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# Practical Design Methods for Barrier Pillars

UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

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***Cover photographs: Top—Heavily supported bleeder entry adjacent to undersized barrier pillar. Middle—Borehole pressure recorder charts being evaluated that monitor loads on adjacent pillar. Bottom—Total amount of closure and respective rates being evaluated in gate road nearby longwall pillar.***

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**UNITED STATES DEPARTMENT OF THE INTERIOR**
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## ILLUSTRATIONS

## UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|---|---|---|---|
| ft | foot | mm | millimeter |
| h | hour | psi | pound (force) per square inch |
| $in^2$ | square inch | | |

# PRACTICAL DESIGN METHODS FOR BARRIER PILLARS

By J. R. Koehler[1] and Stephen C. Tadolini[1]

## ABSTRACT

Effective barrier pillar design is essential for safe and productive underground coal mining. This U.S. Bureau of Mines report presents an overview of available barrier pillar design methodologies that incorporate sound engineering principles while remaining practical for everyday usage. Nomographs and examples are presented to assist in the determination of proper barrier pillar sizing. Additionally, performance evaluation techniques and criteria are included to assist in determining the effectiveness of selected barrier pillar configurations.

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## INTRODUCTION

Effective barrier pillar design is essential for safe and productive underground coal mining. As a confirmation of current work in the area of health and safety research, the U.S. Bureau of Mines (USBM) summarized the available barrier pillar design methods for everyday usage. The design of barrier pillars has spanned more than 150 years. Serving as the primary abutments for loads generated by production panel mining, barrier pillars provide long-term protection for main, panel, and bleeder entries; adjacent production panels; and mine access and ventilation shafts (*1*).[2] Barrier pillars may also be utilized to isolate abandoned sections from active workings to simplify ventilation, provide independent escape routes, or retain large quantities of mine water. Lastly, barrier pillars must be employed along the outcrop to protect surface features and maintain ventilation courses, and may be left at the property line to separate one mine from another to block the advance of an explosion or fire.

Estimates indicate that from 5% to as much as 15% of recoverable reserves are lost to oversized barrier pillars in modern coal mines. Conversely, undersized barrier pillars can result in significant reserve losses and decreased safety because of excessive load transfer to adjacent openings (*1*). Nowhere is this problem more profound than in the multiple-seam mine setting where seam interaction serves to further the redistribution of damaging high stress.

As with other mine support structures, optimum barrier pillar design is attained through a process of trial and error. From simple observations of entry conditions to the more involved collection of entry closure and load redistribution data, in situ study of a baseline design can provide the information needed to successfully determine changes in pillar geometry that will result in improved performance. The first step in this process is to develop the baseline pillar design from which an optimum pillar configuration may be evolved. Over the past 150 years, mining research has produced a variety of relatively simple empirical approaches to determine baseline dimensions for barrier pillars. A discussion of these approaches as well as instructions for the in situ monitoring of a baseline design follows.

## DUNN'S RULE

The earliest known barrier pillar design method was proposed by Dunn in 1846. "Dunn's rule" states that the width of a barrier pillar "should be 5 yards at 180 ft of depth, to be increased by 1 yard for each additional 60 feet of depth." Dunn's rule is expressed mathematically by the following equation:

$$W = \frac{(D - 180)}{20} + 15, \qquad (1)$$

where W = barrier pillar width, ft,

and D = depth of mining cover, ft.

**Example application:**

D = 750 ft

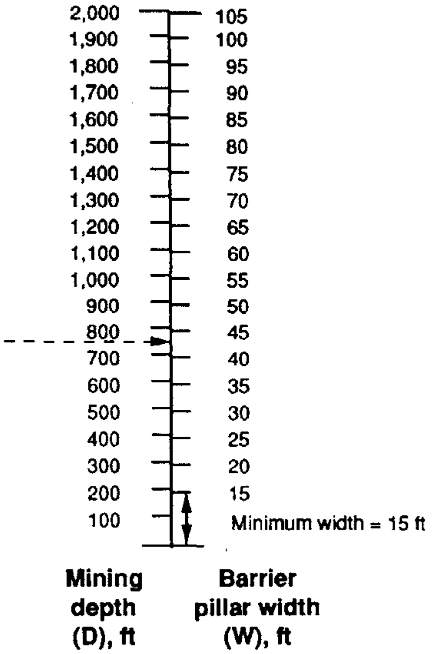
$$W = \frac{(750 - 180)}{20} + 15, \qquad (2)$$

since D = 750 ft,

then W = 44 ft.

A nomographic representation of Dunn's rule for mining cover depths to 2,000 ft is presented in figure 1.

*Figure 1*



*Dunn's rule for mining cover depths to 2,000 ft. Solution to example application indicated by dashed arrow.*

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[2] Italic numbers in parentheses refer to items in the list of references at the end of this report.

Recent barrier pillar research suggests that Dunn's rule specifies significantly undersized pillar dimensions for a given depth of mining cover, especially for Western U.S. applications where thick, competent sandstone roof members promote high load transfer distances. In addition, Dunn's rule does not account for varying seam thickness, nor does it consider coal strength, suggesting it was derived from experience in a single seam. Finally, Dunn's rule does not account for side loads applied by impounded water, thus rendering this formula invalid for the design of barrier pillars intended to act as retention dams.

## OLD ENGLISH BARRIER PILLAR LAW

The 1928 "Coal Miner's Pocketbook" presents an empirical formula for barrier pillar design referred to in the text as the "mine inspectors formula for barrier pillars." This design equation, also known as the "Old English barrier pillar law," is cited in several publications by Ash and others (*2-4*) that address barrier design in anthracite coal seams. Ash's publications, however, created confusion about the proper mathematical expression for the Old English law by presenting different formulas in each report. For example, in one of his publications, Ash substituted a value of 1,000 (rather than 100) for the denominator of the first term. The original mathematical expression for the Old English law is presented below:

$$W = \frac{H \times T}{100} + 5T, \tag{3}$$

where H = hydrostatic head, ft, or depth below drainage level, ft,

and T = coal seam thickness, ft.

**Example application:**

H = 750 ft

T = 8 ft

$$W = \frac{(750 \times 8)}{100} + (5 \times 8), \tag{4}$$

since H = 750 ft

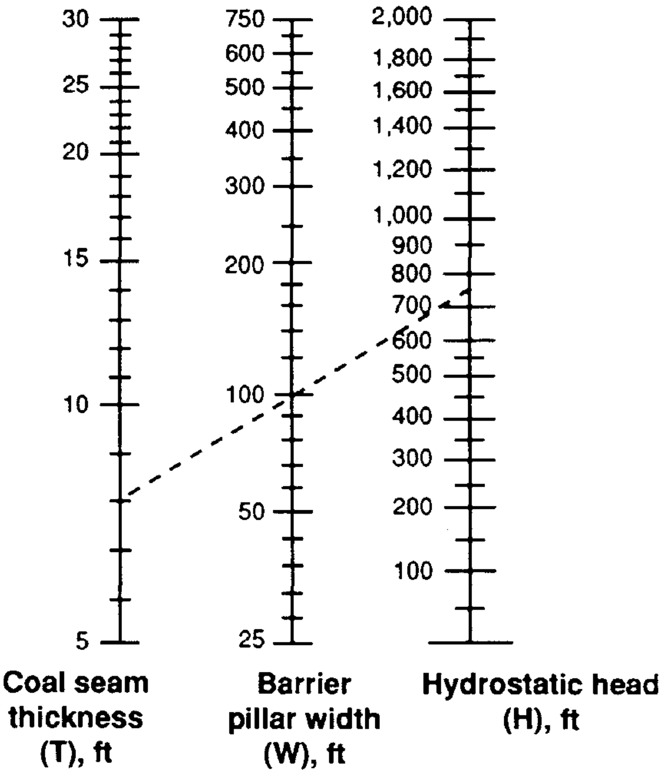
and T = 8 ft,

then W = 100 ft.

A nomographic representation of the Old English barrier pillar law, for hydrostatic head to 2,000 ft and seam thicknesses ranging from 5 to 30 ft, is presented in figure 2. To use the nomograph, a straight line is drawn between the known values of the coal seam thickness and hydrostatic head to find the required barrier pillar width.

Examination of the Old English barrier pillar law suggests that it is based on studies of barrier pillars utilized as water impoundment dams. This method should not be used for the design of a barrier pillar whose intended function is other than that of an impoundment dam because, if no water pressure exists (hydrostatic head equals 0 ft), equation 3 specifies the same barrier pillar width (five times the coal seam thickness) for all mining depths. Also, like Dunn's rule, the Old English formula does not provide for variations in coal strength, further underscoring the need to exercise caution when applying this method. Lastly, the Old English formula was derived from experience in anthracite coal seams, suggesting additional caution be exercised when applying this approach to coal seams in excess of 15 ft in thickness.

*Figure 2*



*Old English barrier pillar law formula for hydrostatic head to 2,000 ft. Solution to example application indicated by dashed line.*

## PENNSYLVANIA MINE INSPECTOR'S FORMULA

In 1930, the State of Pennsylvania enacted legislation, amending an earlier act of 1911 for barrier pillar design, that specified the required barrier size for mining coal in any seam. In his report on these new rules, Ashley (*5*) stated that "the Legislature of the Commonwealth of Pennsylvania at its last session passed a new act dealing with barrier pillars, which may have a wide interest in other states." The "Pennsylvania mine inspector's formula," as it became known, states that "the minimum (barrier) pillar shall not be less than 20 feet, plus four times the thickness of the coal bed, plus ten feet for each 100 feet or fraction thereof of cover at the boundary in question." The Pennsylvania mine inspector's formula is expressed mathematically by the following equation:

$$W = 20 + 4T + 0.1D, \qquad (5)$$

where D = depth of mining cover, or height of hydro static head if greater than thickness of overburden, rounded up to nearest 100 ft.

**Example application:**

$$W = 20 + (4 \times 8) + (0.1 \times 800), \qquad (6)$$

since T = 8 ft

and D = 750 ft (round up to 800 ft),

then W = 132 ft.

The Pennsylvania mine inspector's formula for coal seam thicknesses ranging from 4 ft to 12 ft, and mining cover depths (or hydrostatic head) to 2,000 ft, is presented in graphical form in figure 3.

An advantage of the mine inspector's formula over Dunn's rule and the Old English barrier pillar law is that it accounts for variations in both depth of mining cover and coal seam thickness. Also, the mine inspector's formula provides for the effects of water pressure; therefore, application of this approach to the design of an underground water retention structure is appropriate. As with Dunn's rule and the Old English law, the mine inspector's formula does not provide for variations in coal strength; however, this approach resulted from experience with the bituminous coals of the Eastern United States, suggesting it is most applicable to those coals having similar compressive strengths.

## ASH AND EATON IMPOUNDMENT FORMULA

In 1948, Ash and Eaton proposed a design equation that considered a barrier pillar as a water impoundment dam. The Ash and Eaton "impoundment formula" was intended for use in a coal bed with a slight dip (*3*). The mathematical expression for the impoundment formula is shown below:

$$W = 50 + 0.426\,D. \qquad (7)$$

**Example application:**

$$W = 50 + (0.426 \times 750), \qquad (8)$$

since D = 750 ft,

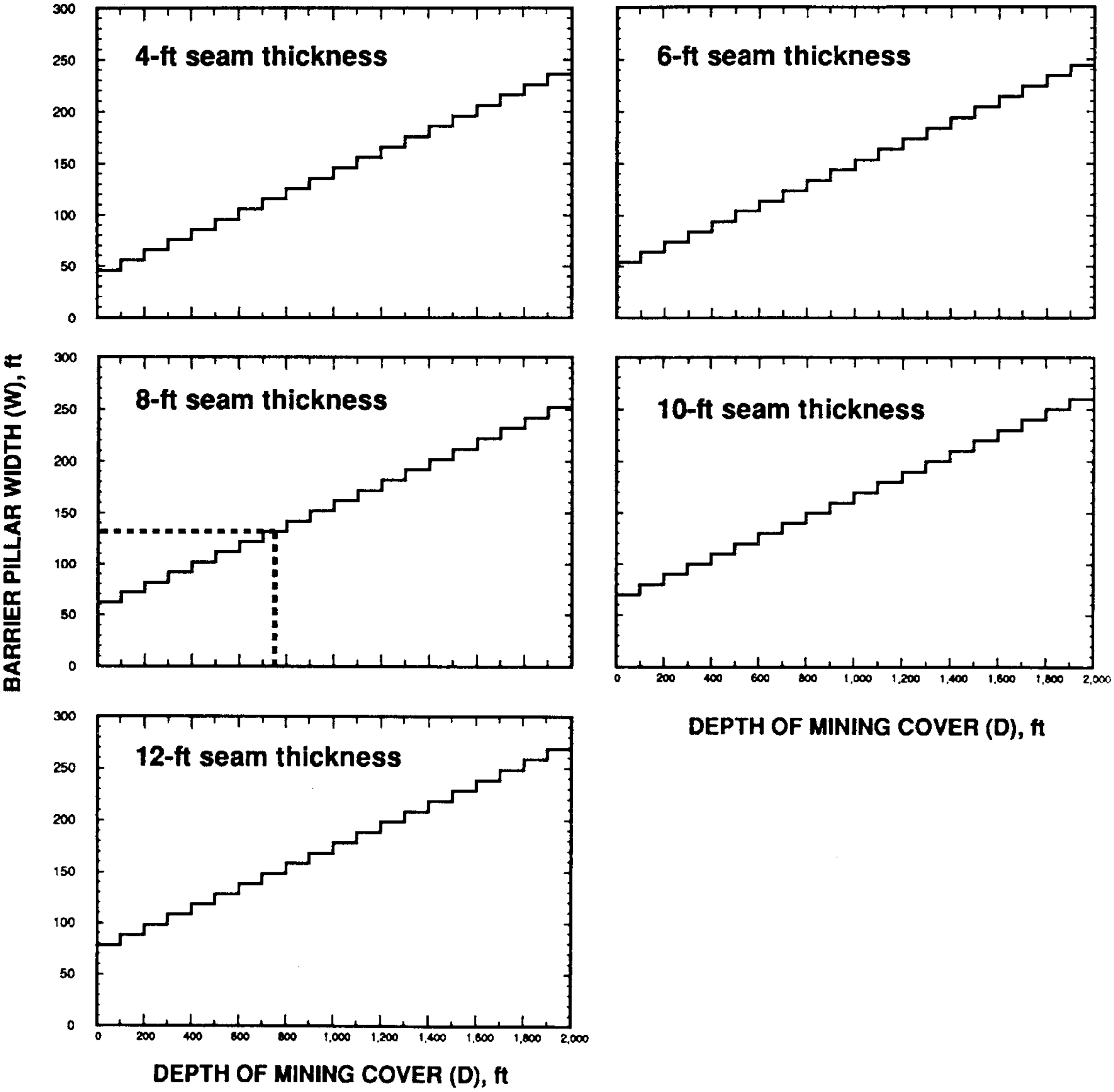
then W = 370 ft.

The impoundment formula for mining cover depths to 2,000 ft is presented as a nomograph in figure 4.

Although the Ash and Eaton impoundment formula was developed for the design of barrier pillars intended as underground retention dams, there is no provision in equation 7 for variations in hydrostatic pressure. As demonstrated by the example application above, this approach specifies extremely conservative barrier pillar sizes for the given depth of mining cover. This implies that the effect of side loading from retained water is indirectly accounted for in the conservative pillar widths generated using this approach.

Other considerations in applying the Ash and Eaton impoundment formula are that it does not account for variations in coal seam thickness and compressive strength. The empirical observations from which this formula was derived were made in the anthracite coalfields of Pennsylvania. Therefore, this approach is most appropriate for application in coal seams whose compressive strengths are similar to that of anthracite and whose thicknesses do not exceed approximately 12 ft.

*Figure 3*



*Pennsylvania mine inspector's formula for various seam thicknesses and mining cover depths to 2,000 ft. Solution to example application is indicated by dashed line in 8-ft seam thickness graph.*

## PRESSURE ARCH METHOD

Introduced in the 1950's, the "pressure arch method" is derived from empirical observations made in the coalfields of Northern England. Considerably more complex than the design methods discussed thus far, the pressure arch concept proposes that load is transferred across an opening of limited width, or across a series of openings separated by yield pillars (and also of limited width), by a "pressure arch" that forms in the strata (figure 5). Because of pillar yielding, the area under the pressure arch is a zone of low stress, since most of the overburden load is transferred to the adjacent solid coal or barrier pillar(s). The width of the pressure arch increases proportionally with the width of the workings until the span across the workings becomes greater than the maximum pressure arch width that can be developed. In this situation, one stress abutment lies on the yielded pillars and the other lies on the unmined solid; severe ground stability problems are likely because the yielded pillars cannot adequately support the abutment loads.

Field data indicate that the maximum width of the maximum pressure arch is influenced by the strata comprising the overburden, whereas the minimum width of the maximum pressure arch is primarily a function of the overburden depth. It is from the minimum width of the maximum pressure arch that the minimum barrier pillar width and maximum allowable span of the workings can be calculated. The minimum width of the maximum pressure arch is represented very closely by the following equation:

$$A = 3\left(\frac{D}{20} + 20\right), \tag{9}$$

where $A$ = minimum width of maximum pressure arch, ft.

**Example application:**

$$A = 3\left(\frac{750}{20} + 20\right), \tag{10}$$

since $D$ = 750 ft,

then $A$ = 173 ft.

Equation 9 is not appropriate for overburden depths of less than 400 ft or greater than 2,800 ft.

Once the minimum width of the maximum pressure arch is known, the proper panel and barrier pillar widths may be calculated. The total width of the developed panel should not be wider than 75% of the minimum width of the maximum pressure arch. Mathematically, this statement can be represented by the following equation:

$$S \leq 0.75A, \tag{11}$$

where $S$ = total allowable width of developed panel, ft.

**Example application:**

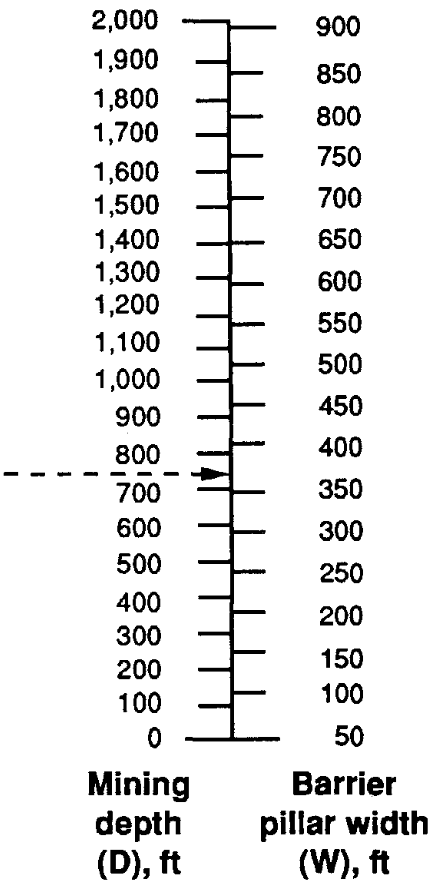
$$S \leq 0.75(173) \tag{12}$$

and

$$S \leq 130 \text{ ft} \tag{13}$$

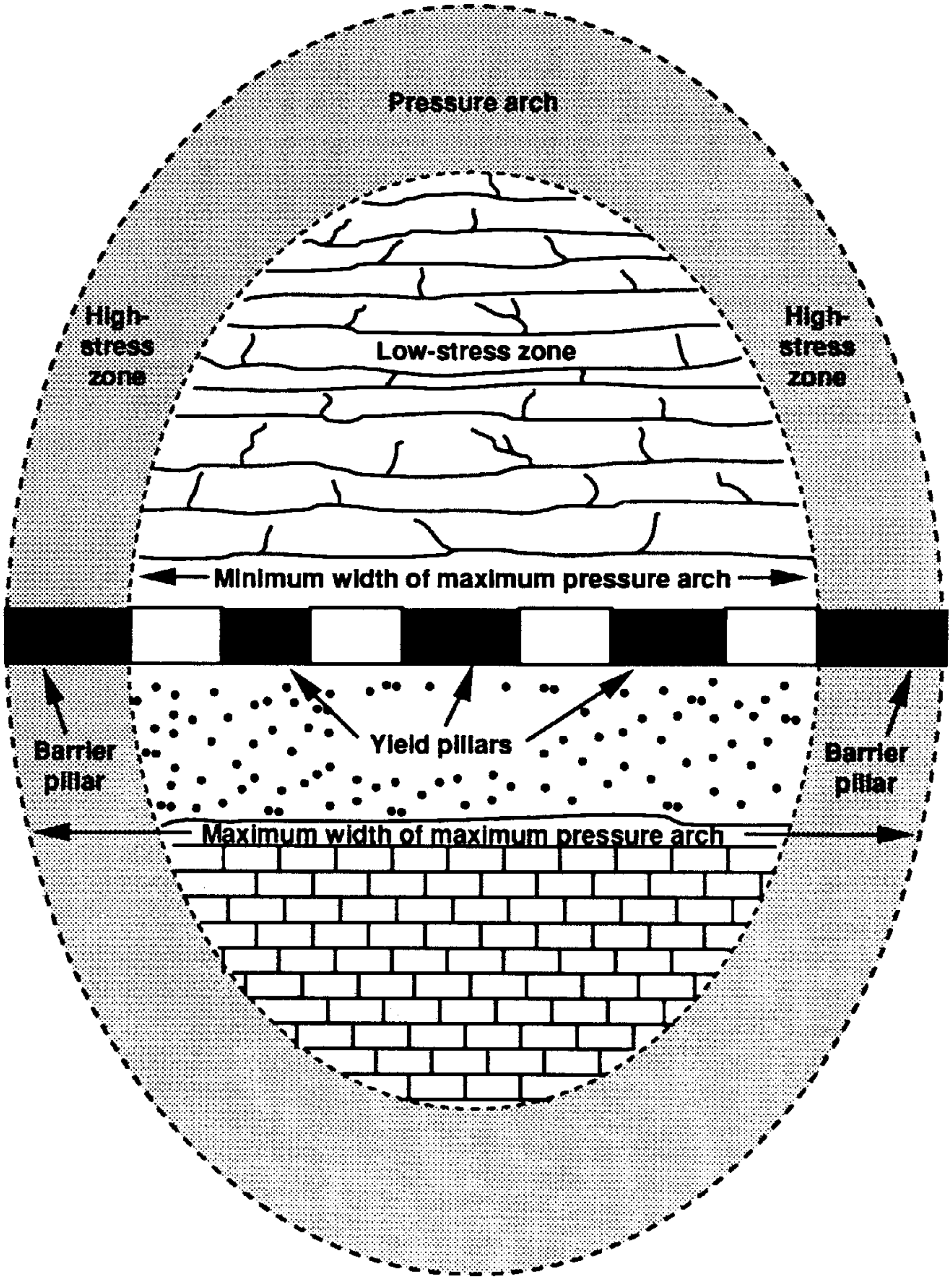
since $A$ = 173 ft.

*Figure 4*



*Ash and Eaton impoundment formula for mining cover depths to 2,000 ft. Solution to example application indicated by dashed arrow.*

*Figure 5*



**Not to scale**

*Conceptual illustration of maximum pressure arch.*

In the example application above, the total width of the panel including entries and pillars should not exceed 130 ft. The *minimum* width of the adjacent barrier pillars must be equal to or greater than the mean (average) of the actual panel width and the minimum width of the maximum pressure arch. Mathematically, this statement can be represented by the following equation:

$$W = \frac{(S_A + A)}{2}, \tag{14}$$

where $W$ = *minimum* barrier pillar width, ft,

and $S_A$ = actual panel width, ft.

**Example application:**

$$W = \frac{(130 + 173)}{2}, \tag{15}$$

since $S_A$ = 130 ft

and $A$ = 173 ft,

then $W$ = 152 ft.

The mining configuration in the example application above, a panel of yielding pillars with adjacent barrier pillars, is just one of many possible applications of the pressure arch method. Barrier pillars intended to withstand the stress abutment(s) from longwall mining can be designed using this approach. For example, where two longwall panels wider than the maximum pressure arch are to be mined side by side with a barrier pillar between them to isolate one panel from the other, the interpanel barrier pillar should be at least as wide as the minimum width of the maximum pressure arch ($W => A$). Discussion of all of the possible mining configurations that might be designed using the pressure arch method is beyond the scope of this report. However, for additional information describing further applications of the pressure arch method to panel and/or barrier pillar design, the reader is directed to publications by Holland and others (*6-10*).

## BRITISH COAL RULE OF THUMB

The "British Coal rule of thumb," reported by King and Whittaker (*11*) in 1971, is a design formula developed and used successfully by British mine operators. The formula states that the width of a barrier pillar should be one-tenth of the overburden height plus 45 ft (*11*). A mathematical representation of the British Coal approach follows:

$$W = \left(\frac{D}{10}\right) + 45. \tag{16}$$

**Example application:**

$$W = \left(\frac{750}{10}\right) + 45, \tag{17}$$

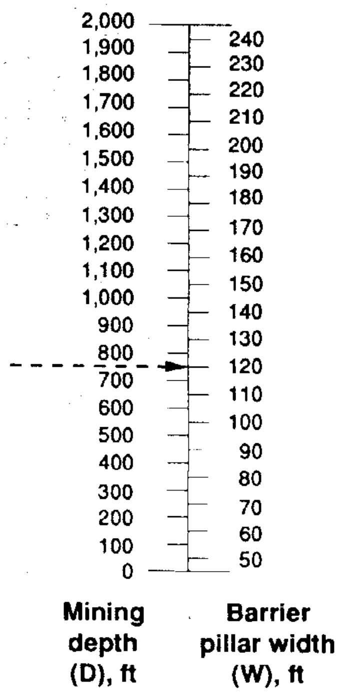
since $D$ = 750 ft,

then $W$ = 120 ft.

The British Coal rule of thumb for mining cover depths to 2,000 ft is presented as a nomograph in figure 6.

As with Dunn's rule and the Ash and Eaton impoundment formula, the British Coal rule of thumb does not account for variations in coal seam thickness. The beds of the British coalfields, however, rarely exceed 10 ft in thickness, suggesting this value as an upper bound for valid application of this approach. The British Coal approach does not provide for variations in compressive strength. Typically, the coal seams of Great Britain possess compressive strengths that are considered low by U.S. standards. Finally, no provision is made in the British formula for the effects of hydraulic head, rendering this method unsuitable for the design of underground water-retention dams.

*Figure 6*



***British Coal rule of thumb for mining cover depths to 2,000 ft. Solution to example application indicated by dashed arrow.***

## NORTH AMERICAN METHOD

The "North American method" is an empirical barrier pillar design formula developed from observations made in the coal mines of the United States and Canada. The North American method can be expressed mathematically by the following equation:

$$W = \frac{(D \times P)}{7{,}000 - D}, \qquad (18)$$

where P = width of adjacent panel, ft.

**Example application:**

$$W = \frac{(750 \times 600)}{7{,}000 - 750}, \qquad (19)$$

since D = 750 ft

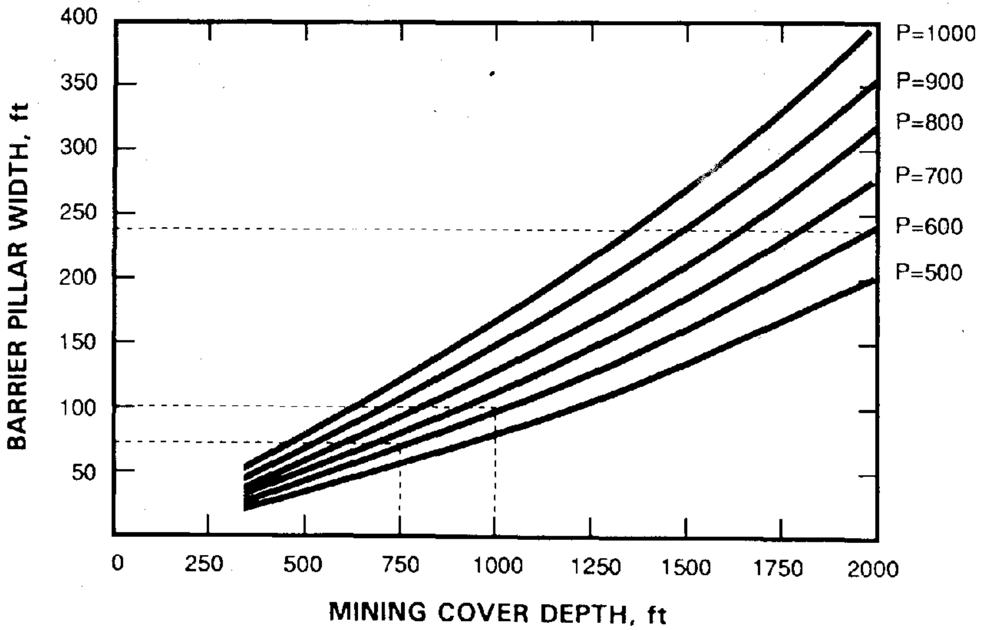
and P = 600 ft,

then W = 72 ft.

The North American method, for mining cover depths ranging from 300 to 2,000 ft and adjacent panel widths ranging from 500 to 1,000 ft, is presented in graphical form in figure 7.

The North American method is similar to the pressure arch method in that it includes the effect of variations in adjacent panel width. Several problems, however, exist with this approach. Provided that adjacent panel width remains constant, calculated barrier pillar width increases nonlinearly with depth of mining cover, resulting in possible overdesigned pillars at great depth. For example, a 600-ft-wide panel at a depth of 1,000 ft requires a 100-ft-wide barrier pillar; the same panel located at a depth of 2,000 ft requires a 240-ft-wide barrier pillar. As with Dunn's rule, the Ash and Eaton impoundment formula, and the British Coal rule of thumb, there is no provision in the North American formula for variations in coal seam thickness. In addition, the North American method does not provide for variable coal strength, nor does it account for the effects of water pressure.

*Figure 7*



*North American method for various adjacent panel widths (P) and mining cover depths ranging from 300 to 2,000 ft. Solution to example application indicated by dashed line.*

## HOLLAND RULE OF THUMB

In 1973, Holland proposed an empirical barrier pillar design formula based on years of case studies and practical experience (*8*). The "Holland rule of thumb" can be expressed mathematically by the following equation:

$$W = \frac{D}{22.2} + 105. \qquad (20)$$

**Example application:**

$$W = \frac{750}{22.2} + 105, \qquad (21)$$

since $D = 750$ ft,

then $W = 139$ ft.

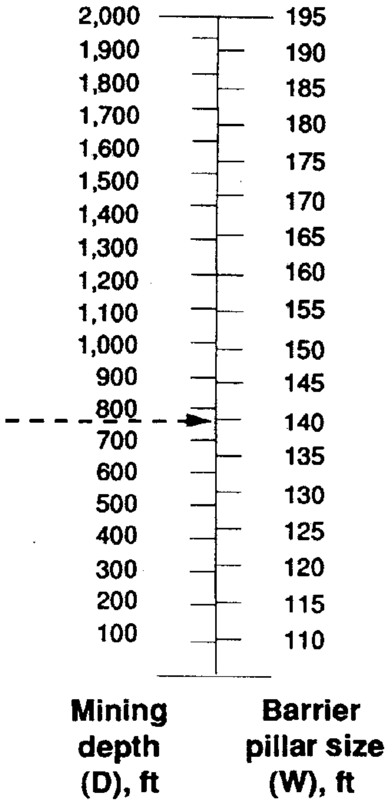
The Holland rule of thumb, for mining cover depths to 2,000 ft, is presented as a nomograph in figure 8.

The Holland rule of thumb, as with most of the approaches described above, does not provide for variations in coal seam thickness. In addition, it does not account for changes in coal strength, nor does it provide for the effects of side loads from impounded water.

## HOLLAND CONVERGENCE METHOD

First introduced in 1973, the "Holland convergence method" is based on room closure studies conducted in several Polish mines by Borecki and Belinski (*12*). Primarily intended for coal mine design, the convergence method utilizes estimated entry closure on the high-stress side of the barrier pillar to determine appropriate pillar size. Entry convergence is estimated using a best fit graph of field data collected in numerous coal seams having similar physical properties. Adjustments for variations in seam thickness and unconfined compressive strength of the coal are made to the estimated convergence value to determine the final convergence value to be used in equation 23. Although the convergence method is relatively complete with regard to accounting for the basic mining variables, it is not for use in the design of barrier pillars intended as water-retention dams. The convergence method can be expressed mathematically by the following equations:

***Figure 8***



***Holland rule of thumb for mining cover depths to 2,000 ft. Solution to example application indicated by dashed arrow.***

The larger of

$$W = 15T \qquad (22)$$

or

$$W = \frac{5(\log 50.8C)}{(E \log e)}, \qquad (23)$$

where $C$ = estimated convergence on high-stress side of barrier pillar, in,

$E$ = coefficient for degree of extraction adjacent to barrier pillar; value $E = 0.07$ should be used if adjacent workings are hydraulically backfilled, value $E = 0.08$ should be used if strip packwalls are built next to the barrier pillar, value $E = 0.085$ should be used if partial extraction is practiced, and value $E = 0.09$ should be used if complete caving will occur in adjacent panel, and e = base of the natural system of logarithm, 2.73.

**Example application:**

$T = 8$ ft;

$D = 750$ ft;

Unconfined compressive strength of a 3-in cube of coal = 2,000 psi;

Elastic modulus of coal = 400,000 psi.

Partial extraction will be practiced in the adjacent panel.

By applying equation 22,

$$W = 15(8) \tag{24}$$

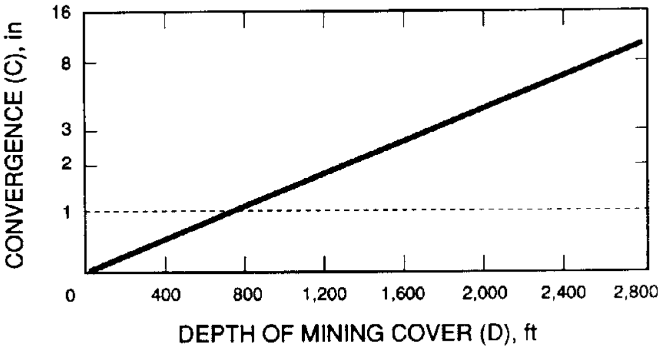
where $W = 120$ ft.

To determine the appropriate estimate of convergence for the given mining conditions, an initial value must first be read from figure 9. At 750 ft of depth, the estimated convergence from figure 9 is 1 in. This value must be adjusted, however, because figure 9 provides convergence versus depth data for a 7-ft-thick seam having an average unconfined compressive strength of approximately 3,000 psi (for a 3-in cube) and an average elastic modulus of 400,000 psi. Since convergence varies directly as the bed thickness and inversely as the strength of the coal, the expected convergence on the high-stress side of the barrier pillar would be

$$C = 1 \text{ in} \times \left(\frac{8 \text{ ft}}{7 \text{ ft}}\right)\left(\frac{3{,}000 \text{ psi}}{2{,}000 \text{ psi}}\right) = 1.7 \text{ in}. \tag{25}$$

Since partial extraction is to be practiced in the adjacent panel, the extraction coefficient is 0.085.

***Figure 9***



***Observed values of convergence for coal seams 7 ft thick and having unconfined compressive strength of 3,000 psi ±10% for 3-in cube. Solution to example application indicated by dashed line. [After Holland (6)]***

By applying equation 23,

$$W = \frac{5(\log 50.8(1.7))}{(0.085 \log 2.73)}, \tag{26}$$

where $W = 262$ ft.

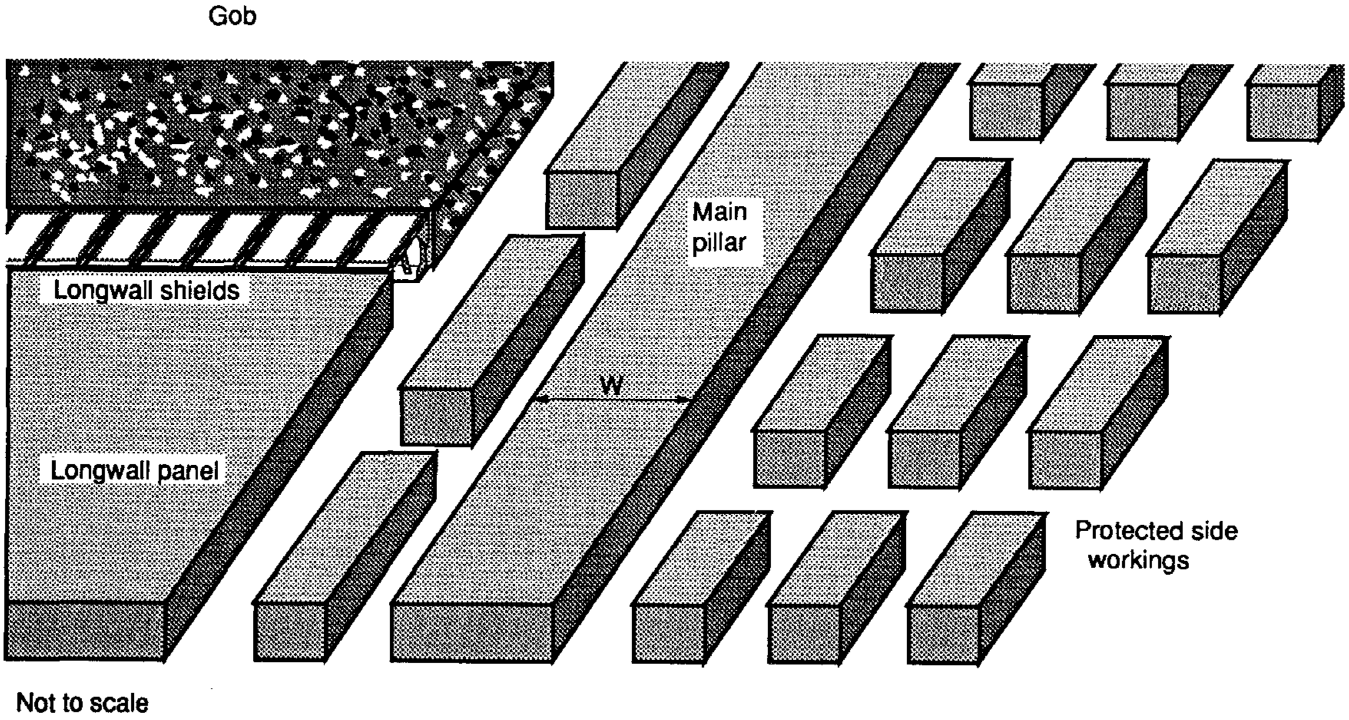
By the rules of the convergence method, the minimum barrier pillar width for the given mining conditions is 120 ft, whereas the pillar width needed to limit convergence to acceptable levels on the low-stress side of the barrier pillar is approximately 260 ft.

As with the other available barrier pillar design methods, appropriate engineering judgment is recommended in applying the Holland convergence method. The graph of estimated convergence versus depth of mining cover is based on field data from a specific coal mining region of Europe and may not be completely applicable to the conditions found in the United States. For example, the coal seams in which these data were collected are approximately 7 ft in thickness; significant errors in appropriate barrier pillar width may be expected for coal seam thicknesses exceeding 15 ft.

## PERFORMANCE EVALUATION TECHNIQUES

Regardless of the level of effort spent on planning, the true effectiveness of any design can only be determined by conducting a full-scale, in-mine performance evaluation of the support structure in question. Rarely is an initial design so sound that areas of improvement cannot be identified. With regard to barrier pillars, the width of the pillar from the active workings to the area to be protected is the critical dimension controlling performance (figure 10). Should the pillar be too narrow, excessive load transfer significantly increases the probability of ground control problems on the protected side. Similarly, when a barrier pillar is employed to retain large volumes of water, the risk of inundation is much greater if the pillar is undersized. Oversized barrier pillars, in comparison, eliminate the safety hazards and risks to production mentioned above, but can substantially reduce the recoverable reserves base by unnecessarily sterilizing otherwise minable coal.

*Figure 10*



***Primary critical dimension (W) controlling barrier pillar performance.***

The primary consideration in designing a barrier pillar is to limit load transfer to the extent that postmining ground instabilities (on the protected side of the pillar) remain within the range of normal activity observed prior to mining. This criterion can be easily satisfied by specifying very conservative pillar dimensions, albeit at the expense of reasonable recovery. Therefore, the *overall* goal of barrier pillar design is to maintain acceptable ground stability and maximize recovery of the resource; this goal can be achieved through the performance evaluation process. Depending on the amount of time and resources the mine operators have at their disposal, several options are available for evaluating the in-mine performance of a barrier pillar.

## GROUND CONDITION LOG

An inexpensive method to aid in evaluating the effectiveness of a barrier pillar design is to keep a detailed log of entry and pillar conditions on the protected side of the pillar. Log entries should include at least the following information:

- Extent of mining on the active side of the barrier pillar for each set of observations. It is often helpful to note the position of the working face relative to the location of observation sites so that changes in ground conditions can be correlated with the advance of mining.
- Evaluation of barrier and production pillar rib conditions at selected sites on the protected side of the barrier pillar. Load transfer from adjacent mining may be reflected in an increase in the rate and severity of pillar rib yielding. This effect will be especially pronounced when the barrier pillar is undersized.
- Evaluation of roof and floor conditions at selected sites along the protected side of the barrier pillar. Load transfer from adjacent mining may affect the condition of the roof and floor on the protected side of the barrier pillar, depending upon the extent and magnitude of stress redistributions. As with the pillar ribs, this effect will be especially pronounced if the barrier pillar is undersized. If time allows, roof conditions can be quantified by noting the number and extent of roof falls per linear foot of entry. Similarly, floor conditions can be quantified by noting the extent and severity of floor heave per linear foot of entry.
- Qualitative evaluation of the frequency and severity of rock noise caused by stress redistribution. Excessive noise emanating from the roof, barrier pillar, and production pillars is a good indication that significant load transfer is occurring across the barrier pillar from the active to the protected side.
- Evaluation of the magnitude and rate of loading on artificial support (on the protected side of the barrier pillar), such as roof bolts, posts, and cribs. A sudden

increase in the magnitude of support loads, or an increase in the rate of loading of the artificial support, may occur as a result of load transfer. For example, relatively soft support components, such as roof bolt header blocks and wood posts and cribs, will suffer visible deformation (squeezing) as applied loads increase.

Initial observations should be made some time after development of the section to be protected (to ensure that the area has come to equilibrium), but before mining begins in the panel on the active side of the barrier pillar. Additional observations, made at regular intervals of face position, should be taken at the same sites as the initial observations. In some instances, the mine operator may choose to take a series of photographs, as mining progresses, that depict entry and pillar conditions at selected points. A convenient way of establishing locations for these photos is to mark selected roof bolts with fluorescent paint, surveyor's ribbon, or metal name tags.

It is unlikely that much useful information will be gained from the observations listed above in the event that the barrier pillar is too large because protected-side ground conditions will change little as mining progresses. However, should the barrier pillar be undersized, all of the observations should provide information useful to the engineer. From a design standpoint, perhaps the most useful of the listed observations is the evaluation of artificial support loads. To approximate the additional width of barrier pillar required, all that has to be done is to locate the point at which load transfer has stopped. Obviously, this is only a crude approximation; it is strongly recommended that additional investigative techniques, such as those discussed below, be considered before design modifications are finalized. Simple observations, although very helpful in understanding pillar behavior, should not be the sole source of information driving design decisions.

## CONVERGENCE MEASUREMENTS

Visual observations of pillar and entry conditions provide qualitative data that are useful from a barrier pillar *performance* evaluation standpoint; however, these data have limited value from the perspective of quantitative design modification. Quantitative measurements, such as entry convergence, are much more useful in developing recommendations for practical design changes, especially if the barrier pillar is undersized. While not a direct measurement of load transfer, entry convergence readings provide a means of approximating the relative magnitude and extent of load redistributions resulting from mining.

Several types of convergence measurements can be made, depending upon available resources and level of detail required. Simple closure, that is, direct measurement of roof-to-floor convergence, is the most inexpensive approach and consumes the least amount of time in data collection and analysis. Differential roof sag and/or entry closure measurements are more complicated in terms of required equipment, station installation, monitoring, and data analysis, but provide detailed information on roof behavior and floor heave. Rib-to-rib closure measurements are at least as complicated and as time consuming as those for differential sag, and data may suffer from accuracy problems because of rib spalling. For barrier pillar design evaluation, simple roof-to-floor closure measurements should be adequate.

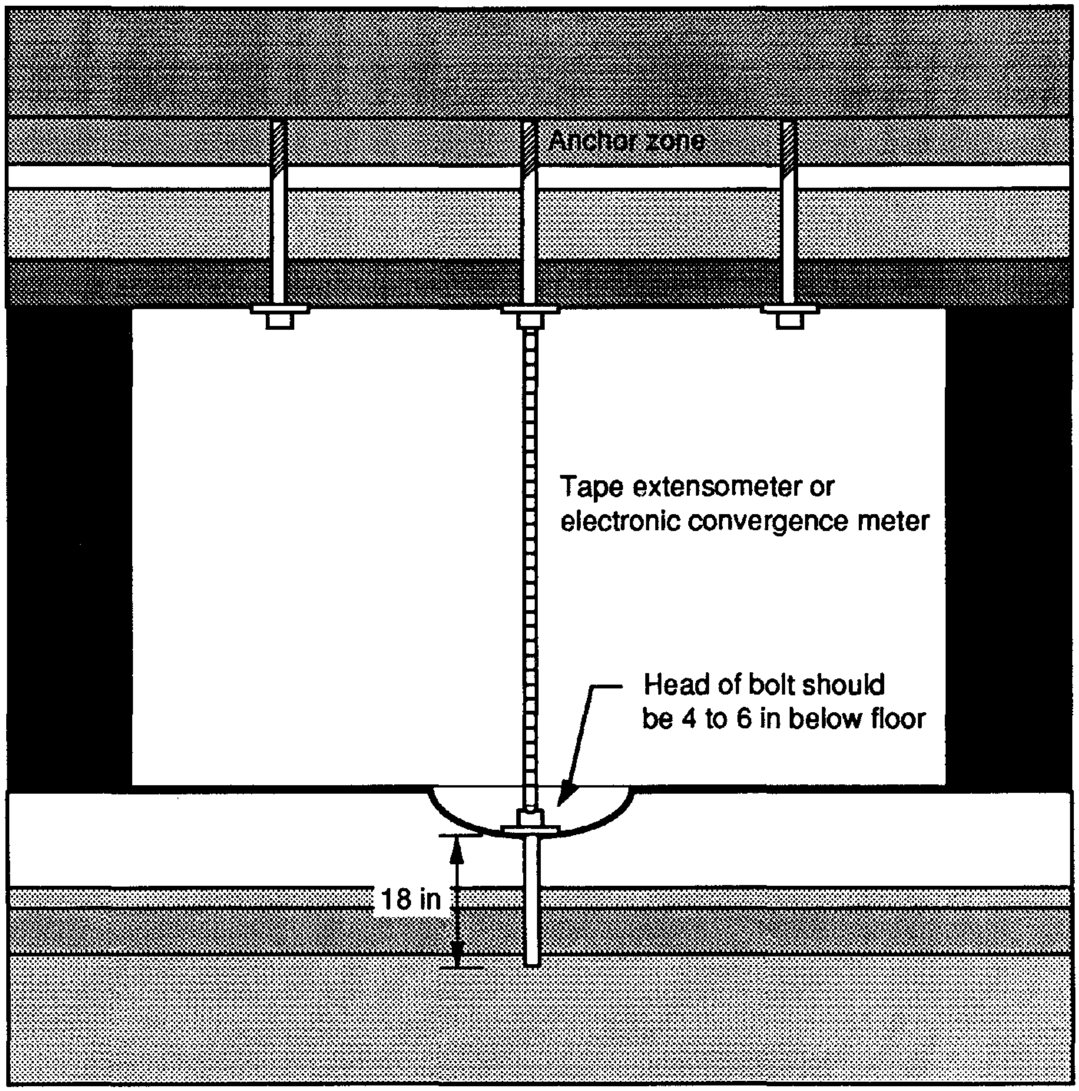
Figure 11 shows a typical roof-to-floor closure station. The top portion of the station utilizes the head of an existing roof bolt as the roof datum. A small hole is drilled in the bolt head so that the measuring rod can be repeatedly set at the same location for each measurement. The bottom portion of the station consists of a foreshortened roof bolt or section of rebar cemented into a hole drilled in the floor. The installation hole is deep enough to allow the bolt head to be positioned from 4 to 6 in below the level of the floor to protect the station during roadway maintenance. As with the top portion of the station, a small hole is drilled in the head of the floor bolt or rebar to provide a precise location for placement of the measuring device.

A number of different styles of closure-measuring devices are currently available from geomechanical and surveying equipment companies, and range from lightweight, telescopic, mechanical-type systems to significantly more costly electronic measuring devices. Regardless of the style of system chosen, the device should be capable of reading to one-hundredth of an inch. Other considerations in choosing a measuring device are weight, bulkiness, ease of reading, permissibility, and cost.

The first step in conducting a performance evaluation is to develop an instrumentation plan that addresses the informational needs of the design engineer. Figure 12 presents a typical closure station instrumentation plan for monitoring barrier pillar performance. Undoubtedly, site-specific requirements will dictate modification of the plan shown; however, several key elements of this scheme should be retained. The closure stations along the line A-A′ will provide data on the following aspects of the mining configuration:

- Confirmation of load transfer across the barrier pillar. Accelerated entry closure should be seen at the uppermost station first, with each successive station demonstrating a closure rate change corresponding to a change in the position of the longwall face.
- How far ahead of the longwall face load transfer from the forward stress abutment affects the protected

*Figure 11*



Not to scale

*Typical roof-to-floor closure station.*

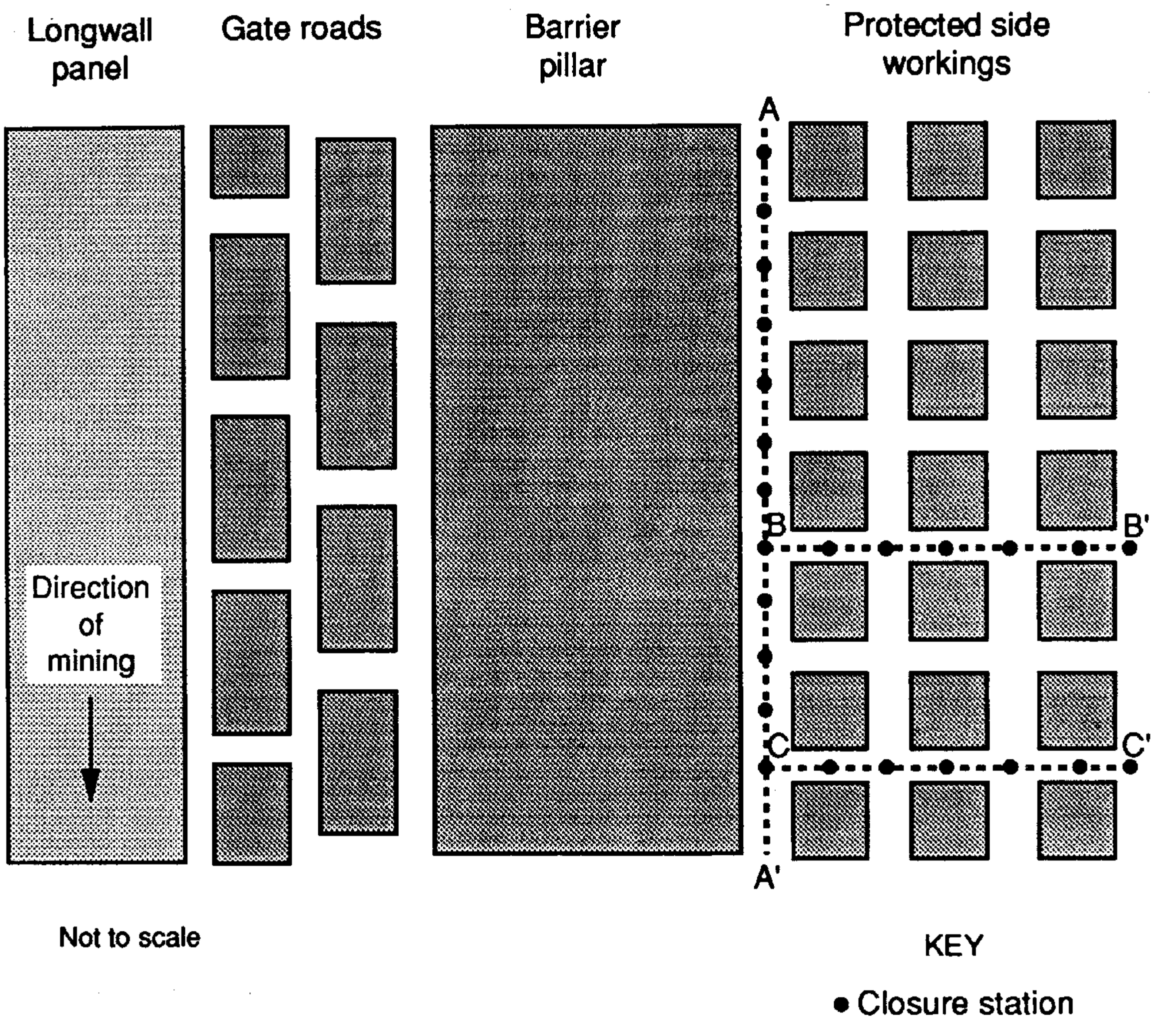
side of the barrier pillar. If needed, additional artificial support can be installed before the roof, floor, and pillars on the protected side are irreparably damaged by the overriding loads.

- Severity of load transfer across the barrier pillar. Should entry closure become uncontrollable, mining equipment and facilities can be relocated before losses are incurred. Also, a contingency plan providing alternatives for haulage, ventilation, escapeways, etc. can be developed as early as possible.

The closure stations along the line B-B′ are important primarily because the magnitude, distribution, and extent of load transfer across the protected workings can be monitored. Unless load transfer is so severe that the entire section is lost, closure data from these stations will provide a reasonable estimate of how wide the barrier pillar should have been. Finally, the closure stations along the line C-C′ are intended to provide a second data set to support the findings from the B-B′ closure stations.

Initial closure measurements should be taken 24 h apart, several times soon after the floor bolt cement has set to establish baseline values for entry height and closure rate. Weekly or biweekly readings should be taken once mining starts, until closure rates begin to increase. In reference to figure 12, closure rates should begin to increase with the approach of the forward stress abutment, and daily measurements will probably be desired. As the

*Figure 12*



*Typical closure station instrumentation plan for monitoring barrier pillar performance.*

longwall passes the instrumentation site, readings should be made each shift to obtain sufficient detail. Following passage of the face, daily readings will probably be sufficient until the area comes to equilibrium.

There are a number of ways to analyze closure data. However, to thoroughly understand the response of the mine configuration to extraction-induced load redistribution, perhaps the most appropriate method is to plot total closure versus face position. The information recorded in the log of ground conditions, combined with these plots, should enable the design engineer to develop a fairly clear picture of what has occurred. From a barrier redesign standpoint, a plot of the final (equilibrium) closure measurements versus distance across the protected area (from the barrier pillar) should shed some light on how wide the barrier should have been.

Obviously, sound engineering judgment should be exercised when evaluating entry closure data. For example, localized roof separations or floor heave can falsely exaggerate actual closure at a given location, possibly resulting in the installation of too much additional artificial support. Or worse, yielding of the pillars on the protected side of the barrier may increase the apparent extent of load transfer, resulting in oversizing of the redesigned barrier pillar.

## GROUND PRESSURE MEASUREMENTS

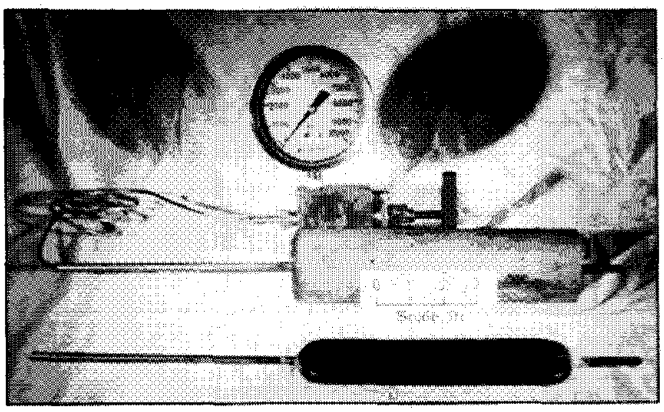
A direct method for determining the magnitude and extent of mining-induced load transfer across a barrier pillar is the monitoring of changes in ground pressure. Should the barrier pillar be oversized, pressure measurements taken across the width of the pillar will provide the location of the point of no load transfer. The appropriate width of the barrier pillar can then be determined from this information. If the barrier pillar is undersized and significant load transfers across it, the required pillar width can be determined using pressure data from instruments in both the barrier and protected-side production pillars.

A variety of instruments are commercially available for conducting ground pressure measurements. Perhaps the two most suitable for application in the coal-measure rocks are the vibrating wire stressmeter (VWS) (figure 13) and the USBM-type hydraulic borehole pressure cell (BPC) (figure 14). The advantages of the VWS over the BPC are that (1) it can provide more accurate data than the BPC, (2) the ease and success rate of installation is about the same as that for the BPC, and (3) the VWS is slightly less complicated to adapt to an automated data collection system. The disadvantages of the VWS over the BPC are that (1) the VWS is not nearly as rugged as the BPC in harsh conditions, (2) permissibility is a factor when using a VWS system, and (3) the VWS cannot be mechanically monitored like the BPC.

*Figure 13*

*VWS and electronic readout-data logger interface.*

*Figure 14*



*USBM-type hydraulic BPC and hydromechanical pressure gauge for cell pressure monitoring.*

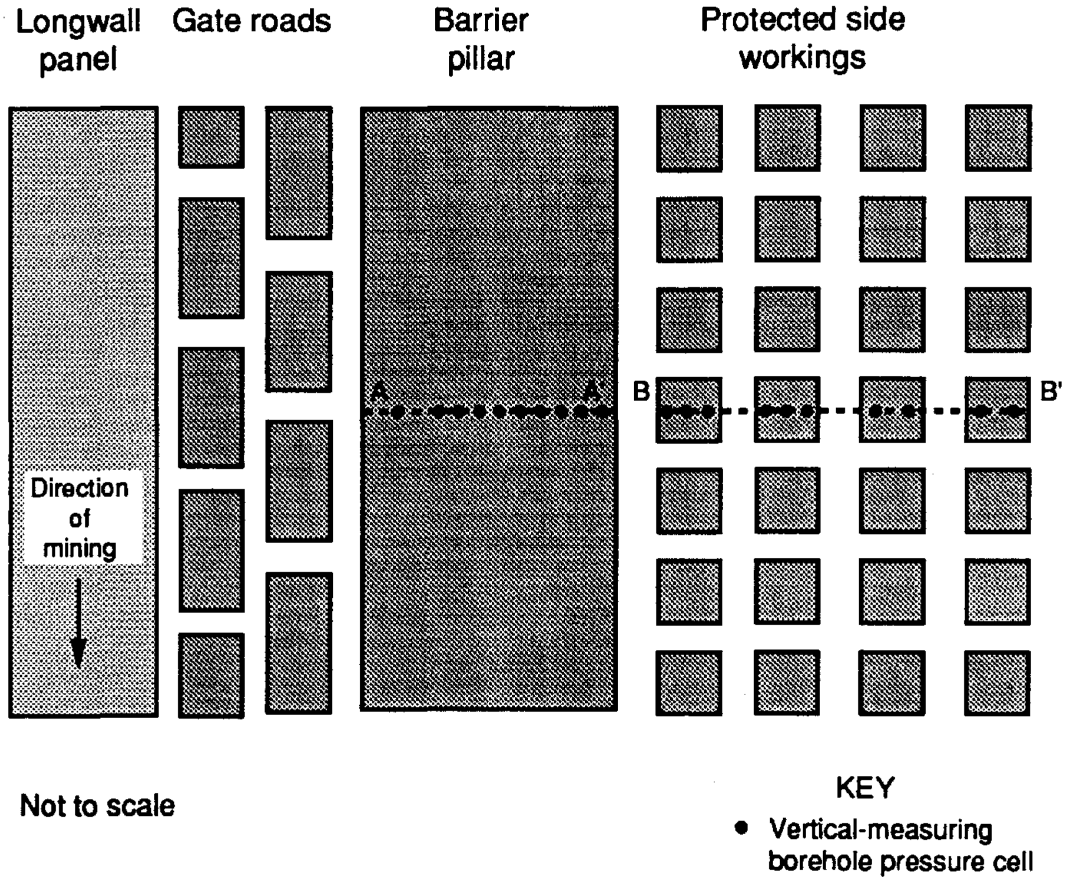
Whichever measuring device is selected, a sound instrumentation plan should be developed prior to installation to optimize the quality and quantity of collected data. The following discussion is based on a monitoring system utilizing BPC's; installation considerations for a VWS system would be nearly identical. Figure 15 presents a typical instrumentation plan for monitoring the in situ performance of a barrier pillar. Site-specific or budgetary considerations may dictate modification of the arrangement shown; however, three aspects of this plan must be retained to collect the required information.

First, the BPC's installed across the width of the barrier pillar (line A-A′) are critical because they provide the data needed to quantify the response of the pillar to mining-induced loads. Second, the BPC's installed in the protected-side production pillars (line B-B′) are important because they provide the data needed to define the magnitude and extent of load transfer. Third, as shown in figure 15, the density of instruments along the line A-A′ should increase after the first 20 to 30 ft of pillar width (from the active side). If the barrier pillar is undersized, three or more data points in the elastic core of the pillar will be needed to determine the load decay profile for redesigning the pillar. Extensive yielding may occur, especially on the active side of the barrier because of the undersized condition. Data from the BPC's located in the yielded portion of the pillar cannot be used in determining the load decay profile; therefore, more instruments should be installed in the center portion of the pillar to ensure that the required data are collected. On the other hand, if the barrier pillar is oversized, the point of no load transfer within the pillar must be known to determine the appropriate pillar width. Increasing the number of measurement points on the protected side of the pillar will more closely pinpoint the location of no load transfer.

Several options are available for monitoring BPC pressures, depending on available budget, time, and level of detail of data desired. High-pressure hydraulic gauges are the least expensive, most simple means of monitoring pressure cells, but are time consuming to read and cannot provide continuous data without continuous attention. Circular chart-type hydraulic pressure recorders are more expensive than pressure gauges and require weekly maintenance but allow continuous data collection while being inherently permissible. Electronic transducer-based automated monitoring systems are relatively expensive and complicated, can be maintenance intensive, and must be permissible if used in return air, but allow continuous data to be collected in a form suitable for immediate analysis.

BPC's should be installed before mining is initiated in the adjacent panel to allow sufficient time for each cell to come to equilibrium with existing ground pressures. Cell

*Figure 15*



***Typical BPC instrumentation plan for monitoring ground pressures in and around barrier pillar.***

pressure monitoring can begin immediately following installation if chart recorders or an automated data collection system is employed. If pressure gauges are used, initial cell pressure readings should be taken immediately following BPC installation and then on a biweekly basis until mining begins. In the example presented in figure 15, barrier pillar loads will begin to increase with the approach of the forward stress abutment, and daily pressure readings will probably be desired. As the longwall passes the instrumentation site, cell pressure readings should be made at least once per shift to obtain sufficient detail; however, in many instances, as the face passes the instrumentation, pillar loads will change so rapidly that hourly readings may be desired. Following passage of the face, daily readings will probably be sufficient until the area comes to equilibrium.

BPC pressure data can be plotted in several ways. Pressure profiles across the barrier pillar and production pillars at selected face positions will allow the engineer to develop a thorough understanding of the response of the workings to mining-induced loads. These profiles will also indicate when the maximum load from mining occurred on the barrier and protected-side pillars so that a load decay profile for the barrier pillar can be developed.

Plots of pressure change data from the BPC's along the line B-B′ (figure 15) will confirm the occurrence of load transfer should the barrier pillar be undersized. Once mining is well past the instrumentation site and the area has come to stress equilibrium, final pressure change readings from these BPC's (line B-B′, figure 15) will define the postmining magnitude and extent of load transfer and can be used to determine the *maximum* size barrier pillar needed. The maximum barrier pillar width is the distance from the active side of the test barrier pillar to the point along the line B-B′ where load transfer stops. A barrier pillar developed at the maximum width will allow absolutely no load transfer, provided mining conditions remain the same as those at the test site.

Plots of final (postmining) pressure change data from the BPC's located in the elastic core of the barrier can be used to formulate an equation that describes load decay across the pillar from the active to the protected side.

*Minimum* allowable barrier pillar widths for selected degrees of load transfer can be calculated using this equation. Although beyond the scope of this publication, a thorough discussion of this approach is presented by Koehler and others (*1*).

Should the barrier pillar be oversized, plots of the pressure change data from the barrier pillar BPC's, taken at the time of maximum mining-induced load, will indicate the point within the pillar of no load transfer. Assuming the primary criterion for a successful design is that *no* load transfer occurs, the distance across the pillar from the active side to the point of no load change is the minimum barrier required. A more conservative approach would be to increase the width of the new design over the "no load transfer" width to provide a factor of safety, or the engineer may decide that some load transfer is acceptable and choose to decrease the width below the no load transfer value. Finally, data from the BPC's along the line B-B′ will provide little useful information if the barrier pillar is oversized, because load transfer will not occur. Nonetheless, because the response of the barrier pillar to mining is unknown prior to extraction of the adjacent panel, it is prudent to invest in some level of instrumentation on the protected side of the barrier.

### SUMMARY OF PERFORMANCE EVALUATION TECHNIQUES

Each of the barrier pillar performance evaluation techniques presented above can provide information useful to the design engineer. Maintaining a log of ground conditions on the protected side of the barrier pillar can provide insight into the response of the pillar and/or entry configuration to mining-induced loads. If the barrier pillar is undersized, simple observational techniques can provide the engineer with enough information to develop a reasonably clear understanding of the overall effectiveness of the design. Also, a rough estimate of the required barrier pillar width can be determined using this approach. If the barrier pillar is oversized, however, this technique will only confirm that the design is adequate from a ground stability viewpoint and will not provide the information needed to downsize the pillar and ensure maximum resource recovery.

Convergence measurements offer the advantage of reliable quantification of the response of the pillar and/or entry system to mining-induced loads. In the case of the undersized barrier pillar, convergence data can be used to improve the estimate of required barrier pillar width developed from visual observation data. Also, convergence monitoring offers first-hand information on the magnitude of load transfer, thereby providing the mine operator with advanced warning of potential ground stability problems ahead of mining. Using this information, important life-of-mine openings and valuable capital equipment and facilities may be adequately protected before losses are incurred. However, should the barrier pillar be oversized, as with simple observations, convergence measurements can only confirm that a given design provides adequate ground stability. A trial-and-error approach, decreasing barrier pillar size incrementally for each iteration, is the only way that resource recovery can be maximized using visual observations and convergence measurements alone.

Ground pressure measurements can provide perhaps the most useful and complete information regarding the response of the mine layout to mining-induced loads. If the barrier pillar is undersized, ground pressure data can be utilized to further zero in on the proper design indicated by visual observations and convergence measurements. Also, highly unstable pillar conditions can be accurately located, thereby affording a further measure of safety. The most important advantage of ground pressure monitoring, however, is that it provides the operator with the ability to quickly pinpoint the barrier pillar design that provides acceptable ground stability *and* maximizes resource recovery, which is the overall goal of proper barrier pillar design. Neither visual observations nor convergence measurements offer the advantage of being able to determine the load profile across a barrier pillar, whether that pillar is too small or too large. In the case of an oversized design, ground pressure measurements stand alone as the only available means of determining if the overall design goal has been achieved.

## SUMMARY AND CONCLUSIONS

The barrier pillar design methods presented here are empirically based scaling laws developed entirely from in-mine observations and measurements of pillar performance, and the results of laboratory research investigating the physical properties of coal and the coal-measure rocks. In general, the earlier approaches should be used with a higher degree of caution than those developed later. The earlier methods did not benefit from the technological improvements in observational and measurement techniques available to the modern researcher, nor were the years of experience in barrier pillar research available to the pioneers in this field.

Most of the available design techniques do not account for variations in one or more important mining parameters, such as coal strength or seam thickness, rendering their use contingent on the application of a fairly high degree of engineering judgment. For this reason, the presented discussions of each approach are intended to direct the design engineer toward those considerations that should be addressed prior to application of the chosen design method. Also, it is unreasonable to assume that any design approach can completely account for all site-specific variations in a mining environment, nor can one barrier pillar design be expected to fulfill the needs of the operation across the property throughout the life of the mine. In fact, the presented barrier pillar design methods are intended only to provide baseline pillar dimensions from which the optimum design for a given mining block may be evolved.

As with other mine support structures, evolution of the optimum barrier pillar configuration, that is, one that provides acceptable ground stability on the protected side *and* maximizes resource recovery, can only be accomplished through a trial-and-error process of in-mine prototype testing. Granted, modern technological advances in laboratory and field measurement techniques, and improvements in analytical and numerical modeling approaches, have narrowed the gap between baseline and optimum designs. However, no method or combination thereof can provide the quality and quantity of performance information that can be obtained from an in situ field trial in the real mining environment.

Visual observations, entry convergence measurements, and ground pressure monitoring all provide a distinct level of detail with regard to the actual in situ performance of a given barrier pillar design. Although visual observations should not be relied upon as the sole source of information driving the redesign of a barrier pillar, this information is very useful in developing an understanding of the performance of the design in question. Entry convergence measurements offer the opportunity to reliably *quantify* load transfer phenomena on the protected side of the barrier pillar at significantly less cost than ground pressure monitoring; however, should the barrier pillar be oversized, convergence measurements can only confirm that a given design provides adequate ground stability. A trial-and-error approach, decreasing barrier pillar size incrementally for each iteration, is the only way that resource recovery can be maximized using this technique.

In comparison, ground pressure measurements can be successfully employed to directly redesign either undersized or oversized barrier pillars. If the barrier pillar is undersized, ground pressure data can be utilized alone or in combination with visual observations and convergence measurements to focus on the proper design. In the case of an oversized design, ground pressure measurements are the only means of finding the point of no load transfer within the confines of the barrier pillar. With this information, the design engineer can apply any one of a number of rational design criteria to develop a barrier pillar configuration best suited to the specific needs of the mining operation.

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