle of draw, subsidence ceases to adversely affect a well. At that point where these adverse effects on a well cease, an angle can be drawn similar to the angle of draw, which is called the angle of break. The angle of break is always less than the angle of draw. In addition, the intensity of the effects of stress and movement decrease as the extraction depth increases

A number of subsidence prediction models are available. Two commonly used models are Surface Deformation Prediction System (SDPS) developed at Virginia Polytechnic Institute and State University and Comprehensive and Integrated Subsidence Prediction Model (CISPM) developed at West Virginia University (WVU). These programs can be used to estimate surface subsidence and ground strain ahead of mining. These types of programs are limited in that (1) they should only be used for the type of topography and mining conditions for which they were developed, and (2) the strain computations of these programs typically do not account for strain concentration along existing discontinuities. Concerning the second point, studies have shown that site topography may have a substantial effect on the development and concentration of horizontal strain.

Computer programs such as SDPS[5] and CISPM[6] can be used for evaluation of stress for varying mine configurations, structure and topographic conditions, and subsidence parameters (settlement, horizontal displacement, curvature, and tilt). Based on empirical or site-specific regional parameters, SDPS calculates the ground deformation factors using both the profile function method and the influence function method. The profile function method requires the following minimum input: panel width, overburden depth, seam thickness, and percent of hard rock within the overburden. The influence function

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[5] Karmis, M., Z. Agioutantis, and K. Andrews, 2008, "Enhancing Mine Subsidence Prediction and Control Methodologies," 27th International Conference on Ground Control in Mining, West Virginia University, Morgantown, WV.

[6] Luo, Y., S. Peng, and Z. Zhu, 2008, "Upgraded Comprehensive and Integrated Subsidence Prediction Model CISPM – W," 27th International Conference on Ground Control in Mining, West Virginia University, Morgantown, WV.

method requires that the mine plan and measured subsidence survey information applicable to the area be input, although average parameters applicable for eastern US coal fields can be selected.

4.4   Pillar Failure

Pillar failure occurs when the load on a pillar exceeds its strength. Several formulas have been developed for determining the strength of a coal pillar. Pillar strength formulas are described as being either analytical or empirical. Analytical formulas require material property input, and since these properties differ between coal seams and locality, extensive material testing is required. These procedures are rigorous and require an experienced practitioner to apply these formulas. Wilson's[7] equation is one of the first analytical formulas used for coal pillar design and is still widely used. Rock and coal strength relationships to confinement and normal load are non-linear and a procedure has been developed by Scovazzo[8] that uses these properties in the Wilson equation. Typically, a safety factor of 2.0 or more is used with the Wilson equation based on the confidence and understanding of the input parameters. For the design of a protective pillar for a well, BOYD recommends that a safety factor of 2.5 or more be used according to its long-term requirement.

There are numerous empirical pillar design formulas, but in the United States, and Pennsylvania in particular, the well-accepted approach is the Mark-Bieniawski[9] equation. The NIOSH has developed and published several popular pillar design computer programs based on the Mark-Bieniawski equation including:

- ARMPS[10], for room-and-pillar mines.
- ALPS[11], for longwall mines.
- ARMPS-HWM[12] for highwall mines.

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[7] Wilson, A.H., and D.P. Ashwin, 1972, "Research into the Determination of Pillar Size," The Mining Engineer, Volume 131, Part 9, No. 141, Institution of Mining Engineers, London, June, pp 409-417.

[8] Scovazzo, V.A., 2010, "Analytical Design Procedure Using the Wilson Equation," 3rd International Workshop on Coal Pillar Mechanics and Design, U.S. National Institute for Occupational Safety and Health, Morgantown, West Virginia, July 26.

[9] Mark C, 1999, "Empirical Methods for Coal Pillar Design," 2nd International Workshop on Coal Pillar Mechanics and Design, Vail, CO, National Institute for Occupational Health and Safety IC 9448, pp. 145-154.

[10] National Institute for Occupational Health and Safety, 2011, "Analysis of Retreat Mining Pillar Stability (ARMPS)," computer program, version 2010.

[11] National Institute for Occupational Safety and Health, 2011, "Analysis of Longwall Pillar Stability", Software Version 5.3.04, Office of Mine Safety and Health Research December 4.

[12] National Institute for Occupational Health and Safety, 2009, "Analysis of Retreat Mining Pillar Stability- Highwall Mining (ARMPS-HWM)," computer program version 1.1.

For the Mark-Bieniawski formula, the recommended stability factors for room-and-pillar operations are 1.5 for mines less than 750 ft deep and 0.9 for pillars deeper than 1,250 ft with scaled stability factors between 750 ft and 1,250 ft. The typical in-situ coal strength used in these programs is 900 psi. Because of the long-term requirements of a well protection pillar, it is recommended to add 0.5 to the established stability factors.

For longwall operations a stability factor of 1.3 is employed for all depths. In both longwall and room-and-pillar mine configurations, the stability factor can be modified based on the Coal Mine Roof Rating (CMRR). NIOSH developed the CMRR for coal pillar and roof support design so that important geologic conditions in the mine roof can be considered. The CMRR rating varies from 0 to 100 with high values representing strong roof. The stability factor for longwall can be adjusted from 0.7 for strong roof (CMRR = 75) to 1.3 for weak roof (CMRR = 35).

Multiple seam mining and other complicated mine environments may require a numerical analysis. LaModel[13] is a computerized numerical technique frequently employed in pillar design and pillar load determination.

5.0   Company Research

Coal and gas industry participants have completed studies on the effects of mine subsidence on gas and oil wells. This section presents a discussion of these prior research projects. Also presented is a summary of the significant field experiment completed by CONSOL in support of this Gas Well Pillar Study Update. A more detailed presentation of that work is provided in Appendix B of this report.

5.1   Alpha Natural Resources, Inc.

Cyprus Cumberland Resources Corp. (now Alpha) completed a study[14] in 1999 on the effects of longwall mining around gas well W-510 at the Cumberland Mine in Greene County, Pennsylvania. Alpha developed gate entries to this well and established a pillar around it. Figure 1, following this text, illustrates the configuration of the 3-Left Section at the well location.

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[13] Heasley, K., 2011, "A Retrospective on LaModel," 30th International Conference on Ground Control in Mining, West Virginia University, Morgantown, WV.

[14] Luo, Y., S.S. Peng, and Y.Q. Zhang, 1999, "Analysis of the Observed Failure on the Inner Tubing of Gas Well W-510 Below the Coal Seam," for Cyprus Cumberland Resources Corp. from College of Engineering and Mineral Resources, West Virginia University, May 24.

The 200-ft wide (center to center) gate road section employed 16-ft[15] wide entries and crosscuts. The entries were reported to be 8 ft high and the Pittsburgh Seam thickness was reported at 6.1 ft. The crosscuts were driven 60 degrees off the strike of the entries. The two adjacent longwall panels were 900 ft wide with Panels 2-Left and 3-Left being approximately 8,000 ft and 7,600 ft long, respectively. The overburden at the well is 1,007 ft.

As the gate entries were developed to the gas well, pillars were widened to protect the gas well. The pillar surrounding the well was widened from 100 ft to 120 ft but the pillar length was reduced from 130 ft to 104.3 ft.

The gas well was spud in 1983 and was completed to a depth of 6,030 ft with a production zone from 5,941 ft to 5,925 ft. A 4 1/2 in. steel pipe was installed to a depth of 5,970 ft and is protected by a 12-in. diameter casing from the surface to a depth of 30 ft and an inner casing, 8 5/8 in. in diameter, installed to a depth of 2,210 ft. This outer casing is cemented to the borehole wall and cement fills the annulus between casings and between casing and pipe.

Dr. Syd S. Peng[16] predicted the subsidence that could occur at gas well W-510 and, after mining, the movement was surveyed[17]. The predicted and actual surveyed surface movement is presented in the following table:

| | Predicted | | Surveyed | |
| | Vertical Movement (ft) | Horizontal Movement (ft) | Vertical Movement (ft) | Horizontal Movement (ft) |
After Retreat of				
2-Left Panel	-0.13	-0.3	-0.32	-0.4
3-Left Panel	-1.29	-0.1	-1.40	-0.1

Note: For horizontal movement, negative values are toward 2-Left Panel

Dr. Peng also predicted the subsurface ground movement down the gas well. After mining the 2-Left Panel, the predicted vertical movement from the coal seam to 400 ft above the seam was noted as "insignificant" and increased to about 0.13 ft at the ground surface. From the coal seam to 250 ft above the coal seam "very little horizontal

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[15] CHENgaswell.xls Created March 20, 1998.
[16] Luo, Y. and S.S. Peng, 1997, "Assessment of Subsidence Influences on Active Gas Well No. W-510," for Cyprus Cumberland Resources Corp. from College of Engineering and Mineral Resources, West Virginia University, February 19.
[17] Reilly, Joanne, 2002, "Time Line: Gas Well W-510", February 16.

movement" was predicted but the horizontal movement above 250 ft was predicted to increase linearly and reach 0.3 ft at the ground surface.

After mining the 3-Left Panel, the predicted vertical movement in the coal seam was approximately 0.12 ft. Vertical movement increased slightly from the coal seam to 500 ft above the coal seam, then increased to the ground surface to about 1.29 ft. The predicted horizontal displacement after the second panel showed no movement in the bottom 400 ft then increased slightly to 0.11 ft near the surface.

Dr. Peng assumed a worst case; all the ground movement and deformation would be transferred to the outer casing because this casing is cemented to the surrounding ground. The calculated strain and curvature in the outer casing after completion of the 2-Left Panel showed a compressive axial strain. Because of the lack of movement from the coal seam to 400 ft above the mine, no strain was calculated but the compressive strain increased from that point to the ground surface reaching a maximum axial strain of around 2.9×10^{-4} or about 8,500 psi compressive stress. This strain is less than the casing's permissible strain of 1.23×10^{-3}.

WVU[16] estimated the following parameters for casing steel in both compression and tension:

Ultimate Strength	54,000 to 60,000 psi
Permissible Stress	36,000 psi
Young's Modulus	2.84×10^7 to 2.99×10^7 psi
Average Young's Modulus	2.92×10^7 psi
Average Permissible Strain	1.23×10^{-3}
Ultimate Allowable Strain	1.85×10^{-3} and 2.05×10^{-3}

Stress and strain caused by casing bending was also considered by Dr. Peng. The maximum curvature on the outer casing caused by 2-Left Panel was estimated at around 2.3×10^{-6} 1/ft or a maximum stress of 24 psi on the outer casing, which was well below the permissible stress of 36,000 psi.

The axial strain and lateral curvature along the outer casing of the gas well after the extraction of 3-Left Panel was analyzed. The trend is that the axial strain increases toward the ground surface. It is still less than the permissible strain in the section within 600 ft above the coal seam. The maximum axial strain at the ground surface is about 3.25×10^{-3} which is above the ultimate allowable strain. It is above this allowable strain to a depth of 300 ft so therefore, the outer casing can plastically yield. It was noted that slippage along the outer casing and the well wall will reduce this strain.

Dr. Peng also investigated the effects on the inner pipe, which carries the gas to the surface. He noted that the upper 2,210 ft of this pipe "floats" within the outer casing, a statement that appears to contradict the well's time line, which notes this annulus is cemented. If this pipe floats, the movements, stresses, and strains of the outer casing will not be transmitted to the inner casing. The movement, stress, and strain on the inner pipe are due to surface subsidence and caused by shortening. WVU predicted this shortening and the resultant strain in the upper 2,210 ft of the pipe which all fall below allowable:

After Retreat of	Maximum Shortening (ft)	Maximum Compressive Strain
2-Left Panel	0.13	5.88×10^{-5}
3-Left Panel	1.29	5.84×10^{-4}

The maximum strain generated in the pipe by its weight was determined to be 2.33×10^{-4}, and adding this strain and that produced by subsidence, the resulting strain is still below allowable.

Dr. Peng, using the ALPS[18] computer program, investigated the gate pillar's stability. The highest load on the well protection pillar will occur when both longwall panels have retreated. At this point the ALPS determined a stability factor of 1.31. (Alpha[15] reports this stability factor as 1.07.) This factor is reported to be larger than the stability factor of 1.17 recommended for the Pittsburgh Coal Seam in Pennsylvania indicating that the gate pillar will be stable.

The WVU researchers determined that the gas well is located in an area of the larger gate pillar where the stress distribution is relatively uniform. At that location, the predicted vertical stresses were approximated at 1,221 psi (virgin ground, no mining), 1,350 psi (when the gate road was developed), 1,790 psi (after the retreat of the first panel), and 1,930 psi (after both panels are mined). These values represent a 10%, 46%, and 58% increase over virgin vertical stress. These values were calculated assuming an overburden density of 158.4 pcf and a Mohr-Coulomb failure criterion. BOYD notes that ALPS employs the Mark-Bieniawski pillar formula which does not rely

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[18] Mark, C.,1992, "Analysis of Longwall Pillar Stability (ALPS)—An Update," in Proceedings, Workshop on Coal Pillar Mechanics and Design, US Bureau of Mines IC 9315, pp. 238-249.

on the Mohr-Coulomb failure criterion. The values were used to estimate the horizontal stress:

	Vertical Stress (psi)	Horizontal Stress (psi)	Confined Coal Strength (psi)
Development	1,350	579	2,640
1st Longwall	1,790	767	3,201
2nd Longwall	1,930	827	3,375

Based on these pillar strengths and stress at the gas well location, Dr. Peng concluded that "This indicates that the failure of the coal surrounding the gas well is impossible." Alpha implemented a program consisting of subsidence surveys to determine ground movement and a down-hole camera to observe the inner pipe. These surveys and observations were made before longwall subsidence affected the well, after the first longwall mined 2,000 ft past the well, and finally after the second longwall mined 2,000 ft past the well. WVU[14] believes these programs verified the predicted subsidence and effect on gas well structure.

However, what is described as plastic failure was observed to have occurred in the inner pipe 16.5 ft below the coal seam after the second longwall panel was mined. This plastic failure was not associated with any pipe fractures and did not disrupt gas production.

Although production was maintained, PADEP believes well integrity was compromised and considers well W-510 to be a case of failure due to mining.

Since this plastic failure below the coal seam was not anticipated, Dr. Peng found it necessary to evaluate the stress field in the floor strata under the pillar using a two-dimensional finite element model. The model was 265 ft wide and extended from the mine floor to 40 ft below the coal seam. A single layer of sandy shale, based on the provided geological column, was modeled in the floor.

The vertical stress in the model is the largest among the three stress directions with the maximum vertical stress around 2,000 psi. The maximum horizontal stresses, σ_2 and σ_3, were determined to be 1,229 psi and 1,098 psi, respectively. The maximum stresses occurred near or at the pillar—floor contact with all stress decreasing with depth. The magnitude of these horizontal stresses are smaller than the uniaxial compressive strength of the sandy shale, typically in the range from 3,000 psi to 5,000 psi, concluding that the stresses under the pillar were not likely the cause of the inner pipe plastic failure.

Dr. Peng then assumed that weak parting, such as fireclay, is sandwiched between the sandy shale. This weak layer can fail or flow plastically under the floor stresses

determined above. This flow can be toward the free surface of the drill hole. The flowing material then can compress the inner pipe equal to the vertical stress in the floor.

The inner pipe's outer diameter is 4.5 in. but the wall thickness was not known to WVU, thus Dr. Peng assumed likely thicknesses of 1/8 in. and 1/4 in. Thus, the maximum tangential stress in the inner pipe's wall may range from around 15,000 psi to about 33,000 psi. The vertical stress caused by the gravity at the failure location is around 3,469 psi. The vertical stress caused by the shortening of the inner tubing in the upper 2,210 ft is approximately 17,462 psi.

The principal stress on the inner surface of the steel tubing can be determined from the maximum tangential and total vertical stresses. For the thinnest pipe, the calculated principal stress at the location of the plastic failure is 39,100 psi. This stress is larger than the 36,000 psi permissible stress for casing steel, and it is below the ultimate strength of pipe steel which ranges from 54,000 psi to 60,000 psi. For thicker pipe, the principal stresses are smaller than the permissible stress. How the principal stress was determined was not shown in the report.

The calculated stresses are summarized below:

Wall Thickness (in.)	Tangential Stress (psi)	Vertical Stresses (psi)			Principal Stress (psi)
		Gravity	Shorting	Total	
1/8	33,029	3,469	17,462	20,931	39,102
1/4	15,059	3,469	17,462	20,931	25,785

Dr. Peng summarizes by noting that "… it is still unlikely for the determined principal stresses to cause the observed failure. The last possibility is that there could exist some type of imperfection or impurity on the tubing steel. However, the effects of material imperfection are difficult to evaluate."

5.1.1   BOYD's Discussion of Alpha's Findings
In trying to establish the cause of the plastic failure observed in the inner pipe 16.5 ft below the coal seam, Dr. Peng developed two scenarios:

1. The floor is a single layer of sandy shale, based on a geological column supplied to WVU.
2. The floor contains a weak parting, such as fireclay interbedded between the sandy shale.

BOYD requested from Alpha three to four geologic or geophysical borehole logs near the W-510 gas well and received four driller's logs of which three were drilled to more than 16.5 ft below the coal. Geophysical logs were also provided for two of those three

deeper holes. The three holes were located 600 ft (CR-94-08), 320 ft (CR-94-07), and 1,780 ft (CR-93-06) from gas well W-510.

CR-94-07 (geophysical log)			CR-94-08 (geophysical log)			CR-93-06 (driller's log)		
Rock Description	Thickness (ft)	Depth Below Coal (ft)	Rock Description	Thickness (ft)	Depth Below Coal (ft)	Rock Description	Thickness (ft)	Depth Below Coal (ft)
Carbonaceous Shale	0.7	0.7	Carbonaceous Shale	0.6	0.6	Gray Shale	2.70	2.70
Limestone	2.2	2.9	Limestone	2.3	2.9	Gray Sandy Shale	6.80	9.50
Shale	6.6	9.5	Shale	6.7	9.6	Gray Shale	2.60	12.10
Carbonaceous Shale	4.9	14.4	Carbonaceous Shale	5.5	15.1	Dark Gray Shale	2.65	14.75
Argillaceous Limestone	1.1	15.5	Argillaceous Limestone	1.1	16.2	Limestone	1.90	16.65
Claystone	1.3	16.8	Claystone	1.5	17.7	Gray Shale	1.55	18.20
Shale	-	-	Shale	-	-	Black Shale	0.75	18.95
-	-	-	-	-	-	Gray Limy Shale	-	-

Geophysical logs for boreholes CR-94-07 and CR-94-08 show claystone (1.3 ft and 1.5 ft thick) at the depth of the noted plastic failure in the pipe. The driller's log for borehole CR-94-07 closely matched the geophysical log and it noted in that log that the claystone layer was soft.

Claystone tends to be the weakest member of a coal sequence and it is not uncommon for a soft claystone to be located below a limestone as it is here. A limestone bed exists in all three holes just above the location of the plastic failure. However, the drillers did not note the presence of claystone in two of the holes, CR-94-08 and CR-93-06. However, a claystone was identified in the geophysical log of hole CR-94-08. Since both geophysical logs identified the claystone, it is expected that a soft claystone existed at the depth of noted plastic pipe failure.

It is probably not coincidental that the pipe's plastic failure and the claystone coincide and that failure may be contributed to by the shear stress created due to lateral movement of the weak claystone, as is common in pillar foundation failure. As this lateral movement in the claystone pushes against the stiffer casing, load on the pipe will increase as a clay wedge forms behind the pipe. This wedge would accumulate load increasing shear against the casing. If this occurs, the shear will dramatically increase. However, with a burial depth of 16.5 ft below the mine opening, BOYD could not model the type of free face that would allow such lateral movement.

WVU noted that at the pillar horizon the vertical virgin (no mining) stress was approximately 1,221 psi. The vertical stress increased to 1,930 psi after both panels are mined. If this stress is projected to a depth of 16.5 ft below the coal and the Poisson's ratio of the claystone is taken as 0.3, then the horizontal stress is calculated to be 827 psi, as follows:

$$\sigma_H = \frac{v}{1-v}\sigma_V = \frac{0.3}{1-0.3}\,1{,}930\text{ psi} = 827\text{ psi}$$

Equation 1

This will only occur if the claystone moves against all sides of the pipe. If this movement entails plastic flow or failure of the claystone, the horizontal load against the pipe would approach hydrostatic. The original virgin horizontal stress, which existed before mining and drilling, would be reduced once the claystone is drilled, and dissipated once the claystone enters plastic flow or fails. Thus, the only remaining horizontal stress is due to Poisson's ratio or hydrostatic loading.

The table below compares the applied horizontal stress to the collapse pressure of the pipe (as later derived in Equation 23 and discussed in section 6.1.1, Collapse Pressure) and de-rating the casing (as discussed later in section 6.1 Allowable Stress and Strain) and calculating the allowable stress (as discussed later in section 6.1.3, Standard Cement and Steel Allowables).

Vertical	Horizontal Stress (psi)		Collapse Pressure (psi)		
Stress (psi)	Poisson's	Hydrostatic	Not Adjusted	De-rated	Allowable
1,930	827	1,930	1,610	1,290	850

The collapse pressure is at the elastic-plastic transition which would generate the type of failure noted in W-510, thus it can be reasoned that the plastic failure of the outside casing caused the plastic failure of the inner pipe.

5.2 CONSOL Energy Inc.
In 2009, Dr. Wen H. (Daniel) Su, Senior Geomechanical Engineer for CONSOL completed two-dimensional finite element analysis simulations on a hypothetical CNX gas well using ABAQUS[19]. CONSOL modeled core hole NV-057 which was completed to a depth of 1,084 ft while intersecting the top of the 5.7 ft thick Pittsburgh Seam at a depth of 1,032 ft.

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[19] Dassault Systèmes, 2002, Abaqus Unified FEA, Vélizy-Villacoublay, France.

For the model, CONSOL assumed the well to be located at a hill top and drilled into an abutment pillar of an abutment-yield (three-entry) gate road system. The center to center measurements of the pillars are 160 ft and 70 ft with 16 ft wide entries resulting in pillar widths of 144 ft and 54 ft.

Dr. Su was the first to introduce the use of horizontal slip elements into subsidence models, which has dramatically improved subsidence analysis. He employed such elements in this model at contacts between hard (sandstone, limestone, etc.) and softer (shale, claystone, etc.) strata. The models were completed after longwalls passed on either side of the gate entries and CONSOL reported the horizontal slip, (Figure 2) and horizontal (Figure 3) and vertical (Figure 4) stress above and below the abutment pillar in 20-ft increments across the pillar. These figures show the calculated ground slip and strain above and below the center of the abutment pillar, as well as the slip and strain 20 ft to either side.

BOYD reviewed the log of core hole NV-057 assigning stratigraphic names to the various layers. The contacts between hard and soft stratigraphic members were overlaid on Figures 2, 3, and 4. The overlays show more slip and greater strain occur at the contacts between stiff and soft strata.

5.2.1   BOYD's Discussion of CONSOL's Findings

CONSOL's maximum predicted shear above the top of the coal and center of the abutment pillar is 210 psi and occurs at the base of the Benwood Limestone where it contacts shale. The largest shear below the pillar center is 42.7 psi. Both values are well below the allowable shear of 1,230 psi (as shown by Equation 21 in Section 6.2, Allowable Subsidence).

The change in vertical stress, and not the total vertical stress, affects the casing. Figure 4 shows the predicted total vertical stress in the rock surrounding the casing. The vertical stress that can be transferred from the surrounding rock to the casing is dependent on the amount of slip that occurs between the rock and casing and the elastic modulus of the rock and steel.

A few rock types, such as sandstone and limestone, found in association with coal, can have an elastic modulus greater than steel, and thus stresses in the casing will be less than the stresses in the surrounding rock. Most rock types have a lower modulus than steel and lower modulus rocks are the weaker members in a coal sequence. These rocks with lower modulus than steel will transfer more load to the casing resulting in

more stress in the pipe than with high modulus rocks. However, this is sometimes counteracted because weaker rock allows for more slip than stronger rock thus limiting stress transfer.

If one assumes the vertical stress in the rock is transferred to the casing without change and is the same in both the rock and casing, then the maximum change in vertical stress of 1,700 psi, as determined by CONSOL, is below the casing's allowable body stress of 2,030 psi (as shown by Equation 20). Still, the rock stress and allowable stress are close enough to be a concern.

In situations where the rock containing the casing is failing, the rock's elastic modulus is quickly reducing transferred load to the casing. Foundation failure of a pillar that typically occurs in claystone would cause the body stress in the casing to quickly overwhelm the casing. This may have contributed to the plastic failure previously discussed relative to Alpha's findings.

5.3   The Pennsylvania State University

In 2012, Penn State, under the direction of Dr. Rostami[20] and others, completed a numerical modeling study to evaluate the distribution, along a projected vertical gas or oil well, of stresses, strains, and deformations caused by longwall mine subsidence.

5.3.1   Longwall Panels Modeled

The stresses, strains, and deformations above the gate road pillars were modeled after each adjacent longwall panel was mined. Panels were projected at a 370-m (1,200 ft) width and the assumed horizontal coal seam was 2 m (6.6 ft) thick and located below a horizontal surface. The induced movements determined by this modeling were used to evaluate longwall subsidence effects on gas and oil wells drilled into the pillars of the gate road using the following two gate road geometries:

1. A three-entry system which included one row of yield pillars 15 m (49 ft) wide and one row of abutment pillars 30 m (98 ft) wide separated by an entry 5 m (16 ft) wide resulting in an accumulated pillar width of 45 m (148 ft).

2. A single row of pillars with a width of 60 m (197 ft).

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[20] Rostami, Jamal, Derek Elsworth, and Robert Watson, 2012, "Final Report on the Study of Borehole Stability for Gas Wells in Longwall Mining Areas" prepared for Range Resources – Appalachia, LLC, December, as Range_resources_Gas_Well_Stability_Final 16-July-2012.pdf last modified July 31, 2012, May.

For this analysis, a vertical gas well was placed in the center of the yield pillar and at various locations within the abutment pillar as tabulated below:

Location	Pillar	Distance to Panel 1 (m)	Distance to Entry (m)	Distance to Panel 2 (m)
1	Yield	7.5	7.5	42.5
2	Abutment	27.5	7.5	22.5
3	Abutment	32.5	12.5	17.5
4	Abutment	37.5	17.5	12.5
5	Abutment	42.5	22.5	7.5

For the gate road that contained a single row of pillars the well was placed in the center of the pillar.

Three scenarios were completed representing seam depths of 100 m (328 ft), 200 m (656 ft), and 300 m (984 ft). Penn State evaluated overburden behavior after extraction of the first and then after the second longwall panel was completed on either side of the gate road. Three geologic settings were examined:

1. Homogeneous strata calibrated against a measured subsidence profile (I-79 undermining[21]).

2. Alternating 10-m thick layers of shale with elastic moduli of 725 ksi (5 GPa), and sandstone with elastic moduli of 2,900 ksi (20 GPa).

3. Layered as in number 2 above but with the shale—sandstone contact having a friction angle of 20 degrees.

The well casings and pipe were not present in the analysis thus its stiffness was ignored.

5.3.2   Software Used and Calibration of the Model

The two-dimensional numerical models were analyzed using both FLAC by Itasca International Inc., a finite difference program, and PHASE[2] by Rockscience, Inc., a finite element program. Rostami believes that FLAC was more relevant because it reproduced a subsidence profile that closely follows the ground subsidence models.

A two-dimensional model, using FLAC, comprised of 24,400 elements, was employed. The model was constructed perpendicular to the direction of panel advance. All materials in the model were modeled as elastic-plastic with elastic moduli of 2,900 ksi (20 GPa), Poisson's ratios of 0.25, and density of 165 pcf (2,640 kg/m^3). The deformation response was yield combined with Mohr-Coulomb failure and with a relative contact stiffness of the roof and floor once the coal is removed.

The model was calibrated using the subsidence survey and tiltmeter measurements of Interstate 79[21] when it was undermined by longwall panels 51 and 52 of the Cumberland Mine. These panels were at depths that varied from 195 m (640 ft) to 244 m (800 ft). To calibrate the model, Penn State varied cohesion, friction angle, and seam thickness at different depths to match the measured subsidence results.

5.3.3   Model Evaluation
Penn State evaluated several combinations of geologic settings and gate configuration:

1. Homogeneous strata and three-entry system.
2. Alternating 10-m layers of shale and sandstone and three-entry system.
3. Alternating 10-m layers of shale and sandstone and two-entry system.
4. Layered as above with bed slippage and three-entry system.
5. Layered as above with bed slippage and two-entry system.

For the three entry cases, the first longwall retreated on the yield pillar side of the longwall. Our discussion focuses on the first or homogeneous case because values used were calibrated against actual Pennsylvania subsidence and on the fourth case as it is closest to simulating actual conditions.

For the homogeneous strata, the distortions assume continuous lateral displacements along the well length. Rostami conjectured that shear movement along beds can concentrate the displacements at selected locations. This concentration may occur between thick rigid beds such as sandstone and softer beds such as shale. They approximated this concentration by multiplying the local shear strain by the bed thickness resulting in an offset at the bed boundary. To calculate this offset, bed thickness was assumed at 1 m (3.3 ft) and 10 m (33 ft) as they considered these to be reasonable bounds of bed thicknesses in coal bearing strata.

Penn State concentrated on the distortions caused by lateral displacement of the well bore during subsidence noting that a well could not survive an offset greater than its

[21] Gutierrez, J.J., Vallejo, L.E., Lin, J.-S., 2010, "A Study of Highway Subsidence Due to Longwall Mining Using Data Collected from 1-79," Pennsylvania Department of Transportation, Contract #510601.

diameter if applied over a short distance. The shear results for the homogeneous model above the gate road are presented in the following table:

Mine Depth (m (ft))	Scenario	First Mined Panel				Second Mined Panel			
		Peak Strain	Peak Strain Depth (m)	Bed Thickness (m)	Shear Offset (cm)	Peak Strain	Peak Strain Depth (m)	Bed Thickness (m)	Shear Offset (cm)
100 (328)	1	10^{-2}	50	1	1	Unaffected by the removal of the 2nd panel			
				10	10				
	2	10^{-4}	50	1	-	10^{-3}	50	1	0.1
				10				10	1
	5	10^{-4}	50	1	-	10^{-2}	50	1	1
				10				10	10
200 (656)	1	10^{-3}	150	1	0.1	10^{-3}	150	1	0.1
				10	1			10	1
	5	10^{-3}	150	1	0.1	10^{-2}	0	1	1
				10	1			10	10
300 (984)	1	10^{-3}	0	1	0.1	10^{-3}	250 to 300	1	0.1
				10	1			10	1
	2 through 5	10^{-4}	50	1	-	10^{-3}	250	1	0.1
				10				10	1

The retreat of the second longwall panel counteracts the movement from the first longwall panel.

The horizontal movements above the gate road were also determined for the homogeneous case. These movements are largest at the surface and are largest for the 100-m deep seam with movement approximately 25 cm (9.8 in.) horizontal after the first longwall is completed. Horizontal strains above the gate road after the first longwall panel is extracted are greatest at the surface and approach 20 millistrains in extension at the surface and reduce with depth to below 5 millistrains at a depth greater than 50 ft. Vertical strains are below 6 millistrains and are largest near the surface and above and below the pillar. In the model, these strains are tensile at the surface and compressive near the seam.

Penn State estimated the shear strain and horizontal displacement around a three-entry gate system consisting of a single row of yield pillars and a single row of abutment pillars with the strata being comprised of alternating layers of sandstone and shale. Bed contacts between these layers were allowed to delaminate and slip. This condition examined the effects of alternating layers of shale and sandstones with their contrasting

stiffnesses and strengths. Each layer was assumed to be 10 m thick with the coal seam placed between two layers of shale. The assumed properties of these layers are:

	Elastic Modulus (GPa)	Poisson's Ratio	Friction Angle (Degrees)	Cohesion (MPa)
Shale	5	0.25	30	21
Sandstone	20	0.25	30	88

The friction angle between layers was assumed to be 20 degrees.

Shear strains, within the layers generated in this model are approximately one half of those shown in the homogeneous case. Rostami believes that bedding slip dissipates some of the shear stress that would have occurred within the rock layers. Thus, shear movement is concentrated at the bed that separated one layer from the next.

Shear displacements of the beds are largest above the panel and reached a maximum of about 20 cm (8 in.) for a 10-m (33-ft) layer above the pillar edges of the first retreated longwall panel. The shear offsets then reduce to around 10 cm (4 in.) over the pillars.

5.4 Comparison of CONSOL and The Pennsylvania State University Results

The comparison of CONSOL and The Pennsylvania State University results shows similar findings. These two studies can only be compared for shear displacement as this is the only area of overlap. CONSOL's seam depth for their analysis is 1,032 ft which is similar to Penn State's depth of 984 ft, so offset is compared at these depths. Here, Penn State reported magnitude of change while CONSOL reported scaled change.

		Location Above Coal (ft)	Thickness of Stiff Bed (ft)	Offset (in.)
CONSOL		109	7.6	0.47
		135	4.5	0.91
		191	1.6	0.64
		193	9.8	0.60
The Pennsylvania State University	Homogeneous	164	3.3	0.04
		164	32.8	4
	Layered	328	32.8	4

CONSOL's locations for the maximum offsets are above, and below Penn State's location of 164 ft (50 m) above the coal and all of CONSOL's stiff beds, except one, are between the Penn State thicknesses of 3.3 ft (1 m) and 32.8 ft (10 m). Also, all of CONSOL's offsets are between the Penn State offsets of 0.04 in. (0.1 cm) and 4 in. (10 cm). This indicates the Penn State results are supportive of CONSOL's research.

5.5   CONSOL and Alpha

The results from CONSOL's finite element analysis from below the pillar give further insight into the plastic failure noted in the inner pipe by Alpha. This failure occurred 16.5 ft below the pillar. CONSOL reported results above and below this location:

	Pillar Width (ft)	Depth Top of Coal (ft)	Depth Below Pillar (ft)	Vertical Stress (psi)	Horizontal Stress (psi)	Shear Stress (psi)
CONSOL – Dr. Su	160	1,032	30.3	2,919	2,874*	22.4
			6.3	2,856	2,770*	42.7
Alpha – Dr. Peng	160	1,007	16.5	1,994	986.2	503.9*

* Calculated.

5.6   Pad NV-35 Experiment

The most significant experiment completed to study the effects of mining on gas or oil well integrity was completed by a consortium of coal and shale gas industry participants led by CONSOL. The field study was conducted in 2013 and 2014 and is referred to by its location on Well Pad NV-35 in Washington County, Pennsylvania.

The field experiment integrated surface, overburden, pillar, and pillar foundation monitoring with the construction and monitoring of various gas well designs to test the effects of mining two adjacent longwall panels. The work also involved the construction and calibration of finite element models to estimate movements, and stress and strain changes in the ground and well string. A more complete and comprehensive summary of the experiment is presented in Appendix B of this report.

The site selected for the experiment is located above CONSOL's Enlow Fork Mine approximately 6.5 miles southwest of Washington, Pennsylvania on top of a narrow ridge flanked by Tenmile Creek to the east and an unnamed drainage to the west. Relief of the terrain is approximately 150 ft with maximum slopes of approximately 20 degrees.

Pad NV-35 is approximately 610 ft above the base of the Pittsburgh Coal Seam and is sited above an abutment pillar in the gateroad between longwall panels E-24 to the south and E-25 to the north. The study monitored the effects of mining panel E-24 in 2013 and E-25 in 2014.

5.6.1   Test Wells

The field experiment focused on the study of mining effects on four non-producing test wells (TW) that were constructed in the same manner as contemporary production gas

wells. These wells were terminated just below the Pittsburgh Seam. Subsidence effects on these wells were monitored using borehole calipers and video cameras.

The test wells did not contain an intermediate casing or production string in order to accommodate the internal measurement of movement in the coal protection casing by caliper and camera. Following are the constructed casing details for the wells:

		Test Well Casing Parameters			
		TW #1	TW #2	TW #3	TW #4
		CONSOL	Innovative	Chevron	Innovative
Surface Casing	Hole Size, in.	36	36	30	36
	Depth, ft	80	80	80	80
	Casing Size, OD in.	30	30	24	30
	Casing Grade	H-40	H-40	H-40	H-40
Water String	Hole Size, in.	26	26	18¾	26
	Depth, ft	266	266	272	282
	Casing Size, OD in.	20	20	16	20
	Casing Grade	J-55	J-55	H-40	J-55
	Wall Thickness, in.	0.438	0.438	0.375	0.438
	Casing Weight, lbs/ft	94	94	65	94
Coal Protection	Hole Size, in.	17½	18¾	15	18¾
	Depth, ft	642	642	642	642
	Casing Size, OD in.	13⅜	16	11¾	13⅜
	Casing Grade	J-55	H-40	H-40	J-55
	Wall Thickness, in.	0.38	0.375	0.333	0.38
	Casing Weight, lbs/ft	54.5	65	42	54.5

All wells were installed in 2013 to a depth of 642 ft. from a surface elevation of 1,225 ft (MSL).

5.6.2   Caliper Logs
The significant information from the field test is the determination of the change in diameter and lateral displacement of the coal string casing as determined by caliper measurement.

Caliper surveys, employing a 60-arm caliper tool, were carried out on all test wells after the completion of each longwall panel. One set of logs was recorded about eight months after the E-24 longwall retreated and before the influence of the E-25 longwall. The

second set was completed when the E-25 longwall progressed about 1,200 ft past the test site.

The downhole locations of deformation of the coal string are plotted along with the geologic units as shown in Figure 5, following this text. There is strong correlation among the wells for the location of the significant deformations except for TW #3 where two additional significant deformations were noted in the lower portion of the coal string. TW #3 has the smallest casings and the thinnest coal string of all four test wells which may have contributed to the disparity.

In all cases the deformation occurred in the weak strata layer close to contact with a strong layer. The following identifies the geologic unit at the deformation location:

	Deformation
Depth (ft)	Occurs in
290	Waynesburg Coal and underlying shale
360	Shale between two layers of the Uniontown Sandstone
390	Top of Limestone C
480	Shale layer within the Benwood Limestone
605	Pittsburgh Coal and underlying shale

The data were analyzed to determine (1) the minimum inside diameter of the coal string at any point, and (2) the maximum diameter of a 4-ft long cylinder that can fit down the coal string (also known as the minimum 48-in. drift diameter).

The casing diameter reduction from deformation is summarized as follows:

60-Arm Caliper Results, Maximum Inside Diameter Reduction				
	TW #1	TW #2	TW #3	TW #4
Initial Pre-mining Diameter				
Diameter (in.) - Reported (Spec.)	12.750	15.250	11.050	12.750
- Measured	12.615	15.250	11.084	12.615
Minimum Diameter After Mining E-24 Panel				
Minimum Diameter (in.)	11.328	14.378	9.550	10.856
Depth (ft)	395.6	397.2	396.0	396.8
Reduction (in.) - From Reported	1.422	0.872	1.500	1.894
- From Measured	1.287	0.872	1.534	1.759
Minimum Diameter After Mining E-25 Panel				
Minimum Diameter (in.)	11.547	14.360	9.465	10.588
Depth (ft)	396.5	397.1	396.5	396.6
Reduction (in.) - From Reported	1.203	0.890	1.585	2.162
- From Measured	1.068	0.890	1.619	2.027
Minimum 48-in. Drift Diameter After Mining E-24 Panel				
Drift Diameter (in.)	10.950	14.010	9.894	10.896
Depth (ft)	392.5	393.5	396.1	396.8
Reduction (in.) - From Reported	1.800	1.240	1.156	1.854
- From Measured	1.665	1.240	1.190	1.719
Minimum 48-in. Drift Diameter After Mining E-25 Panel				
Drift Diameter (in.)	11.441	13.592	9.219	10.876
Depth (ft)	396.8	393.8	393.6	396.6
Reduction (in.) - From Reported	1.309	1.658	1.831	1.874
- From Measured	1.174	1.658	1.865	1.739

The diameter reduction data indicate that casing size and strength are not related to the reduction. The maximum diameter reduction occurred at around a depth of 390 ft, where shale lies above the contact with Limestone C.

The 60-arm caliper can also provide a measurement of the lateral displacement although the direction of this horizontal movement is not known.

Each test well showed similar horizontal movement. The data shows there was typically more horizontal movement due to the first longwall than the second. Except for TW#3, some of the horizontal movement due to the first longwall was counteracted by the second longwall.

The three highest horizontal movements for each well after each longwall occur at the same depth with similar movements as summarized below.

Three Highest Horizontal Movements (in.)
at Depth (ft) in Each Test Well

Reference Depth, ft	TW #1	TW #2	TW #3	TW #4
	After Mining E-24 Panel			
290	1.245	1.597	0.786	1.135
	288.7	289.4	288.8	289.3
360	1.022	1.260	0.854	0.910
	357.0	363.8	362.2	365.1
390	4.989	5.520	1.982	3.967
	392.1	393.0	392.4	393.2
	After Mining E-25 Panel			
290	0.556	1.435	1.515	0.633
	289.4	289.5	289.4	287.7
360	0.910	1.515	1.781	0.766
	363.7	358.5	358.0	364.3
390	3.477	5.160	4.669	2.746
	393.1	392.9	393.0	393.2

The caliper measurements showed the maximum displacement in all four test wells occurred at a depth around 390 ft at the same location as the diameter change. Figure 6, following this text, shows the likely depiction of this deformation as developed from the caliper log data.

5.6.3   Overburden Monitoring

Ground movements were monitored at all four monitoring wells (MW) on Pad NV-35 before, between, and after the mining of two adjacent longwall panels. The overburden was monitored by one extensometer, and three inclinometers using In-Place Inclinometer (IPI) sensors as follows:

	Feet		
	Hole Depth	Target Zone	Monitored Depth
MW 1 Inclinometer	200	0 to 200 depth	38 to 198
MW 2A Extensometer	647	150 above and 50 below coal	459 to 639
MW 3 Inclinometer	400	200 to 400 depth	197 to 367
MW 4 Inclinometer	607	200 depth to 10 below coal	208 to 408

The monitoring wells were installed in the same abutment pillar as the test wells down through and into the floor of the Pittsburgh Seam. Inclinometers were installed to measure lateral movements in MW 1, MW 3, and MW 4 and the extensometer was installed in MW 2A (replacing MW 2) to measure vertical movements.

The extensometer in MW 2A was initially read four times from July 19 to 22, 2013 to establish baseline measurements. Subsequent readings were intended to be made at a minimum of five positions of the longwall face in 2013 and again in 2014. The face positions are:

- Approaching MW 2A at a distance of 200 ft.
- Directly alongside MW 2A.
- Past MW 2A at distances of 200 ft, 500 ft, and 1,000 ft.

Eleven measurements were made from July 26, 2013 through May 30, 2014.

The IPI system is similar in concept and function to a conventional borehole inclinometer except that the conventional inclinometer consists of a single sensor that is incrementally lowered down the borehole each time that readings are taken, whereas the IPI system consists of multiple sensors positioned at selected depths that remain in place at specified downhole depths for the duration of the monitoring program.

As ground movements take place, the angle of the casing changes. The IPI sensors measure this angle which is subtracted from the initial casing angle. The change in angle is used to compute the lateral displacement knowing that the sensor gage length is 10 ft. The data were corrected for temperature.

The three IPI systems were installed as E-24 longwall approached 924 ft from MW 1, 864 ft from MW 3, and 820 ft from MW 4. At these distances, ground movements resulting from the E-24 longwall would not have affected the MWs.

Monitoring well data for combined movement caused by both longwall E-24 and E-25 is graphed in Figure 7, following this text, that shows:

- The maximum measured horizontal movement is 1.44 in.

- The maximum measurement after longwall E-25 is greater than after E-24 (1.21 in.) although this value should be less.

- An angle of draw of 25 degrees would result in the effects of subsidence from longwall E-25 on the monitoring wells starting at a depth of 553 ft for longwall E-24

and 576 ft for longwall E-25, with a general increase in effect as depth decreases. The deepest measured horizontal movement is at 367 ft (MW 3) thus movement is likely greater than 1.44 in.

- The increase of strain within the coal pillar as determined by MW 2A extensometer is 1.79%.

- The MW 4 horizontal data shows extreme movements that are not possible in this setting. The data is believed to be faulty as the inclinometer likely became un-calibrated following reported installation problems and rough downhole handling of the instrument.

5.6.4   In-Mine Monitoring

Monitoring in the mine occurred within the gate roads between longwall panels E-24 and E-25 and between crosscuts 24 and 25. The instrumentation consists of borehole pressure cells (BPC) and closure stations. BPCs were used to measure changes in stress within the abutment pillar. Eight BPCs were installed within the abutment pillar; four installed from the center entry (T1 thorough T4) and four from longwall E-25 tailgate (R1 thorough R4).

The final change in pillar stress recorded by the BPC during E-24 Longwall retreat was 435.3 psi on August 27, 2013. The final change in pillar stress measured was 1,028.9 psi. when the E-25 longwall face was 630.5 ft from the "R" BPC around May 21, 2014. If the change in pressure is added from both the E-24 and E-25 BPC the total change in pressure in the abutment pillar would be 1,464.2 psi.

5.6.5   Subsidence

Surface subsidence surveying was conducted from five stations on the pad (parallel to wells) along with 27 additional stations spaced at 50 ft intervals along a total survey line length of 1,400 ft. The line was surveyed twice prior to mining, once after mining E-24 panel, and once after E-25 panel was mined.

The measured surface subsidence movement is typical for longwall mining in southwestern Pennsylvania. Horizontal movement over the E-24 Panel is toward the center of that panel. The net horizontal movement is lessened as movement is then toward the adjacent panel mined.

Maximum measured subsidence movements are summarized below:

Maximum Surface Subsidence Measurements (ft)		
	Vertical	Horizontal
E-24 Panel (E-24 Retreated)	-4.60	1.26
E-24 Panel (E-25 Retreated)	-4.63	1.12
E-25 Panel (E-25 Retreated)	-4.60	1.87

5.6.6   ABAQUS 3D Finite Element Model

CONSOL applied finite element analysis using ABAQUS 3D[22] to model the geology, coal pillars, and well casing, and predict the effects due to mining subsidence. ABAQUS is a general-purpose finite element program that employs implicit integration schemes and can solve highly nonlinear systems with complex contacts under transient loads.

The primary aim of the analysis is to assess the effects of subsidence from two longwall panels on the gas well intermediate casing and production string if:

- The annuli between coal string, intermediate casing, and production string are cemented.

- The annulus between the coal string and the intermediate casing is cemented but the annulus between the intermediate casing and production pipe is left open or uncemented.

- The annuli between coal string, intermediate casing, and production pipe are left open or uncemented.

Referring to the annuli as being open or uncemented can include filling of the space with bentonite, gel, or viscous materials.

The critical input for the finite element analysis is the number, locations, and properties of the interfaces between weak and strong rock. The model contained 3D interface elements which defined the contacts between rock types. Weak interfaces include coal-limestone, coal-sandstone, coal-sandy shale, limestone-claystone. Such contacts are assigned a cohesion value of zero and a low friction value.

Calibration of the finite element model was accomplished by adjusting friction values above and below the major deformation detected by the installed instruments. Friction values of 0.2 and 0.02 above and below the C Limestone member of the Sewickley Formation were assigned, respectively.

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[22] Dassault Systèmes, 2002, Abaqus Unified FEA, Vélizy-Villacoublay, France.

The elastic, plastic, or strain softening properties of the rock that were used in the finite element model are:

		psi			
			Onset of	Angle of	
	Young's	Compressive	Strain	Friction	
Rock Type	Moduli	Strength	Softening	(degrees)	Note
Coal	105,000	903	833	35	
Claystone	130,000	993	993	-	Perfect plastic
Shale	300,000	1,486	1,389	38	
Sandy Shale	375,000	1,700	1,545	38	
Limey Shale	400,000	1,986	1,806	38	
Sandstone	525,000	2,479	2,222	40	
Limestone	750,000	3,722	3,472	42	

The gob was treated as a hyperelastic material which behaves as non-linearly elastic, isotropic, incompressible, and generally independent of strain rate.

5.6.7   ABAQUS Results

The ABAQUS model shows strong agreement with the actual surface subsidence survey measurements as compared below:

Maximum Vertical Surface Subsidence (ft)		
	Surveyed	ABAQUS
E-24 Panel (E-24 Retreated)	-4.60	-4.606
E-24 Panel (E-25 Retreated)	-4.63	-
E-25 Panel (E-25 Retreated)	-4.60	-4.618

The ABAQUS analysis predicted the horizontal movement (deformation) and the inelastic strain that occurred in all four test wells and two of the monitoring wells (MW 3 and MW 4) as well as the inelastic strain for the intermediate casing and the production pipe within the test wells. The total strain was not reported but can be calculated by:

Total Strain = Elastic Strain + Inelastic Strain

Figures 8 and 9, following this text, show the ABAQUS model predicted the location of the major movement at 390 ft depth as was evidenced by the caliper logs.

A comparison of the measured movements to those predicted by the ABAQUS model shows reasonable agreement, as follows:

		TW #1	TW #2	TW #3	TW #4	MW 3	MW 4
				Measured and Modelled Test and Monitoring Well Horizontal Movement (inches) at a Depth of 390 ft			
After Panel E-24	- Measured	4.99	5.52	1.98	3.97	-	-
	- ABAQUS	4.29	4.08	4.19	4.10	4.76	4.16
After Panel E-25	- Measured	3.48	5.16	4.67	2.75	-	-
	- ABAQUS	2.68	2.99	2.96	3.10	1.47	2.81

The finite element analysis predicted strain in the coal protection casing in TW #3 that is nearly 10 times the strain in the other test wells.

ABAQUS Inelastic Strain in the
Coal Protection Casing After E-25

	TW #1	TW #2	TW #3	TW #4
@ 390 ft	0.0934	0.0162	0.0399	0.0015
@ Pittsburgh Seam	0.0060	0.0077	0.0599	0.0065

5.6.8   ABAQUS and Alternate Casing Designs and Depth of Seam

Alternate casing designs were studied using ABAQUS to determine if it is possible to reduce casing deformation and eliminate inelastic casing strain. Cementing options are addressed in the following comparison.

ABAQUS Inelastic Strain after E-25
for Various Cementing Options, TW #1 Configuration

	All Strings Cemented	Uncemented	
		Production String	Production String and Intermediate Casing
		@ 390 ft depth	
Intermediate Casing	0.016	0.037	0.000
Production String	0.016	0.000	0.000
		@ Pittsburgh Seam	
Intermediate Casing	0.016	0.173	0.000
Production String	0.016	0.000	0.000

If the intermediate casing and production strings are cemented, inelastic strain occurs in both. If the intermediate casing or production string is not cemented, inelastic strain does not occur in that string. The only case analyzed where strain can result in rupture is

where the intermediate casing is located within the Pittsburgh Seam and the production string is uncemented. This is shown as strain of 0.173 in the preceding table, and where:

Total strain = inelastic strain + elastic strain = 0.173 + 0.005 = 0.178 > 0.120 allowable strain

In considering alternate casing thickness, the finite element analysis demonstrates lower strain is found in thicker casing:

Finite Element Strain in Coal Protection
Casing, TW #1 Configuration @390 ft depth

Casing	Inelastic Strain	
Thick. (in.)	Longwall E-24	Longwall E-25
0.38	0.0246	0.0351
0.05	0.0107	0.0107

The finite element analysis also considered the effect of mining depth.

ABAQUS Inelastic Strain in Coal Protection
Casing at Various Depths, TW #1 Configuration

Overburden Depth (ft)	Longwall E-24	Longwall E-25
	Casing @ 390 ft depth	
604	0.0583	0.0934
1,100	0.0100	0.0022
	Casing @ Pittsburgh Seam	
604	0.0044	0.0060
1,100	0.0090	0.0187

The deeper the mine, the less strain occurs in the coal protection casing located in the overburden and the greater the strain in the casing located within the extracted coal seam.

5.6.9   Pillar Stress and Strain

Stress changes in the coal were measured by BPCs and the final readings were 435 psi and 1,029 psi due to E-24 and E-25 longwall retreat, respectively.

The change in pillar stress as measured by the BPCs and the same pressure estimated by ABAQUS shows strong agreement.

Longwall Panel	Coal Pillar Pressure (psi)	
	BPC	ABAQUS
E-24	435	469
E-25	1,029	917
Total	1,464	1,386

The known changes in stress and strain within the coal pillar allow the estimate of Young's Modulus. The estimate should be less than but within a magnitude of the actual Young's modulus especially noting that some plastic deformation may have occurred in the pillar.

Comparison of the calculated Young's modulus to that used in the ABAQUS model shows good agreement.

	Change		Young's Modulus (psi)	
	Stress (psi)	Strain (%)	Calculated	ABAQUS
August 2013	435	0.99	43,939	105,000
May 2014	1,464	1.79	81,800	105,000

5.6.10 Field Test Findings

The field test instrumentation readings are consistent with the present understanding of ground movement and pillar behavior associated with longwall mining. Significant agreement is found between the test results and the calibrated finite element analysis modelling.

The measurements and analysis for this mine configuration and geologic environment showed that:

- Casing deformation is identified in two settings: at the weak/strong rock contacts and within the Pittsburgh Coal Seam.

- Casing deformation is in response to ground movement occurring at weak/strong rock contacts and is above the well's intersection with the angle of draw.

- The most significant movement is found at the weak/strong rock contact on top of Limestone C with horizontal movements in all four test wells from 2.0 in. to 5.5 in.

- The finite element analysis showed the inelastic strain of the coal protection casing was consistent at 0.006 for all test wells except for TW #3 in which inelastic strain was 10 times higher approaching 0.060.

- TW #3 employed the weakest coal protection casing. The finite element analysis for varying wall thicknesses showed this accounted for the higher strain.

- If all strings are cemented, inelastic strain occurs in both the intermediate casing and production pipe. If the intermediate casing or production string is not cemented, inelastic strain does not occur in that string.

- Among all conditions, the highest inelastic strain is shown to occur at coal seam level in the coal protection casing of TW #3. This is because the casing was the weakest of all the test wells and was cemented in place.

- As overburden increases, the strain in the casing due to movement along weak/strong rock planes decreases.

- Strain in the coal protection casing at coal seam level increases as the overburden increases.

- Site specific geology has significant impact on the outcome.

BOYD's comments and recommendations resulting from the Pad NV-35 Experiment include the following:

- Geologic analysis for the identification of weak/strong rock contacts is key in determining the mining effects on well strings.

- Casing and well pipe should be kept at half the minimum elongation required of the steel grade.

- Particular attention should be paid to the strength of the coal protection casing especially at depth.

- Uncemented annuli surrounding the intermediate casing and the production string in the overburden and through the coal seam floor mitigates the effect of subsidence and improves the survivability of these elements.

6.0   The Well System

This report is aimed to address the integrity of wells common to the petroleum industry. References to "wells" are intended to be consistent with their definition in Title 58 of Pennsylvania Consolidated Statutes, Subchapter A, § 3203, Oil and Gas. The findings and recommendations presented here may not be applicable to unrelated types of wells.

6.1   Allowable Stress

The American Petroleum Institute (API) and International Organization for Standardization (ISO) provide standards for casing and cement in the petroleum

industry. API standards are published in API Bulletin 5C3[23], which serves as the basis for ISO 10400:1993. Relative to this study is the question of the point at which the well does not function or fails and potentially leaks fluid. Confining pressure around the pipe (referred to in the petroleum industry as collapse pressure) and loading along the length of the casing (body yield) are of concern and are examined below.

In addition to the published standards, oil and gas companies may derate material properties such as those for casing. For example, Range Resources Corporation[24] derates casing to 80% of its original strength because drilling occurs through this casing and may cause undiscovered damage to it.

6.1.1   Collapse Pressure

The collapse mechanism is a complex phenomenon because elasticity theory cannot directly determine the stresses in the pipe. The load determination is dependent on the ratio of outer casing diameter and its wall thickness (D/t). Four conditions exist and thus four collapse equations are needed:

1. Yield.
2. Plastic.
3. Transition.
4. Elastic.

The selection of the appropriate condition and thus the equation depends on the D/t ratio and the material yield strength of the steel used in the casing.

Yield strength collapse pressure, P_{YP}, which is the external pressure that causes the minimum casing yield, Yp, is calculated by:

$$P_{Y_P} = 2Y_p \left[\frac{D/t - 1}{(D/t)^2} \right]$$

Equation 2

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[23] American Petroleum Institute, 1994, Bulletin on Formulas and Calculations for Casing, Tubing, Drillpipe, and Line Pipe Properties, Sixth Edition, API Bulletin 5C3, October 1.

[24] Nguyen, Minh, 2012, personal communication, June 7.

This formula is dependent on the D/t ratio of:

$$\left(D/t\right)_{YP} = \frac{\sqrt{(A-2)^2 + 8\left(B + C/Y_P\right)} + (A-2)}{2\left(B + C/Y_P\right)}$$

<div align="right">Equation 3</div>

where A, B, and C are factors found in Table 2 of API Bulletin 5C3. Similarly, <u>plastic</u> external pressure collapse occurs at:

$$P_P = Y_P\left[\frac{A}{D/t} - B\right] - C$$

<div align="right">Equation 4</div>

$$\left(D/t\right)_{PT} = \frac{Y_P(A-F)}{C + Y_P(B-G)}$$

<div align="right">Equation 5</div>

And for the elastic-plastic <u>transition</u> pressure:

$$P_T = Y_P\left[\frac{F}{D/t} - G\right]$$

<div align="right">Equation 6</div>

$$\left(D/t\right)_{TE} = \frac{2 + B/A}{3\,B/A}$$

<div align="right">Equation 7</div>

where F and G are factors found in Table 3 of API Bulletin 5C3.

For <u>elastic</u> external pressure collapse:

$$P_E = \frac{46.95 \times 10^6}{\left(D/t\right)\left(\left(D/t\right) - 1\right)^2}$$

<div align="right">Equation 8</div>

Equation 8 is unit sensitive and provides P_E in psi. Internal pressure within the casing would reduce the external pressure by a formula given in API Bulletin 5C3, but this reduction will be ignored in this study because of the variability over time of this internal pressure.

6.1.2 Body Yield Strength

Body yield strength is determined in API Bulletin 5C3 using the following formula for both compressive and tensile loading:

$$P_y = \frac{\pi}{4}(D^2 - d^2)Y_P$$

<div align="right">Equation 9</div>

where D and d are the outside and inside casing diameter, respectively.

6.1.3 Standard Cement and Steel Allowables

To protect structures from the effects of mine subsidence movement, it is typical to limit the stress or strain to allowable levels. Other considerations include limits to vertical and horizontal movement, inclination, and curvature. Stress and strain can be compressive, tensile, or shear. However, once a protective pillar is established around a gas or oil well, the well is only subjected to the tensile zone of the subsidence profile. Therefore, these wells will be subjected to horizontal tension and shear and vertical compression.

Well structures are comprised of a system of steel casing and pipe with concrete surrounding the outside casing and within the annuluses. Allowable standards[25] for most types of steel are typically based on the following:

Allowable tension, F_a:

$$F_a = 0.66F_y$$

<div align="right">Equation 10</div>

And allowable shear, F_v:

$$F_v = 0.40F_y$$

<div align="right">Equation 11</div>

where, F_y, is the specified yield-point stress. The equivalent a safety factor for allowable tension is 1.5 and for shear it is 2.5. Similarly for concrete:

Allowable tension and shear, v_c:

$$v_c = 1.1(f_c')^{0.5}$$

<div align="right">Equation 12</div>

where, f_c', is the ultimate compressive strength of the concrete at 28 days.

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[25] American Institute of Steel Construction, 2011, Steel Construction Manual, 14th Edition, Chicago, Illinois.

These allowable standards assume the structural elements have free or fixed ends such as columns and beams. However, wells are systems of steel and concrete with earth and subsidence loading and these concrete allowable standards may not be directly applicable. To BOYD's knowledge, specific allowable standards have not been developed for oil and gas well composite systems.

Permissible standards have been developed for concrete and steel pipe (oil and gas transmission) affected by subsidence[26].

Element	Maximum Allowable in Tension	
	Strain x 10^{-3}	Stress (psi)
Plain Concrete	0.15	55*
Buried Steel Pipe	0.60	18,500

* 10% of tensile stress at cracking.

These permissible values were developed for near surface and surface structures. Principally, these structures are affected by horizontal subsidence generated stress and strain. Well structures (casing and pipe) are near vertical thus the loading conditions are different. In addition, current subsidence prediction programs do not generate vertical profiles.

6.1.4   Performance of Cement-Steel Casing

The interaction of steel pipe, cement infilling, and surrounding ground is rarely addressed and consequently allowable standards for the cement-steel casing system have not been developed. However, a paper by Fleckenstein, et al[27] does address this system's performance. This paper notes that "The burst and collapse resistance of casing may increase or decrease by 60% to 70%, depending on the true stresses acting upon the casing." The following is summary of this paper's findings.

According to Fleckenstein, casing systems are designed for burst and collapse, which discount the effects of cement and assume a uniform and hydraulic loading stress. Casing design for burst resistance is based on the lowest internal yield resistance of the pipe with safety factors applied, which are typically established by the company and based on loading conditions.

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[26] Kratzsch, Helmut, 1983, Mining Subsidence Engineering, Springer-Verlag, New York.
[27] Fleckenstein, W.W., A.W. Eustes, W.J. Rodriguez, A. Berger, F.J. Sanchez, 2005, "Cemented Casing: The True Stress Picture," American Association of Drilling Engineers, National Technical Conference and Exhibition, Houston, Texas, AADE-05-NTCE-14, April 5-7.

The resistance to burst pressure is determined by Barlow's equation:

$$p_b = 0.875 \frac{2Y_p h}{d}$$

Equation 13

where: p_b = Casing burst strength

h = Casing thickness

d = Casing diameter

The casing yield point is the minimum yield strength of steel.

As discussed in the preceding section (6.1.1 Collapse Pressure), casing design for collapse requires a selection of a suitable equation which depends upon the outer diameter and wall thickness ratios (D/t). This ratio places the pipe into four failure states: yield, plastic, transition, and elastic.

Fleckenstein used ANSYS[28] finite element analysis to analyze a two-dimensional model. The model used to examine burst and collapse pressure incorporated the casing, cement, and rock. Varying the rock elastic modulus from 2×10^6 to 8×10^6 psi, rock Poisson's ratio from 0.10 to 0.49, and "soft" and "hard" cement, they showed the importance of rock properties in determining the amount of stress placed on the casing for collapse condition. The confining stress applied to the rock varied from 1,000 psi to 5,000 psi, although one figure shows a confining stress of 8,000 psi. These confinements would correspond to a horizontal stress field from 450 ft to 2,270 ft (8,000 psi – 3,640 ft), when assuming a horizontal to vertical stress field ratio of 2. The calculated stresses in casing ranged from 19,119 psi to 51,969 psi.

Casing deformation will be constrained by the cement and surrounding rock, thus increasing the collapse strength. For burst conditions, Fleckenstein notes that it has been well documented that a cemented casing has higher burst resistance than that of un-cemented casing. What has not been well documented is the importance of the confining stress of the surrounding formation. Both soft or ductile and hard or brittle cements have nearly inverse linear relationship between the stresses in the casing versus the rock confining stress. The improved burst resistance of the casing caused by the cement can be of critical importance in de-rating the casing for wear or corrosion.

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[28] ANSYS, Inc., 2004, ANSYS, Simulation Technology, Canonsburg, PA.

In addition, conventional casing design fails to account for the collapse stresses present in non-uniform loaded casing including eccentrically centered casing. Fleckenstein et al do not address the non-uniform load on casing caused by or similar to subsidence. An underlying assumption in equations defining the collapse and burst resistance is that the stress is applied uniformly to the outside surface of the casing.

A casing not cemented in the center of the borehole is referred to as eccentric. Eccentricity is the linear distance between the center of the borehole and the center of the casing and Fleckenstein determined that eccentric casing, surrounded by cement, does not significantly affect the collapse and burst resistance of the casing.

The paper concludes that:

- Cement filling the annulus between the casing and borehole increases the burst resistance of the casing.

- The increase of burst resistance is dependent on the surrounding rock in-situ stress and the larger the confining in situ stress, the greater the resistance.

- Cement also increases collapse resistance of the casing if the cement exhibits a softer and more ductile behavior, which require lower values of Young's elastic modulus and higher Poisson's ratio.

- Conventional design equations for both burst and collapse are acceptable under uniform stress conditions.

6.2   Allowable Strain
The API established the following standards for well casings and pipe:

					Calculated	
					Elastic Strain	
		API			Based on	Acceptable
API	Yield Strength (psi)		Elongation	Strain	Yield Strength	Total Strain
Grade	Minimum	Maximum	Minimum	TUL	Minimum	Maximum
H40	40,000	80,000	0.295	0.005	0.00138	0.147
J55	55,000	80,000	0.240	0.005	0.00190	0.120
P-110	110,000	140,000	0.150	0.006	0.00379	0.075

TUL = Total Under Load

Yield strength is the stress at which a material exhibits a deviation from the proportionality of stress to strain, known as elastic. Materials, such as API casing and pipe, are necessarily moderately ductile, and do not have a clear yield point; thus they

have a yield zone. This zone is between the minimum and maximum yield strength as determined by the offset-yield-method typically at 0.001 to 0.002 strain.

To understand the elongation characteristic, the strain as determined by the total-extension-under-load method (usually at a strain of 0.005 or 0.006) is presented. As part of grade testing, the metal must prove ductility by not rupturing before a minimum elongation is reached. Because of this, we should expect the casing not to rupture if strain is kept below the minimum elongation. However, during the minimum elongation test, the force is applied in one direction, which is not the circumstance for well casing and pipe subject to subsidence loading. Thus, it is BOYD's opinion that the casing and pipe total strain should be kept to one half the minimum elongation.

6.3   Allowable Subsidence Stresses

For the development of updated well pillar requirements, it is BOYD's opinion that the focus should be directed toward protection of the casing because it shields the production pipe and aids in isolating fugitive fluids from the mine. To determine the allowable stresses applied to casing by subsidence, the following rationale and assumptions are used.

API lists several approved casing types and materials. The weakest is H-40 which has a yield, Yp, of 40,000 psi. This value is referred to as the yield-point by the American Institute of Steel Construction (AISC) which uses a different symbol, F_y, to represent this parameter. Using the yield-point AISC specifies, the allowable tension, F_a, in the steel using Equation 10 is:

$$F_a = 0.66F_y = 0.66 \times 40,000 \text{ psi} = 26,400 \text{ psi}$$

Equation 14

and allowable shear, F_v, using Equation 11 is:

$$F_v = 0.40F_y = 0.40 \times 40,000 \text{ psi} = 16,000 \text{ psi}$$

Equation 15

Equation 14 and Equation 15 are modified when considering a derating of 80% of allowable:

$$F_{0.8a} = 0.80 \times 26,400 \text{ psi} = 21,120 \text{ psi}$$

Equation 16

$$F_{0.8v} = 0.80 \times 16,000 \text{ psi} = 12,800 \text{ psi}$$

Equation 17

The H-40 casing is produced in various wall thicknesses and outside diameters. The thicker the wall, the stronger is the casing. However, the larger the casing diameter, the more stress can be applied through subsidence. Thus, the worst case available is H-40, that is, the case with the lowest ratio of strength to applied load, has an outside diameter of 13.375 in. and an inside diameter of 13.045 in. Appling Equation 9 and using $F_{0.8}$ as the minimum casing yield, Yp, the permissible load in pounds, can be determined:

$$P_y = \frac{\pi}{4}(D^2 - d^2)F_{0.8a} = \frac{\pi}{4}((13.375 \text{ in})^2 - (12.715 \text{ in})^2)21{,}120 \text{ psi} = 285{,}600 \text{ \#}$$

Equation 18

$$P_y = \frac{\pi}{4}(D^2 - d^2)F_{0.8v} = \frac{\pi}{4}((13.375 \text{ in})^2 - (12.715 \text{ in})^2)12{,}800 \text{ psi} = 173{,}100 \text{ \#}$$

Equation 19

Applying the reaction area to obtain the allowable applied stress, A, provides:

$$A_a = \frac{285{,}600 \text{ \#}}{\frac{\pi}{4}(13.375 \text{ in})^2} = 2{,}030 \text{ psi}$$

Equation 20

$$A_v = \frac{173{,}100 \text{ \#}}{\frac{\pi}{4}(13.375 \text{ in})^2} = 1{,}230 \text{ psi}$$

Equation 21

The 13.375-in. diameter H-40 casing has a D/t Ratio of 40.53 which places this casing in the transition zone which extends from a D/t of 27.01 to 42.64 with $F = 2.063$ and $G = 0.0325$. The minimum collapse pressure for the elastic-plastic transition is given by Equation 6:

$$P_T = Y_P\left[\frac{F}{D/t} - G\right] = 40{,}000\left[\frac{2.063}{40.53} - 0.0325\right] = 736 \text{ psi}$$

Equation 22

For H-40 casing of 8.625-in. diameter, the same diameter of the Alpha plastic failed casing, with a wall thickness of 0.304 in., the collapse pressure is:

$$P_T = Y_P\left[\frac{F}{D/t} - G\right] = 40{,}000\left[\frac{2.063}{28.37} - 0.0325\right] = 1{,}610 \text{ psi}$$

Equation 23

7.0   Development of Protective Pillar Size

7.1   Approach

The protective pillar around a well must address two concerns:

1. The pillar has to be wide enough to reduce the effects of subsidence to a point where stresses and strains are below the allowable values for the casings and pipe. The limiting distance that determines the width is referred to in this study as the safeguard distance.

2. The pillar has to be strong enough for long-term stability.

The protective pillar around the well must remain stable until and after the well has been safely plugged because a failure of the protective pillar could crush and rupture the casings and pipe.

For the purpose of this study, to assess the required protective pillar size for long-term support, BOYD has applied an empirical approach supported by analytical techniques. For the empirical approach, ALPS[11] and ARMPS[12] are applied, because these programs are readily used and understood by the coal mining industry and PADEP agencies. These programs employ the Mark-Bieniawski pillar equation.

For the analytical approaches, the Wilson[8] equation is used to develop pillar sizes and Terzaghi[29] will be used to assess the pillar foundation as this is one of the few bearing capacity equations where rock specific bearing capacity factors have been developed.

The selected input parameters for the Wilson and Terzaghi equations are based on the least-strength available data for the Pittsburgh and Upper Freeport seams developed from testing at Pennsylvania sites. Our approach considers three mine settings: longwall, retreat room-and-pillar section, and non-retreat room-and-pillar section.

7.2   Safeguard Distance

A limiting distance between the well and the mine opening is required to protect the well from the adverse subsidence effects from coal extraction and the resulting caving and ground movement.

To address the need for protective pillar sizes that can be applied to modern drilling practices involving variably spaced multiple wells (clusters), our recommendations are

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[29] Bowles, Joseph E., 1996, Foundation Analysis and Design, 5th Edition, McGraw-Hill, New York.

based on the concept of a limiting "safeguard" distance. The safeguard dimension represents the minimum distance from any single well (isolated or in a cluster) to the mine opening susceptible to caving (i.e., to the limit of secondary recovery defined by the extent of excavation for a longwall or retreat room-and-pillar panel).

Gas and oil wells are required to be located through protection pillars of an active mine. This limits the well's exposure to many of the adverse effects of subsidence. If the well is instead located over an area susceptible to active caving, it would be exposed to ground movement of the caving, along with vertical and horizontal movements, compressive and tensile stress and strain, tilt and convex and concave curvature as well as shear.

Locating the well through the pillar places the well within the tensile zone of the subsidence, and it will not be exposed to most of the destructive forces of subsidence. However, the well will be exposed to:

- Horizontal tensile stress and strain; the worst possible effect of which would be to pull the well bore wall away from the casing and cement of the well. Cement is weak in tension and could crack leaving the casing undamaged.

- Tilt and convex curvature which will be imperceptible and occur over such distances as to not affect pipe operations such as bailing.

- Vertical and horizontal movement which will result in:
  - Vertical compressive body stress.
  - Horizontal shear.

- High vertical compression above, within, and below the protection pillar due to abutment loading. Abutment loading occurs as mining approaches the protection pillar and the load once carried by the coal being extracted is transferred to adjacent pillars, which, in this case, is the protection pillar.

Horizontal shear is transferred into the casing by ground movement caused by shear stress in the surrounding rock. This movement can be converted to shear stress, τ, in the casing using the shear modulus, G, of steel which is 11.2×10^6 psi[25].

$$\tau = G\frac{\delta}{l} = \frac{(\delta_1 + \delta_2)/2}{(l_1 + l_2)/2}$$

Equation 24

where δ = lateral displacement, l = height of element, as illustrated in Figure 10, following this text.

Horizontal shear is not calculated in available subsidence programs and must be derived. To derive this value, a 1-ft vertical, two dimensional square element is examined as illustrated in Figure 10. The vertical and horizontal movements of all four corners of this element are determined and the shear stress calculated using Equation 24.

For this task the commonly used subsidence equation based on the hyperbolic tangent function[30] ($tanh$) is employed. This equation adequately predicts subsidence movement in the Appalachian Coal Fields and is the basis for the subsidence prediction programs distributed by Virginia Polytechnic Institute, West Virginia University, West Virginia Institute of Technology, and others:

$$s = 0.5S_{max}\left(tanh\frac{2x}{B}\right)$$

Equation 25

$$S_{max} = \alpha m$$

Equation 26

$$\alpha = 0.92 - 1.33P$$

Equation 27

$$B = 0.5w - 0.16h$$

Equation 28

$$v = 0.4Bs'$$

Equation 29

where:

s = Vertical movement.
S_{max} = Maximum vertical movement.
m = Extraction thickness.
P = Percent hard rock such as sandstone and limestone. Taken as 0% to give maximum subsidence.
w = Panel width up to critical width. Critical width taken as 2×h×tan19°.
h = Panel depth
x = Distance from inflection point (point occurs at 0.16h from the pillar rib into the gob).
v = Horizontal movement.
s' = First derivative of vertical movement.

[30] Kohli, Kewal and Thomas Jones, 1986, "A simplified Computerized Method to Predict Maximum Subsidence and the Subsidence Profile for the Appalachian Coal Basin," Chapter 5 Mine Subsidence, ed by Madam Singh, Society of Mining Engineers.

The scalar for the vertical movement is derived from $v_{max} = 0.4\ S_{max}$ as recommended by Kratzsch[26]. Once the shear strain is determined, a safeguard distance from the pillar edge is determined by finding the point at which the allowable shear of 1,230 psi (see Equation 21) is reached on the surface. That requires all points along a vertical casing below this surface point to be below the allowable shear.

To provide the means to determine these safeguard dimensions, BOYD developed three equations according to extraction height range and a look-up table.

A good trend line fit (regression) to the safeguard pillar sizes can only be accomplished by a six or five order polynomial depending on extraction height. The recommended equations for determining the safeguard distance in feet, S_d, given by Equations 30a, 30b, and 30c.

For panel extraction height from 8 ft to 10 ft:

$$S_d = -5.152 \times 10^{-16} * D^6 + 2.2777 \times 10^{-12} * D^5 - 3.9427 \times 10^{-9} * D^4 + 3.3870 \times 10^{-6} * D^3 - 1.5849 \times 10^{-3} * D^2 + 0.49282D - 12.628$$

<div align="right">Equation 30a</div>

For panel extraction height from 6 ft to 8 ft:

$$S_d = -5.0738 \times 10^{-13} * D^5 + 1.4314 \times 10^{-9} * D^4 - 1.4715 \times 10^{-6} * D^3 + 5.7515 \times 10^{-4}D^2 + 0.034234D + 20.138$$

<div align="right">Equation 30b</div>

For panel extraction height less than 6 ft:

$$S_d = -7.7206 \times 10^{-15} * D^6 + 2.1431 \times 10^{-11} * D^5 - 2.3606 \times 10^{-8} * D^4 + 1.3139 \times 10^{-5} * D^3 - 4.0041 \times 10^{-3} * D^2 + 0.73591D - 23.763$$

<div align="right">Equation 30c</div>

where D is the maximum depth of the seam, in feet, anywhere within an angle of 20 degrees from the well. These computations are sensitive to, and should be used with, the significant figures shown.

A corresponding pillar size for an individual well can be determined by doubling the safeguard distance so as to represent a centrally located well point equidistant from the pillar edge.

The safeguard pillar size varies with mine depth and extraction height. A table of recommended safeguard distances and minimum pillar widths follows:

Extraction Height (ft):	Safeguard Dimension (ft)					
	Less than 6		6 to 8		8 to 10	
Mine Depth (ft)	Distance	Minimum Pillar Width	Distance	Minimum Pillar Width	Distance	Minimum Pillar Width
200 to 300	50	95	55	110	60	115
300 to 400	55	110	65	155	70	140
400 to 600	65	125	85	170	90	175
600 to 800	65	125	85	170	100	200
800 to 1,000	60	120	85	170	105	205
1,000 to 1,200	-	-	85	165	105	210
1,200 to 1,470	-	-	-	-	105	210

Note - the minimum pillar width assumes a single, centrally located well.

The safeguard pillar size varies with mine depth and extraction height as shown on Figure 11, following this text, where it is compared to the 1957 recommendations. The comparison shows that at depths shallower than 600 ft, the safeguard pillar sizes are in general agreement with the step function recommendations of the 1957 study, particularly for extraction heights between 8 ft to 10 ft. For pillars deeper than 600 ft, the safeguard pillars are smaller than those recommended by the 1957 study.

At certain depths, the effects of subsidence are so dissipated that the strain cannot reach the allowable limit and the safeguard distance is no longer the controlling factor. At depths shallower than 650 ft, the safeguard distance controls the pillar size in all mine configurations. At depths greater than 1,460 ft the safeguard distance is not the key consideration and appropriate pillar strength designs (e.g., ALPS or ARMPS) can be employed for sizing of the protective gas well pillar.

At depths between 650 ft and 1,460 ft, the consideration of safeguard distance over the pillar strength design is dependent on extraction height and mine configuration.

The preceding table of recommended safeguard distance and minimum pillar width is applicable for pre-subsidence situations (i.e., where subsidence is planned to occur). In non-subsidence situations (i.e., where subsidence is not planned or has already occurred by prior mining) the required minimum pillar width can be determined by appropriate pillar strength design methods (e.g., ALPS or ARMPS).

7.3 Comparison of Recommendations to 1956 Data

Figure 12, following this text, illustrates the recommended safeguard pillar size compared to the well failure data used to develop the 1957 recommended pillar protection size. The comparison shows the distribution of the data and demonstrates that the updated recommendation for the safeguard pillar better fits the original data than the 1957 recommendations. While the recommendations appear to honor the failure data, the disparity is that most failures in the 1956 data occurred at, or close to, mine level, while the safeguard pillars in this update are based on potential failure that can occur at or near the ground surface.

7.4 Longwall Gate Pillars

To compare and integrate the recommended safeguard pillar width to the results of ALPS, the following inputs into ALPS are applied to present a maximal case (largest gate pillar) for a Pennsylvania longwall:

- Panel width of 2,000 ft. This width is within sight of present technology and greater widths should not affect protection pillar size recommendations.

- 10-ft pillar height, 90 degrees cross cut angle, and 20-ft wide openings (entries and crosscuts).

- Square pillar configuration.

- Gate roads analyzed as a two-entry system to account for any loss of strength of the non-protective pillars in the gate road.

- Pillars are subjected to isolated loading, a NIOSH term to describe the gate load which includes the development load and two side abutment loads from the first and second longwall.

The NIOSH recommends a stability factor of 1.3 for gate road and bleeder protection pillars but because of the long-term requirement of a well protection pillar, BOYD applies an increased stability factor of 1.5.

A stability factor of 1.3 is correlated with a CMRR of 32. If the pillar area being designed has a stronger roof, it is not recommended to reduce the stability factor below 1.5 because of the permanency of the protective pillar.

Longwall bleeder protection pillar sizes are similarly established through ALPS and are illustrated for comparison in Figure 13, following this text, with the gate pillar sizes developed with the Wilson equation for gate road pillars, and the 1957 pillar recommendations.

The Wilson equation pillar results are derived using similar loading conditions as in the ALPS analysis. A safety factor of 2.0 is used to determine the protection pillar size by using the strength data from the Upper Freeport and Pittsburgh Seams from Pennsylvania sites. The analytical approach of the Wilson equation results in pillars that are smaller than those recommended by ALPS. This is expected noting the conservatism inherent and needed in developing empirical approaches.

Figure 13 also presents the pillar foundation requirements using input parameters from the Upper Freeport Seam in the Terzaghi equation and employing a safety factor of 2.0. An obvious outcome of these is the demonstration of how conservative ALPS and the 1957 recommendations are when compared to the analytically derived pillar sizes (Wilson and Terzaghi formulas).

The recommended longwall gate road and bleeder protection pillars are shown in Figure 14, following this text. The recommended pillar sizes are derived according to the safeguard distance up to the depth at which stresses do not reach the allowable limits for a well, after which ALPS can be used to determine the well pillar minimum width requirements. For gate road and bleeder pillars, the safeguard distance will control the width of the protection pillar up to a depth of 720 ft while pillar strength will be the determining factor at depths over 1,400 ft. Between the depth range of 720 ft to 1,400 ft, the mine configuration and extraction thickness will govern whether the safeguard distance or pillar strength controls the determination of pillar width.

7.5   Room-and-Pillar

BOYD developed three sets of protection pillar recommendations for room-and-pillar mining based on whether the well is located in a non-retreat panel, a retreat panel, or a barrier pillar. To present a maximal case (largest pillar) for a Pennsylvania room-and-pillar situation, the following inputs into ARMPS are applied:

- Equal area loading.
- 10-ft pillar height, 90 degrees cross cut angle, and 20-ft wide openings (entries and crosscuts).
- Square pillar configuration.
- 10 entries per panel.
- For retreat panels:
    - Two side gobs assumed and both are 2,000 ft wide.
    - Active gob of 6,000 ft length.

- No bleeder pillar or slab cut.

- All default parameters of ARMPS are maintained.

- A stability factor of 1.5 is applied for barrier pillars between panels (not including the barrier pillars surrounding a well).

For all room-and-pillar section recommendations, protective well pillars were designed at 0.5 above the NIOSH suggested stability factors because of the long-term nature of these pillars. The NIOSH recommended stability factor is 1.5 for mines shallower than 650 ft and 0.9 for pillars having more than 1,250 ft of overburden. For pillars at depths between 650 ft and 1,250 ft, the stability factor is scaled. NIOSH cautions that at depths greater than 1,000 ft, there is risk of pillar failure when the pillar stability factor is less than 1.5 for panels wider than 425 ft wide, which is assumed here. Thus, for this analysis, BOYD applied stability factors of 2.0 up to a depth of 650 ft, 1.5 for pillars over 1,250 ft, and scaled the stability factor between 650 ft and 1,250 ft of depth.

The recommended well pillar sizes for room-and-pillar mining are shown in Figure 14. The recommended pillar sizes are derived according to the safeguard distance up to the depth at which stresses do not reach the allowable limits for a well, after which ARMPS can be used to determine the well pillar minimum width requirements. For pillars in a room-and-pillar panel, the safeguard distance will control the width of the protection pillar up to a depth of 780 ft while pillar strength will control the determination where deeper than 1,470 ft. Between the range of 780 ft to 1,470 ft, the mine configuration and extraction thickness will govern whether the safeguard distance or pillar strength controls the determination of pillar width.

8.0   Recommendations

BOYD recommends that the design of a protective pillar surrounding a gas or oil well address two concerns:

- The pillar has to be wide enough to reduce the effects of subsidence to a point where stresses are below the allowable stress for the casing. This is referred to in this study as the safeguard pillar width.

- The pillar has to be strong enough for long-term stability.

To address the need for protective pillar sizes that can be applied to variably spaced multiple wells (clusters), recommendations are based on a safeguard distance. The safeguard dimension represents the minimum distance from any single well (isolated or

in a cluster) to the mine opening that is susceptible to caving. This opening can be located at the limit line of secondary recovery (defined by the extent of excavation for a longwall or retreat room-and-pillar panel) or, adjacent to a pillar not designed to the recommended stability factors to resist equal area loading and abutment loading (e.g., yield pillars).

The minimum width of the safeguard pillar is approximately twice the safeguard distance provided the well can be located at the center of the pillar. Deviation from the center location will require a larger pillar that can maintain this safeguard distance. Placement at the center of the minimum-width safeguard pillar is required to reduce the well's exposure to horizontal (shearing) movement. This horizontal movement can occur in the coal (as the pillar adjusts to the added load resulting from adjacent mining), and in the floor (if pillar foundation failure occurs).

To provide the means to determine the safeguard dimensions, BOYD developed three equations (Equations 30a, 30b, and 30c) according to extraction height and having mine depth as an input variable. A look-up table is also provided as follows:

Extraction Height (ft):	Safeguard Dimension (ft)					
	Less than 6		6 to 8		8 to 10	
Mine Depth (ft)	Distance	Minimum Pillar Width	Distance	Minimum Pillar Width	Distance	Minimum Pillar Width
200 to 300	50	95	55	110	60	115
300 to 400	55	110	65	155	70	140
400 to 600	65	125	85	170	90	175
600 to 800	65	125	85	170	100	200
800 to 1,000	60	120	85	170	105	205
1,000 to 1,200	-	-	85	165	105	210
1,200 to 1,470	-	-	-	-	105	210

Note: the minimum pillar width assumes a single, centrally located well.

If a post mining well enters a protection pillar after movement due to subsidence has ceased, the safeguard distance is not the key determinant. The key requirement for the protection pillar is its strength for long-term stability.

The protective pillar around the well must remain stable over the long term because a failure of the protective pillar would likely crush or rupture the casings and pipe. To determine the protective pillar size for long-term support, BOYD recommends the empirical approach as developed in the latest version of ALPS or ARMPS. These programs employ the Mark-Bieniawski pillar equation.

A stability factor of 1.5 is to be applied when using ALPS in such cases. This is greater than the NIOSH recommended stability factor of 1.3 for gate road and bleeder pillars because of the long-term stability requirement of a well protection pillar.

For all room-and-pillar mining, the protective well pillar size determined by ARMPS is to be based on stability factors greater than those otherwise suggested by NIOSH because of the long-term nature of these pillars. The recommended stability factor is then 2.0 at depths shallower than 650 ft and 1.4 for pillars having more than 1,250 ft of overburden. For pillars at depths between 650 ft and 1,250 ft, the stability factor is scaled. NIOSH cautions that for panels wider than 425 ft, and where deeper than 1,000 ft, there is risk of pillar failure when the stability factor is less than 1.5. Thus, for these cases, BOYD recommends a stability factor of 2.0 up to a depth of 650 ft, 1.5 for pillars over 1,250 ft deep, and a scaled stability factor between 650 ft and 1,250 ft of depth.

When retreat mining is practiced and the well protection pillar is on the retreat line, the pillar recovery should stop at or before the out-by crosscut, maintaining all pillars along a perpendicular retreat line. If the retreat is re-established out-by, the protective pillar will be susceptible to a second abutment load, and this load must be considered when designing the protection pillar.

In these procedures, the protection pillar size is calculated based on both the adverse effects of subsidence (safeguard distance) and the required pillar strength. The largest of the calculated pillars is chosen as the recommended protection pillar size. In general, subsidence effects (i.e., safeguard distance) will control the width of the protection pillar up to a depth of 650 ft while pillar strength will control the determination where deeper than 1,470 ft. Between the range of 650 ft to 1,470 ft, the mine configuration and extraction thickness will govern whether the safeguard distance or pillar strength controls the determination of pillar width.

A deviation survey of the wellbore from surface to the base of the coal seam is recommended, with the surveyed location of the well at the level of the coal translated to the mine coordinate system, to verify the location of the wellbore at the level of the coal.

9.0   Other Considerations

The recommended safeguard dimensions provided in this report represent setback distances from secondary (retreat) mining at which no adverse subsidence effects to an

active well (producing or capable of producing) are expected. The following alternate situations exist when the recommended safeguard limit would not apply:

1. **A well is adequately plugged in advance of mining**. Potential impacts to a wellbore from mine subsidence are expected up to several hundred feet above the coal seam. Potential impacts due to compression could occur within or just beneath the coal seam. Plugging the well below the coal seam prior to the advance of mining will mitigate the risks due to potential impacts of subsidence and compression regardless of the well configuration above the coal. Prior to being placed back into production following mining, a well should demonstrate good mechanical integrity. Integrity testing should be conducted following the majority of post-mining subsidence.

    Typically, minor non-damaging subsidence movements will be completed two years after total extraction. However, the damaging effects of subsidence from any particular panel will typically be complete within a few weeks after mining once the retreating mine face has progressed a distance of 1.2 × Depth.

2. **A site-specific engineering analysis is performed, demonstrating that a well not meeting the safeguard distance would maintain adequate mechanical integrity during and following mining.** The Pad NV-35 Experiment involved test wells that did not meet the recommended safeguard distance. While the effects of mining were experienced in the test wells, the test results indicated that wellbore components inside the coal protective casing would not have been adversely impacted during or after subsidence if the annular space inside the mine string was uncemented. In addition, the finite element analysis correctly predicted the deformation observed in the coal protective casing. The experiment demonstrates the appropriateness of a finite element modelling approach to protection pillar design as an alternative to application of the safeguard distance recommended in this study. If such an approach is adopted, the analysis should include the following:

    - The geology must be well established in the overburden, through the target seam, and a minimum of 20 ft below the seam. At a minimum a detailed geologic log and geophysical logs of a core hole should be employed.

    - A finite element analysis should follow a procedure similar to that undertaken by CONSOL during the Pad NV-35 Experiment.

    - The finite element analysis should be calibrated based on movement within the casing.

3. **Drilling in a pillar after mining has occurred.** In situations where mining precedes the well installation and ground movement has ceased, the well will not be exposed to the changing stress fields. The consideration of safeguard distance for mitigation of subsidence effects is not applicable to these situations.

In the alternate situations described above, where the recommended safeguard distance is not observed, it is important that the pillar containing the well and supporting the overburden meets the minimum size required for long-term pillar stability as determined by ALPS or ARMPS, applied as described in section 8.0 of this report. Further, it is important that the well be located a reasonable distance from the edge of the pillar. The recommended minimum setback distance from a well to the edge of the pillar in these alternate situations is at least one-third of the least pillar width from the rib (edge) of the pillar and at least 2.5 times the pillar height from the rib (edge) of the pillar.

A deviation survey of the wellbore from surface to the base of the coal seam is recommended, with the surveyed location of the well at the level of the coal translated to the mine coordinate system, to verify the location of the wellbore at the level of the coal.

The Pad NV-35 Experiment (section 5.6) and the Alpha experience (section 5.1) show that stress at coal level and in the underclay can cause considerable yielding in the casings. The use of ALPS and ARMPS at the higher stability factors, as suggested here, will eliminate this concern for typical floor conditions in Pennsylvania. However, for protection pillars with abnormally weak floor conditions, it should be determined that the coal protection and intermediate casing, along with the production pipe will not exceed acceptable total strain (section 6.2) or collapse pressure (section 6.1).

Based on the results of the Pad NV-35 Experiment, and other factors discussed elsewhere in this report, it is clear that leaving sufficiently wide uncemented annuli around inner casings (i.e., casings inside the coal protection casing), from below the coal (minimum of 30 ft) to the surface, will reduce the risk of adverse impact to such inner casings during or following mining operations. Suitable muds, gels or other fluids in the uncemented annular space would prevent deformation at the coal protection casing from being transmitted to inner casings.

This report does not address situations of drilling into active, closed, or abandoned mines where specific evaluations should be made according to the conditions at mine level. Future study should be made to address risk issues and mitigation measures for drilling through gob areas or uncharted mine workings.

The recommendations of this report are applicable to active and inactive wells. They are also applicable to plugged wells having undocumented plugging procedures or those

otherwise plugged but not intended for mining through. Protective pillars are inessential where wells are plugged in accordance with PADEP regulations for mining through.

Following this page are:

Figures:
1: Underground Mine Map, Portion of 3 - Left Section, Cumberland Mine.
2: Predicted Horizontal Slip Due to Longwall Mining.
3: Predicted Horizontal Shear Stress Due to Longwall Mining.
4: Predicted Vertical Shear Stress Due to Longwall Mining.
5: Deformations Located on Caliper Log.
6: TW #3 and TW #4 Deformation After Mining E-25 Panel at 390 ft Depth.
7: Overburden Monitoring Plot for Movements Resulting from Both Longwalls E-24 and E-25.
8: Test Well Deformations from Longwall E-24 Determined by ABAQUS.
9: Test Well Deformations from Longwall E-25 Determined by ABAQUS.
10: Movement and Distortion in a Two Dimension Vertical Plane Due to Subsidence.
11: Recommended Safeguard Pillar and 1957 Study Recommendations.
12: 1957 Study Results and Well Failure Data Compared to Updated Recommendations.
13: Comparison of Gate Road Pillar for Bieniawski and Wilson Equations.
14: Recommended Longwall and Room-and-Pillar Well Protection Pillars.

Appendices:
A: Joint Coal and Gas Committee, Gas Well Pillar Study
B: Pad NV-35 Field Experiment
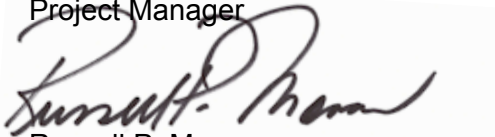
Respectfully submitted,

JOHN T. BOYD COMPANY
By:

Vincent A. Scovazzo
Project Manager

Russell P. Moran
Vice President

FIGURE 1

UNDERGROUND MINE MAP
PORTION OF 3 - LEFT SECTION
CUMBERLAND MINE
PITTSBURGH SEAM
ALPHA NATURAL RESOURCES, INC.
Greene County, Pennsylvania

Prepared For
PENNSYLVANIA DEPARTMENT OF
ENVIRONMENTAL PROTECTION
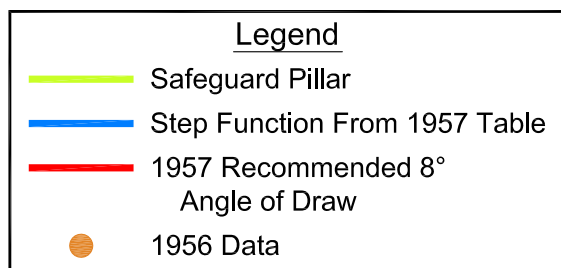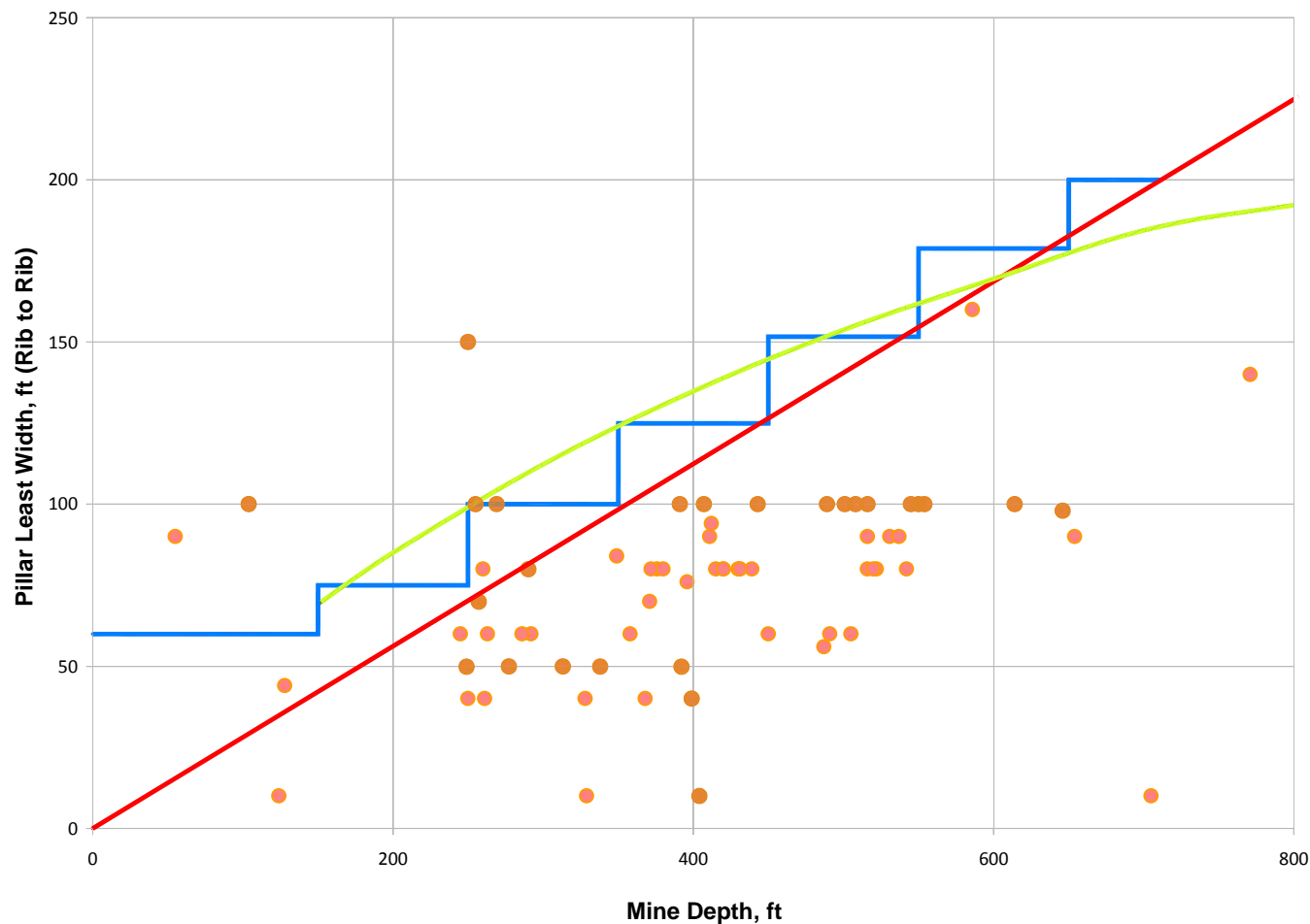BUREAU OF OIL AND GAS MANAGEMENT

John T. Boyd Company

March 2016
Scale 1" = 400'

Legend

Underground Mine Workings

Longwall Panels

Direction of Longwall Mining

CR9407   Drill Hole Locations

W-510   Gas Well Location

—900—   Overburden Contours (ft)

Note : Base Map Provided by Alpha Natural Resources, Inc.
with Additions by John T. Boyd Company.

SCALE (ft)
400 300 200 100 0   200   400

P:\CAD_GROUP—jfg\3577.001\FIGURE 1.DWG

Note, Sandy Shale Sequence contains the Deep Valley Sandstones and Middle Washington Limestone.

FIGURE 2

PREDICTED HORIZONTAL SLIP DUE TO LONGWALL MINING

Prepared For

PENNSYLVANIA DEPARTMENT OF ENVIRONMENTAL PROTECTION BUREAU OF OIL AND GAS MANAGEMENT

John T. Boyd Company

March 2016
Scale as Shown
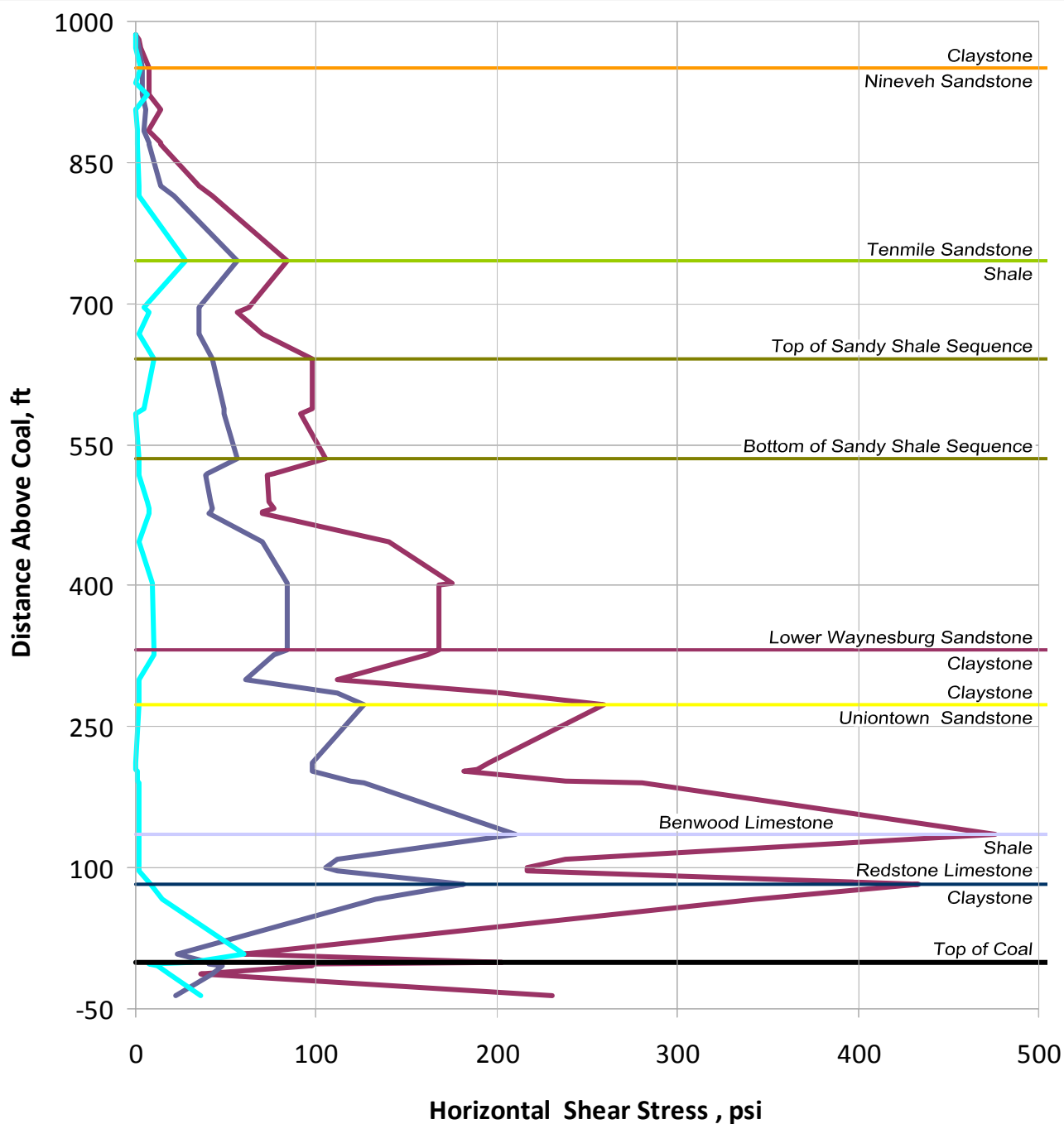
Note, Sandy Shale Sequence contains the Deep Valley Sandstones and Middle Washington Limestone.
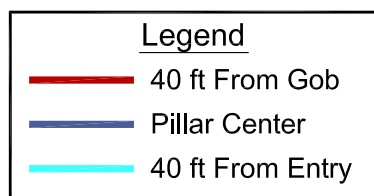
FIGURE 3

PREDICTED HORIZONTAL SHEAR STRESS DUE TO LONGWALL MINING

Prepared For

PENNSYLVANIA DEPARTMENT OF ENVIRONMENTAL PROTECTION BUREAU OF OIL AND GAS MANAGEMENT

John T. Boyd Company

March 2016
Scale as Shown

Note, Sandy Shale Sequence contains the Deep Valley Sandstones and Middle Washington Limestone.

Legend

- 40 ft From Gob
- Pillar Center
- 40 ft From Entry
- Change in Stress Above Pillar Center

FIGURE 4

PREDICTED VERTICAL SHEAR STRESS DUE TO LONGWALL MINING

Prepared For

PENNSYLVANIA DEPARTMENT OF ENVIRONMENTAL PROTECTION BUREAU OF OIL AND GAS MANAGEMENT

JB John T. Boyd Company

March 2016
Scale as Shown
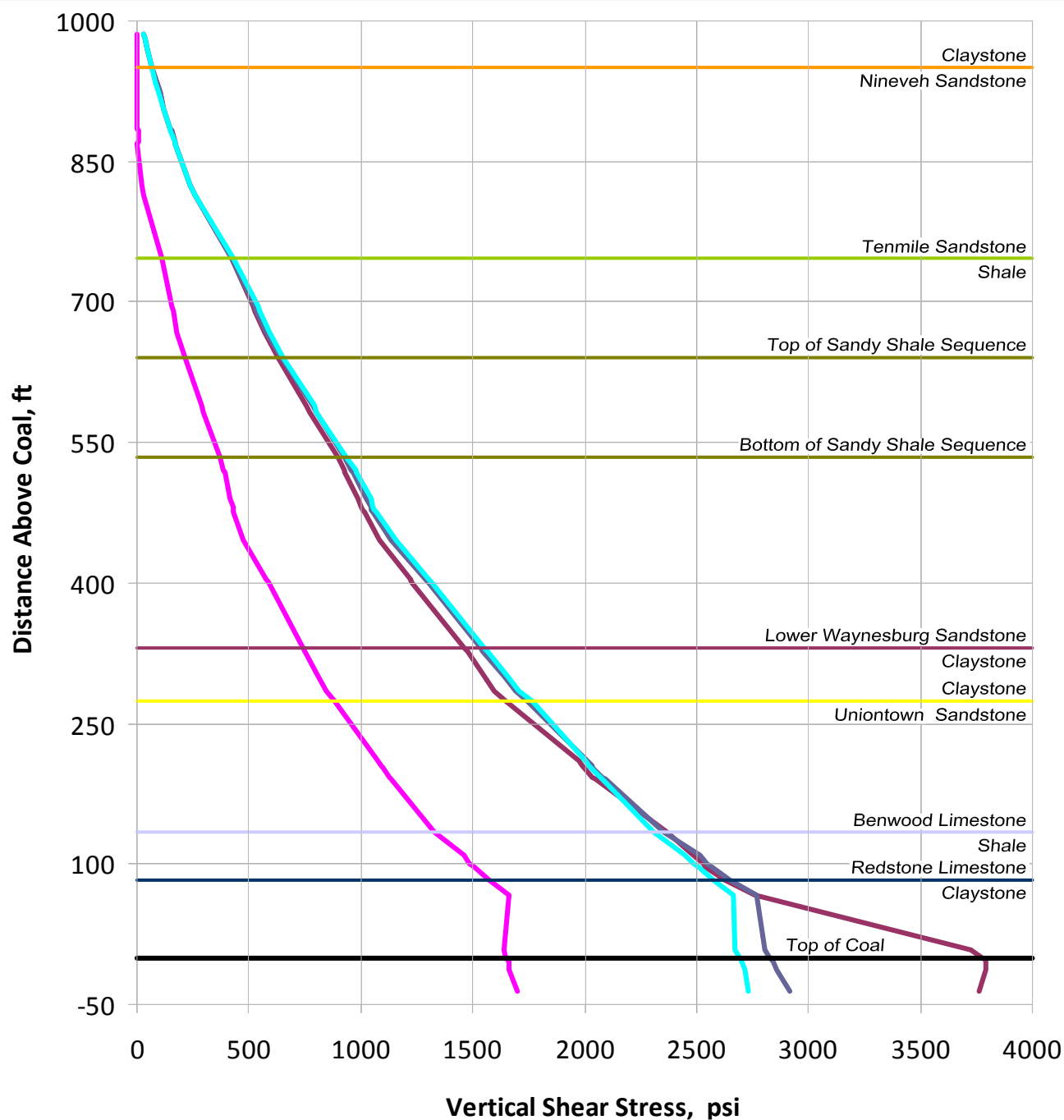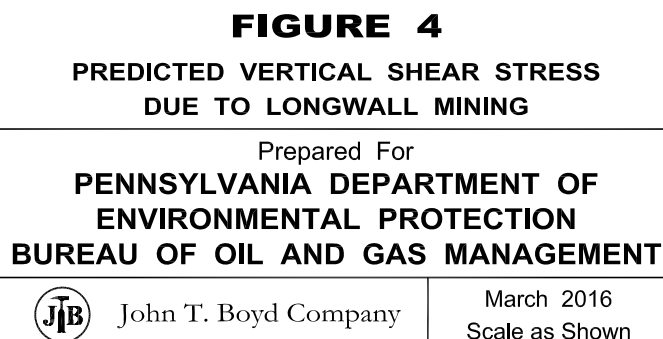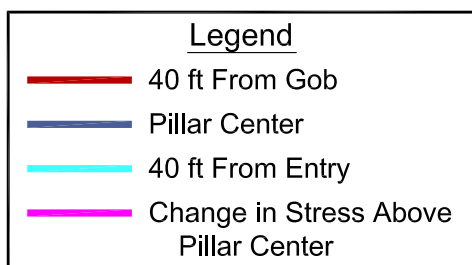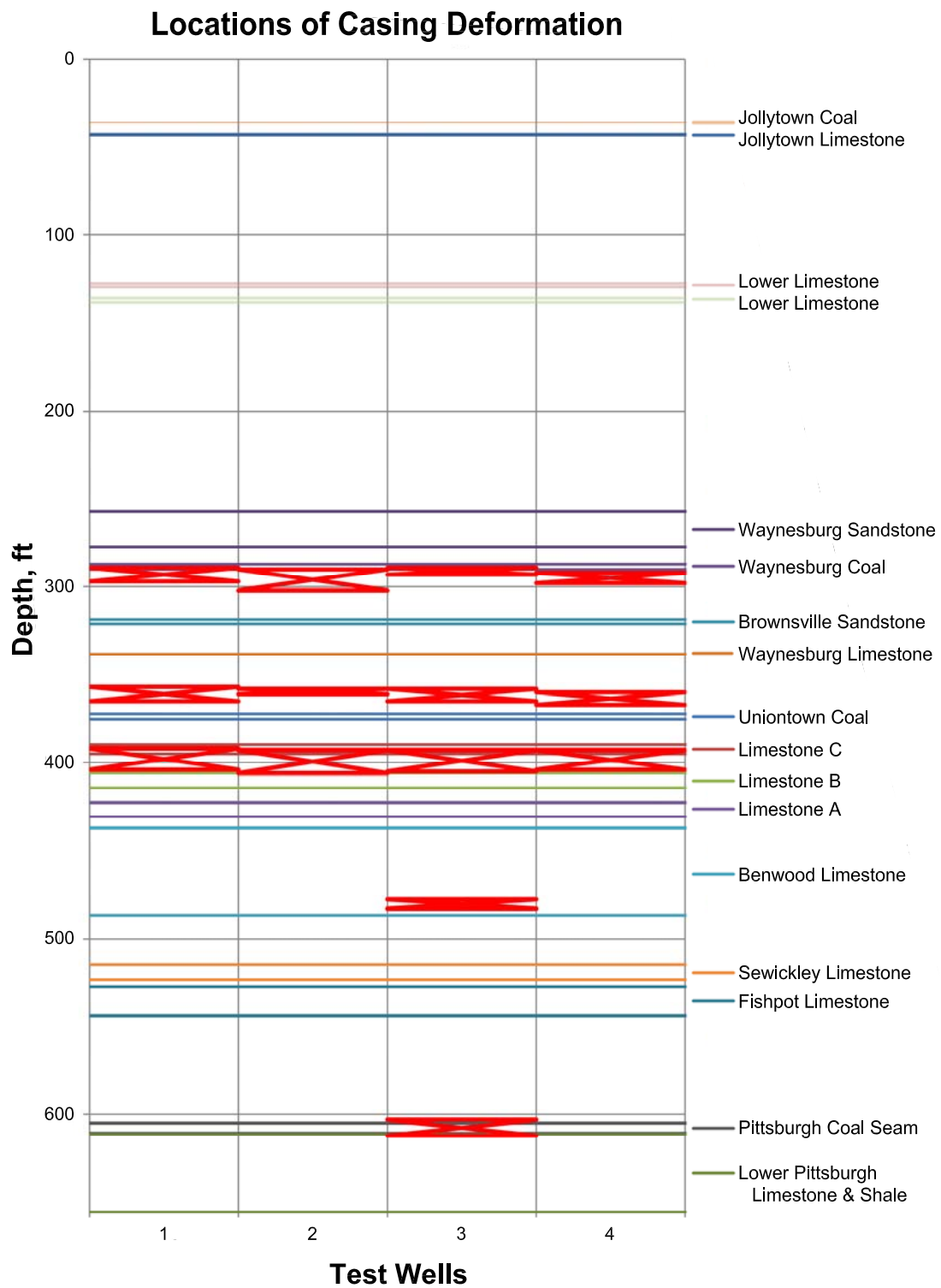
FIGURE 5

DEFORMATIONS LOCATED
ON CALIPER LOG

Prepared For
PENNSYLVANIA DEPARTMENT OF
ENVIRONMENTAL PROTECTION
BUREAU OF OIL AND GAS MANAGEMENT

John T. Boyd Company

March 2016
Scale as Shown

Well Name: NV-35 \ WH-03
Depth: 389.343 - 405.920
Deviation Magnification: 1
Radial Magnification: 1
Aspect Magnification: 3
Image Magnification: 1.00
Color Contour:

Well Name: NV-35 \ WH-04
Depth: 388.928 - 405.504
Deviation Magnification: 1
Radial Magnification: 1
Aspect Magnification: 3
Image Magnification: 1.00
Color Contour:

P:\CAD_GROUP—jfg\3577.001\FIGURE 6.DWG
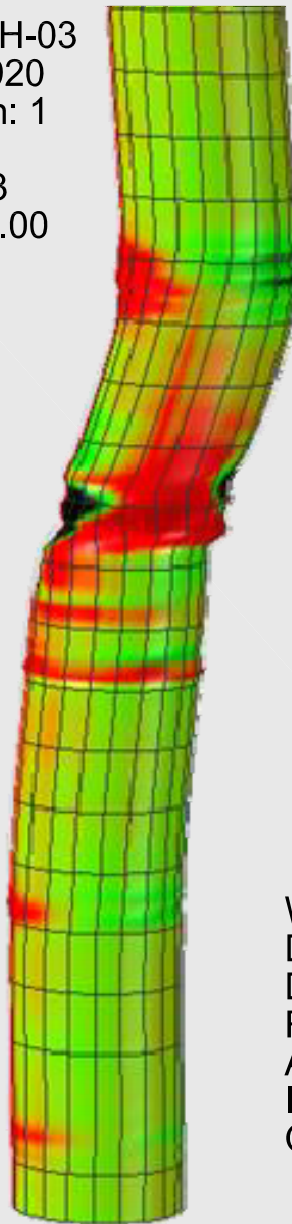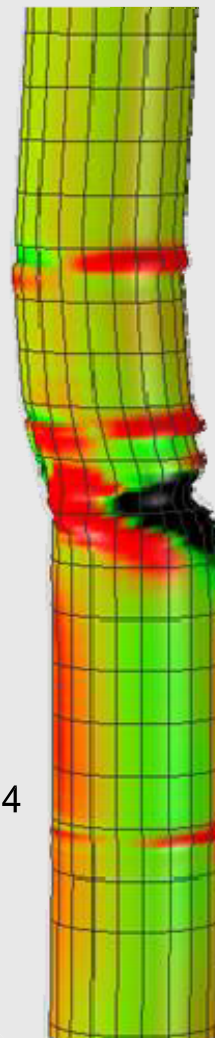
FIGURE 6

**TW #3 AND TW #4 DEFORMATION
AFTER MINING E-25 PANEL
AT 390 ft DEPTH**

Prepared For
**PENNSYLVANIA DEPARTMENT OF
ENVIRONMENTAL PROTECTION
BUREAU OF OIL AND GAS MANAGEMENT**

(JTB) John T. Boyd Company

March 2016
No Scale

Note: Deformation Depictions by Weatherford International PLC.
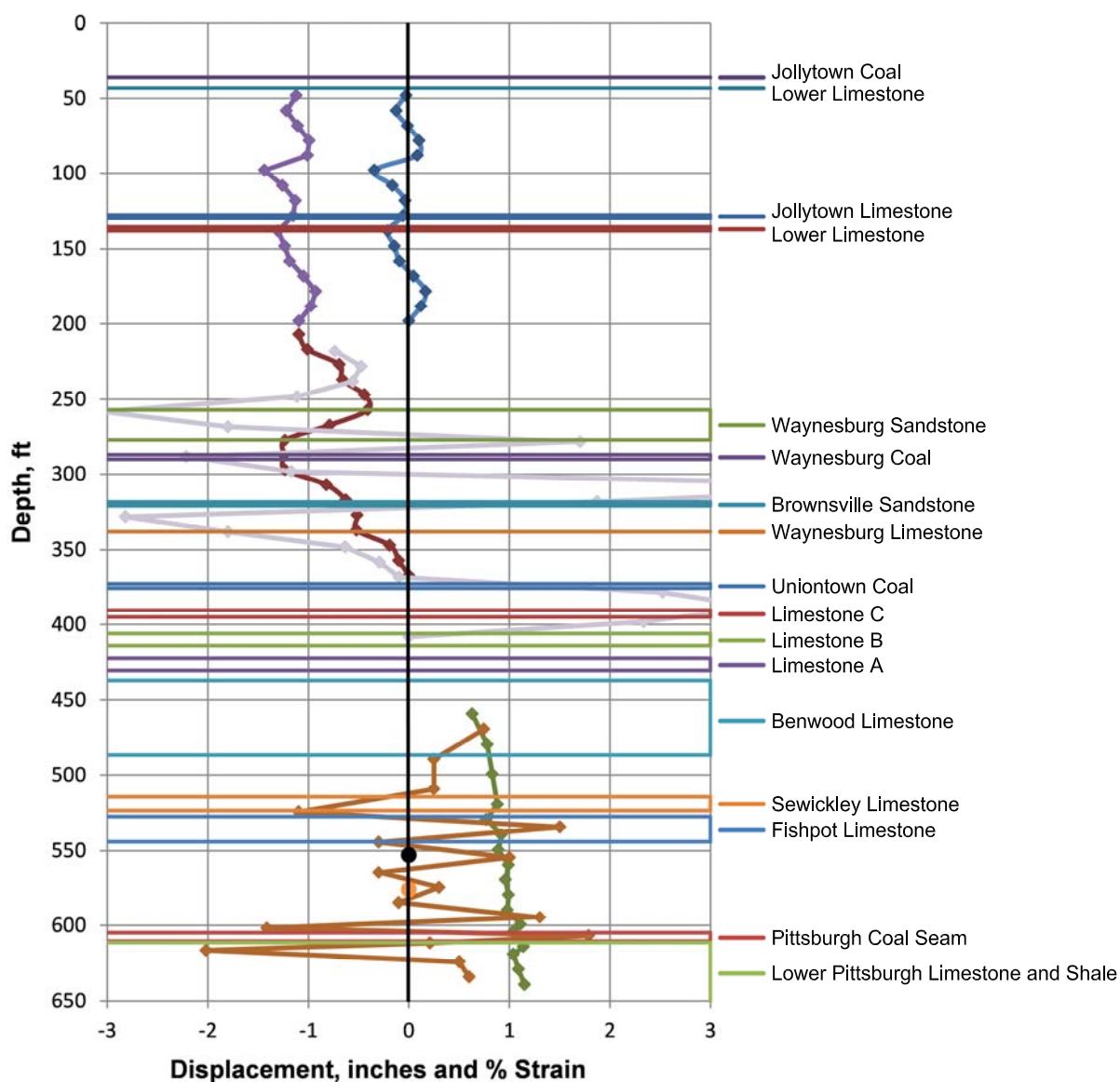
Note, Positive displacement is, as shown on the plot,
towards Longwall E-25 and negative displacement is towards Longwall E-24.

Legend
- Horizontal Displacement MW1 - Inclinometer
- MW1 Adjusted
- Vertical Displacement MW2A - Extensometer
- Vertical Strain MW2A - Extensometer
- Horizontal Displacement MW3 - Inclinometer
- Horizontal Displacement MW4 - Inclinometer
- ● E-24 Angle of Draw
- ● E-25 Angle of Draw

FIGURE 7

OVERBURDEN MONITORING PLOT
FOR MOVEMENTS RESULTING FROM
BOTH LONGWALLS E-24 AND E-25

Prepared For
**PENNSYLVANIA DEPARTMENT OF
ENVIRONMENTAL PROTECTION
BUREAU OF OIL AND GAS MANAGEMENT**

JᴊB John T. Boyd Company

March 2016
Scale as Shown

P:\CAD_GROUP—jfg\3577.001\FIGURE 7.DWG

Test Well #1

Surface

North-South Deformation Along the Deformed Option 1 Casing After E24 Mining

North

390-ft Level

Coal Seam Level

Test Well #2

Surface

North-South Deformation Along the Deformed Option 2 Casing After E24 miming

North

390-ft Level

Coal Seam Level

Test Well #3

Surface

North-South Deformation Along the Deformed Option 3 Casing After E24 Mining

North

390-ft Level

Coal seam Level

Test Well #4

Surface

North-South Deformation Along the Deformed Option 4 Casing After E24 Mining

North

390-ft Level

Coal Seam Level

P:\CAD_GROUP−jfg\3577.001\FIGURE 8.DWG
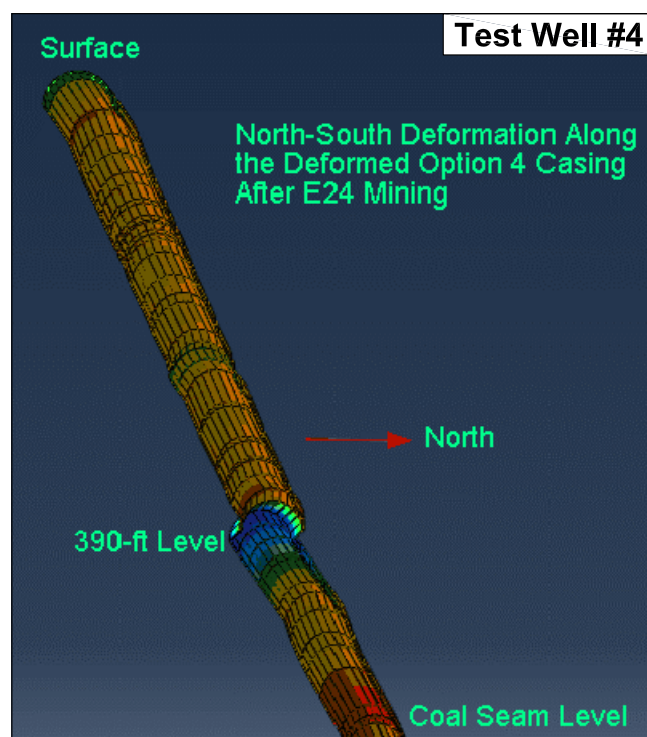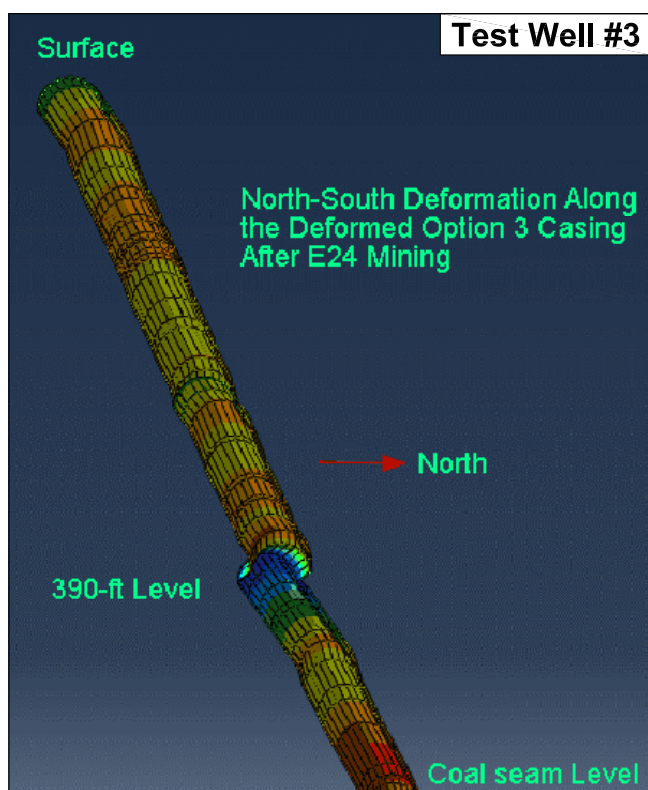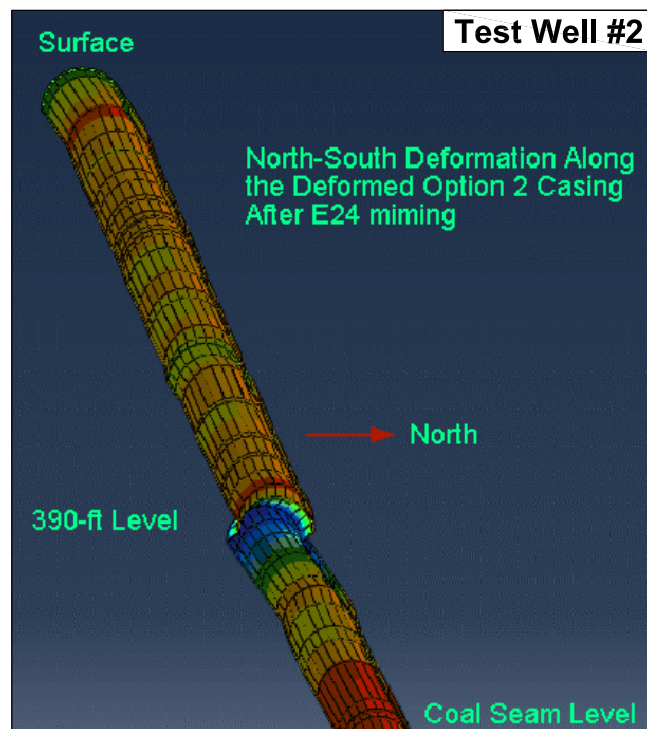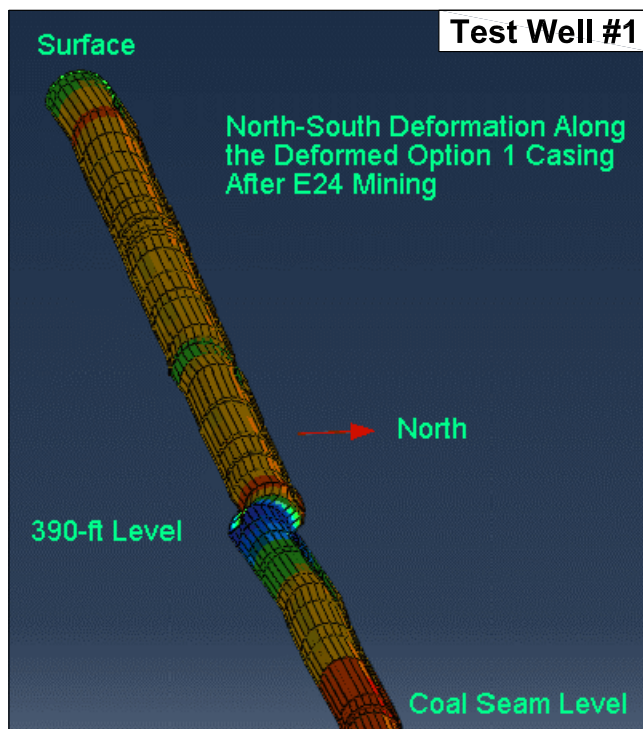
FIGURE 8

TEST WELL DEFORMATIONS FROM LONGWALL E-24 DETERMINED BY ABAQUS

Prepared For

PENNSYLVANIA DEPARTMENT OF ENVIRONMENTAL PROTECTION BUREAU OF OIL AND GAS MANAGEMENT

JB John T. Boyd Company

March 2016
Scale as Shown

Test Well #1

Surface

North-South Deformation Along the Deformed Option 1 Casing After E25 Mining

North

390-ft Level

Coal Seam Level

Test Well #2

Surface

North-South Deformation Along the Deformed Option 2 Casing After E25 miming

North

390-ft Level

Coal Seam Level

Test Well #3

Surface

North-South Deformation Along the Deformed Option 3 Casing After E25 Mining

North

390-ft Level

Coal seam Level

Test Well #4

Surface

North-South Deformation Along the Deformed Option 4 Casing After E25 Mining

North

390-ft Level

Coal Seam Level
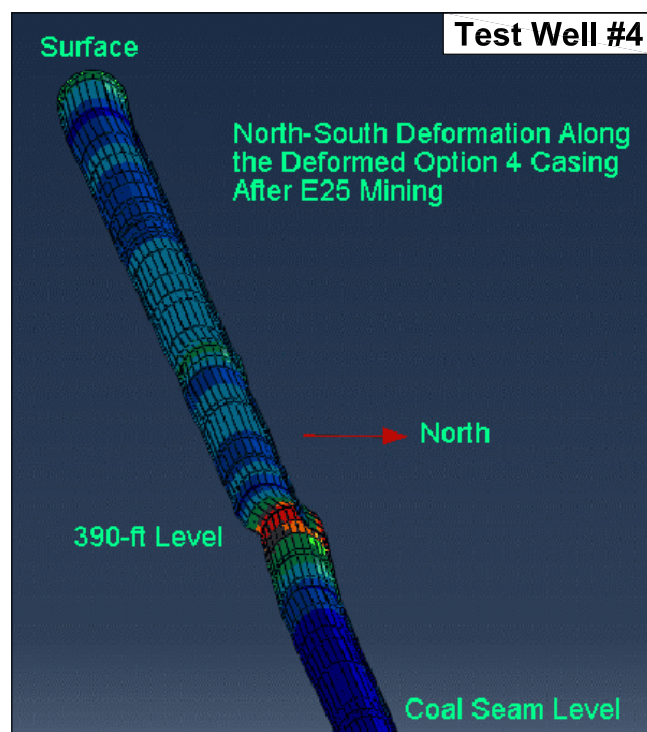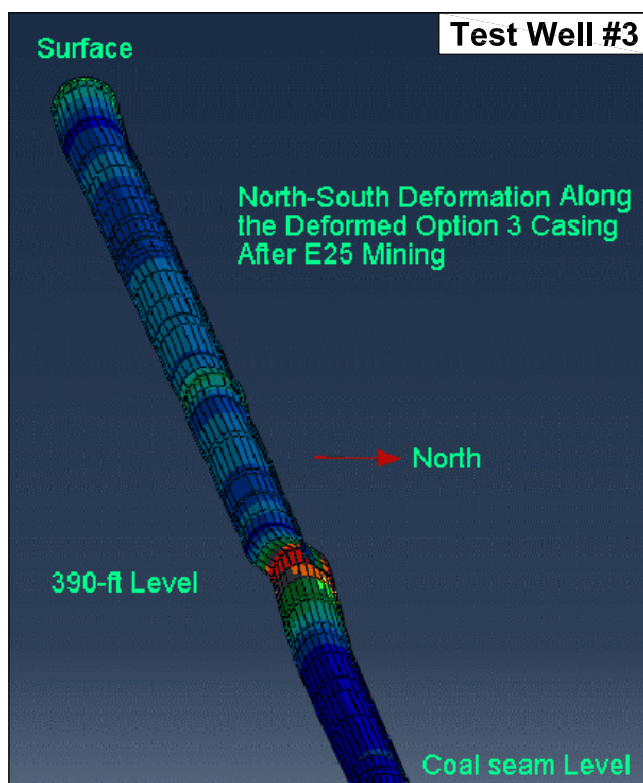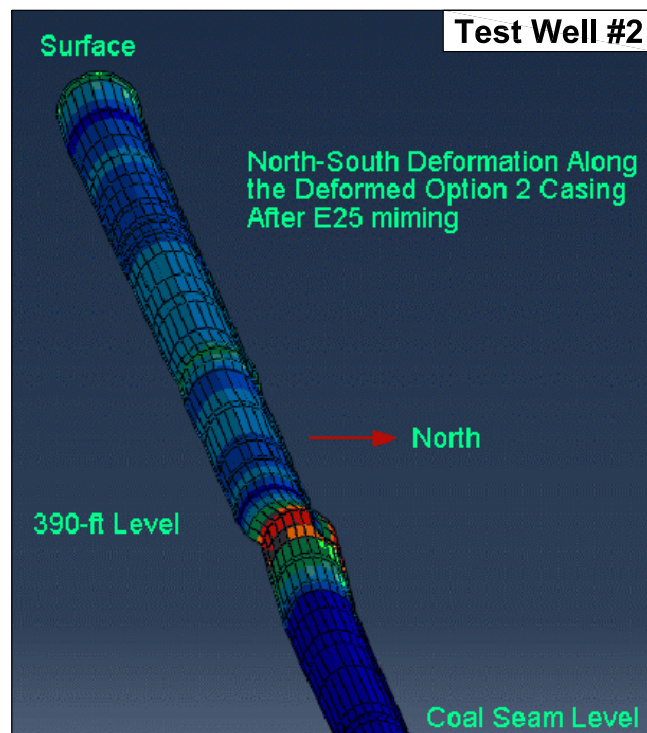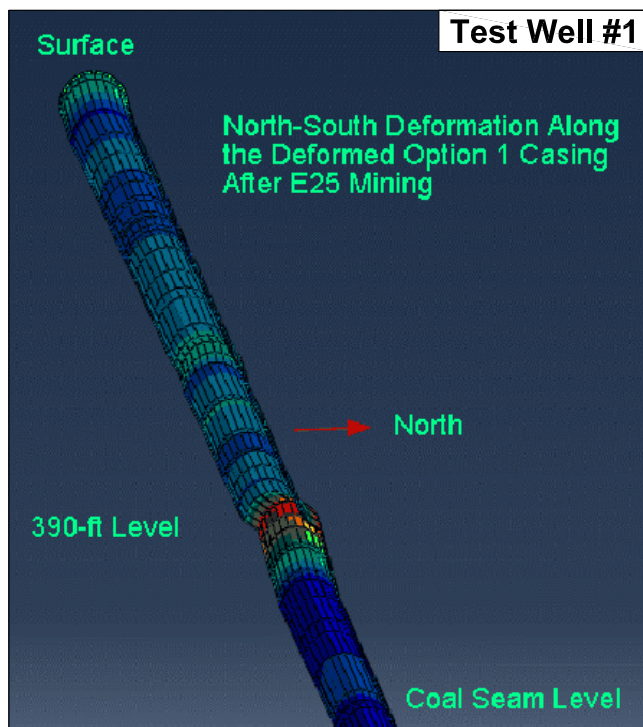
FIGURE 9

TEST WELL DEFORMATIONS FROM LONGWALL E-25 DETERMINED BY ABAQUS

Prepared For

PENNSYLVANIA DEPARTMENT OF ENVIRONMENTAL PROTECTION BUREAU OF OIL AND GAS MANAGEMENT

JTB   John T. Boyd Company

March 2016
Scale as Shown
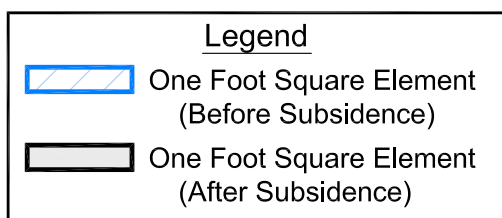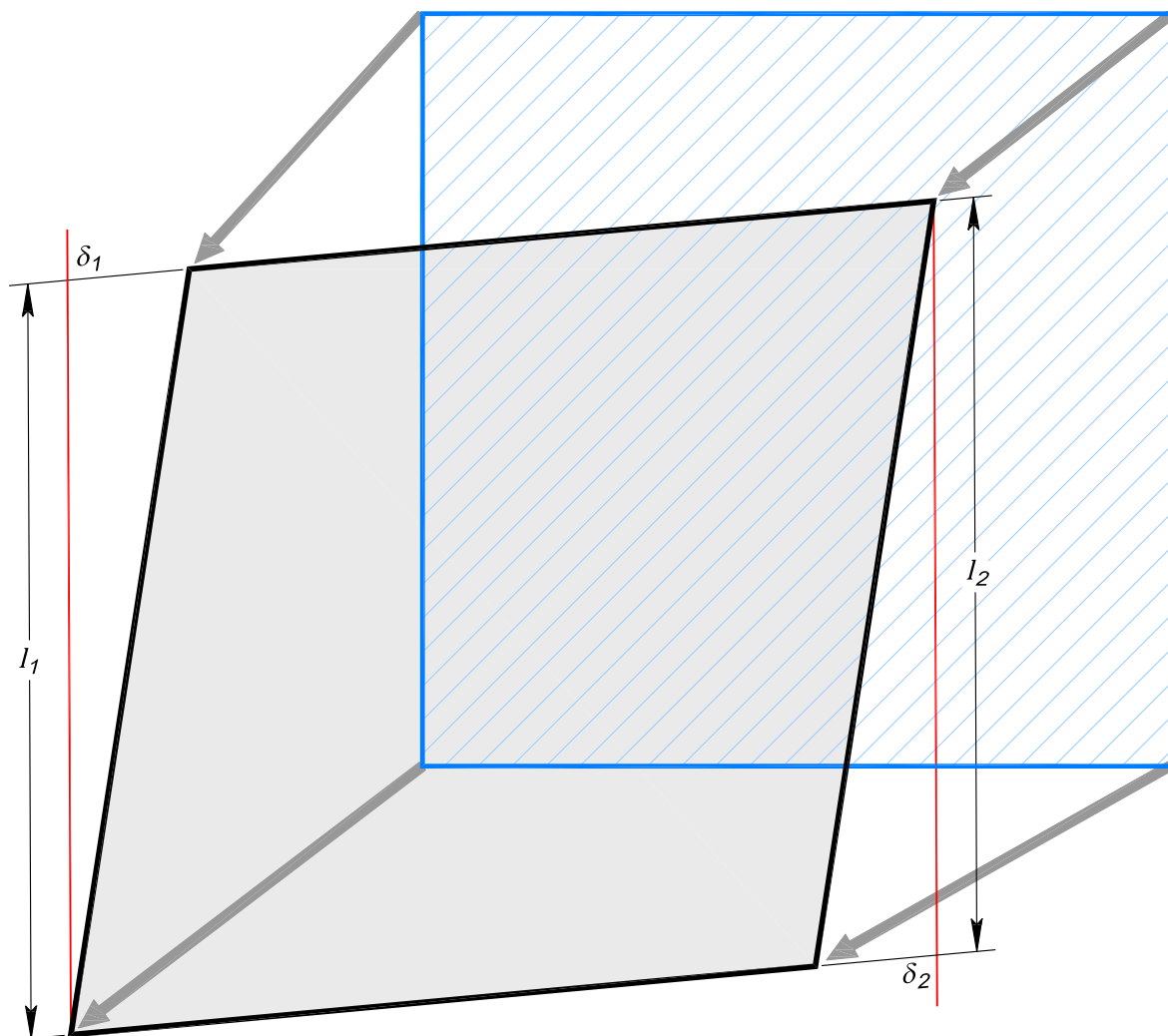
FIGURE 10

MOVEMENT AND DISTORTION IN A
TWO DIMENSION VERTICAL PLANE DUE TO
SUBSIDENCE OF A ONE FOOT SQUARE
ELEMENT (BLUE) TO A NEW POSITION
AND SHAPE (BLACK)

Prepared For
PENNSYLVANIA DEPARTMENT OF
ENVIRONMENTAL PROTECTION
BUREAU OF OIL AND GAS MANAGEMENT

John T. Boyd Company

March 2016
No Scale

Legend
One Foot Square Element
(Before Subsidence)
One Foot Square Element
(After Subsidence)

P:\CAD_GROUP-jfg\3577.001\FIGURE 10.DWG

FIGURE 11

RECOMMENDED SAFEGUARD PILLAR
AND 1957 STUDY RECOMMENDATIONS

Prepared For
**PENNSYLVANIA DEPARTMENT OF
ENVIRONMENTAL PROTECTION
BUREAU OF OIL AND GAS MANAGEMENT**

John T. Boyd Company

March 2016
Scale as Shown
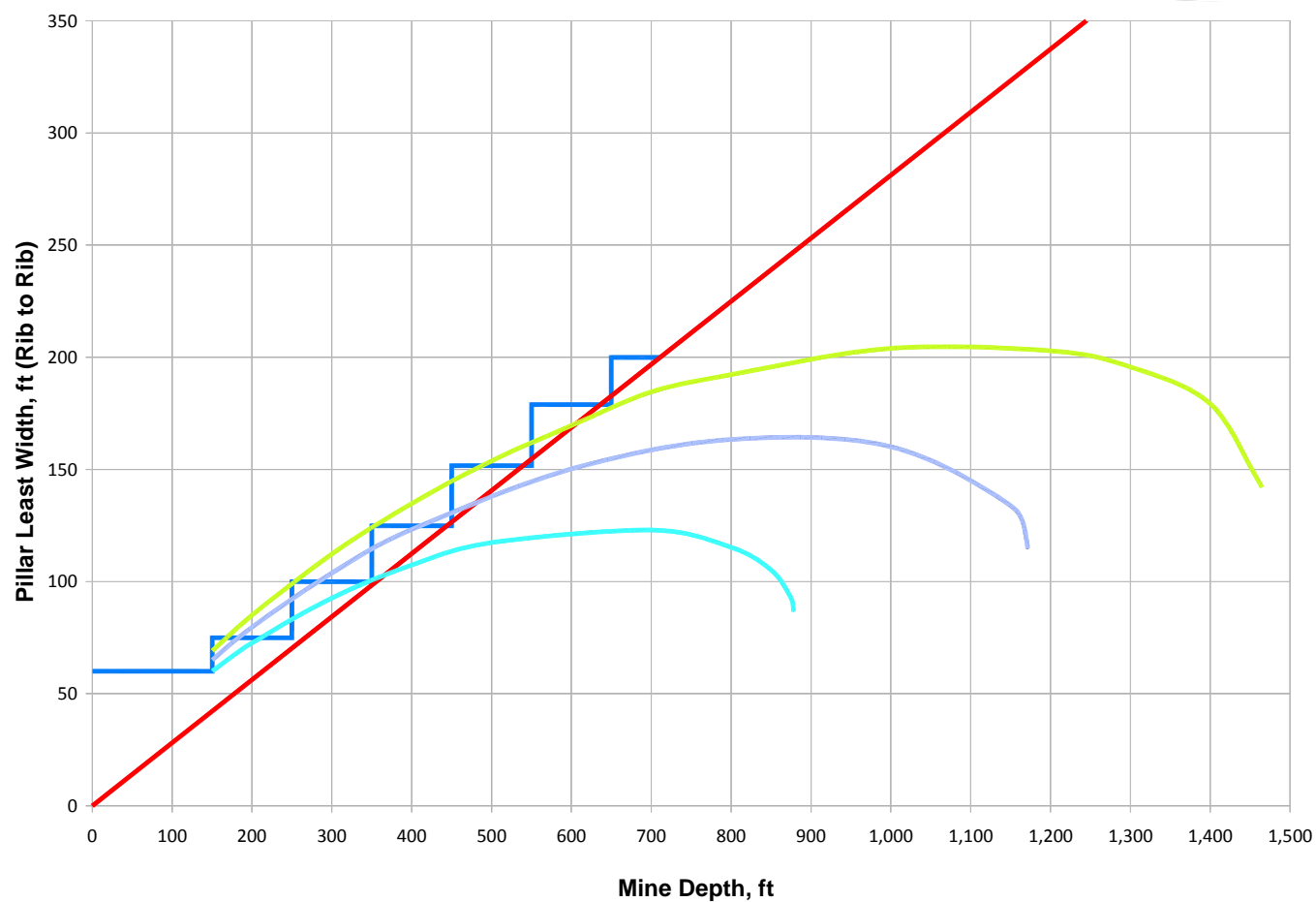
Legend
— Safeguard Pillar, 4 to 6 ft Extraction
— Safeguard Pillar, 6 to 8 ft Extraction
— Safeguard Pillar, 8 to 10 ft Extraction
— Step Function From 1957 Table
— 1957 Recommended 8°
  Angle of Draw

FIGURE 12

**1957 STUDY RESULTS
AND WELL FAILURE DATA COMPARED TO
UPDATED RECOMMENDATIONS**

Prepared For
**PENNSYLVANIA DEPARTMENT OF
ENVIRONMENTAL PROTECTION
BUREAU OF OIL AND GAS MANAGEMENT**

John T. Boyd Company

March 2016
Scale as Shown

Legend
Safeguard Pillar
Step Function From 1957 Table
1957 Recommended 8°
Angle of Draw
1956 Data

P:\CAD_GROUP–jfg\3577.001\FIGURE 12.DWG
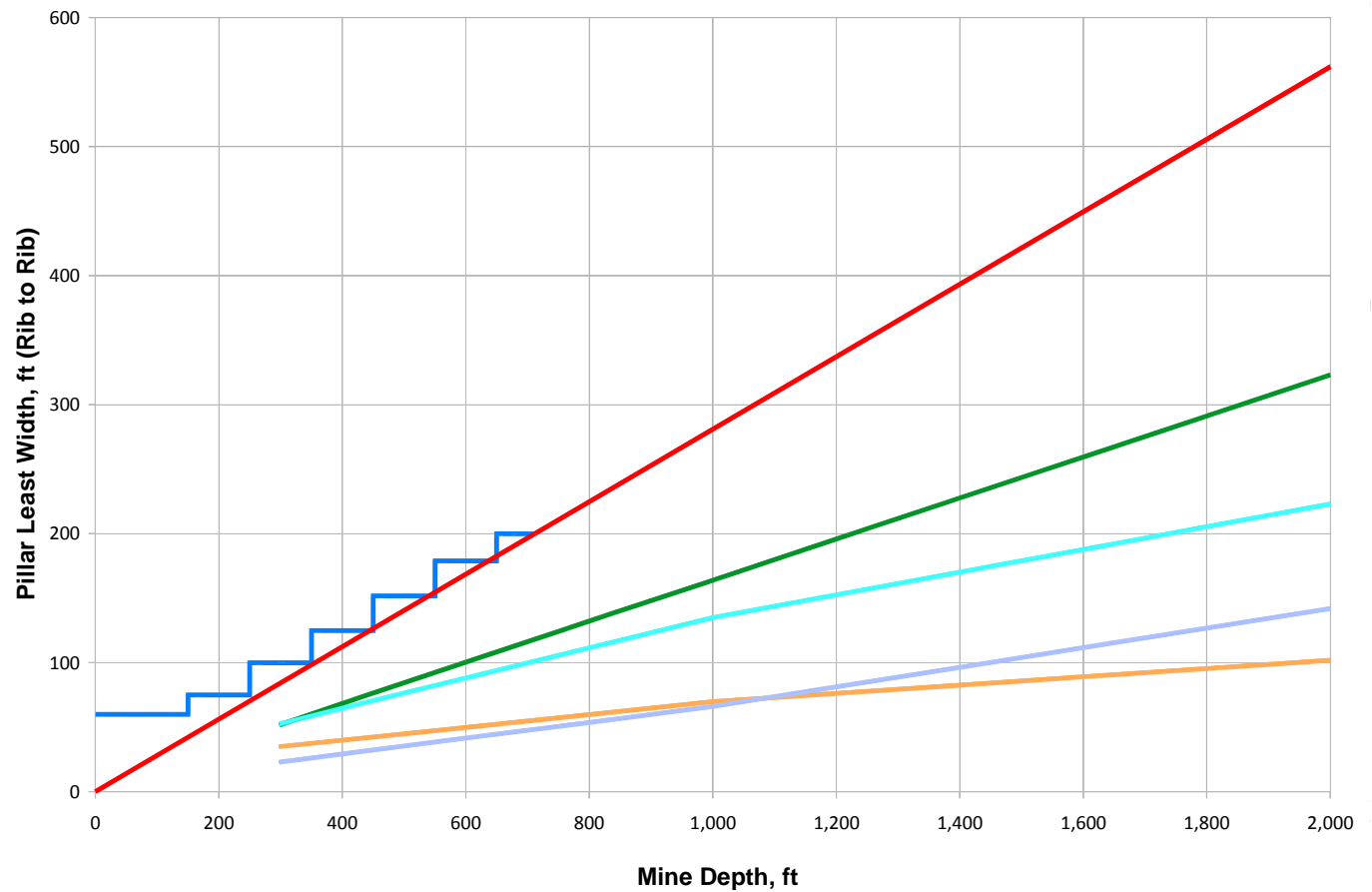
Legend

———	Step Function From 1957 Table
———	1957 Recommended 8° Angle of Draw
———	ALPS Recommended Gate Pillar
———	Wilson-Upper Freeport Seam
———	Wilson-Pittsburgh Seam
———	Upper Freeport Seam Foundation

FIGURE 13

COMPARISON OF GATE ROAD PILLARS FOR
BIENIAWSKI AND WILSON EQUATIONS

Prepared For
**PENNSYLVANIA DEPARTMENT OF
ENVIRONMENTAL PROTECTION
BUREAU OF OIL AND GAS MANAGEMENT**

John T. Boyd Company

March 2016
Scale as Shown

FIGURE 14

**RECOMMENDED LONGWALL AND
ROOM - AND - PILLAR WELL PROTECTION PILLARS**

Prepared For

**PENNSYLVANIA DEPARTMENT OF
ENVIRONMENTAL PROTECTION
BUREAU OF OIL AND GAS MANAGEMENT**

John T. Boyd Company

March 2016
Scale as Shown

APPENDIX A

JOINT COAL AND GAS COMMITTEE
GAS WELL PILLAR STUDY

COMMONWEALTH OF PENNSYLVANIA

DEPARTMENT OF MINES

AND

MINERAL INDUSTRIES

OIL AND GAS DIVISION

FOREWORD

We gratefully acknowledge the aid and assistance of the Joint Coal and Gas Committee and Sub-committee who directed the engineering phase of the study contained herein. The members of this committee were:

COMMITTEE	SUB-COMMITTEE

COMMITTEE

H. C. Rose
President   (now retired)
Pittsburgh Coal Company

W. G. Stevenson
General Manager
J. H. Hillman & Sons Company

William Foster
General Attorney
United States Steel Corporation

J. V. Goodman
Vice President
Equitable Gas Company

C. P. Duncan
Chief Geologist
Manufacturers Light & Heat Company

G. J. Donaldson, Jr.
Mining Engineer
The Peoples Natural Gas Company

SUB-COMMITTEE
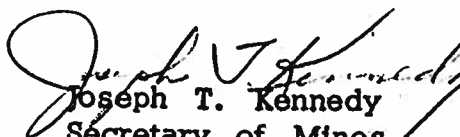
G. J. Donaldson, Jr.
Mining Engineer
The Peoples Natural Gas Company

A. R. Werft
Chief Engineer
United States Steel Corporation

J. G. Tilton
Mining Engineer
Equitable Gas Company

J. S. Whittaker
Vice President
Pittsburgh Coal Company

We likewise acknowledge the invaluable assistance given by the management of the industries involved who made the necessary information available to the Committee and contributed greatly to the success of this project.

Joseph T. Kennedy
Secretary of Mines
and Mineral Industries
Commonwealth of Pennsylvania

JOINT COAL AND GAS COMMITTEE
GAS WELL PILLAR STUDY

INTRODUCTION

This report completes a study of well pillar failures in the
Pittsburgh and Double Freeport seams of coal in southwestern
Pennsylvania.   The report includes a study of seventy-seven well
failures extending over a twenty-five year period where the coal seam
was sixty inches or more in thickness.   Inasmuch as no well failures
of wells drilled through thin seams of coal were called to the attention
of the Committee, no recommendations could be made for pillar sizes
in the thin coal areas.

In the acceptance of this proposal as a minimum standard,
it was understood that neither the Oil and Gas Division nor the well
operators waived their right to object to any pillar as projected.

We have been told, by members of the Committee and
others, that this study, based on scientific and engineering
principles, was the first of its kind made in the United States.

HISTORY OF STUDY

The Pennsylvania Gas Operations, Well-Drilling, Petroleum, and Coal Mining Act was passed by the State Legislative Session of 1955 and was approved November 30, 1955 by Governor George M. Leader. This Act regulates the drilling, operating, and plugging of wells, and the underground storage of gas under workable coal seams. The Act created the Oil and Gas Division within the Department of Mines and Mineral Industries. It was further required that the Division be supervised by a Deputy Secretary who was accordingly appointed by the Governor at the request of the Secretary of the Department.

Section 203 of the Act provides that a pillar of coal shall be left around any oil or gas well and states in part: "The Division shall not require the coal operator to leave a pillar in excess of one hundred feet in radius, except if it is established that unusual conditions exist, requiring the leaving of a larger pillar, the Division may require a pillar up to, but not exceeding one hundred fifty feet in radius." 'Pillars', as defined in the Act means, "A solid block of coal surrounded by either active mine workings or a mined out area." At first glance this provision seemed adequate, a closer look, however, disclosed to the mine and gas engineers that only a maximum sized pillar had been defined and that no real workable size pillar was

provided.   Consequently, the Deputy Secretary was confronted with many conferences in dispute pertinent to the need for certain sized pillars.

As a starting point, the Oil and Gas Division proposed the following plan as a minimum requirement until such a time as a workable agreement could be reached between the parties concerned:

Depth	Radius of Pillar
0 - 500 feet	50 feet
500 - 700 feet	75 feet
700 - feet plus	100 feet

These standards were put into effect immediately.

On May 24, 1956, the Deputy Secretary called a conference with representatives of the various coal operator associations from the Bituminous regions of Pennsylvania.   The purpose of this meeting was to discuss the problem of well pillar size and to get the benefit of their opinions as to what should constitute a safe pillar for the protection of a well, and the safety of the coal mines.   The coal operators offered the following proposal:

1.   On any active well:

Cover	Radius of Pillar
0 - 500 feet	50 feet
500 - feet plus	75 feet

2.   With an adequately plugged well, a flat 50 foot

radius pillar should be left for any depth of cover.

3.   An inadequately plugged well, by their standards,

should be treated as an active well.

On May 31, 1956, the Deputy Secretary called a conference

of the representatives of the Oil and Gas Associations for the purpose

of discussing well pillar sizes and to get the benefit of their opinions

as to what should constitute a safe coal pillar for well protection.

These representatives indicated that a detailed study should

be made to determine what size coal pillar should be left to protect a well.

A mining engineer from one of the larger gas companies had made a

partial study of some thirty wells that had failed because of sheared or

pinched off coal pillars.   However, since his information was by no

means complete, nothing substantial could be concluded.   It was

suggested, at the close of this meeting, that an engineering study be

made in cooperation with representatives from the coal mining industry.

At the suggestion of the Oil and Gas Division, the "Joint

Coal and Gas Committee" was organized.   The following agreed to

organize and complete a detailed well pillar study:

H. C. Rose, President   (now retired)
Pittsburgh Coal Company

W. G. Stevenson, General Manager
J. H. Hillman and Sons Company

William Foster, General Attorney
United States Steel Corporation

J. V. Goodman, Vice President
Equitable Gas Company

C. P. Duncan, Chief Geologist
Manufacturers Light and Heat Company

G. J. Donaldson, Jr., Mining Engineer
The Peoples Natural Gas Company

A meeting of the Joint Committee was called on June 25, 1956, to discuss methods to be followed and data to be assembled in making this comprehensive study. The form (Figure 1) was prepared to be sent to oil and gas companies for completion. Upon completion of their portion of the form, it was then forwarded to the coal companies for additional information. In addition to the completed form, coal companies submitted maps indicating the topographic location and a portion of their mine map, scale 1" = 100' for each damaged well penetrating their coal holdings. All completed forms and maps were returned to the Joint Coal and Gas Committee.

At this same meeting, a sub-committee was appointed for the purpose of making the engineering study of the compiled material and to do the necessary field work. Members of this Sub-committee were:

G. J. Donaldson, Jr., Mining Engineer
The Peoples Natural Gas Company

A. R. Werft, Chief Engineer
United States Steel Corporation

J. G. Tilton, Mining Engineer
Equitable Gas Company

J. S. Whittaker, General Superintendent (now Vice President)
Pittsburgh Coal Company

Information on seventy-seven well failures, received by

the Committee, was turned over to the Sub-committee for further

study. These wells were grouped according to county and township

and the data was then tabulated.

OUTLINE OF STUDY

After compiling the information received, the Sub-committee

unanimously agreed that the following items were pertinent and would

receive precedence during the study:

1. General Location Map - Scale - 62,500
   Topo Sheets

2. Calculate Angle of Support - Depth vs
   Minimum Radius

3. Plot of Depth vs Minimum Radius

4. Calculate Area of Pillars

5. Plot Area vs Depth

6. Plot Terrain as to four Categories:

a. Level   c. Steep Slope

b. Gentle Slope   d. Top of Hill

The seventy-seven wells involved in this study were located in five counties, namely:

1. Allegheny   4. Washington

2. Fayette   5. Westmoreland

3. Greene

The location of the wells were spotted on topographic maps to determine if the damaged wells were confined to a definite area. It was determined that the damaged wells were distributed generally throughout the area.

Originally, prior to making this study, it was thought that well casings were being damaged above coal horizons by action of draw during and after mining operations. However, after establishing the study data, it was apparent that the point of damage to well casings was located in the coal horizons, indicating that pillar failure was the cause of damage. This observation led to the calculation of the angle of depth of cover against the minimum mining radius and was called the angle of support.

The minimum mining radius is the shortest distance from the point of the well on the surface to a mined out area. The calculated angles were tabulated statistically and a frequency curve was constructed. This curve indicated that the greatest frequency of pillar failures was found when the angle of support fell between 5° and 6°. At 8° the curve dropped to one well and continued in a straight line relationship for isolated wells.

As a result of this study, it was decided to construct a graph plotting the depth of cover of each well against its minimum mining radius. Eight degrees was chosen experimentally to be plotted on this graph to observe the number of wells which fell below and above the deciding line.

Following this, a study of the wells that fell above the 8° line indicated that causes of failure were other than just pillar failures. Some of these causes were:

1. The well not being centrally located in the pillar.

2. Inadequate stumps having been left around a small pillar.

3. A hillside shift.

Up to this point of the study, all work had been based on the minimum mining radius and depth of cover to confirm the tentative

conclusions reached previously.   It was decided to determine the relation of the bearing surface in square feet of the pillar with the depth of cover.   The pillar area is the actual amount of coal left to support the well as scaled from the mine map previously submitted by the coal companies.   The pillar areas were calculated and results tabulated.

Various shaped pillars were encountered.   It was quite evident, in many instances, that sufficient total area pillar was left to prevent failure had the pillar been concentric with the well, and had the corners of the pillars not been removed.

A graph was then constructed by plotting the depth of each well against the area of its pillar.   The 8° area curve was then superimposed upon the graph.   The graph showed that the majority of the damaged wells fell below the 8° area curve.   Those wells that fell above 8° area curve were examined individually.   It was found that the causes of failure were similar for those wells which fell above the 8° minimum radius curve.   The reasons for failure follows:

1. The well not being centrally located in the pillar.

2. Inadequate stumps having been left around the original small pillar.

3. A hillside shift.   (The pillar would have been adequate to support the well under normal conditions)

A summary of the terrain at each well was classified into the following categories:

1. Level   3. Steep Slope

2. Gentle Slope   4. Top of Hill

With the exception of one and possibly two wells, the committee did not feel that the terrain was a contributing factor to well pillar failures.

The information concerning the character of the roof and bottom strata of the coal seam was not used by the committee in arriving at their recommendations, since there was no way to correlate this data to actual failures.   It was also felt that the direction and the per cent grade of the coal seam had no bearing on pillar failure.

Following a detailed examination of the data and constructed graphs, the Sub-committee on January 22, 1957, made the following recommendations to the Joint Coal and Gas Committee:

1. The pillar or pillars comprising the required
   pillar plan should be in the form of a square.

2. The well should be centrally located within
   the required pillar plan.

3. The required pillar plan should conform to the
   following specifications, wherein the greatest

depth of cover shall be used in each range

to determine the total bearing area as applied

to the 8° area curve.

Cover	Req'd Solid Pillar Area	Req'd Additional Pillar Area (Solid or Split)	Total Area Bearing Surface Required
0 – 99 ft.	1,600 sq. ft.	–	1,600 sq. ft.
100 – 149 ft.	3,600 sq. ft.	–	3,600 sq. ft.
150 – 249 ft.	5,625 sq. ft.	–	5,625 sq. ft.
250 – 349 ft.	10,000 sq. ft.	–	10,000 sq. ft.
350 – 449 ft.	10,000 sq. ft.	5,600 sq. ft.	15,600 sq. ft.
450 – 549 ft.	10,000 sq. ft.	13,000 sq. ft.	23,000 sq. ft.
550 – 649 ft.	10,000 sq. ft.	22,000 sq. ft.	32,000 sq. ft.
650 – ft. (plus)	10,000 sq. ft.	30,000 sq. ft.	40,000 sq. ft.

Note 1. 40,000 square feet is the maximum bearing area

except under unusual conditions.

Note 2. As to the additional pillar area required, the

following specifications must be adhered to:

a. The excavated area shall not exceed

15 feet in width.

b. The shortest pillar dimension shall not

be less than twice the width of the

excavated area.

It was felt that the split pillar would facilitate mining

operations, haulage, ventilation, drainage, etc., without destroying

the value of the pillar plan.

January 31, 1957, the Joint Committee met to consider the report and recommendations of the Sub-committee. The report was approved with minor changes and one recommendation was added pertaining to wells abandoned under the Pennsylvania Gas Operations, Well-Drilling, Petroleum, and Coal Mining Act of 1955. Both the Sub-committee and Joint Committee recommended, with respect to wells abandoned since the effective date of the Act that special consideration be given by the Oil and Gas Division in approving pillars smaller than those required for active wells.

February 4, 1957, the report was presented to a meeting of the Western Pennsylvania Coal Operators Association and members of the captive mines in this area. The report was finally approved by those present.

February 5, 1957, the report was presented to a meeting of the representatives of natural gas companies in the area and was approved.

February 15, 1957, the recommendations of the Joint Coal and Gas Committee and Sub-committee were presented to the Deputy Secretary of the Department of Mines and Mineral Industries, Oil and Gas Division. The Deputy Secretary acknowledged the report and submitted it to a Commission of State Mine Inspectors comprised of:

Charles H. Curry, Chairman

George S. McCaa

John V. McKenna (deceased)

This commission approved the report and recommendations with the exception that the minimum size pillar should be no less than 3,600 square feet.   The pillar left for depth of 349 feet or less are solid pillars and cannot be split.   Cover of 350 or more may be solid or split pillars.   The pillar, whether solid or split, must adhere to the minimum bearing area.

April 29, 1957, the Department of Mines and Mineral Industries adopted the recommendations as amended to be used as a minimum standard for well pillars for the protection of Oil and Gas Wells in Pennsylvania for mines mining the Pittsburgh seam of coal and/or the Double Freeport seam of coal.   Since the adoption of the well pillar proposals, as described in this report, there have been no controversies between coal companies, gas companies, and the Oil and Gas Division relevant to well pillars.

There are attached to this report, copies of the information compiled by the Sub-committee.   These appear in the order in which they are described in the narrative portion of this report.   With the help of the Sub-committee and the cooperation of the gas companies and

the coal companies, the Oil and Gas Division is continuing to compile information on any reported well failures. It may be necessary to revise this information periodically. However, the Oil and Gas Division is pleased to report that there have been no failures of any wells since the effective date of the Pennsylvania Gas Operations, Well-Drilling, Petroleum, and Coal Mining Act of 1955.

DESCRIPTION OF EXHIBITS FROM

ORIGINAL WELL PILLAR STUDY

FIGURE 1.   Information from file by coal companies and gas companies.

FIGURE 2.   Examples of pillar plans finally accepted by the Division and the Committee.

FIGURE 3.   Complete history of wells involved in the study.

FIGURE 4.   Listing of wells by numbers under each of the angles by degrees, indicates numbers of wells damaged under each degree.

FIGURE 5.   Frequency distribution curve.

FIGURE 6.   Wells below the 8° line with an explanation by well number.

FIGURE 7.   Graph showing wells – Depth vs Minimum Mining Radius and their location with respect to the 8° angle. This chart was made by plotting each individual well with the depth of the coal against the minimum mining radius. Super-imposed on this graph is the 8° minimum radius of mining curve which is a straight line.

FIGURE 8.   This chart shows the wells by number below the 8° line and reasons for the wells lying below the line.

FIGURE 9.   Graph shows wells plotted – Depth vs Area of Pillar with the 8° area super-imposed. This chart was made by plotting the depth of coal against the area of pillar in 1,000 square foot intervals.

NOTE: The red lines drawn on (Figure (7 and 9) are the lines that give the pillar size as calculated from the charts.

GAS WELL PILLAR STUDY
JOINT COAL AND GAS COMMITTEE

Figure 1.

GAS COMPANY INFORMATION:

Company _____ Well Number _____

Tract _____ Township _____ County _____

Coal Seam _____ Amount of Cover _____

Approximate date of failure _____ Approximate depth of failure _____

Remarks _____

_____

_____

Name of Person Preparing Report _____

COAL COMPANY INFORMATION:

Company _____ Mine Name _____

Coal Seam Name _____Coal Seam Thickness (inches) _____

Elevation – Bottom of coal _____ Surface at well _____

Size of gas well pillar – diameter or sides of square (feet) _____

Type of mining around pillar (check one) Partial extraction ____ Full extraction

_____

% Recovery around pillar _____

Type and condition of bottom – Wet _____ or Dry ___ Hard ___ Soft _____

Type of rock _____

Type of roof rock _____

_____

Approximate date of first mining around well pillar _____

Approximate date of final retreat around well pillar _____

Direction of dip of coal seam and % of dip: % Dip ___ Direction _____

Remarks _____

_____

_____

Name of Person Preparing Report _____

FIGURE 2.

JOINT COAL AND GAS COMMITTEE
GAS WELL PILLAR STUDY
EXAMPLES OF PILLAR PLANS FOR VARIOUS DEPTHS OF COVER

COVER 0' To 149'   COVER 150' To 249'   COVER 250' To 349'   COVER 350' To 449'

(MIN. 10,000□" BEARING AREA)   (MIN. 15,600□" BEARING AREA)(MIN. 22,000□" BEARING AREA)

COVER 450' To 549   COVER 550' To 649'   COVER 650' To 700'+

(MIN. 23,000□" BEARING AREA)   (MIN. 32,000□" BEARING AREA)   (MIN. 40,000□" BEARING AREA)
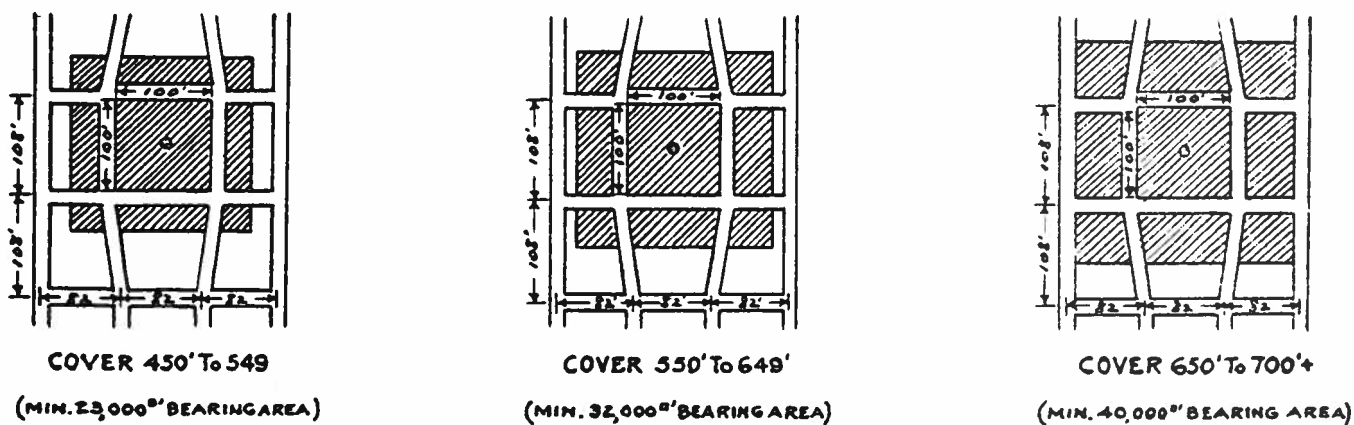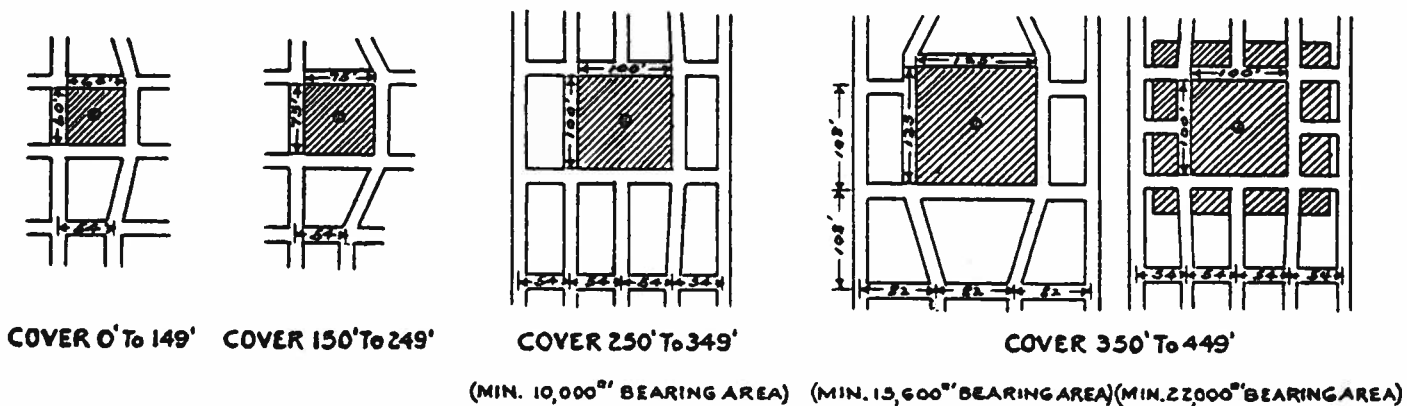
NOTE:
NO PLACE TO EXCEED 15' IN WIDTH.
PILLARS TO BE A MINIMUM OF TWICE THE
WIDTH OF THE EXCAVATION DRIVEN.
SCALE 1 INCH = 200 FEET

FIGURE 3

JOINT COAL AND GAS SUBSIDENCE STUDY

FIGURE 3.

JOINT COAL AND GAS COMMITTEE

GAS WELL PILLAR STUDY

Angle Of Depth To Size Of Pillar

	0°-1°	1°-2°	2°-3°	3°-4°	4°-5°	5°-6°	6°-7°	7°-8°	8°-9°	9°-10°	10°-11°	11°-12°
Well Numbers	9		6	29	1	14	10	15	18	8	49	13
			32	34	5	17	16	23				
				44	7	19	21	37				
				56	11	20	24	42				
				57	12	22	26	48				
				73	25	31	33					
				75	30	35	46					
				76	43	38	51					
					50	39	58					
					65	40						
					67	41						
					68	45						
					70	52						
					71	53						
					77	59						
						60						
						61						
						63						
						64						
						72						
TOTAL	1	0	2	8	15	20	9	5	1	1	1	1

FIGURE 4.

FIGURE 5.

A-24

JOINT COAL & GAS COMMITTEE
GAS WELL PILLAR STUDY

FREQUENCY DISTRIBUTION CURVE,
ANGLE OF DEPTH VS. MINIMUM DISTANCE
TO MINED OUT AREA

Number of Wells

Tan ∠ = Minimum Mining Radius ÷ Depth of Cover
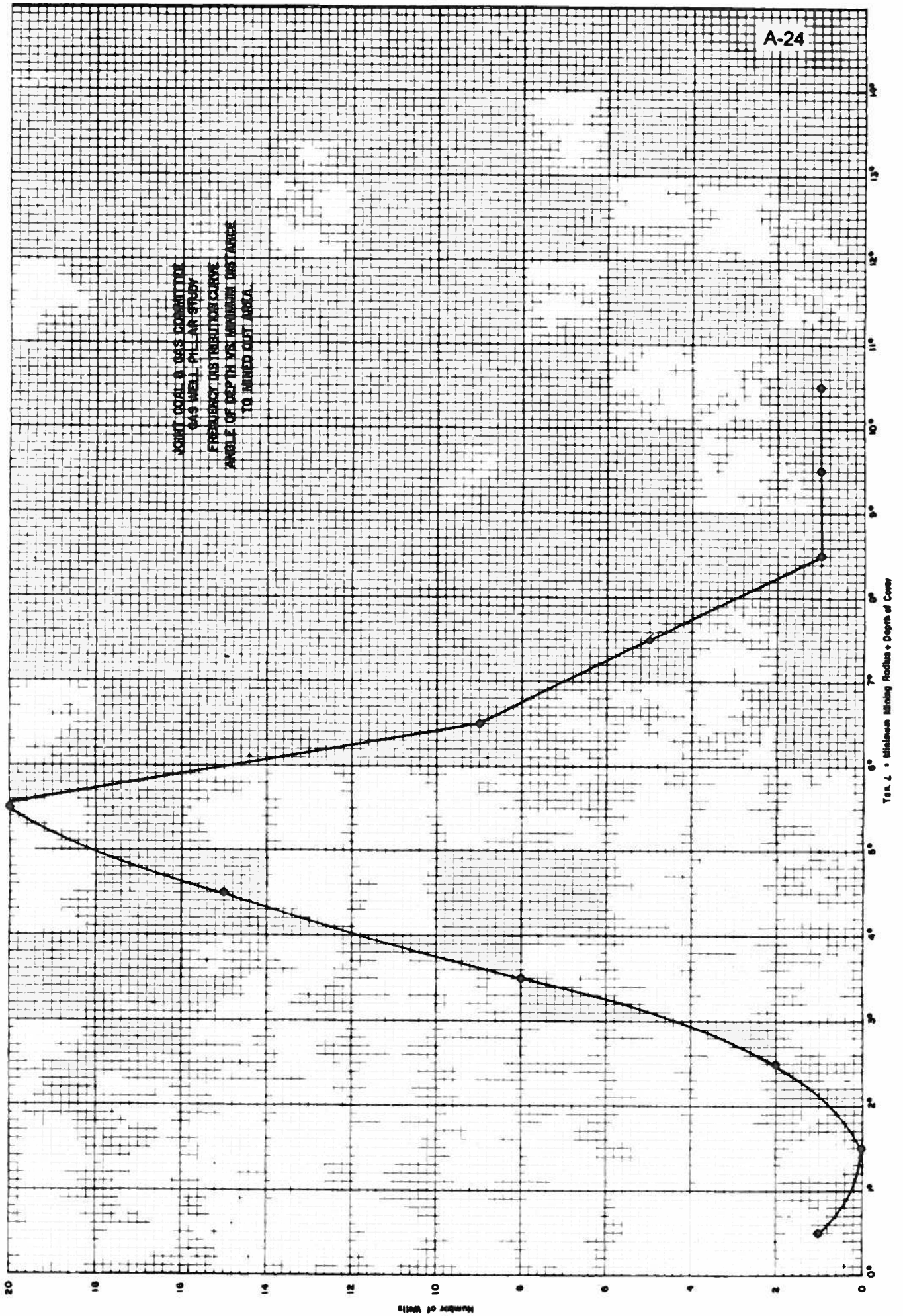
JOINT COAL AND GAS COMMITTEE   FIGURE 6.

GAS WELL PILLAR STUDY

DEPTH vs. NEAREST MINING

Wells Below 8° Line

Well Number

8   Off center. Mining too close.

13   Off center.

18   Close mining.   Pillar too small.

47   Lateral thrust in stumped area.

49   Inadequate stumps left around small
                         pillar.

54   Unexplainable.

55   Terrain - hillside shift.

FIGURE 7.
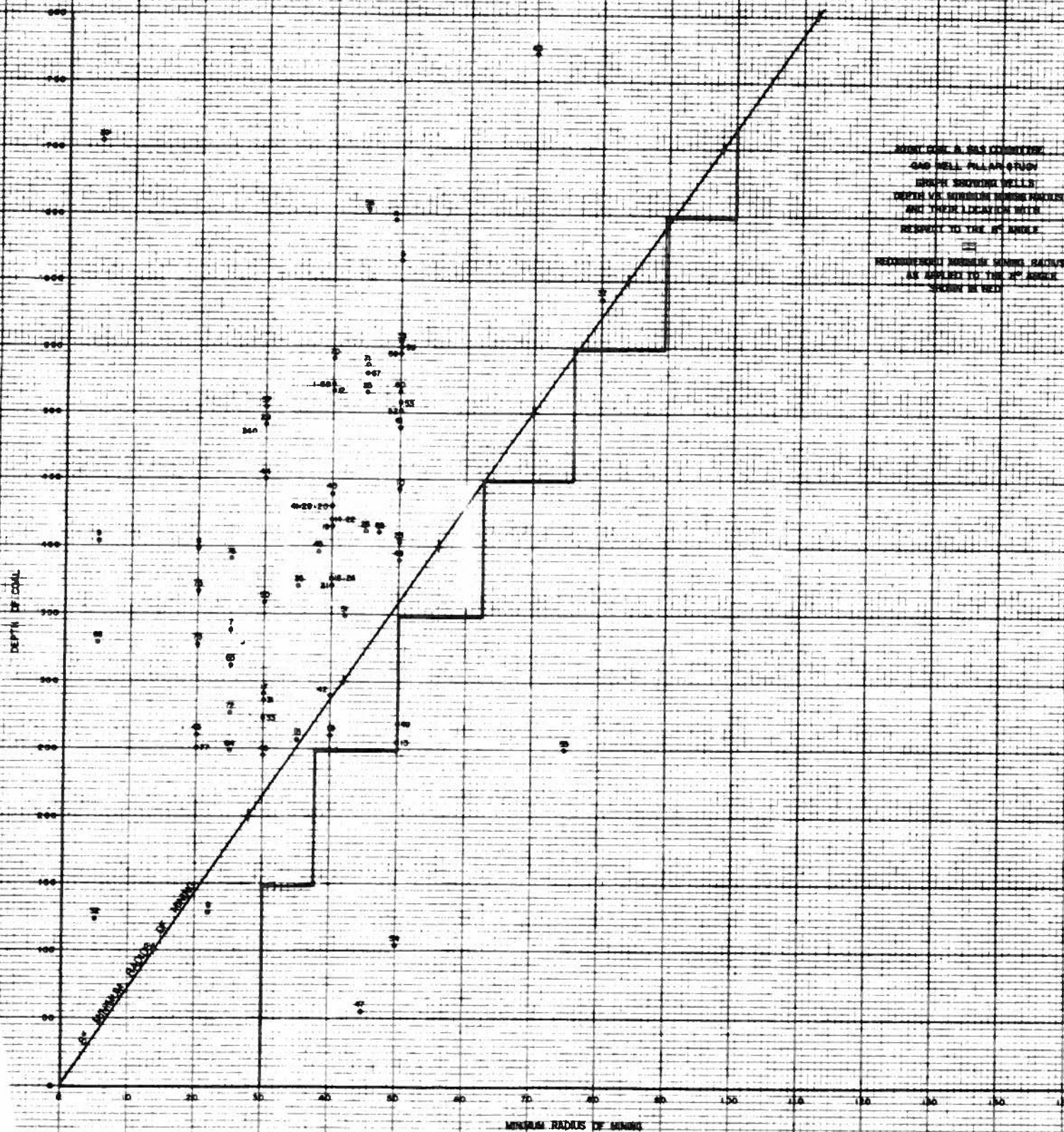
JOINT COAL AND GAS COMMITTEE
GAS WELL PILLAR STUDY

Figure 8.

Area In Square Feet
Wells Below 8° Line

Well Number

8	Off center. Nearest mining 20 feet. Insufficient pillar.
9	Mining too close to well. Insufficient pillar.
15	Pillar rectangular. Close to gob on one side.
18	Close mining. Pillar too small.
31	Close mining. Pillar too small.
32	Close mining. Not enough pillar.
33	Well Drilled in pillar after first mining. Not enough pillar to support well.
42	Pillar too small. Needed more area.
46	Well not in center of pillar – odd shape of pillar. Mining too close.
49	Inadequate stump left around original small pillar.
51	Off center in pillar. Had well been centered, pillar would possibly have been adequate.

13	Off center. Nearest mining 30 feet.
17	Pillar adequate if well had been in center of pillar. Nearest mining 30 feet.
47	Lateral thrust area. Steep hill on both sides of well and full mining under hillsides. Stumped area for stream and road.
55	Terrain – hillside shift. Adequate pillar for well under normal conditions.
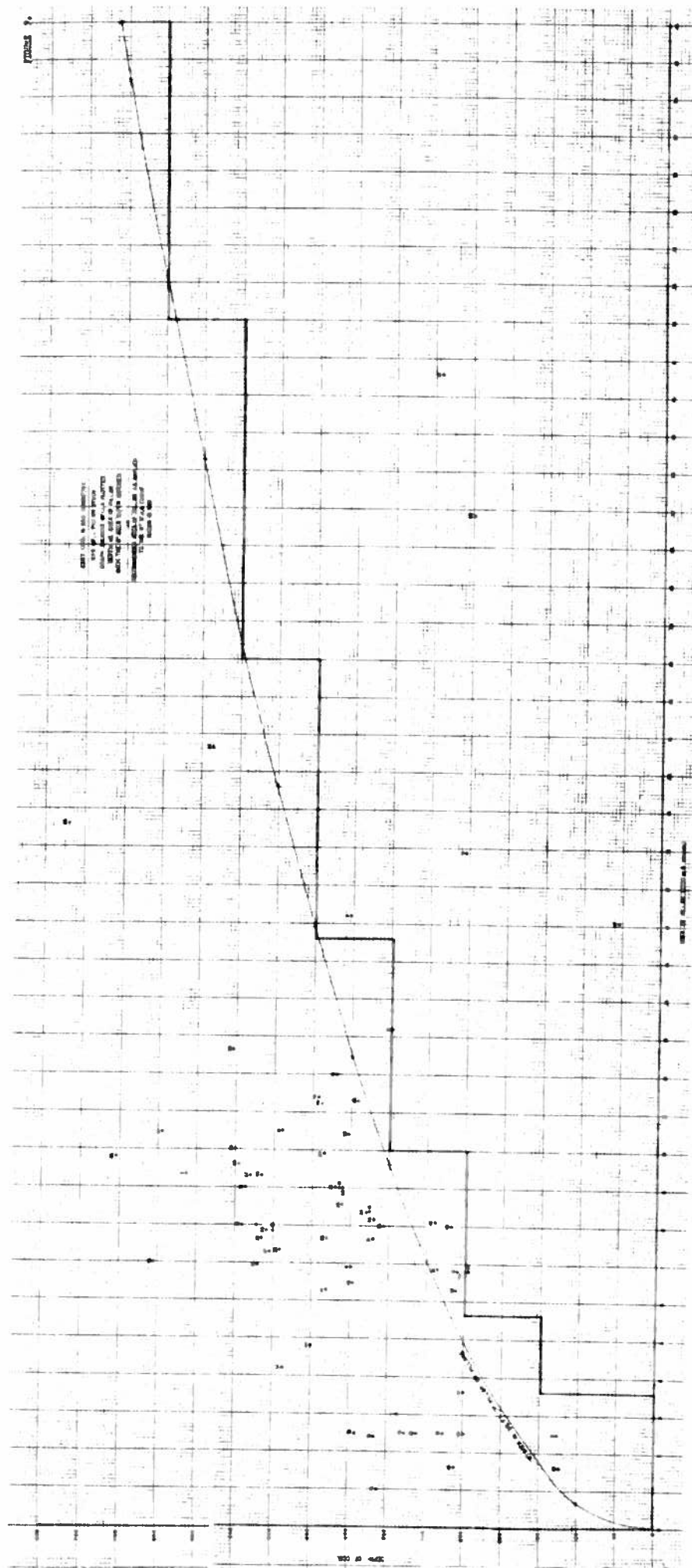
1.0   Introduction

A field study was conducted in 2013 and 2014 by a consortium of coal and shale gas industry members to test the effects of longwall induced subsidence on the stability and integrity of wells drilled through a gate road abutment coal pillar. The project was headed by the Gas Division and Coal Division of CONSOL Energy, Inc. (CONSOL) with participation by Chevron, EQT, Noble Energy, Range Resources, Marcellus Shale Coalition and the Pennsylvania Coal Alliance. The project is referred to by its location on Well Pad NV-35.

Dr. Wen H. Su, Senior Geomechanical Engineer for CONSOL, was the principle investigator and designed the experiment with input from the participants. Several contractors were employed to install the instrumentation and collect the testing data.

Gas well Pad NV-35 is approximately 6.5 miles southwest of Washington, Pennsylvania and is underlain by the workings of CONSOL's Enlow Fork Mine in the Pittsburgh Coal Seam at a depth of approximately 610 ft. The surface site is located on top of a narrow ridge flanked by Tenmile Creek to the east and an unnamed drainage to the west. Relief of the terrain is approximately 150 ft with maximum slopes of approximately 20 degrees.

Pad NV-35 is sited above an abutment pillar in the gateroad between longwall panel E-24 to the south and E-25 to the north. The study monitored the effects of mining panel E-24 in 2013 and E-25 in 2014.

No formal publication of the study results has been issued by the consortium. The following is John T. Boyd Company's (BOYD) summary of the project based on information provided by the participants to aid in the update of the 1957 Joint Coal and Gas Committee report.

2.0   Bedrock Geology

Within the site area, strata exposed at the surface and in the shallow subsurface are comprised of alternating layers of sandstone, siltstone, shale, claystone, limestone, and coal. Surface exposures are limited to rocks included in the Upper Pennsylvanian/Lower Permian age Dunkard Group. The underlying Upper Pennsylvanian age Monongahela Group, which includes the Pittsburgh coal seam, occurs only in the subsurface.

The narrow ridge site of Pad NV-35 is capped by the Upper Limestone, which is the top member of the Washington Formation. The Pittsburgh Seam is the basal member of the

Pittsburgh Formation. The following is a summary of the intervening stratigraphic units and members:

System	Group	Formation	Select Member
Permian	Dunkard	Washington	Upper Limestone
			Jollytown Coal
			Jollytown Limestone
			Deep Valley Sandstone
			Middle Washington Limestone
			Lower Limestone
			Washington Coal Rider
			Washington Coal
		Waynesburg	Little Washington Coal
			Washington A Coal
			Waynesburg Sandstone
Pennsylvanian	Monongahela	Uniontown	Waynesburg Coal
			Brownsville Sandstone
			Waynesburg Limestone
			Uniontown Sandstone
			Uniontown Coal
		Sewickley	Limestone D
			Limestone C
			Limestone B
			Limestone A
			Benwood Limestone
			Sewickley Coal
			Sewickley Sandstone
		Redstone	Sewickley Limestone
			Fishpot Limestone
			Redstone Limestone
		Pittsburgh	Pittsburgh Sandstone
			Pittsburgh Coal Rider
			Pittsburgh Coal
	Conemaugh	Little Pittsburgh	Lower Pittsburgh Limestone & Shale
			Lower Pittsburgh Sandstone

The top of the Pittsburgh coal main seam at Pad NV-35 occurs at a depth of 604 ft. The main seam exhibits a thickness of 5.56 ft but the average extraction height in the area is 7 ft after removal of interbedded layers of shale and coal in the roof.

Bedrock strata can be identified from geologic logs of three boreholes drilled in the immediate area of Pad NV-35; EN0712, BK8816, and WC8231. BOYD correlated the stratigraphy to the gamma ray log completed on borehole MW 2A located on the pad as shown in Figure B-1, following this text.

3.0   Test Wells

The main focus of the field experiment was the study of four non-producing test wells (TW) that were constructed in the same manner as production gas wells to just below the Pittsburgh Seam. Subsidence effects on these test wells caused by the extraction of two longwall panels were monitored using borehole calipers and video cameras.

The wells were constructed in a similar manner but employed different casing and cement types:

	Casing Outside Diameter (in.)			
Casing	TW #1	TW #2	TW #3	TW #4
Surface	30	30	24	30
Water String	20	20	16	20
Coal Protection	13⅜	16	11¾	13⅜

Notes: Surface casing is sometimes referred to as conductor casing.
Water string is sometimes referred to as surface protection casing.
Coal protection casing is sometimes referred to as coal string.
Class A cement with an 8-day strength of 3,000 psi in TW#1, #2, and #3, and 2,000 psi cement in TW#4.

All test wells were fully grouted with Class A cement in annular space between casings and wellbore.

The intermediate casing and production string were not installed in the test wells because one of the goals of the experiment is to measure the movement of the coal string and then to determine if this movement would compromise the intermediate casing or production pipe. If the intermediate casing or production string was installed, the coal string could not be monitored and measured from within.

The test wells included typical designs of CONSOL and Chevron, as well as two innovative designs. All wells were installed in 2013 to a depth of 642 ft from a surface elevation of 1,225 ft (MSL). The following summarizes the test well casings used in the field test.

| | | Test Well Casing Parameters | | | |
| | | TW #1 | TW #2 | TW #3 | TW #4 |
		CONSOL	Innovative	Chevron	Innovative
Surface Casing	Hole Size, in.	36	36	30	36
	Depth, ft	80	80	80	80
	Casing Size, OD in.	30	30	24	30
	Casing Grade	H-40	H-40	H-40	H-40
Water String	Hole Size, in.	26	26	18¾	26
	Depth, ft	266	266	272	282
	Casing Size, OD in.	20	20	16	20
	Casing Grade	J-55	J-55	H-40	J-55
	Wall Thickness, in.	0.438	0.438	0.375	0.438
	Casing Weight, lbs/ft	94	94	65	94
Coal Protection	Hole Size, in.	17½	18¾	15	18¾
	Depth, ft	642	642	642	642
	Casing Size, OD in.	13⅜	16	11¾	13⅜
	Casing Grade	J-55	H-40	H-40	J-55
	Wall Thickness, in.	0.38	0.375	0.333	0.38
	Casing Weight, lbs/ft	54.5	65	42	54.5

3.1   Caliper Logs

Key findings from the field test are derived from the analysis of the data from caliper surveys. The most useful information is from the determination of the change in diameter and lateral displacement of the coal protection casing.

Caliper surveys employing a 60-arm caliper tool were carried out by Weatherford International PLC on all test wells after the completion of each longwall panel. One set of logs was recorded about eight months after the E-24 longwall retreated and before the influence of the E-25 longwall. The second set was completed when the E-25 longwall progressed about 1,200 ft past the test site.

3.1.1 Change in Diameter

The data were analyzed to determine the minimum inside diameter of the coal string which can be viewed in two ways:

1. The minimum inside diameter at any point along the casing or string.

2. The maximum diameter of a 4-ft long cylinder that can fit down the coal string. This is termed the minimum 48-in. drift diameter.

The downhole locations of deformation of the coal strings were plotted along with the geologic units by BOYD as shown in Figure B-2, following this text. There is strong correlation among the wells in the location of the deformations except for TW #3 where two additional deformation locations are noted in the lower portion of the coal string. TW #3 has the smallest casings and the thinnest coal string of all four test wells which may have contributed to the disparity.

In all cases the deformation occurred in the weak strata layer close to contact with a strong layer. The following identifies the geologic unit at the deformation location:

	Deformation
Depth (ft)	Occurs in
290	Waynesburg Coal and underlying shale
360	Shale between two layers of the Uniontown Sandstone
390	Top of Limestone C
480	Shale layer within the Benwood Limestone
605	Pittsburgh Coal and underlying shale

The casing diameter reduction from deformation is summarized as follows:

60-Arm Caliper Results, Maximum Inside Diameter Reduction					
		TW #1	TW #2	TW #3	TW #4
Initial Pre-mining Diameter					
Diameter (in.)	- Reported (Spec.)	12.750	15.250	11.050	12.750
	- Measured	12.615	15.250	11.084	12.615
Minimum Diameter After Mining E-24 Panel					
Minimum Diameter (in.)		11.328	14.378	9.550	10.856
Depth (ft)		395.6	397.2	396.0	396.8
Reduction (in.)	- From Reported	1.422	0.872	1.500	1.894
	- From Measured	1.287	0.872	1.534	1.759
Minimum Diameter After Mining E-25 Panel					
Minimum Diameter (in.)		11.547	14.360	9.465	10.588
Depth (ft)		396.5	397.1	396.5	396.6
Reduction (in.)	- From Reported	1.203	0.890	1.585	2.162
	- From Measured	1.068	0.890	1.619	2.027
Minimum 48-in. Drift Diameter After Mining E-24 Panel					
Drift Diameter (in.)		10.950	14.010	9.894	10.896
Depth (ft)		392.5	393.5	396.1	396.8
Reduction (in.)	- From Reported	1.800	1.240	1.156	1.854
	- From Measured	1.665	1.240	1.190	1.719
Minimum 48-in. Drift Diameter After Mining E-25 Panel					
Drift Diameter (in.)		11.441	13.592	9.219	10.876
Depth (ft)		396.8	393.8	393.6	396.6
Reduction (in.)	- From Reported	1.309	1.658	1.831	1.874
	- From Measured	1.174	1.658	1.865	1.739

There are constancies in this deformation data:

- The diameter reduction amounts suggesting that casing size and strength are not related to the reduction.

- The maximum diameter reduction, for all four test wells, occurs at around a depth of 390 ft and in the softer shale above the contact with Limestone C.

3.1.2 Horizontal Displacement

The 60-arm caliper can detect trajectory of a borehole or casing as small as 0.01 degrees. This trajectory is determined every 0.1 ft (the reading rate of the caliper) and the lateral displacement calculated. This is aided by the caliper's ability to locate the arm that is highest in the borehole. The direction of this horizontal movement is not known.

Each test well showed similar horizontal movement both after the first longwall, E-24, and then the second longwall, E-25 (see Figure B-3). Comparing movement after the first and

second longwall shows that there was typically more horizontal movement due to the first longwall than the second. Except for TW#3, some of the horizontal movement due to the first longwall was counteracted by the second longwall (see Figure B-4).

The three highest horizontal movements for each well after each longwall occur at the same depth with similar movements as summarized below.

	Three Highest Horizontal Movements (in.) at Depth (ft) in Each Test Well			
Reference Depth, ft	TW #1	TW #2	TW #3	TW #4
	After Mining E-24 Panel			
290	1.245	1.597	0.786	1.135
	288.7	289.4	288.8	289.3
360	1.022	1.260	0.854	0.910
	357.0	363.8	362.2	365.1
390	4.989	5.520	1.982	3.967
	392.1	393.0	392.4	393.2
	After Mining E-25 Panel			
290	0.556	1.435	1.515	0.633
	289.4	289.5	289.4	287.7
360	0.910	1.515	1.781	0.766
	363.7	358.5	358.0	364.3
390	3.477	5.160	4.669	2.746
	393.1	392.9	393.0	393.2

The caliper measurements showed the maximum displacement in all four test wells occurred at a depth around 390 ft at the same location as the maximum diameter change. Figure B-5, following this text, shows the likely depiction of this deformation as developed from the caliper log data.

3.2   Borehole Camera
Borehole camera videos were taken of all four wells after mining but did not provide meaningful information due to poor visibility through the borehole water.

4.0   Overburden Monitoring
GAI Consultants, Inc. (GAI) was retained by CNX Gas Company, LLC (CNX; a wholly owned subsidiary of CONSOL) to provide instrumentation and monitor ground movements of four monitoring wells (MW) at Pad NV-35 before, between, and after the mining of two

adjacent longwall panels. This work was reported[1] in 2014 and is summarized here. The overburden was monitored by:

- One extensometer.
- Three inclinometers using In-Place Inclinometer (IPI) sensors.

	Feet		
	Hole Depth	Target Zone	Monitored Depth
MW 1 Inclinometer	200	0 to 200 depth	38 to 198
MW 2A Extensometer	647	150 above and 50 below coal	459 to 639
MW 3 Inclinometer	400	200 to 400 depth	197 to 367
MW 4 Inclinometer	607	200 depth to 10 below coal	208 to 408

The inclinometer casings were 2.75 in. OD / 2.25 in. ID ABS plastic, while the extensometer casing of MW 2A was 2 in. telescoping PVC.

The monitoring wells were installed in the same abutment pillar as the test wells and extended from ground surface down through and into the floor of the Pittsburgh Seam. Inclinometers were installed to measure lateral movements in MW 1, MW 3, and MW 4. An extensometer was installed in MW 2A (replacing MW 2) to measure vertical movements. The instruments were manufactured by Durham Geo Slope Indicator (DGSI) of Stone Mountain, Georgia.

MW 1, MW 2A, and MW 4 are located along the center line of the pillar and in line with the test wells. MW 3, located between test TW #2 and TW #3, is 15 ft off of the centerline and closer to panel E-24. MW 2 was replaced by MW 2A after problems arose during the grouting of TW #2. During the baseline readings for MW 2 on July 5, 2013, the casing was found to be obstructed at and below the depth of 52 ft. It is believed that this blockage was caused by cement that migrated from TW #2. MW 3 developed sensor damaged at 390 ft depth.

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[1] Bruhn, Robert W. and Robert J. Turka, 2014, Instrumentation and Subsurface Ground Movement Monitoring Final Report, NV-35 Well Pad, prepared for CNX Gas Company, LLC, GAI Consultants, Inc. Proj. No. C130275.00, July.

4.1   Extensometer

The DGSI extensometer system employs a casing with 18 magnetic rings (20 were planned) spaced every 10 ft (5-ft spacing at seam depth) attached to the outside of the casing to monitor vertical movements. The casing is grouted in place. The ring locations are detected by a magnetic sensor that is lowered inside the casing. The installed locations of these rings are:

Feet			
Distance From Reference	Depth	Target	Measured
		Spacing	
150	459.5		
130	479.5	20	20.0
110	499.6	20	20.1
90	519.7	10	20.1
80	529.7	10	10.0
70	539.7	10	10.0
60	549.8	10	10.1
50	559.7	10	9.9
40	569.8	10	10.1
30	579.8	10	10.0
20	589.7	10	9.9
10	599.8	5	10.1
5	604.7	5	4.9
0	609.7	-	5.0
-5	614.5	5	4.8
-10	619.5	5	5.0
-20	629.4	10	9.9
-20	639.5	10	10.1

Annular space between the boring wall and the casing was grouted in the monitored zone. Centralizers were installed in the non-grouted intervals.

The extensometer in MW 2A was initially read four times over a three-day period from July 19 to 22, 2013 to establish baseline depth measurements for the rings. Ring depth measurements, after baseline measurements, were intended to be made at a minimum of five positions of the longwall face in 2013 and again in 2014. The face positions are:

- Approaching MW 2A at a distance of 200 ft.
- Directly alongside MW 2A.
- Past MW 2A at distances of 200 ft, 500 ft, and 1,000 ft.

Eleven measurements were made from July 26, 2013 through May 30, 2014.

4.2   Inclinometers

The DGSI inclinometer consists of a 10-ft long unit for measuring changes in inclination. The unit travels down vertical grooves cut into ABS plastic casing. The casing is grouted in the borehole and has internal longitudinal grooves at quarter points around the interior circumference extending the full length of the casing to guide the inclinometer wheels so that the instrument stays oriented during its decent. The internal casing grooves were aligned with the short and long axes of the coal pillar, approximately north-south and east-west.

Inclination of the instrument is recorded during the decent. The inclinometer unit was lowered down the grooves at the time of casing installation and left in place for the duration of the monitoring program. One set of grooves was monitored in the direction of the expected maximum horizontal movement perpendicular to the length of the longwall.

- MW 1 inclinometer was placed into operation on July 4, 2013 and the baseline established on July 7, 2013. System MW 1 consisted of 16 sensors.

- MW 3 was operational on July 5, 2013, and the baseline established on July 7, 2013. System MW 3 consisted of 20 sensors.

- MW 4 inclinometer readings were hindered during monitoring by large pop rivets used to connect the grooved casing. The rivets caught on the instrument at each section of casing during ascent. As a result, the instrument had to be raised and lowered until progress could be resumed. The MW 4 inclinometer was put into operation on July 4, 2013 and the baseline was established on July 10, 2013. System MW 4 consisted of 20 sensors.

The IPI system is similar in concept and function to a conventional borehole inclinometer except that the conventional inclinometer consists of a single sensor that is incrementally lowered down the borehole each time that readings are taken, whereas the IPI system consists of multiple sensors positioned at selected depths that remain in place at specified downhole depths for the duration of the monitoring program.

As ground movements take place, the angle of the casing changes. The IPI sensors measure this angle which is subtracted from the initial casing angle. The change in angle is used to compute the lateral displacement knowing that the sensor gage length is 10 ft. The data were corrected for temperature.

The readings were recorded automatically each hour, until June 7, 2014, and remotely linked to GAI's office. The three IPI systems were installed as E-24 longwall approached 924 ft from MW 1, 864 ft from MW 3, and 820 ft from MW 4. At these distances, ground movements resulting from the E-24 longwall would not have affected the MWs.

4.3   Overburden Movement

The MW 4 horizontal plot shows extreme movements not possible in this setting. GAI specifically noted the following sensors (with depths); IPI 9 (328.18ft), IPI 10 (318.18 ft), IPI 13 (288.18), IPI 14 (278.18ft), and IPI 16 (258.18 ft), "appeared to exhibit somewhat more pronounced deviations than the others."

The movement of IPI 12 at a depth of 298.28 ft is plotted by BOYD as shown in Figure B-6, following this text. The IPI 12 plot shows a consistent rate of horizontal movement suggesting a gradual process. Since movement started sometime near July 17, 2013 the calculated angle of draw would be 55 degrees if this movement was due to subsidence. This is unlikely.

A possible explanation is that the inclinometer slowly became un-calibrated. This is possible because GAI reported MW 4 inclinometer instrument movement was hampered by large pop rivets used to connect the grooved casing. The rivets caught on the instrument at each section of casing as it was lowered and it became necessary to repeatedly raise and lower the instrument until it worked itself past the rivets enough to allow the instrument string to continue down the hole. This treatment of the instrument could have affected its calibration.

BOYD plotted the combined overburden monitoring results for the inclinometers and extensometer to note any interplay between monitors and to assess gaps in the data. Note that:

- The deepest inclinometer reading was held to zero so that the direction and shape of ground movement can be understood.
- The inclinometer data from MW 1 (reading from 38 ft to 198 ft depth) was combined with MW 3 (reading from 197 ft to 367 ft depth) to provide a continuous assessment of movement from 38 ft to 367 ft.
- Only the final readings for longwall E-24 are shown for clarity. This occurred on August 27, 2013.

Plots for all dates are provided in the GAI report. The combined monitoring well data for longwall E-24 is plotted in Figure B-7, following this text, and shows:

- The maximum measured horizontal movement is 1.21 in.
- MW 3 is closer to longwall E-24 than MW 1 thus the combined horizontal calculated movement should be slightly less than 1.21 in.

- An angle of draw of 25 degrees would result in the effects of subsidence from longwall E-24 on the monitoring wells starting at a depth of 553 ft with a general increase in effect as depth decreases. The deepest measured horizontal movement is at 367 ft (MW 3) thus movement is likely greater than 1.21 in.

- The increase of strain within the coal pillar as determined by MW 2A extensometer is 0.99%.

Figure B-8, following this text, is the plot of monitoring well data for movement caused by only longwall E-25 and Figure B-9 is the plot of monitoring well data for movement caused by both longwalls E-24 and E-25. The plots show:

- The maximum measured horizontal movement is 1.44 in.

- The maximum measurement after longwall E-25 is greater than this measurement after E-24 (1.21 in.) although this value should be less,

- An angle of draw of 25 degrees would result in the effects of subsidence from longwall E-25 on the monitoring wells starting at a depth of 576 ft with a general increase in effect as depth decreases. The deepest measured horizontal movement is at 367 ft (MW 3) thus movement is likely greater than 1.44 in.

- The increase in strain within the coal pillar as determined by MW 2A extensometer is 1.79%.

5.0   In-Mine Monitoring

Monitoring in the mine occurred within the gate roads between longwall panels E-24 and E-25 and between crosscuts 24 and 25. Figure B-10, following this text, illustrates all monitoring locations for the field test. The gate system is 184 ft wide center to center (c-c) and consists of three entries with a row of abutment pillars (275 ft × 124 ft c-c) and a row of yield pillars (137.5 ft × 60 ft c-c). Entries and crosscuts are 16 ft wide.

On August 16, 2013, Dr. Vincent A. Scovazzo of BOYD visited the in-mine monitoring site. At that time the E-24 longwall face had progressed 480 ft past the site. The data logger was located in crosscut 23. The yield pillar had taken load and pillar ribs were observed to be spalling. The yield pillar rib was held in place by mesh and 7-gauge steel channels (T Channels by Jennmar). Secondary support in the central entry was provided by two rows cementacious cribbing (CAN®s of Burrell Mining Products Inc.) on 8 ft centers. The abutment pillar ribs only spalled on the corners.

In-mine monitoring consists of borehole pressure cells (BPC) and closure stations. BPCs were used to measure changes in stress within the abutment pillar. Eight BPCs were installed within the abutment pillar; four installed from the center entry (T1 thorough T4) and

four from longwall E-25 tailgate (R1 thorough R4). Each BPC is installed mid-rib (vertically) and 26.3 ft into the pillar in a 26.5 ft deep hole. Each cell is spaced 20 ft along the rib line.

The "T" series BPCs were monitored during the retreat of longwall E-24. However, only T3 was operational and its results are shown in Figure B-11, following this text. The "R" series BPCs were monitored during the retreat of longwall E-25. R1, R3, and R4 were operational with average results shown in Figure B-12.

Four closure stations were installed along the ribs of the abutment pillar, two in E-25 tailgate entry and two in the center entry. These stations were disturbed by support installations and subsequent rib spalls and measurements were not completed.

The final change in pillar stress recorded by the BPC during E-24 longwall retreat was 435.3 psi on August 27, 2013. Eighty-one readings occurred at face position 292.5 ft, corresponding to the face position from July 29 to August 5, 2013 where the face advance was slowed or stopped.

The final change in pillar stress measured was 1,028.9 psi when the longwall face was 630.5 ft from the "R" BPC around May 21, 2014. If the change in pressure is added from both the E-24 and E-25 BPC the total change in pressure in the abutment pillar would be 1,464.2 psi.

6.0   Subsidence

Subsidence surveying for the test was conducted on five survey stations located on the pad (parallel to wells) along with 27 additional stations as illustrated in Figure B-13, following this text. The stations are spaced at 50 ft intervals along a total survey line length of 1,400 ft. The line was surveyed twice prior to mining, once after mining E-24 panel, and once after E-25 panel was mined.

The measured surface subsidence movement is graphed in Figure B-14, also following this text, and shown to be typical for longwall mining in southwestern Pennsylvania. Horizontal movement over the E-24 Panel is toward the center of that panel. The net horizontal movement is lessened as movement is then toward the adjacent newly mined panel. The graph shows the horizontal movement over the E-24 Panel to be less after the E-25 Panel is mined.

Maximum measured subsidence movements are summarized below:

Maximum Surface Subsidence Measurements (ft)		
	Vertical	Horizontal
E-24 Panel (E-24 Retreated)	-4.60	1.26
E-24 Panel (E-25 Retreated)	-4.63	1.12
E-25 Panel (E-25 Retreated)	-4.60	1.87

7.0   ABAQUS 3D Finite Element Model

ABAQUS 3D[2] is part of ABAQUS FEA, a finite element analysis software. ABAQUS is a general-purpose finite element program that employs implicit integration schemes and can solve highly nonlinear systems with complex contacts under transient loads.

CONSOL used ABAQUS to model the geology, coal pillars, and well casing to predict the effects due to mining subsidence. The 3D finite element model used in the analysis contained 39,200 nonlinear 8-node 3D elements. The site lithology for the model is obtained from the MW 2A gamma log.

The primary aim of the analysis is to assess the effects of subsidence from two longwall panels on the gas well intermediate casing and production pipe if:

- The annuli between coal string, intermediate casing, and production pipe are cemented.

- The annulus between the coal string and the intermediate casing is cemented but the annulus between the intermediate casing and production pipe is left open or uncemented.

- The annuli between coal string, intermediate casing, and production pipe are left open or uncemented.

Referring to the annuli as being open can also mean they are filled with bentonite, gel or other viscous materials.

It is important to note that the critical input for the finite element analysis is the number, locations, and properties of weak-strong rock interfaces. The model contained 3D interface contact elements which defined the interface between rock types. Weak interfaces include coal-limestone, coal-sandstone, coal-sandy shale, limestone-claystone, or similar conditions where they are assigned a cohesive value of zero. Below the C Limestone member of the Sewickley Formation, the interfaces were given the friction value of 0.2 and

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[2] Dassault Systèmes, 2002, <u>Abaqus Unified FEA</u>, Vélizy-Villacoublay, France.

interfaces above the C Limestone assigned a friction value 0.02. The locations of the identified weak interfaces are:

Depth to Slip Element (ft)	Upper - Lower Contact	Depth to Slip Element (ft)	Upper - Lower Contact
50		284	
66		288	Waynesburg Coal
82		318	Shale and Brownsville Sandstone
91		322	
104		337	Shale and Waynesburg Limestone
108		340	
118		354	
122		368	
124		380	
129	Lower Limestone and shale	390	Shale and Limestone C
134	Shale and Lower Limestone	488	Benwood Limestone and shale
138		510	Shale and Sewickley Limestone
150		524	
170		548	Fishpot Limestone and shale
186		600	
194		610	Shale and Lower Pittsburgh Limestone
219		648	
234		654	
248			

In this study the elastic, plastic, or strain softening properties of the rock are less critical than the interface mechanical properties. The rock properties employed by CONSOL in the modelling are compressive strength, Young's moduli, and Poisson's ratio. The Young's moduli and compressive strength values of coal, claystone, shale, sandy shale, limey shale, sandstone, and limestone employed in the models were reported to be reduced by a factor of four from known strengths of these rock types. Following are the material properties employed in the finite element model:

	psi				
Rock Type	Young's Moduli	Compressive Strength	Onset of Strain Softening	Angle of Friction (degrees)	Note
Coal	105,000	903	833	35	
Claystone	130,000	993	993	-	Perfect plastic
Shale	300,000	1,486	1,389	38	
Sandy Shale	375,000	1,700	1,545	38	
Limey Shale	400,000	1,986	1,806	38	
Sandstone	525,000	2,479	2,222	40	
Limestone	750,000	3,722	3,472	42	

For all materials, plastic strength was assumed to be zero psi past the plastic strain limit of 0.001.

The gob was treated as a hyperelastic material. Hyperelastic stress-strain relationship can be defined as non-linearly elastic, isotropic, incompressible, and generally independent of strain rate.

Gob Strain Path	
Modulus x 1,000 lbs/ft/ft	Strain
-50	0.000
50	-0.180
2000	-0.219
6000	-0.220
10000	-0.250

The gob modulus increases sharply as the gob is compressed and can compress 25%. Casing and cement elements are formulated using cylindrical coordinates.

Figure B-15, following this text, is an illustration from the ABAQUS finite element model that shows a portion of the constructed 3D mesh used in the analysis.

7.1   ABAQUS Results

The ABAQUS model shows strong agreement with the actual surface subsidence survey measurements as compared below:

Maximum Vertical Surface Subsidence (ft)		
	Surveyed	ABAQUS
E-24 Panel (E-24 Retreated)	-4.60	-4.606
E-24 Panel (E-25 Retreated)	-4.63	-
E-25 Panel (E-25 Retreated)	-4.60	-4.618

The ABAQUS analysis predicted the horizontal movement (deformation) and the inelastic strain that occurred in all four test wells and two of the monitoring wells (MW 3 and MW 4) as well as the inelastic strain for the intermediate casing and the production pipe within the test wells. The total strain was not reported but can be calculated by:

$$\text{Total Strain = Elastic Strain + Inelastic Strain}$$

Figures B-16 and B-17, following this text, show the ABAQUS model predicted the location of the major movement at 390 ft depth as recorded by the caliper logs. This in part was due

to the model assumption of interface friction of 0.02 and 0.2 above and below the C Limestone member, respectively.

A comparison shows the measured movements are in reasonable agreement with those predicted by the ABAQUS Models.

	Measured and Modelled Test and Monitoring Well Horizontal Movement (inches) at a Depth of 390 ft					
	TW #1	TW #2	TW #3	TW #4	MW 3	MW 4
After Panel E-24 - Measured	4.99	5.52	1.98	3.97	-	-
- ABAQUS	4.29	4.08	4.19	4.10	4.76	4.16
After Panel E-25 - Measured	3.48	5.16	4.67	2.75	-	-
- ABAQUS	2.68	2.99	2.96	3.10	1.47	2.81

The finite element analysis predicted strain in the coal protection casing in TW #3 that is nearly 10 times the strain in the other test wells.

	ABAQUS Inelastic Strain in the Coal Protection Casing After E-25			
	TW #1	TW #2	TW #3	TW #4
@ 390 ft	0.0934	0.0162	0.0399	0.0015
@ Pittsburgh Seam	0.0060	0.0077	0.0599	0.0065

7.2   ABAQUS and Alternate Casing Designs and Depth of Seam

Alternate casing designs were examined by CONSOL to determine if it is possible to reduce casing deformation and eliminate inelastic casing strain. Cementing options are addressed in the following comparison.

		Uncemented	
ABAQUS Inelastic Strain after E-25 for Various Cementing Options, TW #1 Configuration			
	All Strings Cemented	Production String	Production String and Intermendiate Casing
	@ 390 ft depth		
Intermediate Casing	0.016	0.037	0.000
Production String	0.016	0.000	0.000
	@ Pittsburgh Seam		
Intermediate Casing	0.016	0.173	0.000
Production String	0.016	0.000	0.000

If all strings are cemented, inelastic strain occurs in both the intermediate casing and production pipe. If the intermediate casing or production string is not cemented, inelastic strain does not occur in that string. The only case analyzed where strain can result in rupture is where the intermediate casing is located within the Pittsburgh Seam and all casing except the production string is cemented. This is shown as strain of 0.173 in the preceding table, and where:

Total strain = inelastic strain + elastic strain = 0.173 + 0.005 = 0.178 > 0.120 allowable strain

In considering alternate casing thickness, the finite element analysis demonstrates lower strain is found in thicker casing:

Finite Element Strain in Coal Protection
Casing, TW #1 Configuration @390 ft depth

Casing	Inelastic Strain	
Thick. (in.)	Longwall E-24	Longwall E-25
0.38	0.0246	0.0351
0.05	0.0107	0.0107

The finite element analysis also considered the effect of mining depth.

ABAQUS Inelastic Strain in Coal Protection
Casing at Various Depths, TW #1 Configuration

Overburden Depth (ft)	Longwall E-24	Longwall E-25
	Casing @ 390 ft depth	
604	0.0583	0.0934
1,100	0.0100	0.0022
	Casing @ Pittsburgh Seam	
604	0.0044	0.0060
1,100	0.0090	0.0187

The deeper the mine, the less strain occurs in the coal protection casing located in the overburden and the greater the strain in the casing located within the extracted coal seam.

8.0   Discussion

8.1   Pillar Stress and Strain

The measured increase in strain within the coal as obtained by the MW 2A extensometer was 0.99% on August 27, 2013 (during E-24 retreat) and 1.79% on May 31, 2014 (during E-25 retreat). The actual values in the coal are likely higher because of slippage and transfer of strain from the coal to the extensometer.

Stress changes in the coal were measured by BPC and the final reading during E-24 longwall retreat was 435 psi. On May 21, 2014 the final reading was 1,029 psi due to mining E-25. Summing the E-24 and E-25 readings results in a stress change of 1,464 psi.

The change in pillar stress as measured by the BPCs and the same pressure estimated by ABAQUS shows strong agreement.

Longwall	Coal Pillar Pressure (psi)	
Panel	BPC	ABAQUS
E-24	435	469
E-25	1,029	917
Total	1,464	1,386

The known changes in stress and strain within the coal pillar allow the estimate of Young's modulus. The estimate should be less than but within a magnitude of the actual Young's modulus especially noting that some plastic deformation may have occurred in the pillar.

Comparison of the calculated Young's modulus to that used in the ABAQUS model shows good agreement.

	Change		Young's Modulus (psi)	
	Stress (psi)	Strain (%)	Calculated	ABAQUS
August 2013	435	0.99	43,939	105,000
May 2014	1,464	1.79	81,800	105,000

8.2   Subsidence

The last inclinometer reading during the retreat of longwall E-24 occurred on August 17, 2013. Subsidence surveys show further monitoring well movement after that date. A comparison of the subsidence recorded on August 17, 2013 to the final subsidence survey for longwall E-24 on September 17, 2013, shows the top of the monitoring wells, on an average, moved downward an additional 0.012 ft and horizontally an additional 0.034 ft.

	Subsidence Movement after Longwall E-24 (ft)					
	Vertical			Horizontal		
	9/17/2013	8/17/2013	Change	9/17/2013	8/17/2013	Change
MW 1	(0.133)	(0.102)	(0.031)	0.182	0.153	0.030
MW 2	(0.162)	(0.143)	(0.019)	0.165	0.152	0.013
MW 3	(0.079)	(0.093)	0.014	0.207	0.168	0.038
MW 4	(0.131)	(0.119)	(0.012)	0.209	0.154	0.056
Average			(0.012)			0.034

Of interest is the inclinometer installed in MW 1 whose top readings are closer to the surface than the other inclinometers. As noted above the maximum measured horizontal movement in this inclinometer is 1.21 inches. Since the maximum horizontal movement in MW 1 occurred 98.1 ft deep, the adjustment to this reading would be a ratio:

$$1.21 \times \frac{0.1821}{0.1527} = 1.44 \text{ inches}$$

Similarly, the last reading of the inclinometers and extensometer installed in the monitoring wells during the retreat of longwall E-25 occurred on May 31, 2014. The subsidence surveys show that these wells moved after that date. A comparison of the subsidence recorded on May 31, 2014 to the final subsidence survey for E-25 on July 10, 2014, shows the top of the monitoring wells moved downward 0.010 ft and horizontally 0.004 ft.

	Subsidence Movement after Longwall E-25 (ft)					
	Vertical			Horizontal		
	7/10/2014	5/31/2014	Change	7/10/2014	5/31/2014	Change
MW 1	(1.017)	(0.113)	(0.904)	0.187	0.188	(0.001)
MW 2	(0.108)	(0.964)	0.856	0.182	0.150	0.032
MW 3	(0.086)	(0.082)	(0.004)	0.164	0.183	(0.019)
MW 4	(0.132)	(0.147)	0.015	0.210	0.206	0.004
Average			(0.010)			0.004

No horizontal adjustment to MW 1 inclinometer data was required after longwall E-25.

9.0   Conclusions

The field test instrumentation readings show significant agreement with the present understanding of ground movement and pillar behavior associated with longwall mining. More significant is the agreement between the instrumentation and finite element analysis.

Calibration of the finite element model was accomplished by adjusting friction values above and below the major deformation detected by the installed instruments.

The measurements and analysis for this mine configuration and geologic environment showed that:

- Casing deformation is identified in two settings: at the weak/strong rock contacts and within the Pittsburgh Coal Seam.

- Casing deformation in response to ground movement occurring at weak/strong rock contacts is above the well's intersection with the angle of draw.

- The most significant movement is found at the weak/strong rock contact on top of Limestone C with horizontal movements in all four test wells from 2.0 in. to 5.5 in.

- The finite element analysis showed the inelastic strain of the coal protection casing was consistent at 0.006 for all test wells except for TW #3 in which inelastic strain was 10 times higher approaching 0.060.

- TW #3 employed the weakest coal protection casing. The finite element analysis for varying wall thicknesses showed this accounted for the higher strain.

- If all strings are cemented, inelastic strain occurs in both the intermediate casing and production pipe. If the intermediate casing or production string is not cemented, inelastic strain does not occur in that string.

- Among all conditions, the highest inelastic strain is shown to occur at coal seam level in the coal protection casing of TW #3. This is because the casing was the weakest of all the test wells and was cemented in place.

- As overburden increases, the strain in the casing due to movement along weak/strong rock planes decreases.

- Strain in the coal protection casing at coal seam level increases as the overburden increases.

- Site specific geology has significant impact on the outcome.

Following this page are:

Figures:

Gamma, In Counts per Second (Gcps)

Jollytown Coal
Jollytown Limestone

Lower Limestone
Lower Limestone

Waynesburg Sandstone

Waynesburg Coal

Brownsville Sandstone

Waynesburg Limestone

Uniontown Coal

Limestone C

Limestone B

Limestone A

Benwood Limestone

Sewickley Limestone

Fishpot Limestone

Pittsburgh Coal Seam

Lower Pittsburgh
    Limestone & Shale

Depth, ft

Gcps

0   50   100   150   200   250

APPENDIX B-1

GAMMA RAY LOG FOR
BOREHOLE MW 2A

Prepared For
**PENNSYLVANIA DEPARTMENT OF
ENVIRONMENTAL PROTECTION
BUREAU OF OIL AND GAS MANAGEMENT**

JB John T. Boyd Company

March 2016
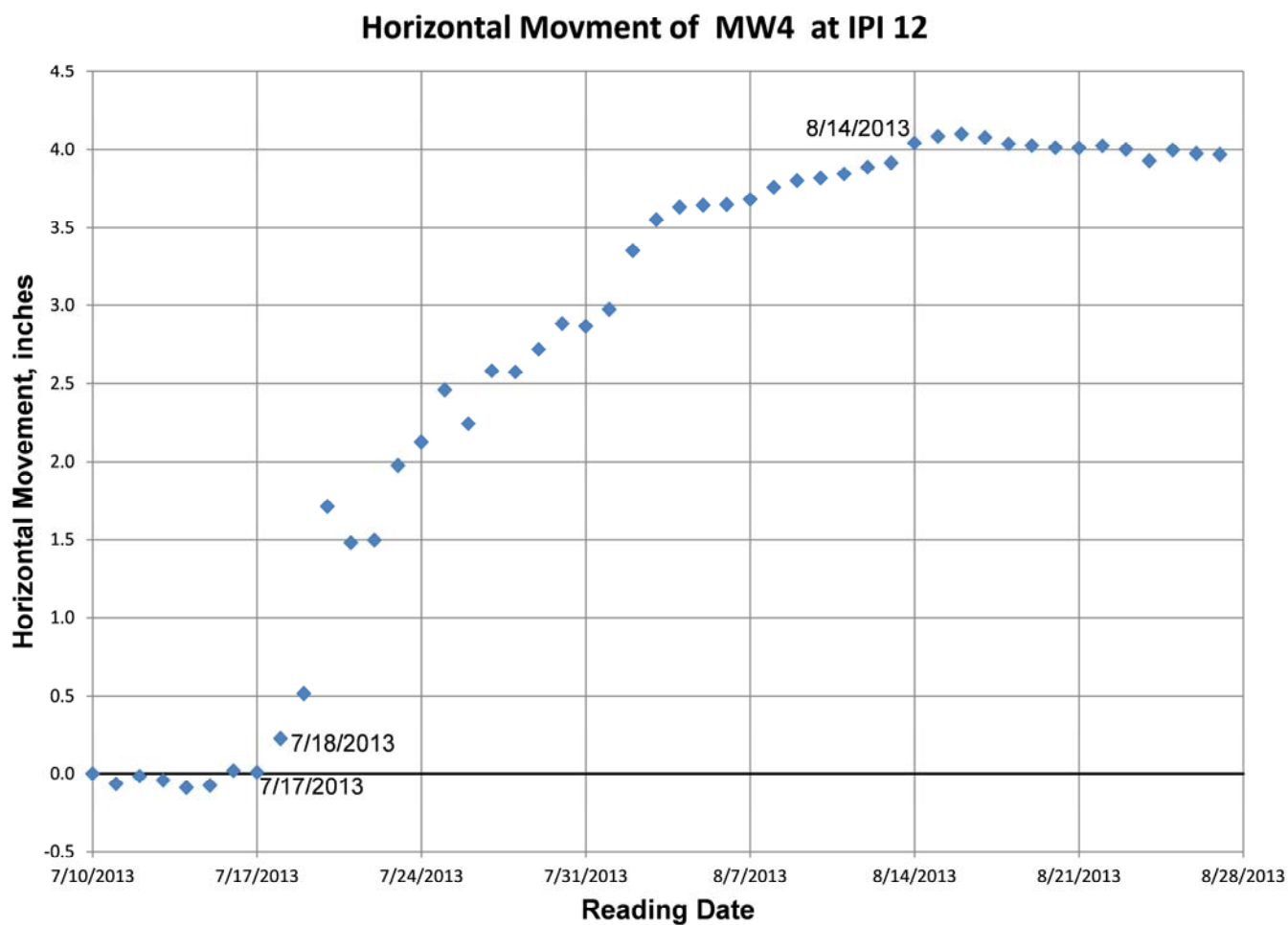Scale as Shown

Locations of Casing Deformation

Depth, ft

0

100

200

300

400

500

600

Test Wells

1   2   3   4

Jollytown Coal
Jollytown Limestone

Lower Limestone
Lower Limestone

Waynesburg Sandstone

Waynesburg Coal

Brownsville Sandstone
Waynesburg Limestone

Uniontown Coal
Limestone C
Limestone B
Limestone A

Benwood Limestone

Sewickley Limestone
Fishpot Limestone

Pittsburgh Coal Seam

Lower Pittsburgh
   Limestone & Shale

APPENDIX B-2

DEFORMATIONS LOCATED
ON CALIPER LOG

Prepared For
**PENNSYLVANIA DEPARTMENT OF
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BUREAU OF OIL AND GAS MANAGEMENT**

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Scale as Shown

Horizontal Movement, Inches

Horizontal Movement, Inches
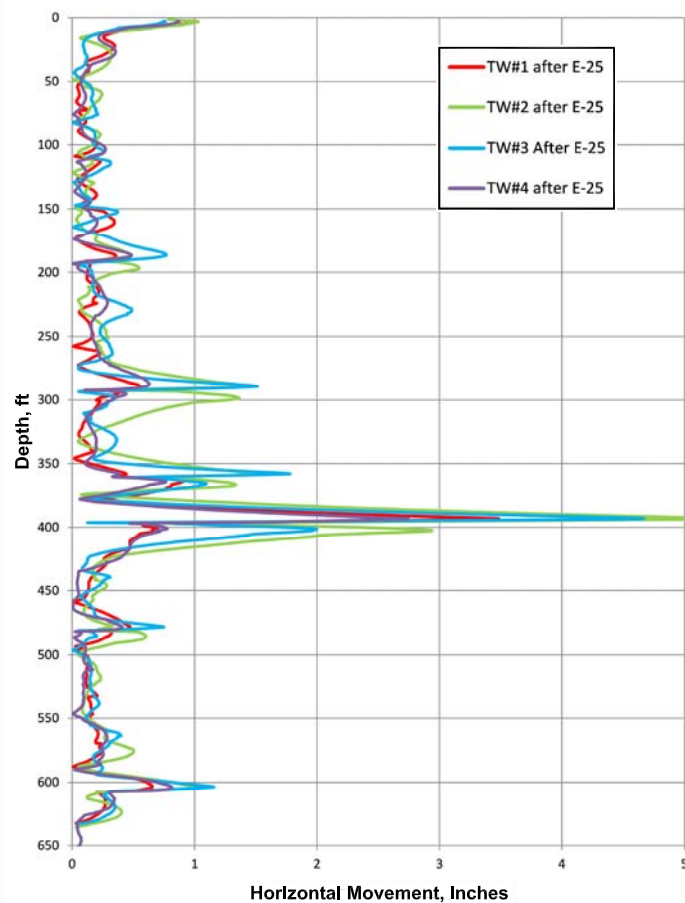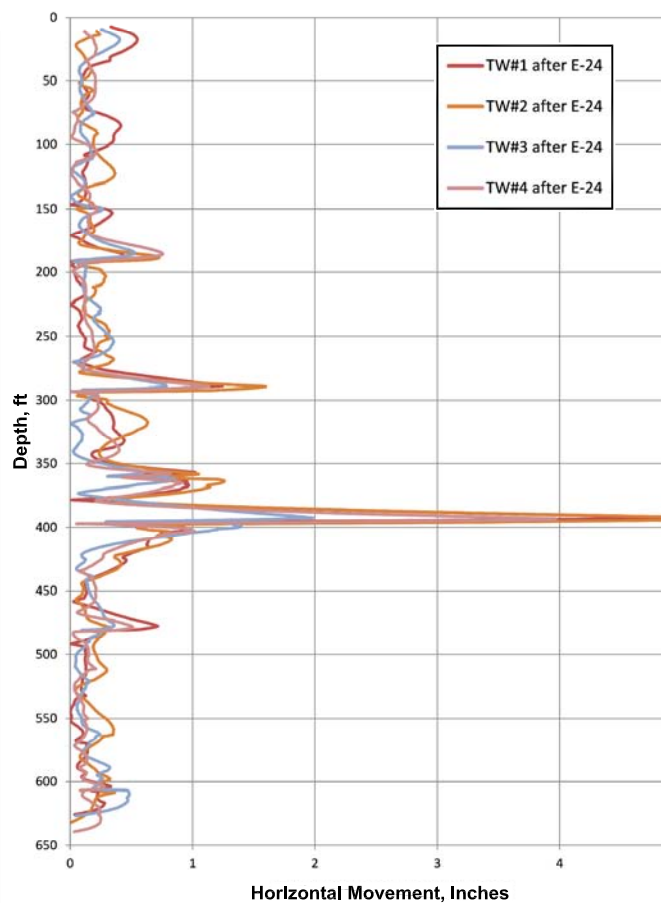
APPENDIX B-3

HORIZONTAL DISPLACEMENTS IN TEST WELLS
AFTER LONGWALLS E-24 AND E-25

Prepared For
**PENNSYLVANIA DEPARTMENT OF
ENVIRONMENTAL PROTECTION
BUREAU OF OIL AND GAS MANAGEMENT**

John T. Boyd Company

March 2016
Scale as Shown

B-25
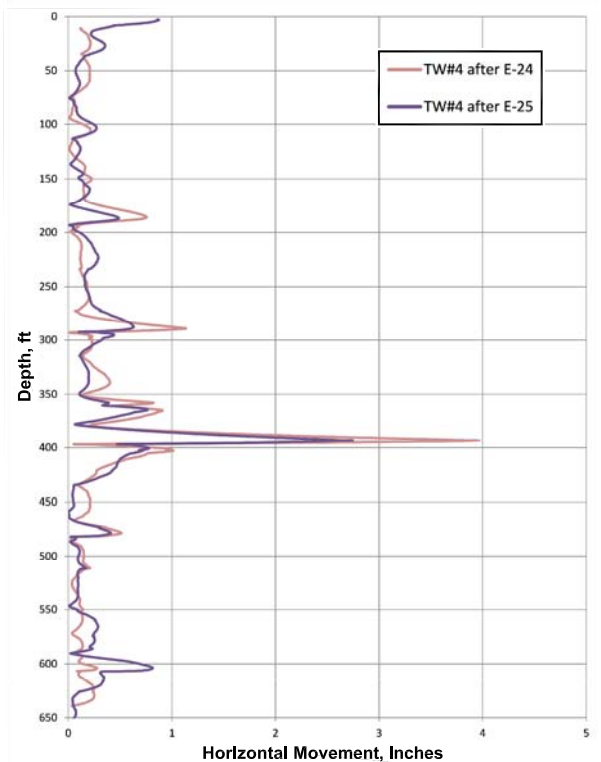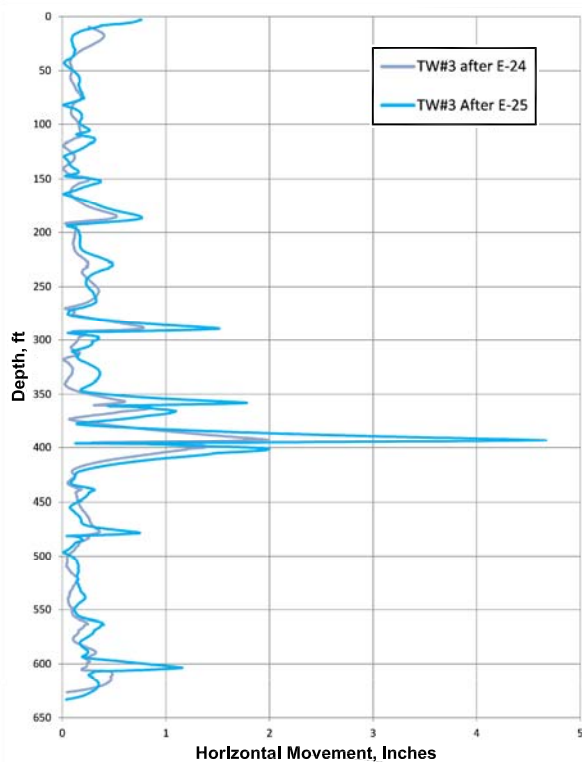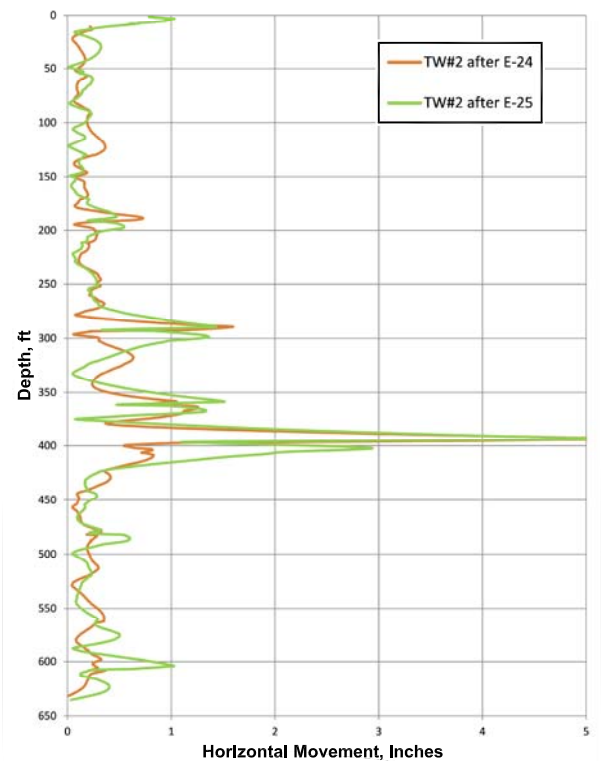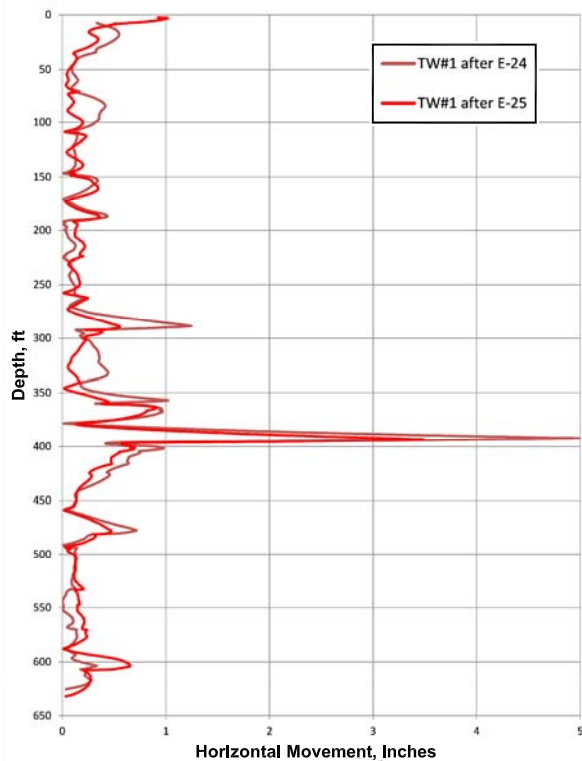
APPENDIX B-4

TEST WELL HORIZONTAL DISPLACEMENTS
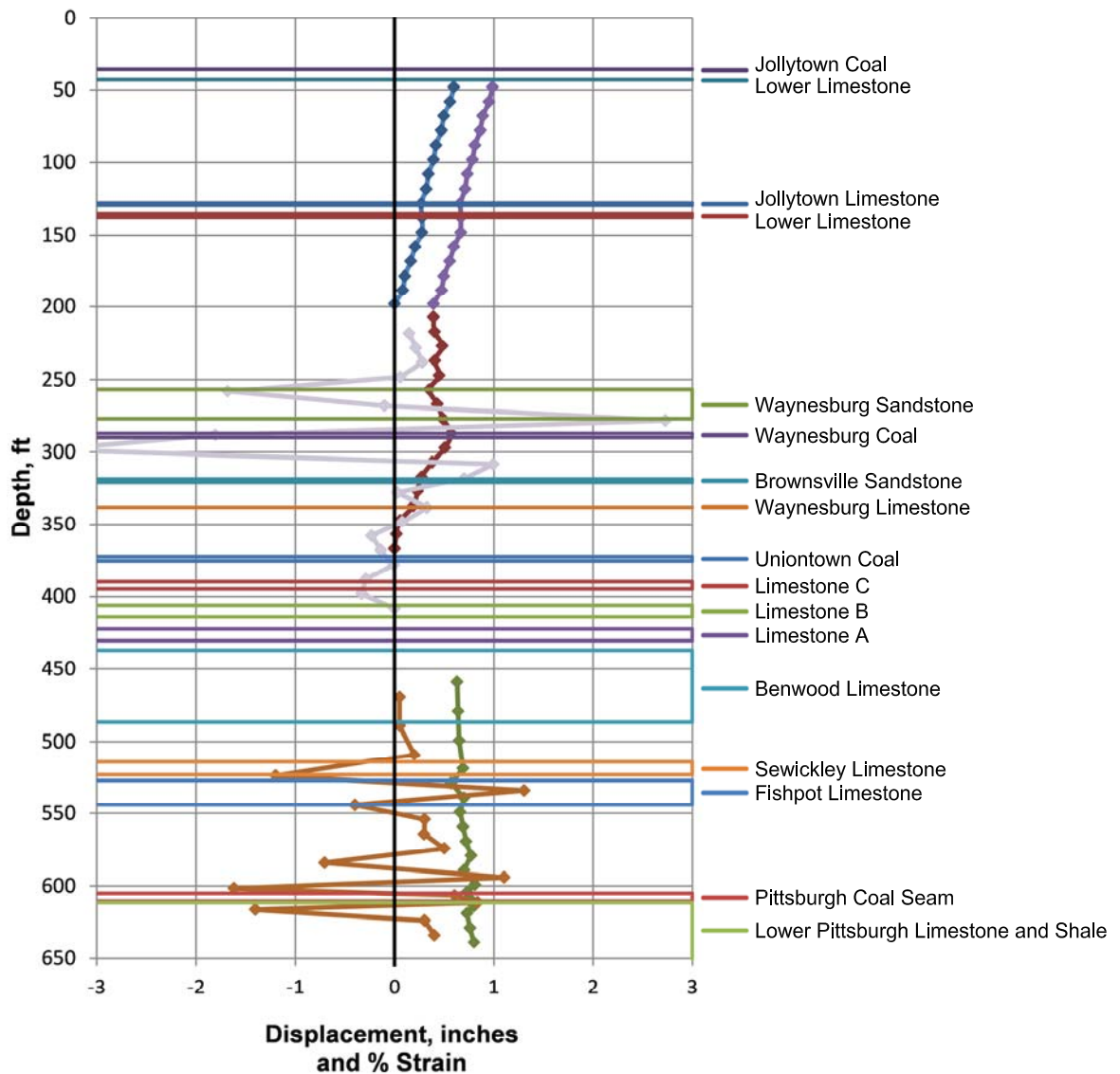AFTER EACH LONGWALL

Prepared For
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BUREAU OF OIL AND GAS MANAGEMENT**

John T. Boyd Company

March 2016
Scale as Shown

P:\CAD_GROUP-jfg\3577.001\FIGURE B-4.DWG

Well Name: NV-35 \ WH-03
Depth: 389.343 - 405.920
Deviation Magnification: 1
Radial Magnification: 1
Aspect Magnification: 3
Image Magnification: 1.00
Color Contour:

Well Name: NV-35 \ WH-04
Depth: 388.928 - 405.504
Deviation Magnification: 1
Radial Magnification: 1
Aspect Magnification: 3
Image Magnification: 1.00
Color Contour:

Note: Deformation Depictions by Weatherford International PLC.

APPENDIX B-5

TW #3 AND TW #4 DEFORMATION
AFTER MINING E-25 PANEL
AT 390 ft DEPTH

Prepared For

**PENNSYLVANIA DEPARTMENT OF
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BUREAU OF OIL AND GAS MANAGEMENT**

JB John T. Boyd Company

March 2016
No Scale

Horizontal Movment of MW4 at IPI 12

Note, Positive displacement is towards Longwall E-25 and negative displacement is towards Longwall E-24.

Legend

- Horizontal Displacement MW1 - Inclinometer
- MW1 Adjusted
- Vertical Displacement MW2A - Extensometer
- Vertical Strain MW2A - Extensometer
- Horizontal Displacement MW3 - Inclinometer
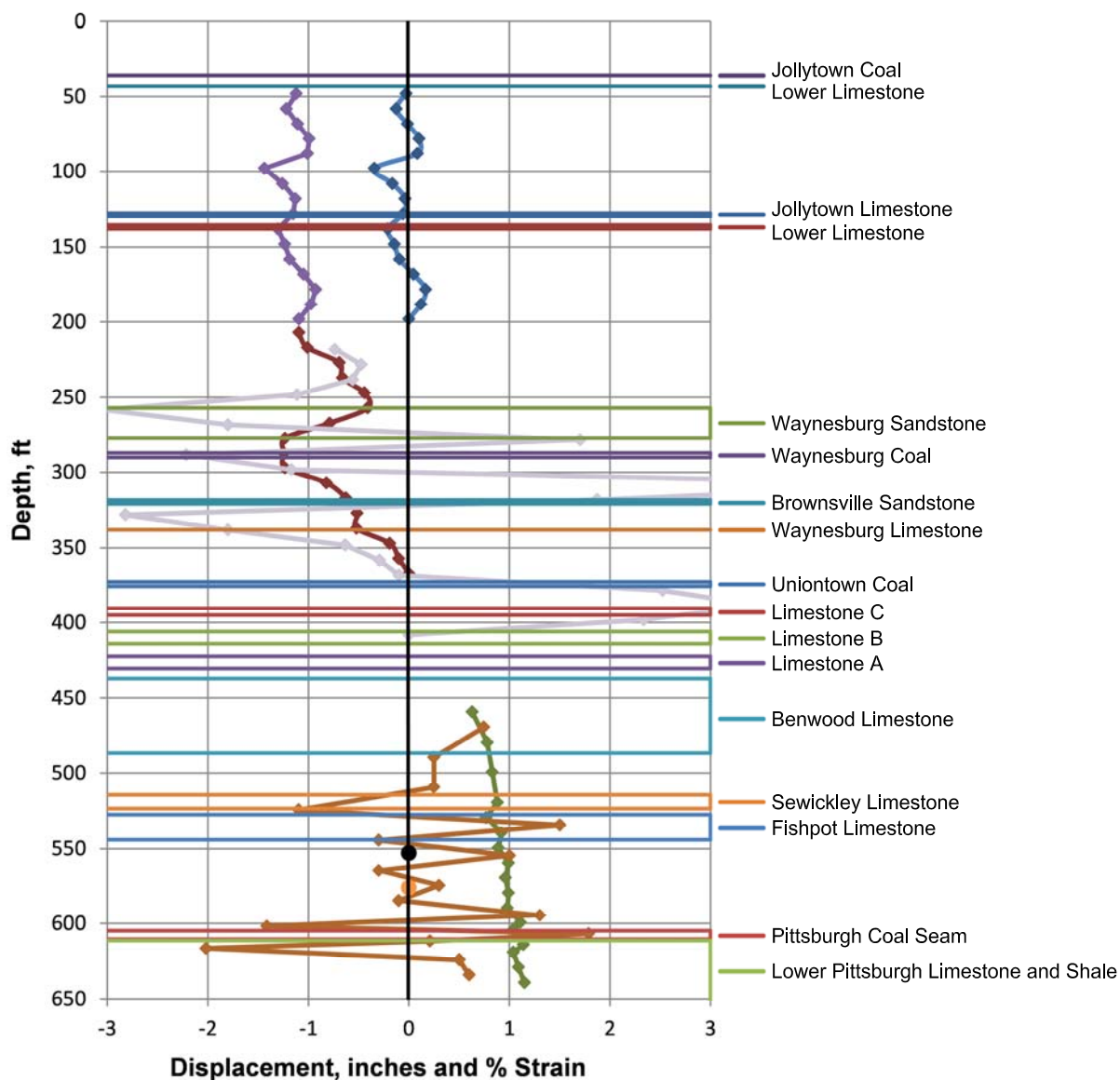- Horizontal Displacement MW4 - Inclinometer
- ● Angle of Draw

P:\CAD_GROUP—jfg\3577.001\FIGURE B−7.DWG

Note, Positive displacement is towards Longwall E-25 and negative displacement is towards Longwall E-24.

Legend

- Horizontal Displacement MW1 - Inclinometer
- MW1 Adjusted
- Vertical Displacement MW2A - Extensometer
- Vertical Strain MW2A - Extensometer
- Horizontal Displacement MW3 - Inclinometer
- Horizontal Displacement MW4 - Inclinometer

APPENDIX B-8

OVERBURDEN MONITORING PLOT
FOR MOVEMENTS RESULTING FROM
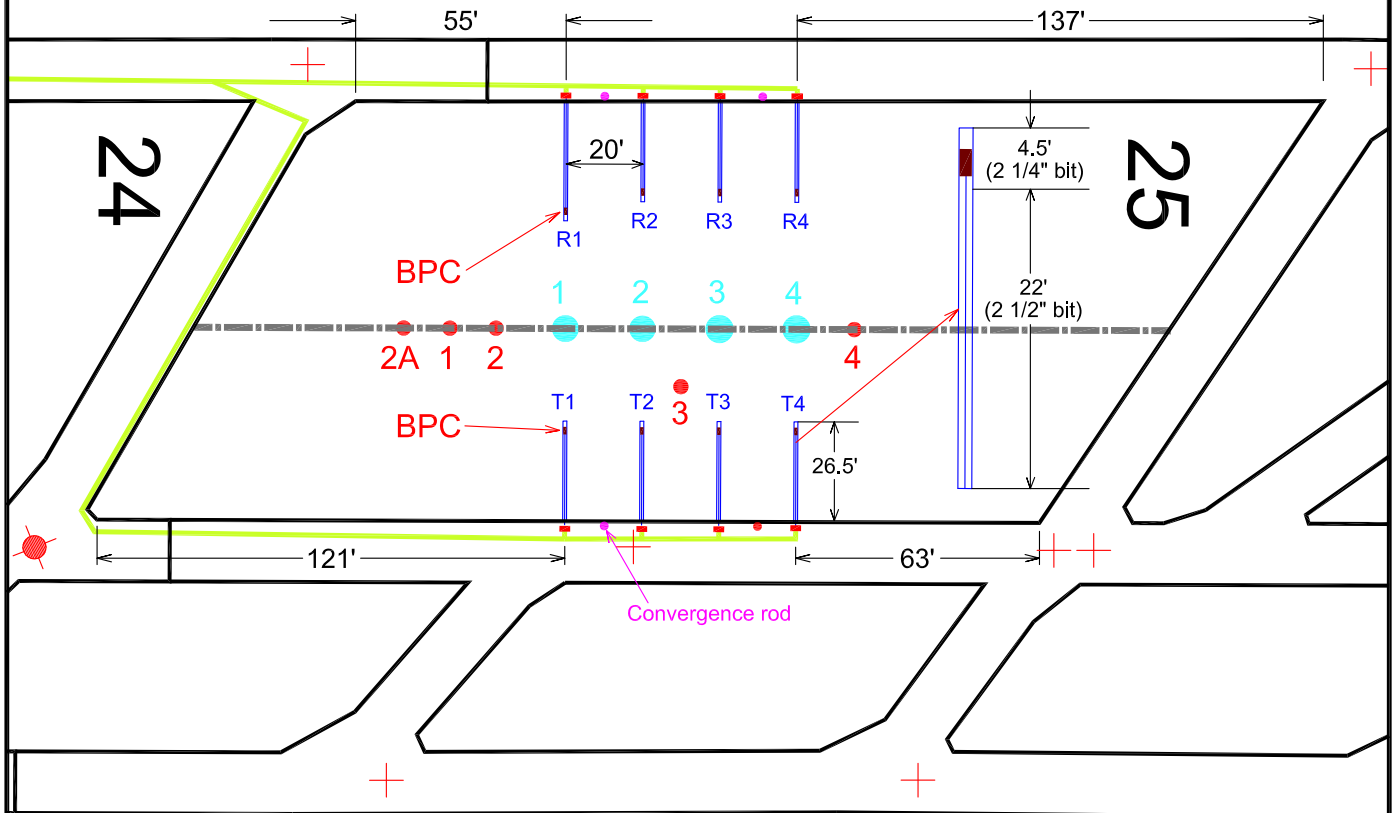ONLY LONGWALL E-25

Prepared For
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BUREAU OF OIL AND GAS MANAGEMENT**

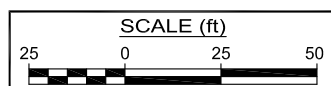JB John T. Boyd Company

March 2016
Scale as Shown

P:\CAD_GROUP—jfg\3577.001\FIGURE B—8.DWG

Note, Positive displacement is, as shown on the plot,
towards Longwall E-25 and negative displacement is towards Longwall E-24.

Legend

- Horizontal Displacement MW1 - Inclinometer
- MW1 Adjusted
- Vertical Displacement MW2A - Extensometer
- Vertical Strain MW2A - Extensometer
- Horizontal Displacement MW3 - Inclinometer
- Horizontal Displacement MW4 - Inclinometer
- E-24 Angle of Draw
- E-25 Angle of Draw

APPENDIX B-9

OVERBURDEN MONITORING PLOT
FOR MOVEMENTS RESULTING FROM
BOTH LONGWALLS E-24 AND E-25

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Scale as Shown

Underground Coal Pillar Instrumentation

Distance to Longwall Face E-24, ft
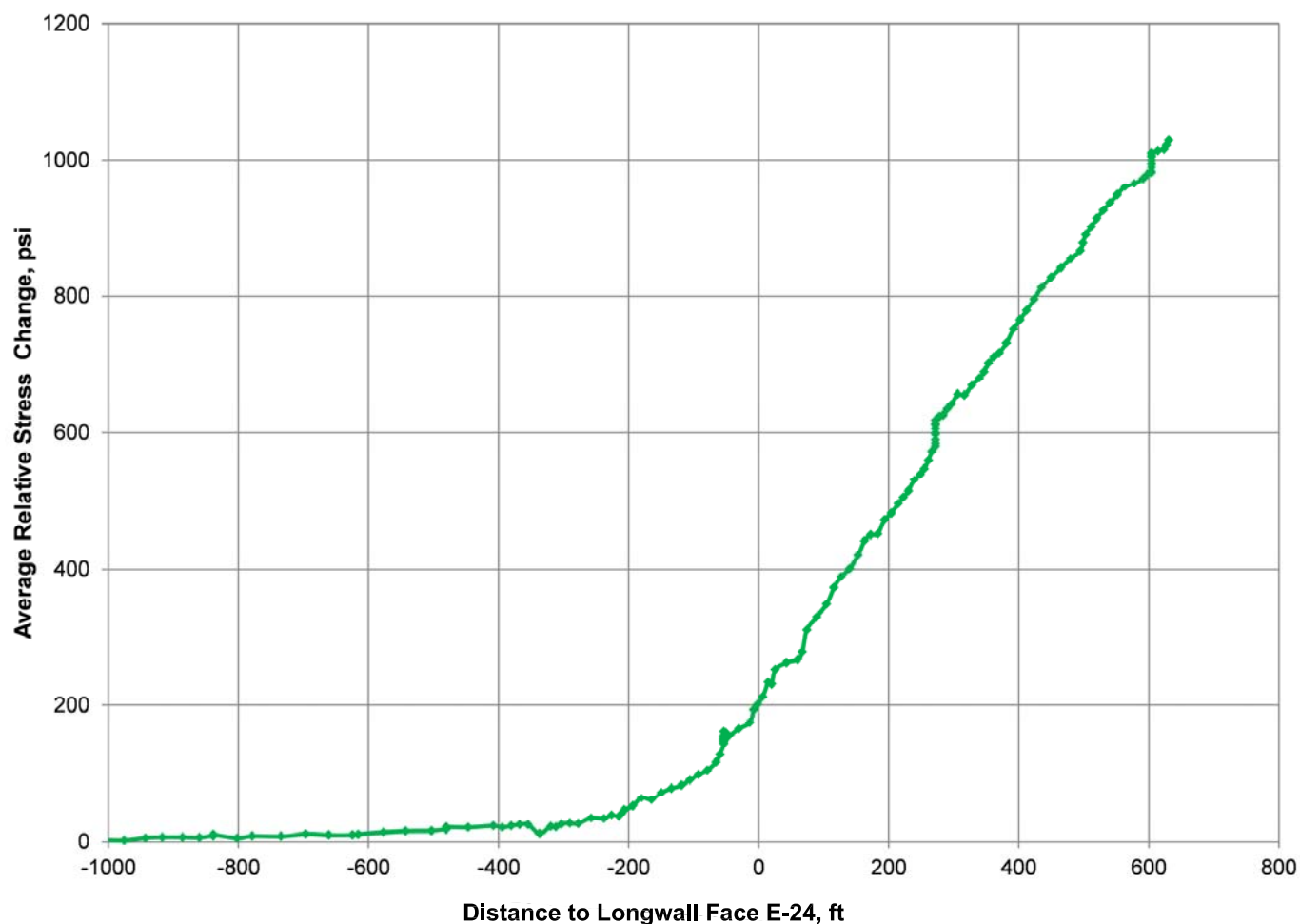
APPENDIX B-11

**BPC T3 PRESSURE CHANGES DURING
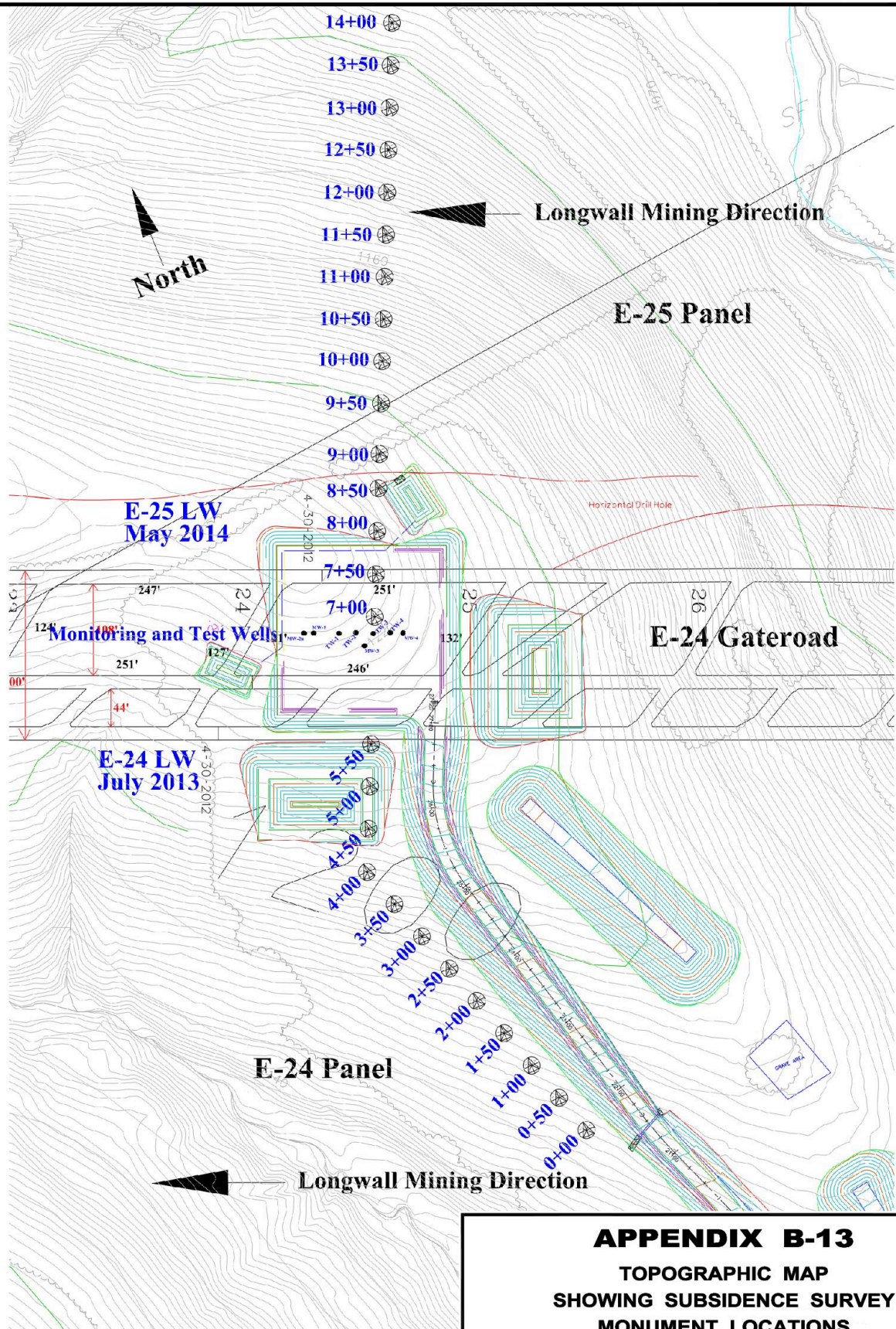LONGWALL E-24 RETREAT**

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March 2016
Scale as Shown

Average Relative Stress Change, psi (y-axis)

Distance to Longwall Face E-24, ft (x-axis)

P:\CAD_GROUP-jfg\3577.001\FIGURE B-12.DWG

B-34

14+00
13+50
13+00
12+50
12+00 ← Longwall Mining Direction
11+50
11+00
10+50
10+00
9+50
9+00
8+50
8+00
7+50
7+00
5+50
5+00
4+50
4+00
3+50
3+00
2+50
2+00
1+50
1+00
0+50
0+00

North

E-25 Panel

E-25 LW
May 2014

Horizontal Drill Hole

247'   251'

Monitoring and Test Wells

E-24 Gateroad

251'   127'   246'   132'

E-24 LW
July 2013

E-24 Panel

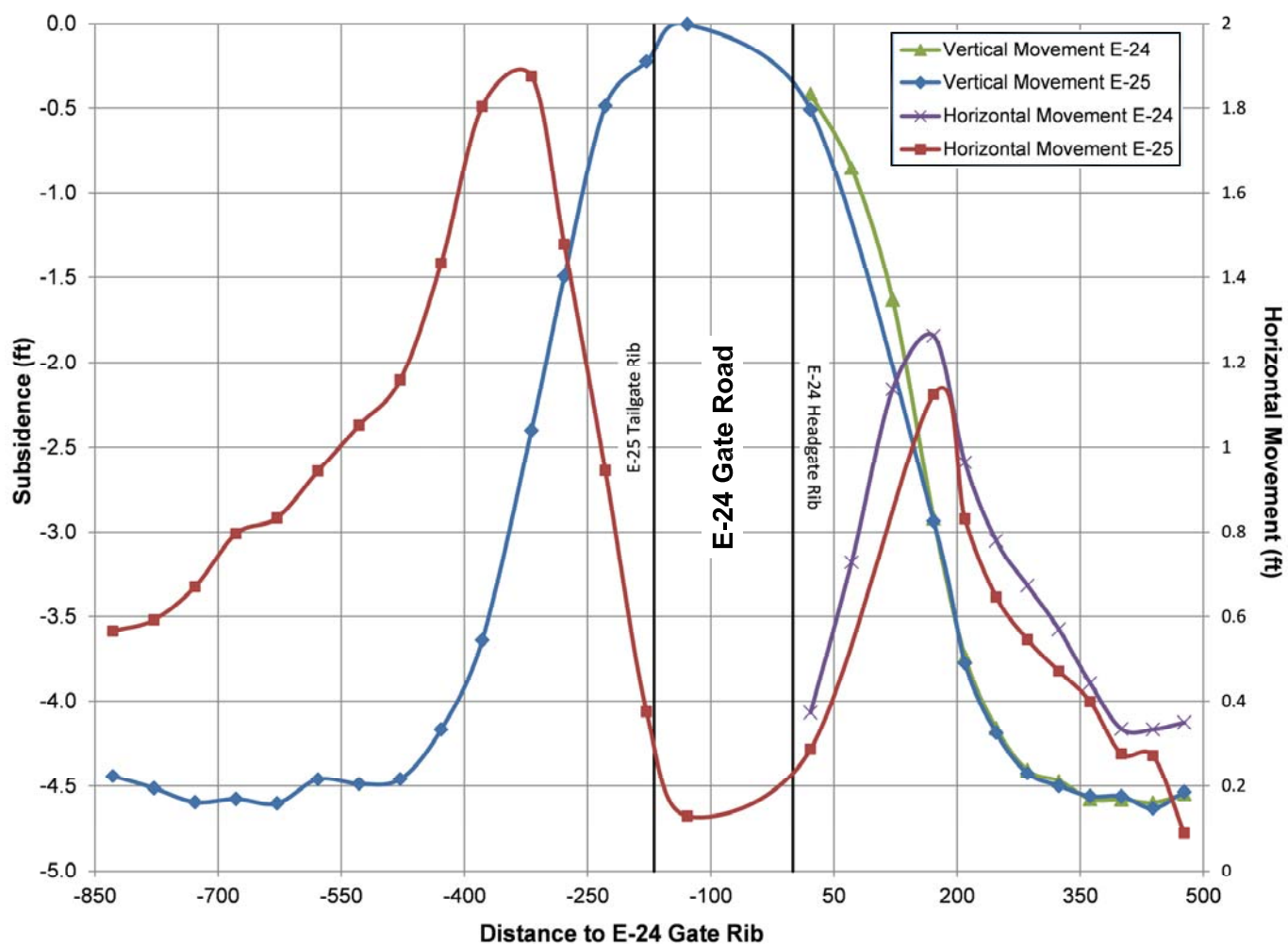← Longwall Mining Direction

APPENDIX B-13

TOPOGRAPHIC MAP
SHOWING SUBSIDENCE SURVEY
MONUMENT LOCATIONS

Prepared For

**PENNSYLVANIA DEPARTMENT OF
ENVIRONMENTAL PROTECTION
BUREAU OF OIL AND GAS MANAGEMENT**

(JTB) John T. Boyd Company

March 2016
Scale 1" = 175'

SCALE (ft)
100   0   100   200

P:\CAD_GROUP-jfg\3577.001\FIGURE B-13.DWG

B-35

APPENDIX B-14

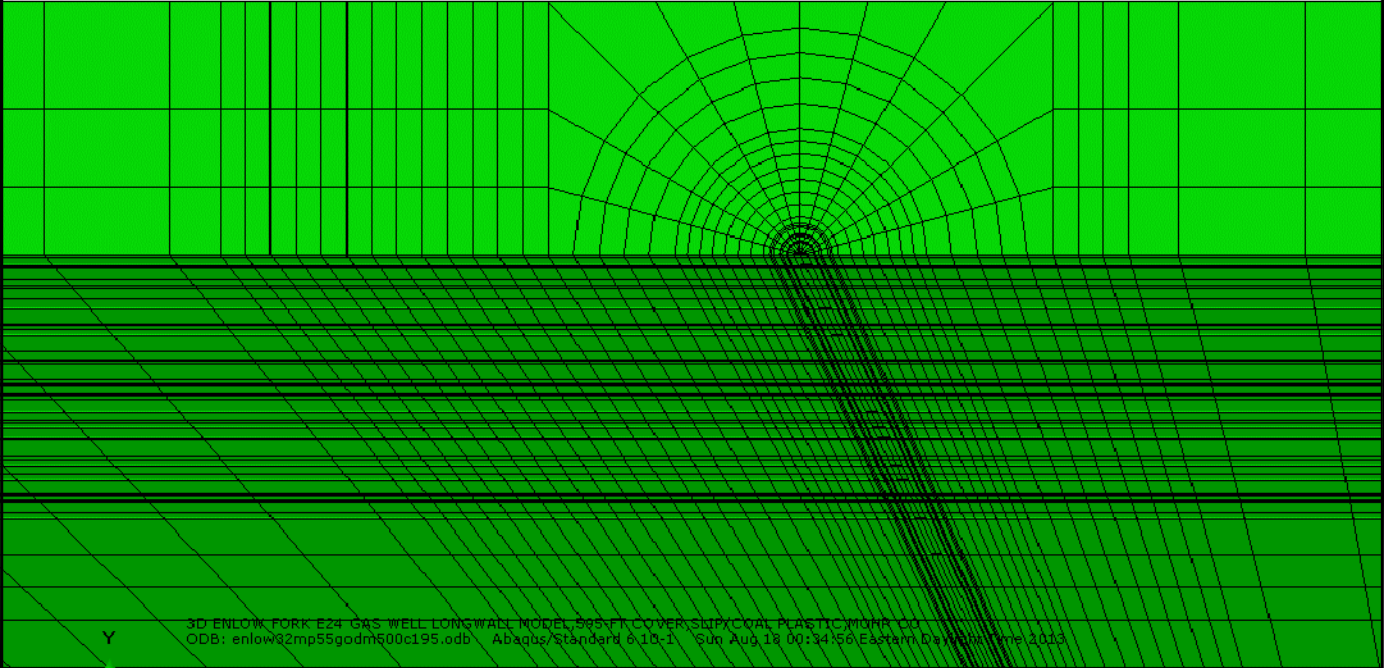VERTICAL AND HORIZONTAL MOVEMENT OF SURVEY MONUMENTS AFTER EACH LONGWALL

Prepared For

PENNSYLVANIA DEPARTMENT OF ENVIRONMENTAL PROTECTION
BUREAU OF OIL AND GAS MANAGEMENT

John T. Boyd Company

March 2016
Scale as Shown

P:\CAD_GROUP—jfg\3577.001\FIGURE B—14.DWG

ENLOW FORK COAL PILLAR STUDY 3D FINITE ELEMENT MODEL

3D ENLOW FORK E24 GAS WELL LONGWALL MODEL,595 FT COVER,SLIP,COAL PLASTIC MOHR CO
ODB: enlow32mp55godm500c195.odb   Abaqus/Standard 6.10-1   Sun Aug 18 00:34:56 Eastern Daylight Time 2013

Y

X   Step: Step-5, E25 LONGWALL EXCAVATION
    Increment   28: Step Time =   1.000
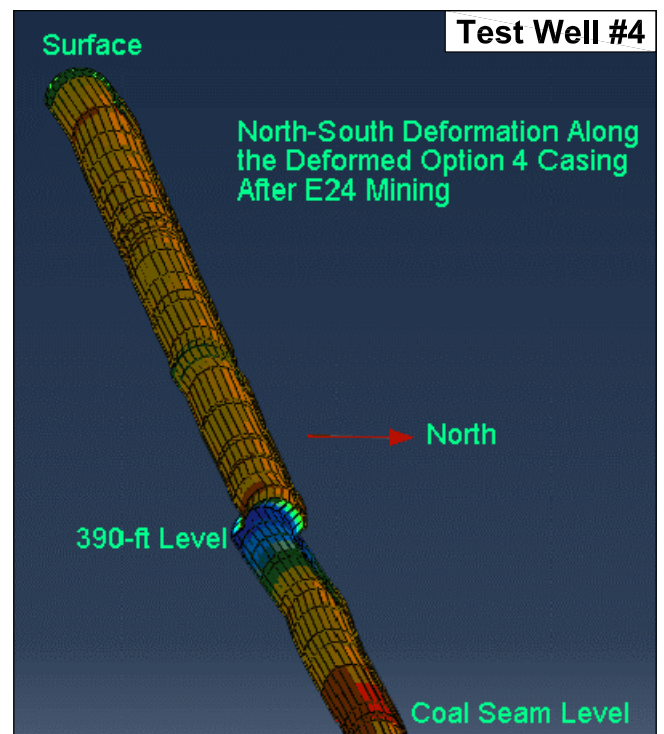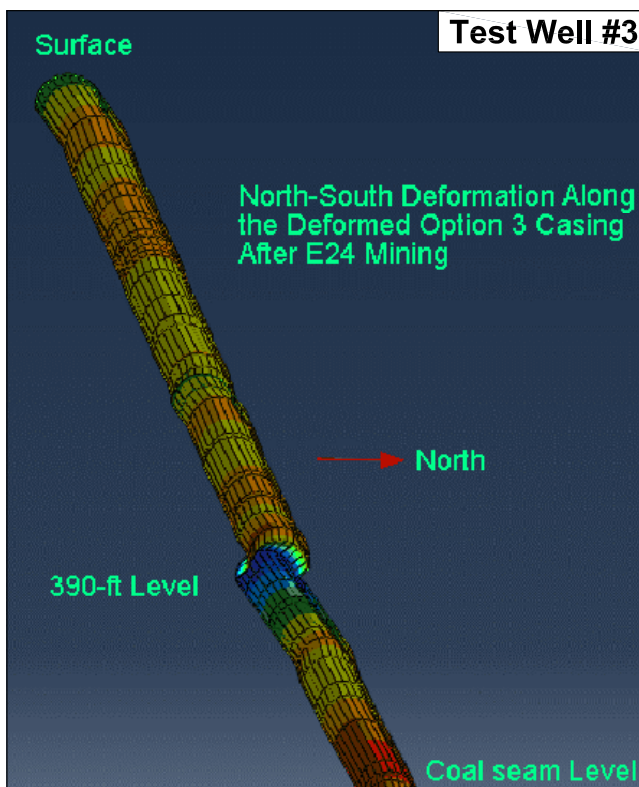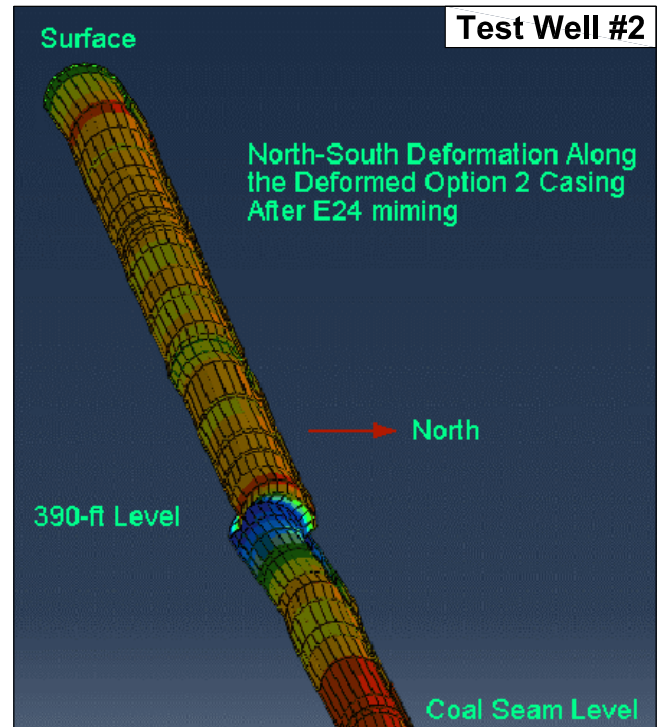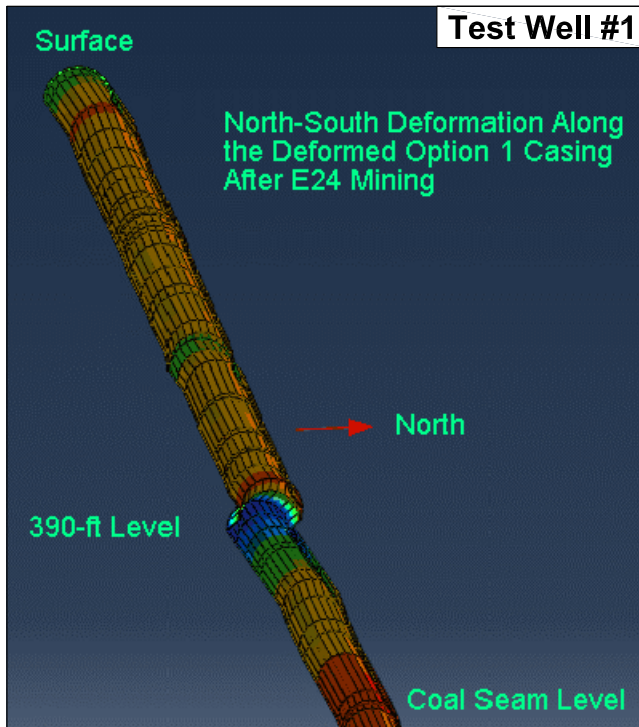
APPENDIX B-15

ABAQUS CREATED GRAPHIC
SHOWING THE MESH USED BY
CONSOL ENERGY INC.

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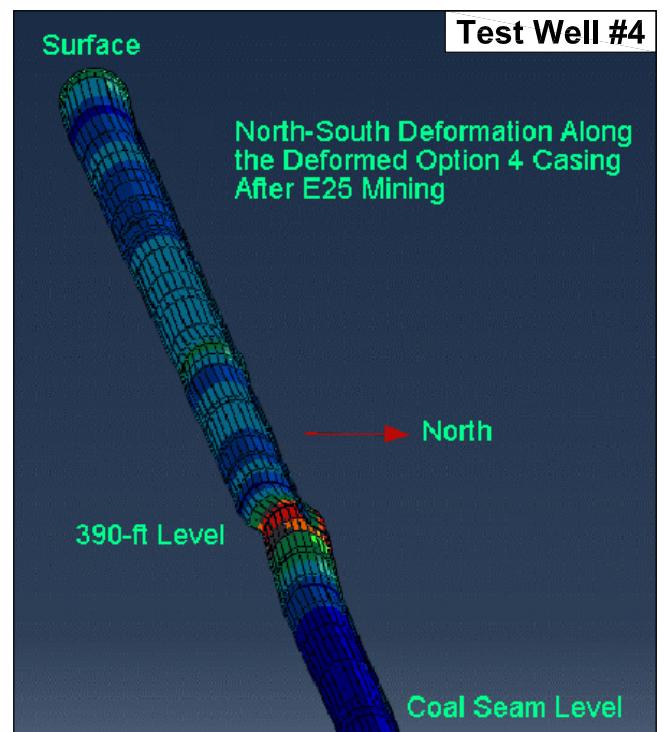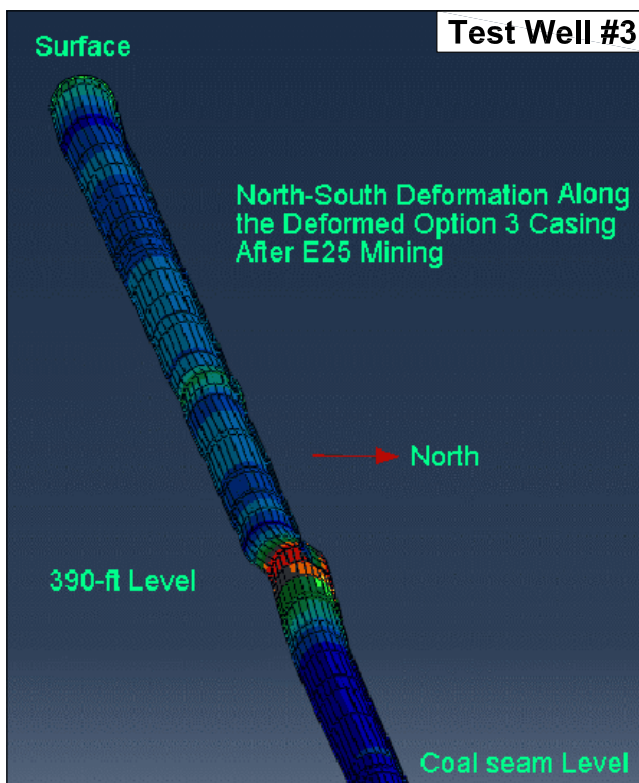
(JB)   John T. Boyd Company

March 2016

No Scale

Test Well #1

Surface

North-South Deformation Along the Deformed Option 1 Casing After E24 Mining

North

390-ft Level

Coal Seam Level

Test Well #2

Surface

North-South Deformation Along the Deformed Option 2 Casing After E24 miming

North

390-ft Level

Coal Seam Level

Test Well #3

Surface

North-South Deformation Along the Deformed Option 3 Casing After E24 Mining

North

390-ft Level

Coal seam Level

Test Well #4

Surface

North-South Deformation Along the Deformed Option 4 Casing After E24 Mining

North

390-ft Level

Coal Seam Level

Test Well #1

Surface

North-South Deformation Along
the Deformed Option 1 Casing
After E25 Mining

North

390-ft Level

Coal Seam Level

Test Well #2

Surface

North-South Deformation Along
the Deformed Option 2 Casing
After E25 miming

North

390-ft Level

Coal Seam Level

Test Well #3

Surface

North-South Deformation Along
the Deformed Option 3 Casing
After E25 Mining

North

390-ft Level

Coal seam Level

Test Well #4

Surface

North-South Deformation Along
the Deformed Option 4 Casing
After E25 Mining

North

390-ft Level

Coal Seam Level

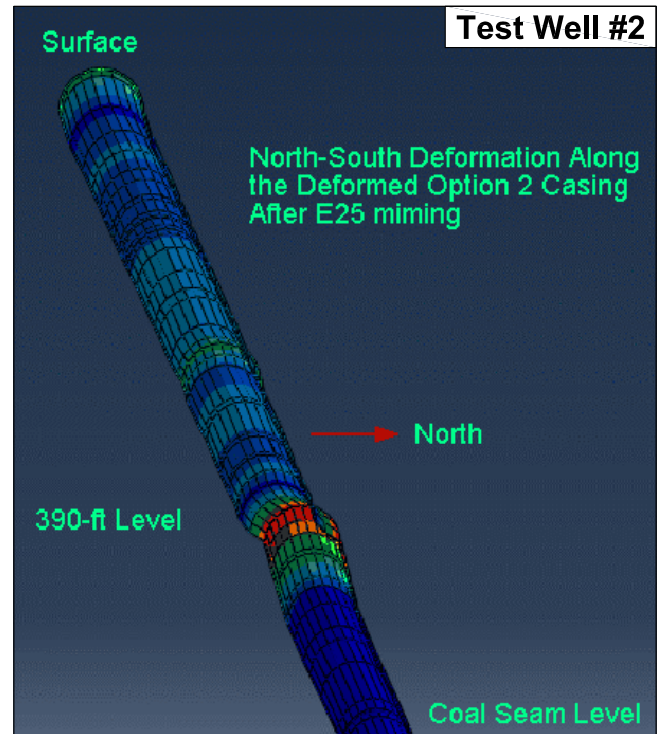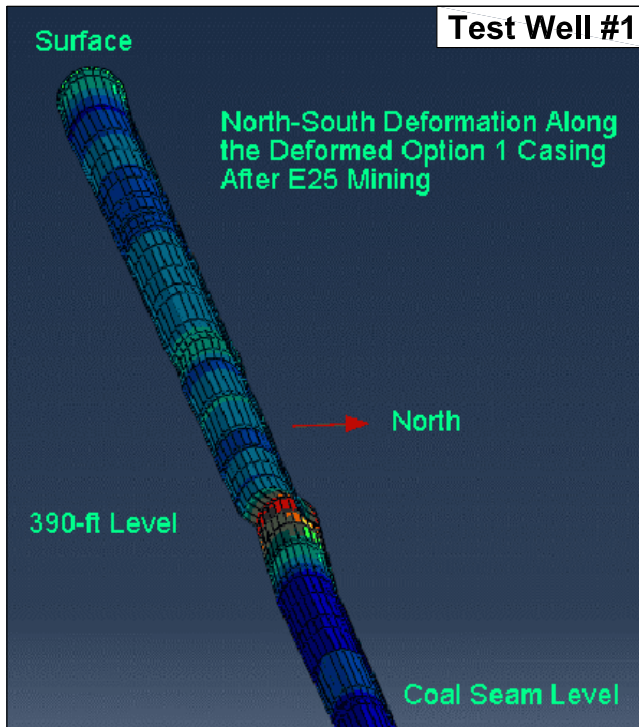P:\CAD_GROUP—jfg\3577.001\FIGURE B—17.DWG

APPENDIX B-17

TEST WELL DEFORMATIONS FROM
LONGWALL E-25 DETERMINED BY ABAQUS

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