DESIGN AND PERFORMANCE OF A LONGWALL COAL MINE WATER-BARRIER PILLAR

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ABSTRACT

The Skyline #3 Mine of Canyon Fuel Company in Utah was planning longwall mine development adjacent to and downdip of older mine workings known to be flooded. Barrier pillar geometries and widths were proposed by mining company personnel. Hydraulic conductivity testing suggested that the general characteristics of the local coal seam, dikes, and faults are only weakly conductive and that leakage through the barriers, if any, would be minor.

The *mechanical performance* of the proposed barrier pillar design was evaluated according to (1) published empirical design methods and (2) numerical stress modeling. Comparison of the proposed design, with the range of barrier widths derived from the empirical methods, served as a first-order check on the adequacy of the proposed design. Numerical modeling was used to evaluate conditions site-specific to the Skyline #3 Mine and barrier geometry. Models were developed to quantify the relationship between barrier width and the abutment stresses onto the future workings. The models were also used to estimate the stress distribution within the barrier pillars. The *hydraulic performance* of the proposed barrier pillar design was evaluated according to (1) published empirical design methods for hydraulic impoundments, (2) empirical method estimates of seepage through coal barrier pillars, (3) numerical hydrogeologic flow modeling, and (4) numerical strain modeling.

Using the techniques described above, and based on relevant industry experience, underground observations, knowledge of local geologic conditions, hydrogeologic measurements, and analytical results, the level of geomechanical risk associated with the barrier design as proposed was considered low and the level of hydraulic risk was considered moderate. The largest uncertainty that remained was the possibility that unfavorable geologic structures, such as faults and dikes, would act as conduits for leakage of impounded water into the new workings. Although the study indicated only minor steady-state leakage would occur through a small number of known structures, the presence and full leakage potential of threatening structures in the barrier could not be reliably known until the barrier was mined.

One longwall panel has been completed adjacent to the barrier with no evidence of water flow even in fractured zones. Thus, as predicted by the modeling and analysis, it appears that abutment stresses imparted on the barrier during mining did not substantially alter the natural hydrogeologic characteristics, or leakage potential, of the barrier. The longwall coal mine water-barrier pillar design and performance are considered a success.

INTRODUCTION

Canyon Fuel Company (CFC) had planned longwall mining downdip of existing workings in the Skyline #3 Mine and Winter Quarters Mine. The mines are flooded and impound water updip from the location of planned development, Figure 1. The mine plan is to isolate future mining from old workings with barrier pillars that will be required to function as both load-carrying and hydraulic barriers.

CFC planned a nominally 350-ft-wide barrier adjacent to the #3 Mine and a 165-ft-wide barrier adjacent to the Winter Quarters Mine. Because the barriers will be subjected to moderate hydraulic pressures (as high as 240 psi, or 550 ft of head, in the #3 Mine), water leakage through natural discontinuities in the barriers, including faults and dikes, is potential. Primary concerns for barrier design were stability of the barrier itself, protection of future mining from abutment stresses from old workings, and prevention of excessive water inflows from flooded updip workings.

MECHANICAL LOAD-CARRYING EVALUATION

The load-carrying performance of the proposed barrier pillar design was evaluated according to published empirical design methods and numerical stress modeling. The empirical design methods are derived from industry experience and represent mainstream engineering practice.

Mechanical Empirical Design Methods

Published empirical design methods were used to estimate the design range of barrier pillar widths for isolating the future North Lease workings from abutment stresses around the existing longwall panels in the #3 Mine. The mathematical expression and a brief description of each method are given according to Koehler and Tadolini (1):

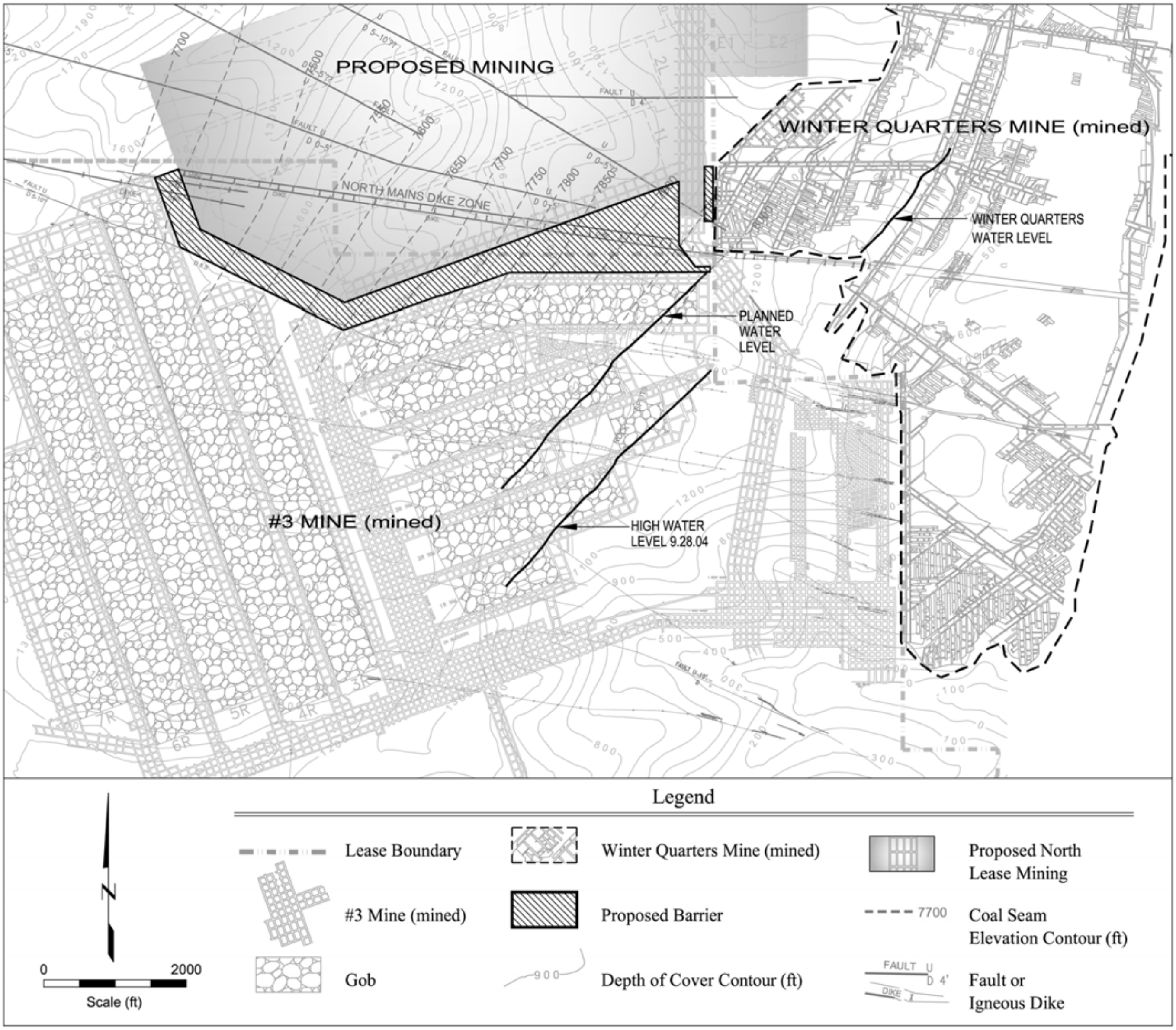

Figure 1. Mine map of the No. 3 Mine showing the barrier pillar study area.

- *Dunn's Rule*—Considers barrier width as a function of depth, and is expressed as:

$$W = \frac{(D - 180)}{20} + 15 \quad \text{(Eqn. 1)}$$

where W is the barrier width (ft) and D is the depth of mining cover (ft). The depth of cover near the planned barrier is about 1,900 ft. Using this limiting depth, Dunn's method estimates a barrier width of 101 ft.

- *Pennsylvania Mine Inspector's Formula*—This approach estimates a barrier pillar width based on depth of cover and seam thickness. The formula is:

$$W = 20 + 4T + 0.1D \quad \text{(Eqn. 2)}$$

where T is the coal seam thickness (ft) and D is the depth of mining cover or height of hydrostatic head acting against the barrier (rounded up to the nearest 100 ft), whichever is greater. Using 10 ft as the seam thickness, this method suggests a 250-ft-wide barrier.

- *Pressure Arch Method*—This method is based on the concept of "pressure arching" and the spans over which loads are transferred. The theory states that the minimum width of the pressure arch is a function of overburden depth. A recommended panel width is suggested to be 75% of the minimum pressure arch width. The average of these widths gives a recommended minimum barrier width of:

$$W = 2.625\left(\frac{D}{20} + 20\right) \quad \text{(Eqn. 3)}$$

Application of the Pressure Arch Method to conditions at Skyline results in a 302-ft-wide barrier design.

- *British Coal Rule of Thumb*—Much like Dunn's Rule, this method has merit in mechanical barrier design, but is limited in terms of appropriate application to western U.S. mines since it is based on experience gained with generally thinner and weaker British coal seams. The width using this approach is expressed as:

$$W = \left(\frac{D}{10}\right) + 45 \quad \text{(Eqn. 4)}$$

The British Coal Rule of Thumb recommends a barrier width of 235 ft for a depth of 1,900 ft.

- *North American Method*—Based on observations in the U.S. and Canada, this approach calculates barrier width as a function of cover depth and adjacent panel width. The width according to the North American Method is expressed by the equation:

$$W = \left(\frac{D \times P}{7{,}000 - D}\right) \quad \text{(Eqn. 5)}$$

where P is the width of the adjacent panel in feet. Assuming a panel width of 850 ft, the method calls for a 317-ft-wide barrier.

- *Holland Convergence Method*—This method implicitly correlates acceptable entry closure to in situ stress level to determine appropriate barrier pillar widths. The recommended barrier width is calculated from:

$$W = \frac{5(\log(50.8C))}{E \log e} \quad \text{(Eqn. 6)}$$

where C is the estimated convergence on the high-stress side of the barrier pillar in inches, and E is the coefficient for the degree of extraction adjacent to the barrier. C is calculated from the relationship:

$$C = 0.001333 \times D \times \frac{T}{7} \times \frac{3{,}000}{\sigma_c} \quad \text{(Eqn. 7)}$$

where σ_c is unconfined compressive strength of a coal sample (psi). Assuming a σ_c of 4,000 psi, a value of 2.71 is obtained for C. A value of 0.09 should be used for E in situations of longwall panel extraction. The method suggests a barrier width of 273 ft for the North Lease barrier at 1,900 ft deep.

The various design methods suggest that width of the main North Lease barrier should fall between about 100 and 320 ft wide at the maximum planned depth of 1,900 ft.

Numerical Modeling

Key considerations for barrier mechanical design are abutment load (stress increase) across the barrier and barrier pillar stability. The width of the barrier controls both the amount of abutment load onto future workings and the average stress on the barrier. The necessary width principally depends upon geological conditions, coal strength, seam confinement, and stress. For conditions at Skyline, in situ (pre-mining) stress and abutment loads are considered the most influential factors affecting mechanical design.

<u>Abutment Load</u>

To assess in situ stress and abutment loads, a site-specific numerical model of the proposed barrier design was developed using AAI's displacement-discontinuity code EXPAREA. Abutment stresses were found to decrease non-linearly from about 3,000 psi greater than the in situ stress at the existing bleeders down to about 100 psi greater than the in situ stress 600 ft into solid coal. Implications are that for barriers sized 200 to 400 ft wide, development mining in the bleeders will be subjected to a stress rise equivalent to approximately 310 to 170 ft of additional cover. This equivalent stress rise decreases to approximately 120 ft when the barrier is widened to about 600 ft.

Pillar strengths were estimated according to the Mark-Bieniawski empirical strength formula (2):

$$\sigma_p = \sigma_1 \left[0.64 + 0.54(w/h) - 0.18\left(w^2/Lh\right)\right] \quad \text{(Eqn. 8)}$$

where
σ_p = Pillar average strength
σ_1 = In situ coal strength
w = Narrowest pillar width
h = Pillar height
L = Pillar length

Mark (3) has suggested that an in situ coal strength of 900 psi may be appropriate for most pillar design applications. This value is considered reasonable for conditions at the Skyline Mine and was used for pillar strength calculations in this study. Pillar height or mined seam thickness is assumed to be 10 ft.

Bleeder pillar stability at 1,900 ft depth is most affected by abutments loads when the barrier is narrower than about 100 ft. Abutment load across the barrier was also evaluated in terms of bleeder pillar stability. Figure 2 describes the tradeoff between barrier width and bleeder pillar stability by defining the safety factor of the bleeder pillars as a function of barrier width. For barriers wider than 200 ft, the safety factor remains relatively constant around 1.7, or approximately 30% above the 1.2 to 1.3 design limit for bleeder pillars suggested by Mark and Chase (4).

Analytical results indicate that abutment load across the proposed 165-ft-wide barrier adjacent to the Winter Quarters Mine (1,300 ft deep) will be acceptable. Future mining conditions next to the barrier are expected to be comparable to current conditions.

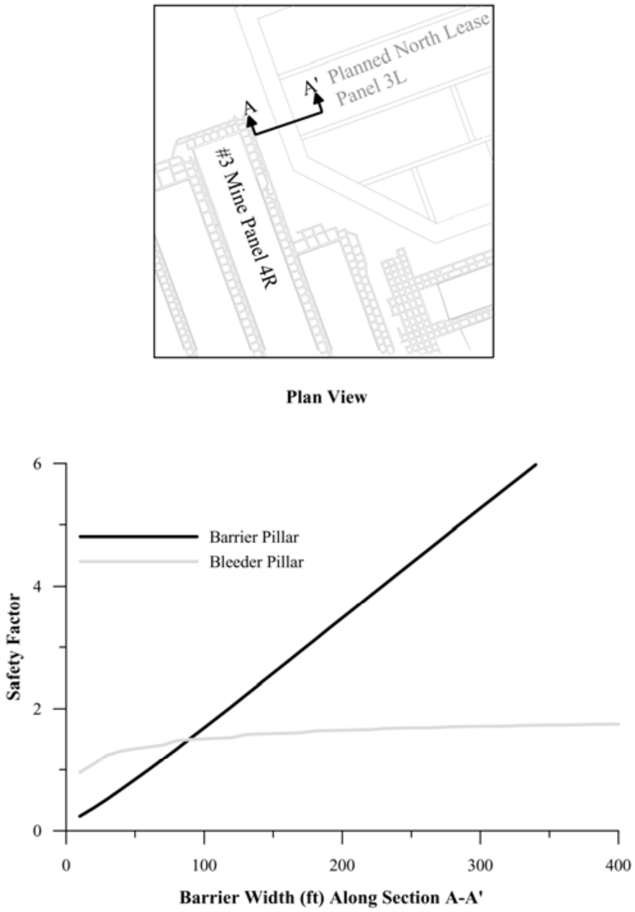

Figure 2. Safety factors (strength: stress ratio) based on Mark-Bieniawski (2) strength equation.

Barrier Stability

Stability of the barrier itself was evaluated according to abutment loading predicted by numerical modeling and the estimated strength of the barrier pillar. Average stress in the barrier was calculated from the (modeled) abutment stress profile and compared to calculated strength and plotted at a safety factor against barrier pillar width in Figure 2. Barrier pillar strength is based on the Mark-Bieniawski Formula (Eqn. 8 (2)). Results show a relatively linear increase in *sr* as a function of width past about 100 ft wide, reflecting increased core confinement in the pillar.

After longwall mining, models show that the strength of the 350-ft-wide western barrier will exceed loading by a factor of more than five at its deepest location (1,900 ft). Similarly, for the 165-ft-wide barrier along the Winter Quarters Mine (1,300 ft deep), strength is estimated to exceed abutment loading by a factor of almost five.

Implications of the barrier stability and abutment load analyses are that the proposed barriers will provide reliable mechanical protection to future North Lease mining.

HYDRAULIC EVALUATION

The hydraulic performance of the proposed 350-ft-wide barrier pillar design was evaluated according to published empirical design methods for hydraulic impoundments, empirical estimates of seepage through the proposed barrier, numerical hydrologic flow modeling, and numerical strain modeling.

Hydraulic Impoundment Empirical Design Methods

Estimates for barrier sizing have been developed using three published empirical methods and produced recommended barrier widths ranging widely from 105 to 859 ft. Each of these barrier design methods have unique limitations and must be balanced with engineering judgment. In this section, only empirical methods that consider a barrier pillar as a water-impoundment dam are presented (1):

- *Old English Barrier Pillar Law*—Estimates barrier width based on hydrostatic head and coal seam thickness. This method is based on barriers as water-impoundment dams and is not recommended for design of barriers whose function is primarily mechanical or where coal seams exceed about 15 ft thickness. The width is calculated from:

$$W = \frac{H \times T}{100} + 5T \qquad \text{(Eqn. 9)}$$

  where H is the hydraulic head, 550 ft, and T is the coal seam thickness, 10 ft. A barrier width of 105 ft is obtained by this method.

- *Pennsylvania Mine Inspector's Formula*—This method is considered appropriate for both mechanical and impoundment barrier designs. Whether for mechanical protection or water impoundment, the method suggests a 250-ft-wide barrier.

- *Ash and Eaton Impoundment Formula*—This method is specifically for the design of water-impoundment barriers. The method is based on observations in anthracite coalfields in Pennsylvania and considers only the depth of cover for barrier sizing. By comparison with other methods and collective industry experience, this approach specifies extremely conservative barrier widths (1). The Ash and Eaton Impoundment Formula is:

$$W = 50 + 0.426D \qquad \text{(Eqn. 10)}$$

  The application of this equation with 1,900 ft of cover produces a barrier width of 859 ft.

Minimal seepage into the North Mains (the mains separating the Proposed Mining and #3 Mine from the Winter Quarters Mine with the words "Planned Water Level" superimposed in Figure 1) suggests that the narrower barrier suggested by the Old English method is more realistic for North Lease conditions than the highly conservative Ash and Eaton design. Only trace seepage is evident across the existing barriers, which narrow to as little as 70 ft wide in places and are subject to around 50 psi hydrostatic head. Under these conditions, the Old English method suggests about a 60-ft-wide barrier pillar, while the Ash and Eaton method suggests a 600-ft-wide barrier. The Ash and Eaton method makes no allowances for less than full hydrostatic head to surface.

Empirical Estimates of Seepage through the Barrier

Darcy's Law assumes that seepage flow through a porous medium, such as rock, is proportional to the pressure head and the permeability of the medium. The coefficient of permeability (or hydraulic conductivity) for water flow, K, which has units of velocity, is material specific and mainly dependent upon rock type, and fine and coarse structure. The permeability in coal is very strongly affected by stress conditions. Numerous reports in the literature all indicate that at stress levels over 1,000 psi, coal becomes very nearly impermeable. Darcy's Law can be stated as:

$$Q = KIA \qquad \text{(Eqn. 11)}$$

where Q is flow rate, I is the hydraulic gradient (defined as $\Delta h/\Delta W$ where Δh is change in head over a length increment ΔW of a flow conduit), and A is the cross-sectional area of the conduit, or HL, where H is the barrier pillar height and L is the barrier pillar length, all in consistent units.

Several researchers have reported empirical relationships for coal permeability as influenced by stress or depth, and are described below.

- Luo et al. (5) established an empirical relationship for the permeability of coal as a function of mean stress defined as:

$$K = 25\left(e^{-5.07\times10^{-3}\sigma_m} + 5.85\times10^{-4}\sqrt[3]{\sigma_m}\right) \qquad \text{(Eqn. 12)}$$

  where K is the coefficient of permeability in ft/day and σ_m is the mean stress (psi) within the barrier. This empirical relationship was developed for vertical stresses in the less than 600-psi range (6).

- Dabbous et al. (7) presented laboratory test data on the permeabilities of various Appalachian coals as a function of confining stress, and AAI developed the following regression equation from their data:

$$K = 0.027414\left(e^{-0.0032\sigma_m}\right)/\,2.436 \qquad \text{(Eqn. 13)}$$

  where K and σ_m are as before.

- Harlow and LeCain (8), as summarized by Minns (9), presented field test data on the permeabilities of southwest Virginia coals as a function of depth, and AAI developed the following regression equation from their data:

$$K = 0.234\left(e^{-0.0017\sigma_m}\right)/\,2.436 \qquad \text{(Eqn. 14)}$$

where K and σ_m are as before.

- Miller and Thompson (10) presented a method of assessing the seepage through coal barrier pillars using a graphical flownet approach, which can be mathematically expressed as:

$$Q = (KW/h)(0.5H)/(W/0.5H) \qquad \text{(Eqn. 15)}$$

  where Q is flow in ft^3/day/ft-length, K is coefficient of permeability in ft/day, W is barrier pillar width in feet, h is water head acting on the barrier pillar in feet, and H is barrier pillar height in feet.

A reasonable order-of-magnitude estimate of the permeability of the Skyline coal is 0.001 ft/day, or about 0.00041 Darcys. Using the methods described above and selected barrier pillar dimensions, barrier pillar seepage rates are estimated in Table 1.

In the calculations that went into making up Table 1, using the several methods of estimating permeabilities as described above, permeabilities were limited to those which are within the range of depths and permeabilities used in the publications. For instance, Dabbous et al. (7) used a maximum stress of 1,000 psi, so the permeability at that stress was calculated, rather than at the anticipated barrier pillar stress from abutment loadings, which is several times greater. Had the actual barrier pillar stress been used, the permeability calculated is nearly zero. For conservatism, the lesser stress was chosen. The Harlow and LeCain (8) data are limited to 350 ft depth, so that figure was assumed for calculating permeability.

Luo et al. (5) is readily available in the coal mining literature, but correspondence with co-author Zhang (6), revealed that they only had two data points near 600 ft depth, so the formula should be used with caution at such depths. It is believed that their research was directed toward shallow mines with high permeabilities for the coal and flow rates that could lead to piping through the barrier pillar, which is the final discussion in their paper. Therefore, the flow rates from the Luo et al. (5) formula are discounted for use at significant depths.

The predictions of seepage through the barrier based on hydrologic flow modeling generally exceed the empirical estimates in Table 1. Flow modeling suggests that seepage through the coal in the barrier will be closer to 2 gpm. However, the hydraulic conductivity of the coal assumed in the flow model is higher than measured and may over-predict the amount of seepage. Because packer tests resulted in no measurable amount of water injected into the coal, the lowest measurable flow rate (0.2 gpm) for the flow meter used in the packer tests was used to estimate the hydraulic conductivity. The total inflow predicted by modeling (162 gpm) included contributions from flow through surrounding strata, including the sandstone in the floor, sand channels and claystone in the roof, and four 10-ft-thick coke zones cutting through the coal. Coke zone surround dikes in the coal. Both the empirical and numerical estimates agree that the uncoked coal is unlikely to be a major source of seepage.

Modeling of Flow through the Barrier

In general, the permeability of rock masses in and around barrier pillars is extremely low (11). As a result, water is unlikely to seep through the barrier coal itself, but rather through dike interfaces, fault zones, or other discontinuities. Observation of seepages during the site visit found this to be the case as all seepages were through partings and most were near dikes or faults. The head pressure currently acting on the current 120-ft-wide barrier between the Winter Quarters Mine and accessible mains is in the 40- to 50-psi range. Seepages along the existing barrier are mainly located

Table 1. Estimated Barrier Pillar Seepage Rates

Method	Barrier Pillar Coal Permeability (ft/day)	Barrier Pillar Coal Permeability (Darcys)	Barrier Pillar Height (ft)	Barrier Pillar Width (ft)	Barrier Pillar Length (ft)	Estimated Flow Through Barrier Pillar (gpm)	Barrier Pillar Length (ft)	Estimated Flow Through Barrier Pillar (gpm)
Estimated *K*	0.001	0.00041	10	350	1,500	0.12	4,500	0.37
	0.001	0.00041	23	350	1,500	0.28	4,500	0.84
Luo et al. (5)	0.187	0.0767	10	350	1,500	23	4,500	68
	0.187	0.0767	23	350	1,500	53	4,500	158
Miller & Thompson (10)	0.000994	0.000407	10	350	1,500	0.00087	4,500	0.0026
	0.000994	0.000407	23	350	1,500	0.0046	4,500	0.014
Dabbous et al. (7)	0.0000459	0.000112	10	350	1,500	0.033	4,500	0.10
	0.0000459	0.000112	23	350	1,500	0.077	4,500	0.23
Harlow & LeCain (8)	0.000271	0.000660	10	350	1,500	0.20	4,500	0.59
	0.000271	0.000660	23	350	1,500	0.45	4,500	1.35

near dike interface zones and are minor in terms of quantity (<1 gpm). The anticipated hydraulic head will be about five times greater along the planned bleeder entries of Panel 3L.

Modeling of Strain-Related Changes in Flow through the Barrier

A two-dimensional numerical model was constructed using the finite-difference code FLAC to estimate longwall mining-induced strain changes in the barrier and their possible influence on flow through the barrier. In the event that large strain changes did occur during North Lease mining, hydraulic conductivity and, consequently, flow in and around the barrier could be affected. Abutment loads are most likely to compress bedding planes and, thereby, reduce lateral hydraulic conductivity. Vertically oriented discontinuities, including joints and cleating in the coal, are subject to either closure or dilation, causing flow to either decrease or increase, respectively, depending upon their orientation relative to the strain field. Only simple strain modeling was conducted as a preliminary check to determine whether strain magnitudes would be sufficient to influence flow.

Strains of significant magnitude can potentially compromise the performance of the barrier as a water-impoundment dam. A strain of 0.1% is suggested as a strain threshold below which rock is expected to behave essentially elastically without significantly increasing the opening of existing flow pathways (12). Although these limits normally apply to vertical permeability, they are assumed to apply to lateral permeability for consideration in this study. No useful lateral permeability criteria are known to exist. The average barrier strains predicted from FLAC modeling are compared in Figure 3, where strain magnitudes refer to the maximum secondary principal strain in the vertical plane of the two-dimensional model; all strains are compressive. Results in Figure 3 reflect maximum abutment loading on the barrier after longwall mining as a function of barrier width. Results indicate that strain within the barriers will not exceed the suggested 0.1% strain threshold. As such, future longwall mining is unlikely to substantially affect the natural conductivity of the planned barriers.

CONCLUSIONS

Our conclusion is that the proposed mining is unlikely to substantially affect the natural conductivity of the planned barriers.

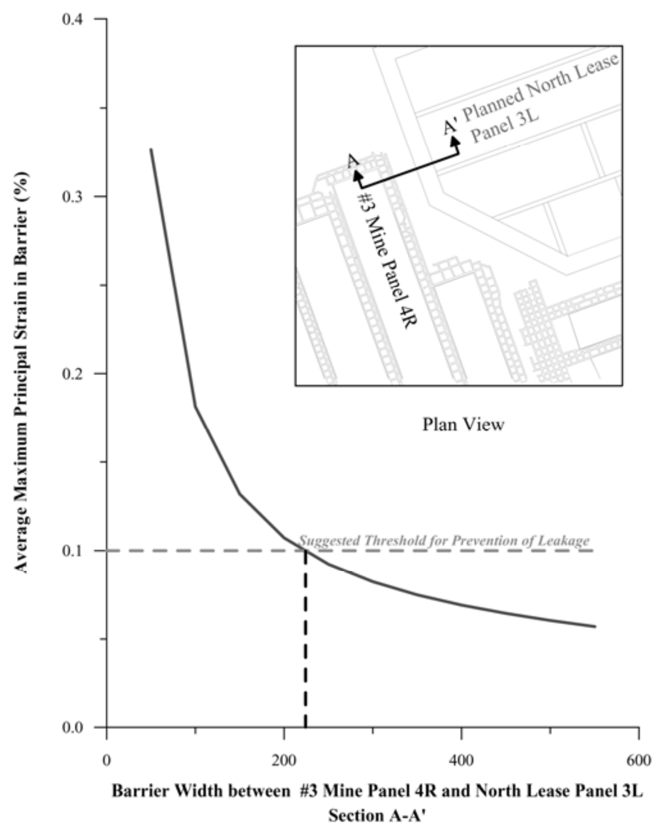

Figure 3. Predicted strains.

Modeling results suggest that strain within the barriers caused by future longwall mining will not exceed published limits for preventing changes in rock mass hydraulic conductivity (<0.1% strain).

The study further finds that the proposed barrier pillar design is adequate to protect future mining from abutment stresses associated with old workings. At the deepest part of the proposed 350-ft-wide barrier, reaching almost 1,900 ft deep, bleeder development is expected to encounter a slight increase in vertical stress levels due to load override equivalent to about a 200 ft increase in depth of cover. Conditions are expected to be comparable to development mining in virgin ground at about 2,100 ft, similar to those already encountered during development of the Panels 5R and 6R bleeders in the #3 Mine. The abutment stress surcharge acting on the future bleeder development area is small compared to the estimated load capacity of the proposed bleeder pillars. Some modest increase in rib and roof maintenance should be anticipated as a consequence of this equivalent increase in depth.

Based on relevant industry experience, underground observations, knowledge of local geologic conditions, hydrologic measurements,

and analytical results, the level of geotechnical risk associated with the barrier design is considered low and the level of hydrologic risk is considered moderate. The proposed design is defensible and consistent with mining industry practice for both mechanical and water-impoundment barrier design.

One longwall panel has been completed adjacent to the barrier with no evidence of water flow even in fractured zones. Thus, as predicted by the modeling and analysis, it appears that abutment stresses imparted on the barrier during mining did not substantially alter the natural hydrogeologic characteristics, or leakage potential, of the barrier. The longwall coal mine water-barrier pillar design and performance are considered a success.

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