VIRGINIA DIVISION OF MINERAL RESOURCES

PUBLICATION 104

EVALUATING THE IMPACT OF MULTI-SEAM MINING ON RECOVERABLE COAL RESERVES IN AN ADJACENT SEAM

Yingxin Zhou

COMMONWEALTH OF VIRGINIA

DEPARTMENT OF MINES, MINERALS AND ENERGY
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Robert C. Milici, State Geologist

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DEPARTMENT OF MINES, MINERALS AND ENERGY
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CONTENTS

	Page
Abstract	1
Introduction	1
Interaction mechanisms	1
Arching and caving	1
Subsidence	3
Vertical load transfer	4
Sub-critical conditions	5
Super-critical conditions	5
Minimum minableinnerburden thickness	7
Minimum recoverable innerburden thickness	7
I'_{min} for complete extraction in lower bed	7
I'_{min} for partial extraction in lower bed	9
Evaluating coal loss with unknown mine geometries	11
Evaluating coal loss with known mine geometries	11
Mine layout and coal loss	11
Sub-critical conditions	11
Super-critical conditions	13
Other considerations	13
Surface subsidence	13
Over- and under-designed lower bed pillars	13
Apparent loss vs real loss	14
Evaluation of multi-seam reserve with no previous mining	14
Upper bed mined first with partial extraction	14
Upper bed mined first with complete extraction	14
Conclusions and recommendations	16
References cited	16
Appendix: **MSCOAL** and **MULEXT** user guides and example	17

ILLUSTRATIONS

Figure

1. Formation of pressure arch and interaction	2
2. Maximum width of pressure arch vs depth of mining	2
3. Derivation of pressure-arch geometries	3
4. Subsidence wave and its effects on upper seam	3
5. Use of influence function in subsidence calculation	4
6. Use of subsidence in multi-seam analysis	5
7. Formation of pressure and high-pressure zone	5
8. Load transfer in overmining operations	6
9. Minimum minable innerburden thickness - average value estimate	8
10. Minimum minable innerburden thickness - upper limit value estimate	8
11. Minimum innerburden thickness requirement - complete extraction in lower seam	9
12. Minimum innerburden thickness requirement - partial extraction in lower seam	10
13. Nomogram for minimum innerburden thickness - partial extraction in lower seam	10
14. Percent coal loss vs innerburden thickness for overmining operations	11
15. Analysis based on lower-seam panel geometries	12
16. An alternative layout for multi-seam mining	13
17. Minimum innerburden requirement for lower-seam stability	15
18. Analysis of lower-seam stress concentration using foundation theory	15

TABLE

1. Calculation of minimum innerburden thickness based on height of caving	3

EVALUATING THE IMPACT OF MULTI-SEAM MINING ON RECOVERABLE COAL RESERVES IN AN ADJACENT SEAM

Yingxin Zhou[1]

ABSTRACT

A reliable estimate of mineable coal reserves is essential to long-range planning and for conservation of energy resources. In Virginia, the majority of the coal beds are found in multiple horizons, with up to 25 coal beds in a given stratigraphic section. The traditional approach to multi-seam coal reserve estimation has been to set a fixed minimum innerburden thickness for all seams under consideration. Any two seams are considered both mineable only when the innerburden thickness between the two seams are greater than this minimum value. However, research into ground control in multi-seam mining has revealed that this distance varies considerably from mine to mine, sometimes even from location to location within the same mine. Among the factors which affect this minimum innerburden thickness are rock type, sequence of mining, methods of extraction, mine geometries and thickness of the two seams.

Coal recovery from coal beds that overlie or underlie mined-out beds may be significantly reduced, depending upon the magnitude of inter-bed interaction. Based on extensive case studies and theoretical analyses, this paper presents evaluation methods which incorporate rock mechanics and geological analysis in the evaluation of recoverable coal reserves influence by multi-seam mining. To facilitate the evaluation process, a computer program called MSCOAL has been developed for the IBM PC. The program is menu-driven and user-friendly with extensive on-line help and complete documentation of the technical details which make up the program. Application of the program to coal beds in Virginia has proven to be successful.

INTRODUCTION

A reliable estimate of minable coal reserves is essential to long-range planning and for conservation of energy resources. In Virginia, the majority of the coal beds are found in multiple horizons. In the Vansant quadrangle, located in south-central Buchanan County, there are up to 25 coal beds in a given stratigraphic section. Ideally, to maximize coal recovery the sequence of mining should proceed in a descending order, starting with the uppermost bed, with complete extraction of each coal bed before the next bed is mined. However, in practice the decision traditionally has been based on factors such as ownership, economy, and accessibility, without considerations for the potential effects on subsequent mining operations.

Today, many coal operators are mining above existing or abandoned mines, some of which exhibit subsidence, pressure arching, and large-scale caving. As a result, special ground control problems from such interactions may occur in an upper bed that is subsequently mined. Coal recovery from coal beds that overlie mined-out beds may be significantly reduced, depending upon the magnitude of interaction. Some coal beds lying in close vertical proximity may be completely lost to caving or intense fracturing, whereas others may only be slightly affected. Complete and partial extraction also tends to create different interaction effects, both in terms of interaction mechanisms and magnitude. The percent of coal loss is, therefore, a function of extraction methods, geological structures, and the innerburden features and thickness.

INTERACTION MECHANISMS

To fully understand how the mining of a lower bed affects coal recovery in an overlying bed, it is important to analyze the mechanisms which govern the interaction effects between coal beds. For overmining operations, three basic mechanisms are relevant: arching/caving, subsidence, and vertical load transfer.

ARCHING AND CAVING

The fundamental concept for the formation of a pressure arch is the fact that rock structures can support themselves by redistributing the ground pressure - a process known as load transfer. When a coal bed is removed, the roof may fail, either in tension or shearing, causing the strata to cave onto the mined area, separating the failed roof material from the remaining strata. An arch is formed when load is shed onto solid abutment or onto caved but compacted waste material, creating zones of stress relief and stress concentration. When the innerburden thickness is greater than the height of the pressure arch, the upper bed is protected by the formation of the pressure arch and will not suffer from any negative interaction effects (Figure 1).

The two critical parameters defining an arch are the arch width and arch height. If either the opening width is greater than the maximum arch width or the depth of mining less than the arch height, no arch will be formed although there will still be load transfer along an arch-shaped path. Arch shapes can be in the form of an ellipse, a circle, or a parabola, with the most commonly occurring form being parabolic.

Using the load transfer concept, the maximum width of the pressure arch is two times the load transfer distance (LTD), which is given by the following empirical equation (Abel, 1982):

$$LTD = -848 + 159 \ln(D) \quad (1)$$

where D is depth of mining of the lower bed in feet.

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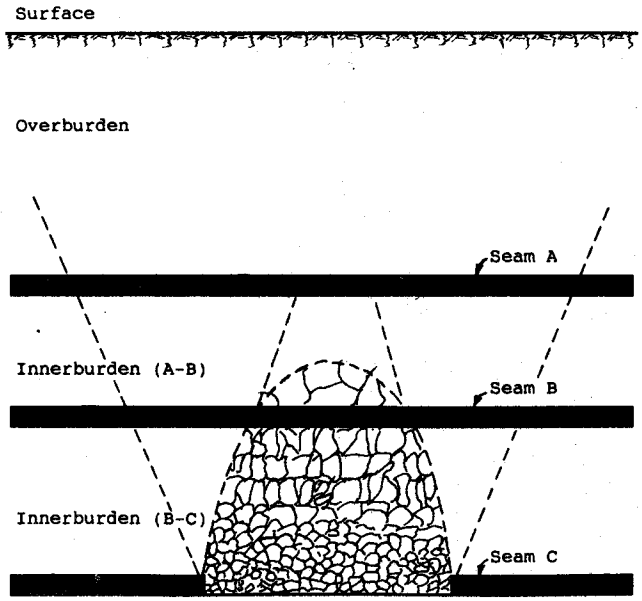


Figure 1. Formation of pressure arch and interaction.

The maximum width of a pressure arch is plotted in Figure 2 against depth of mining, given by the following equation:

$$W_{max} = -1696 + 318 \ln(D+h). \quad (2)$$

The height of the pressure arch has been derived by Zhou (1988). The derivation incorporates a rock property known as the pillar loading angle, generally used in subsidence control and prediction. The equation is given as follows:

$$d = \frac{w}{4\tan\alpha} \quad (3)$$

where d = height of pressure arch; w = width of pressure arch; α = pillar loading angle (18 to 21 degrees for Appalachian coalfields).

Once the height of the pressure arch is determined, the path of the pressure arch at an upper bed level can be obtained

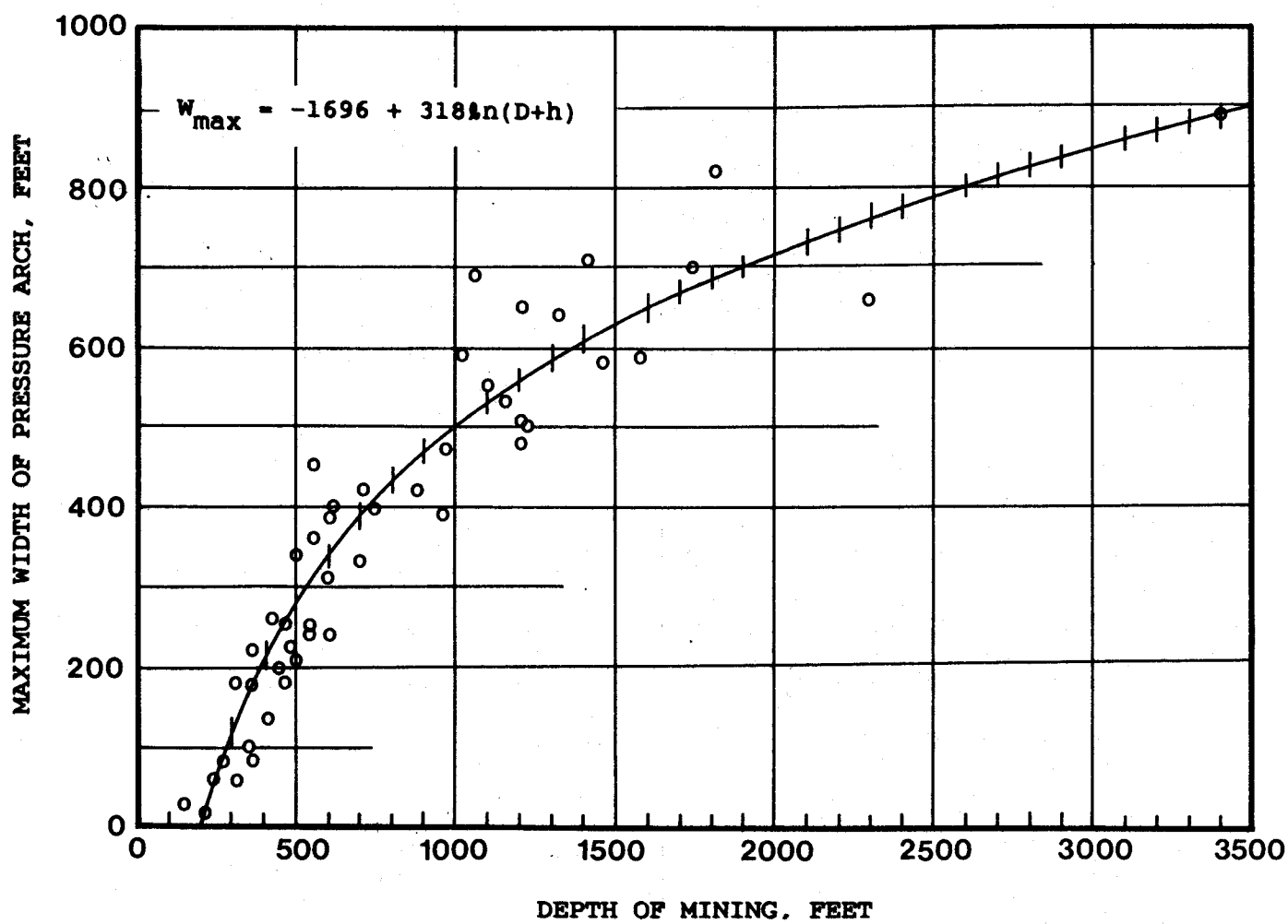


Figure 2. Maximum width of pressure arch vs depth of mining (after Abel, 1982).

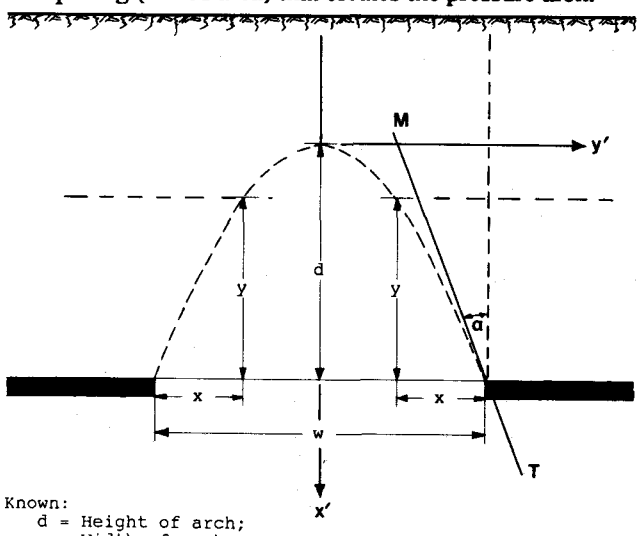
by the equation (Figure 3):

$$x = \frac{w}{2}\left(1 - \sqrt{1-y/d}\right) \qquad (4)$$

where x = distance from the ribside; y = distance from the lower bed; and other variables as defined previously.

Influenced areas in the upper bed can thus be determined by the parameters associated with caving, fracturing, and the pressure arch.

Caving and arching are two closely related strata movements. In fact, it is the caving and sagging of the strata above the opening (mined area) that creates the pressure arch.



Known:
d = Height of arch;
w = Width of arch;

Find:
x = Horizontal distance from abutment edge;
y = Vertical distance from seam level.

Assume:
Parabolic form of arch.

Equation of a parabola:

$$y = \frac{d}{w^2}\left[w^2 - (w-2x)^2\right]$$

$$x = \frac{w}{2}\left(1 - \sqrt{1-y/d}\right)$$

Figure 3 Derivation of Pressure-Arch Geometries

The height of caving and fracturing zones follows a geometric function of the height of mining based on extensive field measurements, given by the following equation modified from Peng and Chiang (1984):

$$h_{c,f} = \frac{100s}{as + b} \pm c \qquad (5)$$

where $h_{c,f}$ = height of caving or fracturing, ft.; s = seam thickness or height of mining, ft.; and a, b, c = constants characteristic of strata properties.

Table 1 lists the values of the corresponding constants, a, b, and c.

SUBSIDENCE

In overmining operations, subsidence is responsible for most of the interaction effects to the upper bed. Subsidence is usually the result of an increased opening span when the pressure arch is no longer capable of obtaining support from the solid sides of the excavation. This results in collapse of the ground above and large-scale strata movements. The effects of trough subsidence on the upper bed can be viewed from the various zones that are created during the subsidence process. As the panel advances in the lower bed, the upper bed will experience a subsidence wave. This wave constitutes a tension zone near the front line of the lower bed, followed by a zone of lateral compression, sometimes accompanied by shearing (Figure 4). The most detrimental effects occur in the tension zone because of the inherently low tensile strengths of coal measure rocks.

Table 1 Calculation of minimum innerburden thickness based on height of caving (after Peng and Chiang, 1984)

Strata Type	Rock Property Constants		
	a	b	c
Hard	0.640	16.0	8.2
Medium hard	1.433	19.0	7.2
Soft	1.890	32.0	4.9
Weathered	2.134	63.0	3.9

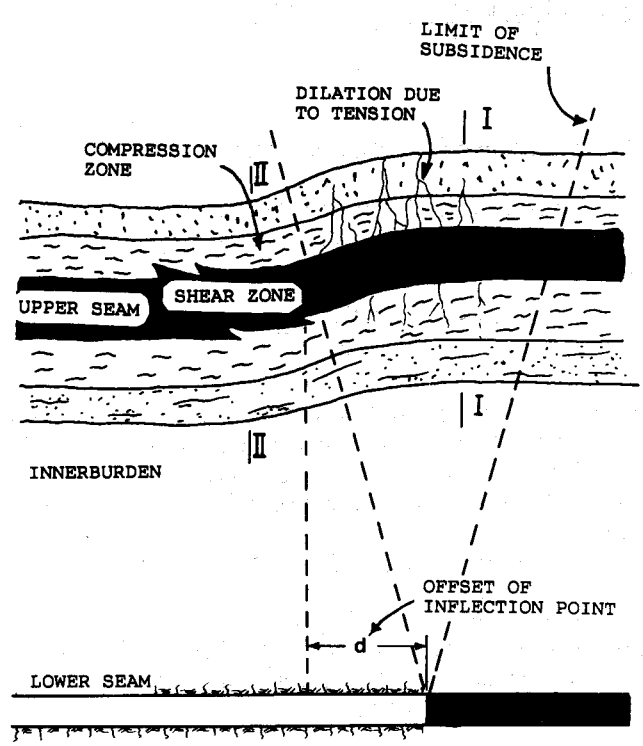


Figure 4. Subsidence wave and its effects on upper seam.

Various theories exist concerning subsidence movements, but the most commonly used generally fall into one of the following three categories: the profile function method (Brauner, 1973; NCB, 1975), the influence function method (Kratszch, 1983), or the zone area method (Marr, 1975). Any one of these methods can be used to predict subsidence, with the choice depending upon the application requirements and the geologic and mining factors.

Using the Budryke-Knothe influence function method, which has been successfully used in the Appalachian coalfields (Karmis and others, 1987), the subsidence at any point A is given by (Figure 5):

$$S(x) = \frac{S_{max}}{r} \int_{-a}^{x} e^{-\pi \frac{x^2}{r^2}} dx \qquad (6)$$

where r = average radius of influence = h/tan(β); h = distance from lower bed level; β = angle of influence; x = horizontal distance from the inflection point (Figure 5); S_{max} = maximum subsidence.

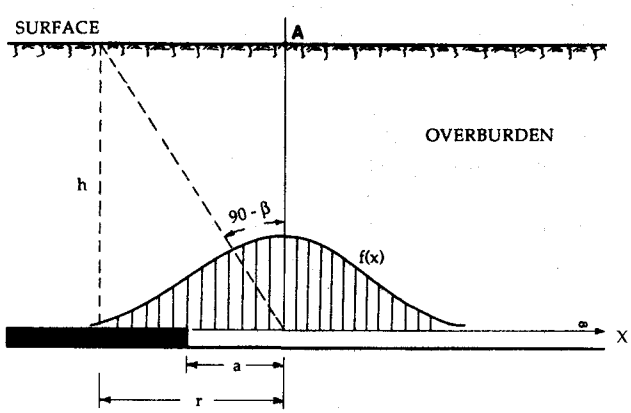


Figure 5. Use of influence function in subsidence calculation.

Tensile strain at the upper bed level, which is a measure of the intensity of disturbance, can be calculated by the following equation:

$$\varepsilon(x) = brK(x) = 2\pi b \frac{S_{max}}{r}\left(-\frac{x}{r}\right)\exp(-\pi x^2/r^2) \qquad (7)$$

where b = constant, and is found to be equal to 0.3 for horizontal beds by the finite element method. A value of 0.35 for b can be derived from results reported by Karmis and others (1987), based on case studies relating strain to curvature.

Figure 6 shows the distribution of subsidence and strain and their relationship.

The subsidence factor, S_{max}/s, is a function of the excavation geometry of the lower bed and lithology of the strata. Based on case studies, an empirical formula has been derived for the Appalachian coalfields:

$$S_{max}/s = (-0.0071*n+0.825)(1-e^{-60\,l/n}) \qquad (8)$$

where S_{max} = maximum subsidence; n = percent of hardrock in strata; l = width/depth ratio = w/D; and D = overburden thickness or depth of mining.

Although subsurface subsidence can be treated as surface subsidence with reasonable accuracy, it is generally believed that subsidence at the upper bed level is greater than that at the surface. This is because as the strata subside, caving at the lower bed level and subsequent strata movement create voids in the strata; otherwise the surface subsidence factor would always have a value of 1.0 under super-critical conditions.

To adjust for this difference in subsidence, the subsidence factor at distance z from the surface, satisfying boundary conditions, is given by:

$$a(z) = a_s + \frac{a_l - a_s}{D} z. \qquad (9)$$

where a(z) = maximum subsidence factor at level z; $a_s \leq a(z) \leq 1.0$; a_s = subsidence factor at surface; z = distance from surface; a_l = subsidence at the lower bed level; D = overburden thickness from the lower bed.

If a(z) cannot be determined, Equation (8) can still be used to estimate the subsidence factor at the upper bed level by substituting the innerburden thickness, h, for the overburden thickness, D.

VERTICAL LOAD TRANSFER

Remnant pillars of substantial size left in the lower bed may create high pressure in an overlying coal bed, because of the continued subsidence of the strata on both sides of the pillar and support provided by the pillar (Figure 7). The magnitude of the strata load bearing on the pillar is governed by the size of the pillar, mining geometry, and loading angle of the strata. Any load from the undermined strata that is not taken up by the gob (caved area) is passed as an additional load to the pillar, which may or may not be transferred to the overlying bed depending on the strata characteristics and innerburden thickness.

Load increase, expressed by an average stress concentration factor in the upper bed, can be derived using the mechanisms of load transfer and pressure arching. As shown in Figure 8, the pillar will have to carry the strata load above the arch, extending to half of the arch width or one load transfer distance on each side. A sub-critical condition exists when a pressure arch is formed. When the lower panel width exceeds the maximum arch width, a super-critical situation arises. Extending the above analysis to the upper bed, the average concentrated load is the total load divided by the area of load increase which is defined by the arch path.

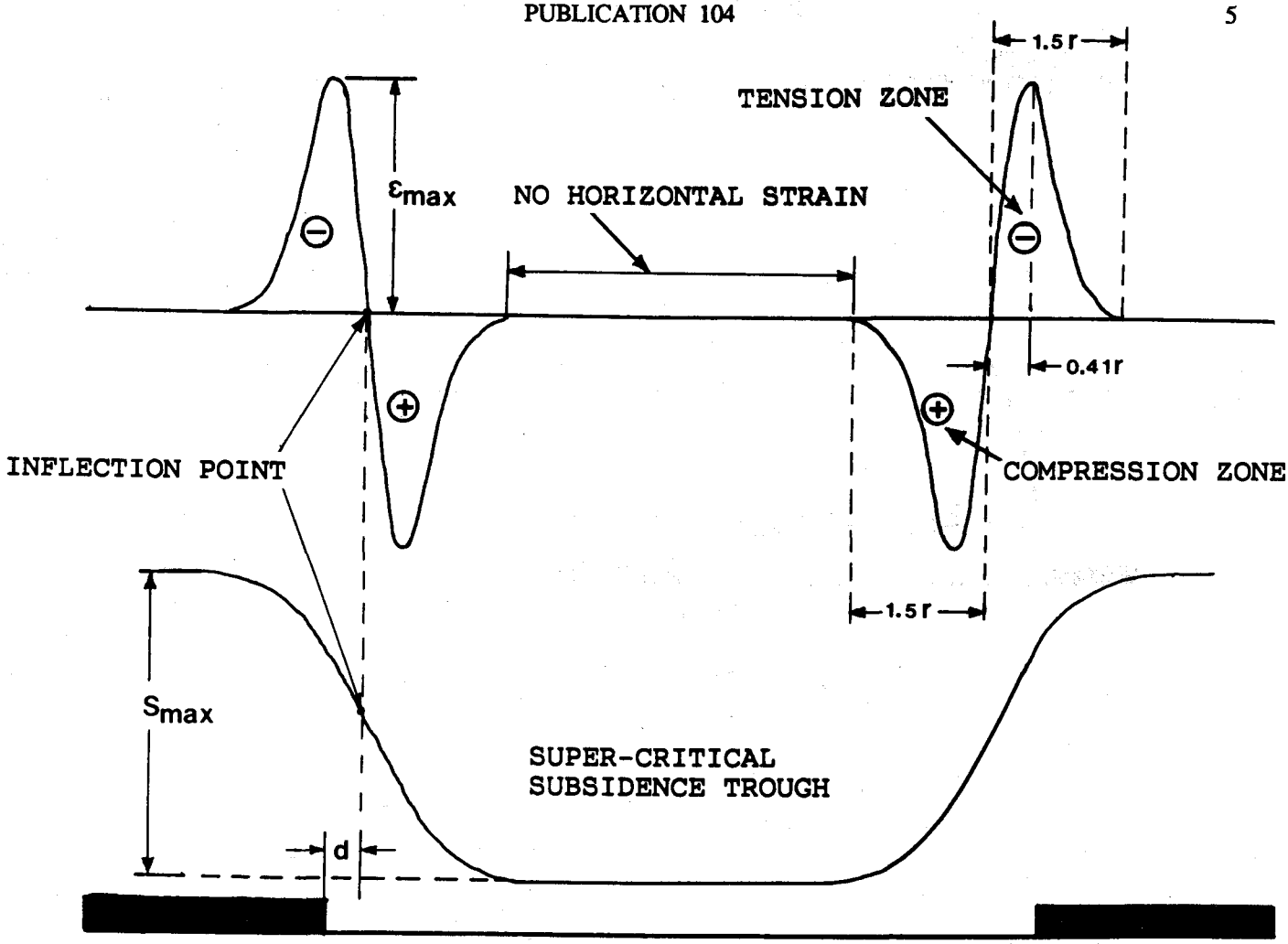


Figure 6. Use of subsidence in multi-meam analysis.

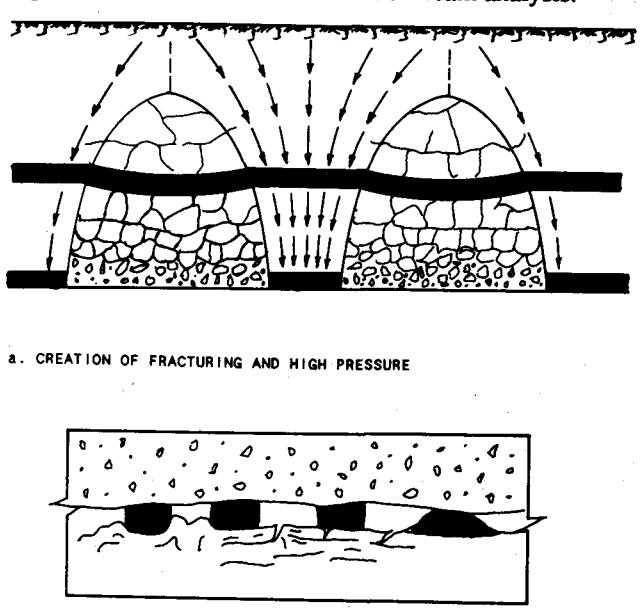


Figure 7. Formation of pressure and high-pressure zone.

SUB-CRITICAL CONDITIONS

When d > h, the average load concentration factor in the upper bed is given by:

$$S = \frac{(Wp+w)D + wh - 2/3(wd+xh)}{D(Wp+2x)} \qquad (10)$$

where D = overburden thickness to the upper bed; and Wp = width of lower bed barrier pillars (Figure 8a).

SUPER-CRITICAL CONDITION

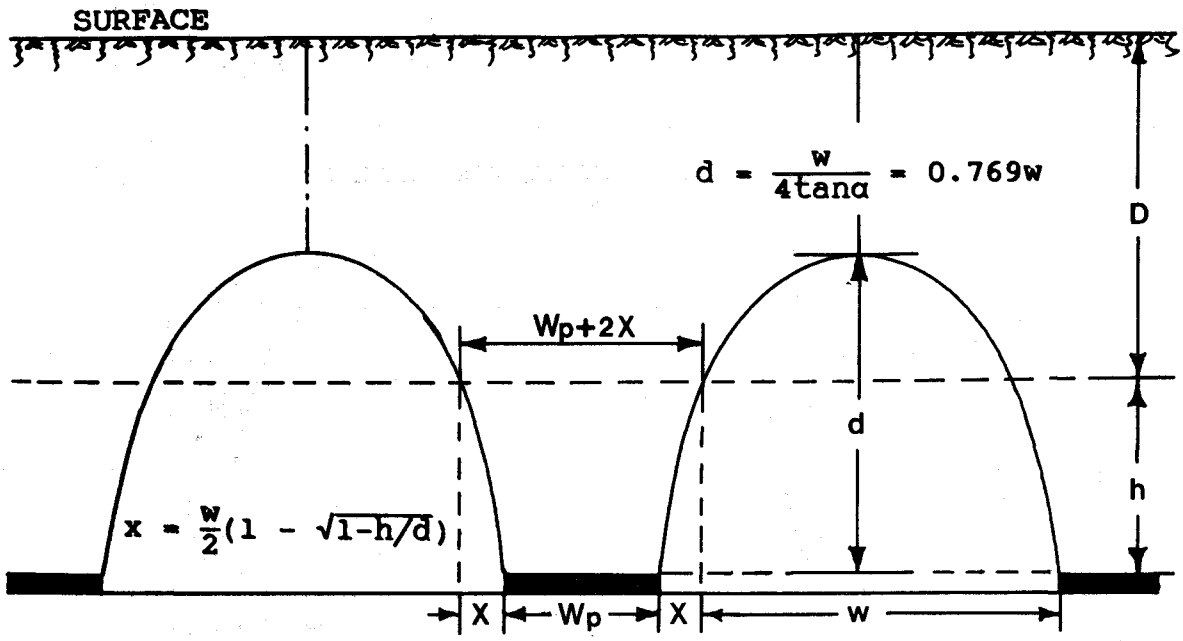
In a super-critical condition, the average load concentration factor is given by:

$$S = \frac{Wp(D+h)+2/3LTD(D+h)-(Wp+2/3xh)}{D(Wp+2x)}$$

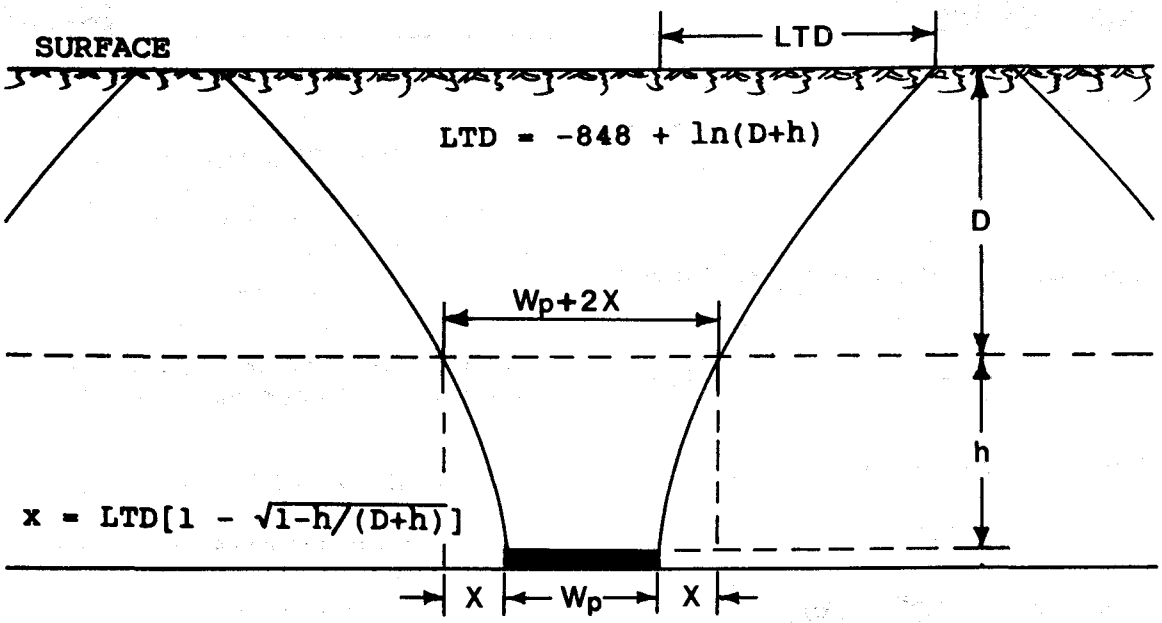
$$= \frac{WpD+2/3[LTD(D+h)-xh]}{D(Wp+2x)} \qquad (11)$$

where LTD and x are as defined previously (Figure 8b).

As can be seen in the analysis for the super-critical condi-



$$S = \frac{(Wp+w)D + wh - 2/3(wd+xh)}{D(Wp+2x)}$$



$$S = \frac{WpD+2/3[LTD(D+h)-xh]}{D(Wp+2x)}$$

Figure 8. Load transfer in overmining operations: a. sub-critical condition (top diagram); b. super-critical condition (bottom diagram).

tion, the stress concentration factor S will always be greater than unity. This means that there will always be some coal affected by subsidence no matter how large the innerburden thickness is unless a maximum acceptable stress concentration factor greater than one can be established. The inherent fact is that in a super-critical condition, all strata above the extracted lower bed will be affected to a certain extent. In a later subsidence analysis relating upper-bed damage to maximum tensile strain, it will be shown that an upper limit for the minimum innerburden thickness can be established.

MINIMUM MINABLE INNERBURDEN THICKNESS

In evaluating overmining operations, a question of immediate concern is how close the upper bed can be to the lower bed without being rendered completely unminable by the mining of the lower bed. It is necessary to introduce a critical innerburden thickness below which all coal will be lost. This value is defined as the minimum minable innerburden thickness.

From the point of view of ground control practice, if the upper bed is within the caving height of the lower bed, it must be concluded that the upper bed will be lost entirely. Conceivably, in order for any mining activities to be conducted, the upper bed must be above the caving zone. In other words, the actual innerburden thickness should be greater than the height of caving. The minimum minable innerburden thickness can thus be determined as the height of caving given by Equation (5), substituting appropriate values for a, b, and c based on geological conditions.

For ease of application, the minimum innerburden thickness is plotted against seam thickness for estimates using both the average value and upper limit value (Figures 9 and 10). Based on average strata conditions (from soft to medium hard) and bed thickness (4.0 to 5.0 ft.) in Virginia coalfields, an average minimum minable innerburden thickness of 20 feet has been established.

Because the minimum minable innerburden thickness is a function of the lower bed mining height, the ratio of the innerburden thickness to mining height, defined as the M-Index, is sometimes used. The minimum minable innerburden thickness is determined by multiplying the minimum M-Index by the lower bed thickness, s:

$$I^{m}_{min} = M^{m}_{min} * s \qquad (12)$$

Given a lower bed thickness, the innerburden thickness is adequate for describing the minimum innerburden requirement for upper bed stability. If the lower bed thickness is unknown or varies, the M-Index becomes a better measure because it describes the requirement dimensionlessly. For the same innerburden thickness and strata conditions, a larger lower bed thickness (or smaller M-Index) will certainly have a profound effects on the overlying bed. In subsidence terms, a thicker lower bed will produce subsidence and strains of a larger magnitude which translate to more severe disturbance of the upper bed. For Virginian coalfields, an average of 5 has been established as the minimum minable M-Index.

MINIMUM RECOVERABLE INNERBURDEN THICKNESS

Even after it has been determined that the upper bed can be mined, it may still be that only a portion of the upper bed is recoverable. Furthermore, for a given set of geologic and mining conditions, there must exist a critical value for the innerburden thickness above which all upper bed coal can be mined without any significant loss due to negative interaction. This value is defined as the minimum recoverable innerburden thickness, and has been determined for two situations: complete extraction and partial extraction in the lower bed.

I^{r}_{min} FOR COMPLETE EXTRACTION IN LOWER BED

Subsidence analysis of over 90 case studies collected from the Appalachian coalfields has shown that tensile strain is the most detrimental interaction to affect the upper bed. Based on results of previous studies (Zhou and Haycocks, 1986), a tensile strain of 12/1000 for average roof conditions in the upper bed is considered the maximum tolerable. That is, if the maximum tensile strain at the upper bed level is smaller than 12/1000, no significant interaction is expected for the upper bed. From Equation (7), the maximum tensile strain in the upper bed is given by:

$$\varepsilon_{max} = 1.52b \frac{a}{\text{M-Index}} \tan\beta \qquad (13)$$

where b = strain factor (0.35 for Applachian coalfields); a = subsidence factor; $\tan\beta$ = tangent of principal influence angle.

Rewriting the above equation, we have:

$$\text{M-Index} = 1.52b \frac{a}{\varepsilon_{max}} \tan\beta \qquad (14)$$

The subsidence factor as a function of percent hardrock in the innerburden has been given by Zhou (1988) as:

$$a = -0.71n + 0.825 \qquad (15)$$

where n is the fraction of hardrock in the innerburden (expressed as a decimal).

For Appalachian coalfields, Karmis and others (1987) have found that $\tan\beta$ takes a value in the range of 2.31±0.4. If the percent of hardrock is introduced, $\tan\beta$ can be given by the following equation:

$$\tan\beta = 2.31 \pm 0.4 = 1.91 + 0.8n \qquad (16)$$

Using ε_{max} = 12/1000, and substituting into Equation (14), we obtain:

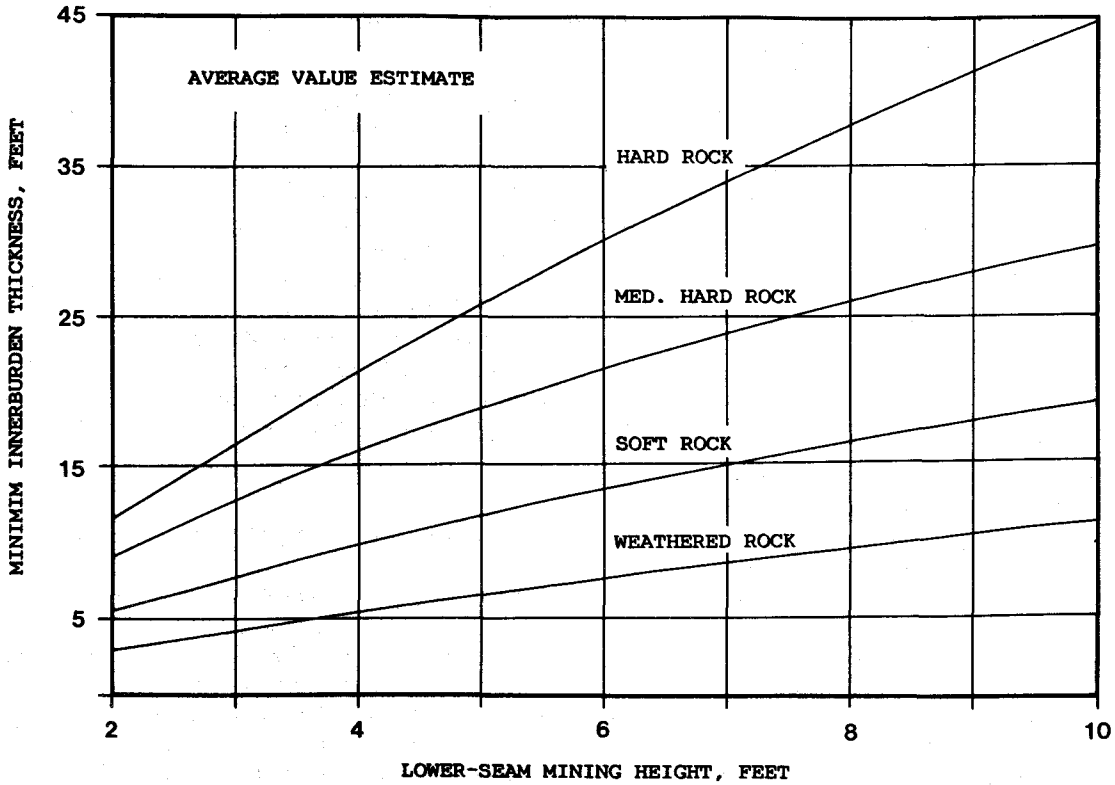


Figure 9. Minimum minable innerburden thickness - average value estimate.

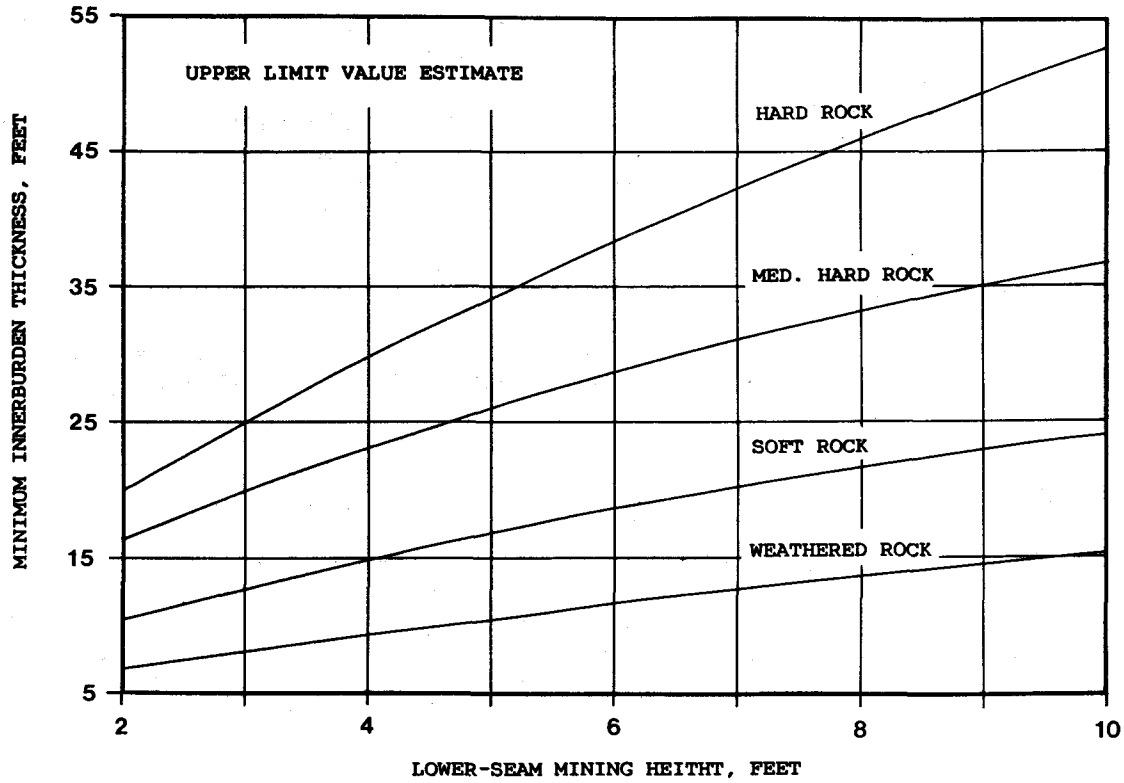


Figure 10. Minimum minable innerburden thickness - upper limit value estimate.

$$\text{M-Index} = 44.3(-0.696n - 0.568n^2 + 1.567) \quad (17a)$$

or

$$I^r_{min} = 44.3(-0.696n - 0.568n^2 + 1.567)s \quad (17b)$$

where s is the lower bed mining height.

The I^r_{min} given here indicates that interaction effects will be minimal if the actual innerburden thickness is greater than this value, and no significant amount of coal will be lost because of interaction. Shown in Figure 11 is a nomogram for Equation (17b).

I^r_{min} FOR PARTIAL EXTRACTION IN LOWER BED

Where the lower bed is only partially extracted, the interaction mechanism is somewhat more complicated but the interaction effect is smaller in scale. Statistical analyses of case studies have shown that, if the overall lower bed extraction ratio is less than 64 percent, there will be no loss of coal because of bed interaction so long as the upper bed is lying above the caving zone, as determined by Equation (5). Coal loss in the upper bed over partially extracted areas in the lower bed is most likely to occur where there is uneven robbing of the lower-bed pillars.

The extraction ratio of the lower bed can sometimes be known either directly from coal companies or by comparing estimated reserves and tons extracted. When such information is available, an estimate of minimum recoverable innerburden thickness can be made by using the following equation (Zhou and Haycocks, 1986):

$$M^r_{min} = -97.3 + 1.51x \quad (18a)$$

or

$$I^r_{min} = (-97.3 + 1.51x)s \quad (18b)$$

where x is the extraction ratio (expressed as a percentage) of the lower bed; and s is the lower bed thickness or mining height. Figure 12 is a nomogram of the minimum recoverable innerburden thickness as a function of the lower-bed extraction ratio and mining height.

If the effect of geology is considered, as expressed by the percent of hardrock in the innerburden, the minimum M-Index can be modified based on an average of 30 percent hardrock in the innerburden into the following form:

$$M^r_{min} = (1.51x - 97.3)(1 - \frac{z - 30}{100}) \quad (19a)$$

or

$$I^r_{min} = (1.51x - 97.3)(1 - \frac{z - 30}{100})s \quad (19b)$$

where z is percent hardrock in the innerburden.

Again a nomogram is generated for ease of application (Figure 13).

If the average width of lower bed openings is known, a check can be made on the height of pressure arches. This arch height will be the minimum recoverable innerburden thickness if it is less than that given by Equation (19b). Also it must

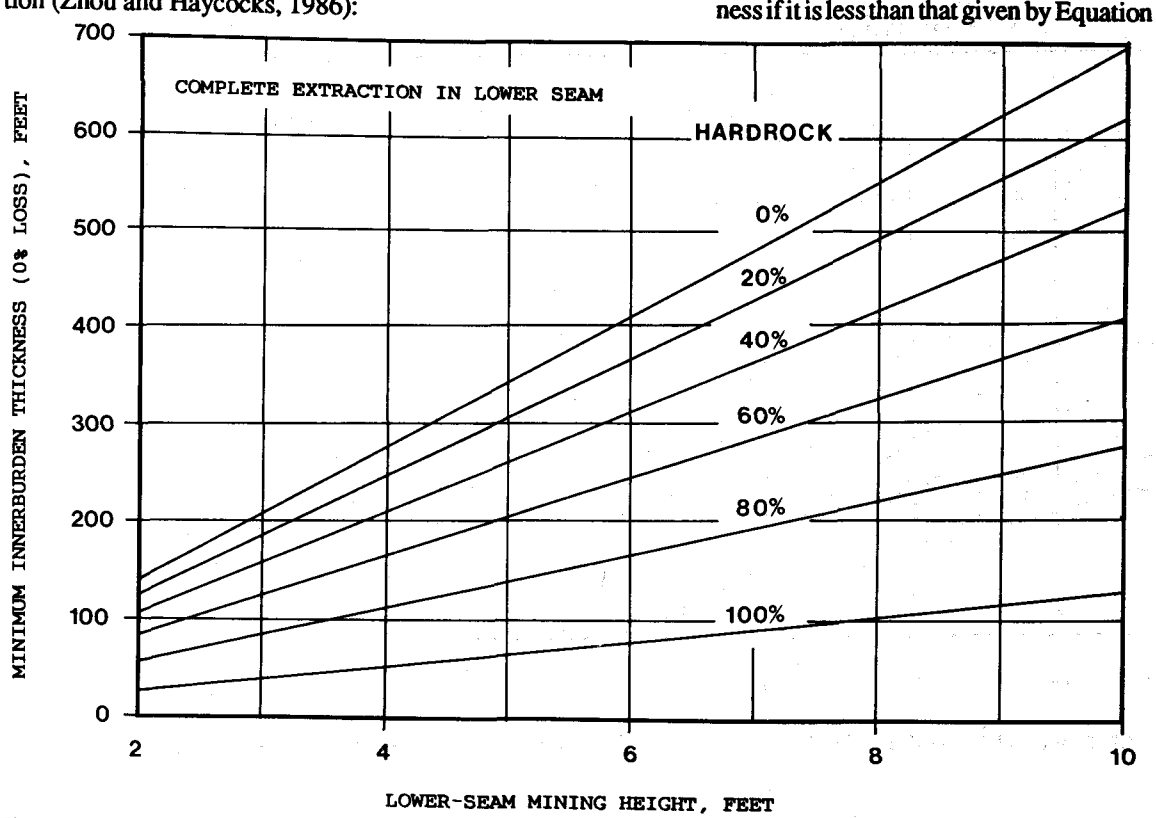


Figure 11. Minimum innerburden thickness requirement - complete extraction in lower seam.

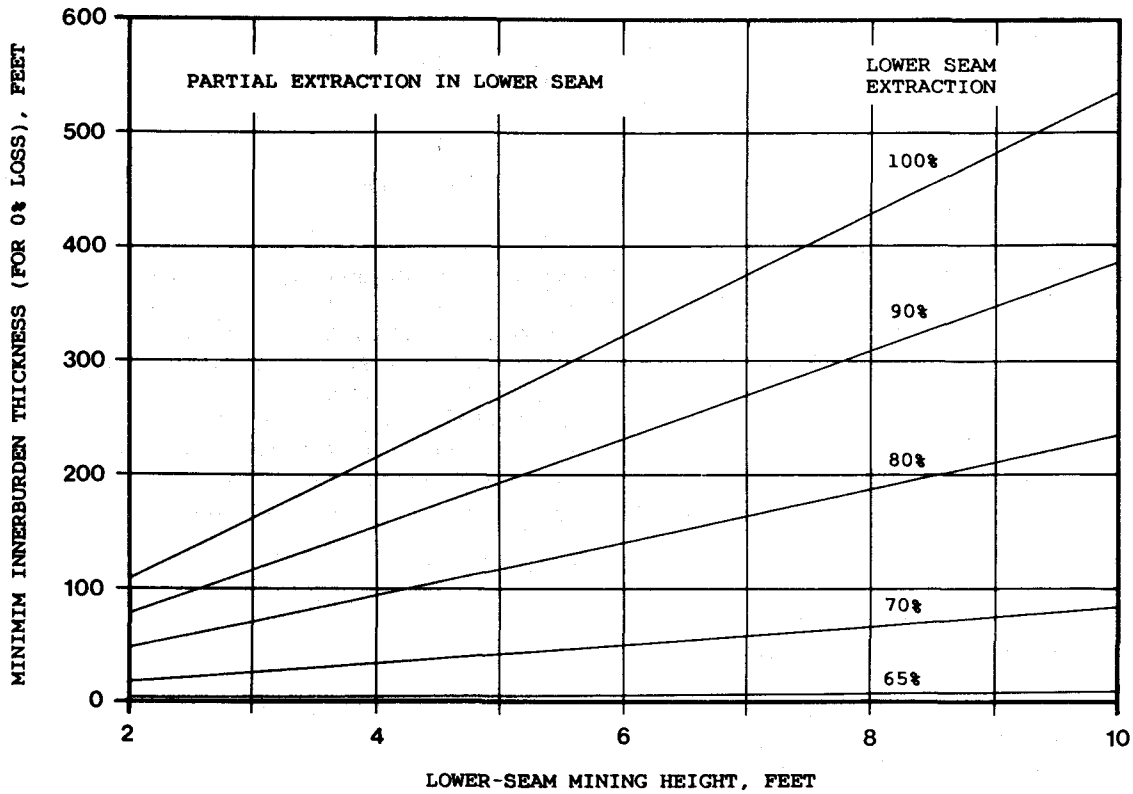


Figure 12. Minimum innerburden thickness requirement - partial extraction in lower seam.

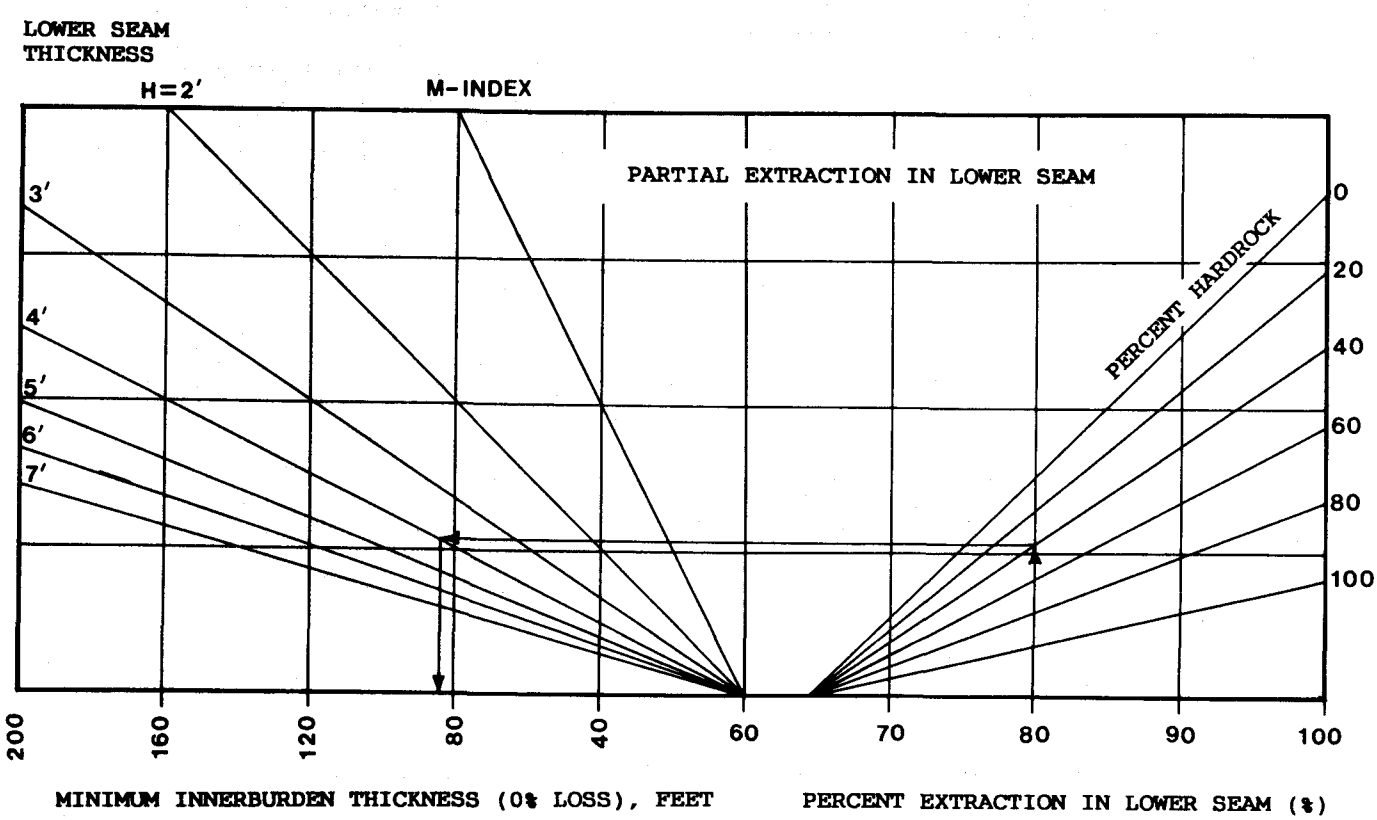


Figure 13. Nomogram for minimum innerburden thickness - partial extraction in lower seam.

be noted that when M_{min} given by Equations (18a) or (19a) is less than 5, a value of 5 for M_{min} should be used.

EVALUATING COAL LOSS WITH UNKNOWN MINE GEOMETRIES

Because of differences in property ownership and time of mining, often the layout geometries of the mined bed are unknown. In order to evaluate the effects of multi-seam mining interaction on recoverable coal reserves, a minimal amount of input information must be used.

So far two minimum innerburden thicknesses have been derived, the minimum minable and the minimum recoverable (for no loss of coal due to interaction). If the actual innerburden thickness is greater than the minimum recoverable innerburden thickness, no coal will be lost as a result of mining a lower bed. On the other hand, if the actual innerburden thickness is less than the minimum required to be minable, then the upper bed is considered totally lost (Figure 14). For those coal beds with an innerburden thickness between the two minimum values, there is a corresponding loss of coal with respect to single-bed mining. Based on analysis of over 90 case studies, the maximum amount of coal lost due to interaction did not exceed 40 percent. Using this value as the upper limit, the percent of coal lost due to interaction can be expressed as follows:

$$L_c = \left(1 - \frac{I - I^u_{min}}{I^r_{min} - I^u_{min}}\right)40\% = \frac{I^r_{min} - I}{I^r_{min} - I^u_{min}}40\% \qquad (20)$$

where L_c is percent of coal lost due to interaction; and I is the actual innerburden thickness.

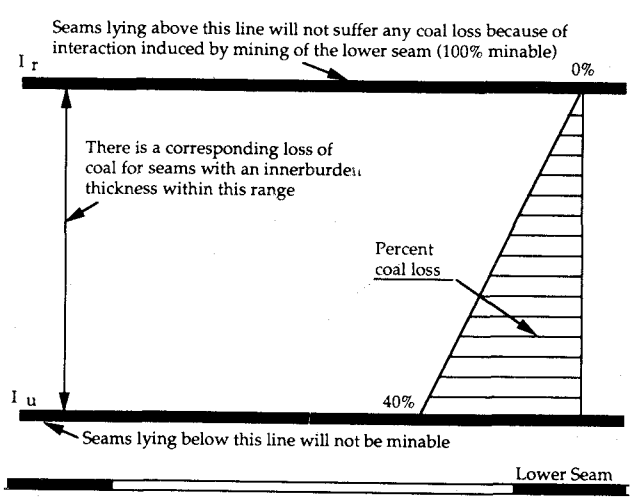


Figure 14. Percent coal loss vs innerburden thickness for overmining operations

EVALUATING COAL LOSS WITH KNOWN MINE GEOMETRIES

MINE LAYOUT AND COAL LOSS

When the mine geometries of the lower bed and properties of the strata surrounding the coal beds are known, the estimate of unrecoverable coal reserves can be made more accurately because this allows identification of areas which are subject to severe interaction effects. The process involves identification of areas of potential interaction in the upper bed by evaluating the various interaction mechanisms. The areas identified to have severe damage are considered unrecoverable.

The amount of coal unrecoverable due to interaction is a function of many factors, of which the most important are the distribution of remnant structures in the lower bed and the structural characteristics and thickness of the innerburden.

When complete extraction of the lower bed is practiced, be it room-and-pillar or longwall, the common practice in upper bed layout is to columnize the barrier pillars of the upper bed with those of the lower bed. Barrier pillars in the upper bed should be so designed that the same factor of safety used for the lower bed is achieved for the upper bed. This is acomplished by increasing successively the size of the barrier pillars in the upper bed (Figure 15). The amount of increase is determined by the load concentration factor in the upper bed. The increased pillar size in the upper bed for protection against load increase is the amount of coal lost due to interaction.

SUB-CRITICAL CONDITIONS

Assuming the increase in pillar size is 2X, the percent of coal loss in an upper bed panel due to multi-bed mining is:

$$L_c = 0.75\ \frac{(2L+2W-4X)X}{LW} \qquad (21)$$

where L is the length of the lower-bed panel; W is the lower bed panel width.

As shown in the preceding discussion on load transfer, pillar size increase can be determined from the stress concentration factor.

For a known stress concentration factor of S, the percent of coal loss can be expressed by:

$$L_c = 0.75\ \frac{(L+W-2X)(S-f)Wp}{LW}\ \frac{D}{D+h} \qquad (22)$$

where $X = (S-f)\frac{Wp}{2}\frac{D}{D+h}$; Wp = width of lower-bed barrier pillars.

In Equation (22) f is defined as the maximum acceptable stress concentration factor ($f \geq 1.0$). If an f value cannot be

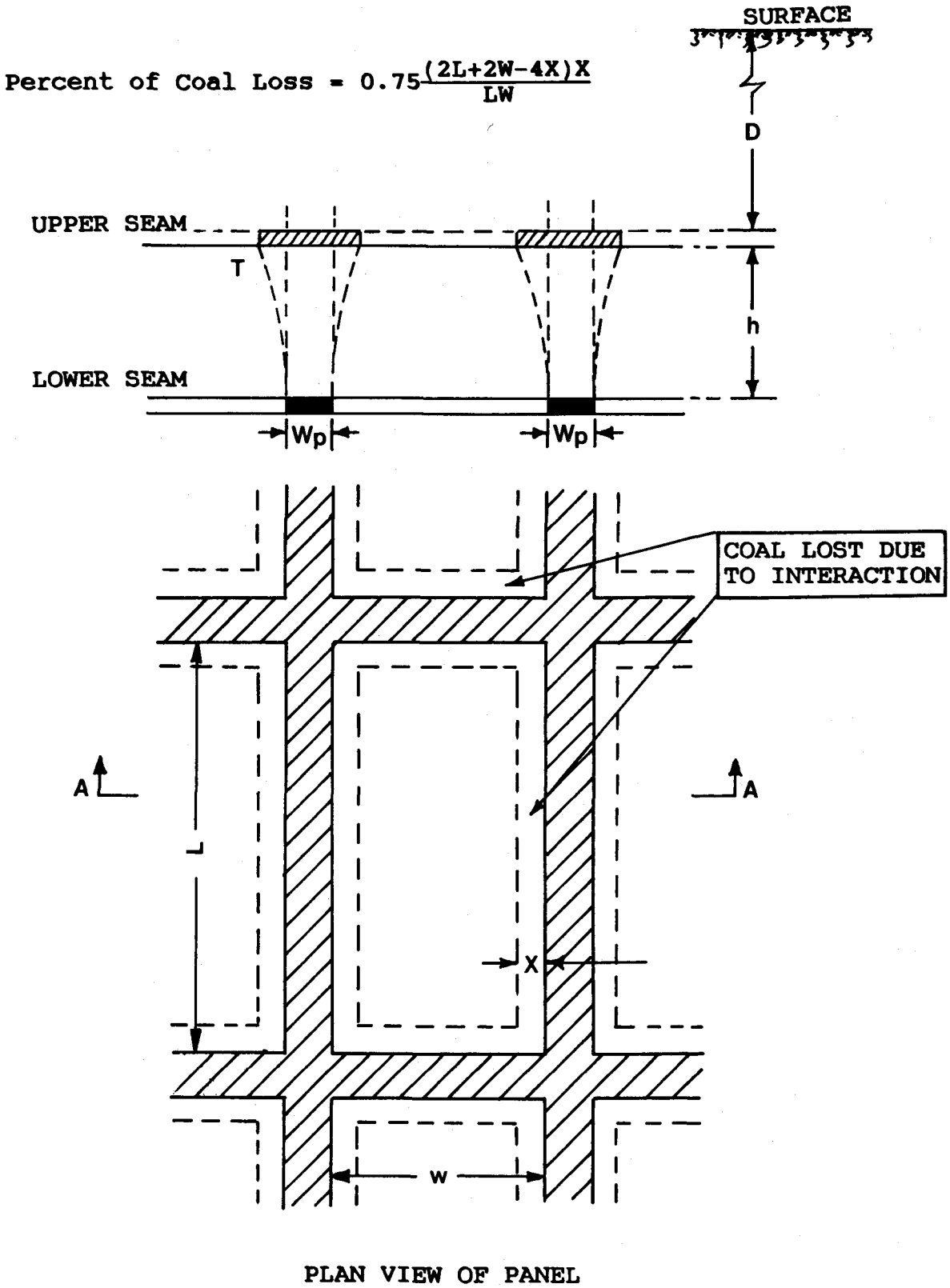


Figure 15. Analysis based on lower-seam panel geometries.

established, an $f \geq 1.0$ should be used. The constant 0.75 is used to account for the amount of coal which will be recovered in driving cross-cuts for the upper-bed barrier pillars. The term D/(D+h) is applied to account for the reduced primitive stress for the upper bed.

SUPER-CRITICAL CONDITIONS

As demonstrated previously, the stress concentration for the upper bed in a super-critical condition is always greater than one. In addition, there is another fact which makes it difficult to estimate coal loss using the stress concentration factor. As the subsidence proceeds, the load toward the center of the lower bed gob will recover to its original stress level. As a result, some of the transferred load to the upper bed will be transferred back to the subsided area of the strata by forming a new pressure arch with one side of the arch resting on the caved but compacted material. This makes the estimate of the average stress concentration much less accurate than that for sub-critical conditions.

To analyze the effects on upper bed coal recovery, subsidence analysis can be used which evaluates the maximum tolerable tensile strain. As discussed earlier, it has been shown that, for Appalachian coalfields, a tensile strain of 12/1000 for average roof conditions at the upper bed is deemed the maximum tolerable. That is, if the maximum tensile strain is smaller than 12/1000, no significant interaction is expected for the upper bed. Based on this fact, the amount of coal that must be sacrificed for upper bed stability is approximately proportional to $E_{max}/12$. The percent of coal loss, given a lower bed panel and its geometry, can be expressed by (Figure 15):

$$L_c = 0.75 \frac{(2L+2W-4X)}{LW} \tag{23}$$

and

$$X = \frac{E_{max}/12}{2} Wp. \tag{24}$$

Substituting X into Equation (23), we have:

$$Lc = 0.75 \frac{(2L+2W-E_{max}/6)E_{max}}{24LW} \tag{25}$$

Note that in the foregoing analysis for complete extraction, the average value of each variable is used for each panel. This is done simply because in practice it is usually undesirable to vary dimensions of mine layouts unless unusual situations arise. Such unusual situations are nevertheless unpredictable.

OTHER CONSIDERATIONS

SURFACE SUBSIDENCE

When surface structures must be protected, the upper bed is either limited to 50 percent recovery or to an alternative layout which will minimize surface subsidence and tensile strains. In the former case, the amount of coal lost due to interaction, if any, becomes relatively unimportant. In the latter case, the practice is to place entries in the upper bed over the lower bed gob (Figure 16). This staggered pillar layout offers several advantages such as a more even subsidence profile, more balanced strain distributions, and better entry protection, among others. If longwall mining is used for the upper bed, this type of layout may actually provide better reserve conservation. Insofar as entry development is concerned, the only source of coal loss would be at the ends of each panel. When such a layout is used, mining will be passing the high-pressure zone periodically, which may make cutting (or shearing) extremely difficult and eventually force mining to stop. A certain amount of coal will be lost in the process. The net result might be a slightly improved recovery ratio. But for the purpose of this study, it is reasonable to assume that the amount of coal lost is the same as in the columnized layout.

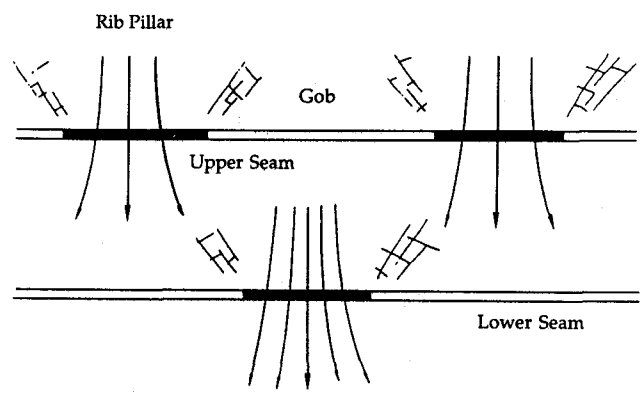


Figure 16. An alternative layout for multi-seam mining (after Whittaker and Pye, 1975).

OVER- AND UNDER-DESIGNED LOWER BED PILLARS

The analysis for upper bed coal loss due to interaction has been based on optimum extraction of the lower bed when panel geometries are used for evaluation. However, the barrier pillars in the lower bed often may have been over-designed or under-designed for one reason or another. When this happens, the estimate of coal loss because of interaction will be larger or smaller than what will actually occur. This situation can be assessed by using the following rule of thumb (Whittaker and Singh, 1979):

$$W' = 0.1(D+H)+49.2 \tag{26}$$

where W' is the width ofthe barrier pillars; H and D are as previously defined.

The amount of coal-loss can then be estimated using Equation (21), substituting X with the following equation:

$$X = \frac{0.1(D+H)S + 49.2 - Wp}{2} \quad (27)$$

APPARENT LOSS VS. REAL LOSS

So far, the calculations of potential coal loss because of multi-seam mining have been based on recoverable reserve. In other words, the coal loss is expressed as a percent of the portion which can be, or has been recovered. This loss is termed the apparent loss. The real loss of coal in terms of total reserve is therefore smaller because there is a certain amount of coal which will be lost without the effect of multi-seam mining. The total of lost coal expressed as a percent of the total reserve is obtained by multiplying the recovery ratio by the apparent loss percentage:

$$l_t = xL_c \quad (28)$$

where l_t is total of lost coal (percent) due to multi-seam mining; x is recovery ratio in the mined lower bed; and L_c = apparent loss of coal due to multi-seam mining (percent).

EVALUATION OF MULTI-SEAM RESERVE WITH NO PREVIOUS MINING

When evaluating multiple coal beds with no previous mining in either bed, several possibilities exist with respect to mining sequence and mining methods. If partial extraction and complete extraction are the two possible methods, and only two beds are considered for mining with either overmining or undermining, four possible combinations must be considered:

1. lower bed first with partial extraction,
2. lower bed first with complete extraction,
3. upper bed first with partial extraction,
4. upper bed first with complete extraction.

The first two situations listed above have been previously discussed with the exception that the extraction ratios are often known when the lower bed is mined first. Because there is no previous mining, no detailed analysis involving mine geometries is conducted. Instead, the analysis will be based on drill-log data and on an estimate of recovery ratio. In order to use the methods which have been developed, it is only necessary to estimate the extraction ratio of each situation, as commonly achieved by the coal industry. For longwall operations with an average panel width of 600 feet and three entries, the average ratio of recovery is about 75 percent. Other conditions being equal, the recovery ratios are 70 percent for four-entry systems and 80 percent for two-entry systems. Room-and-pillar operations usually have recovery ratios in the range of 55 to 65 percent.

UPPER BED MINED FIRST

The situations in which the upper bed being is mined first require separate treatment as they entail different interaction mechanisms and magnitude of influence. Again, there are two basic situations: upper bed mined first with partial extraction and upper bed mined first with complete extraction.

UPPER BED MINED FIRST WITH PARTIAL EXTRACTION

In a study by Grenoble and Haycocks (1985) on lower seam interactions under "close-seam" conditions, an upper limit for innerburden thickness of 110 feet was established. This was based on the maximum effective distance a load can be transferred from an upper bed to a lower bed under the worst (entirely shale) innerburden conditions. Expressed as a function of innerburden geology, the maximum distance (or minimum recoverable innerburden thickness) is given by:

$$I^r_{min} = 110 - 0.65z \quad (28)$$

where z = percent of hardrock in the innerburden.

A second criterion used for evaluating under-mining interaction is based on the number of beds in the innerburden, which is believed to greatly affect the maximum load transfer distance. This is given by:

$$I^r_{min} = 6.8N + 55 \quad (29)$$

where N is number of beds in the innerburden.

To determine the minimum recoverable innerburden thickness, both Equations (28) and (29) are evaluated and the greater of the two is taken. Figure 17 shows the two equations combined to give a nomogram for estimating the minimum recoverable innerburden thickness.

UPPER BED MINED FIRST WITH COMPLETE EXTRACTION

With complete extraction in the upper bed (normally by longwall operations), the area of potential coal loss in the lower bed is in the vicinity of a remnant pillar in the upper bed. The method for estimating coal loss will be similar to that expressed by Equation (21) with the exception that X will be determined differently.

Normally, stress concentration in the lower-bed pillar due to load transfer diminishes when the innerburden thickness is greater than twice the width of the remnant pillar. Similar to overmining operations, there exist two situations: sub-critical and super-critical. Both conditions are defined exactly the same way as those for overmining (Figures 8a and 8b). The process of stress calculation involves first determining the average stress concentration on upper-bed remnant pillars, and then determining the stress concentration transferred to the lower bed. Finally, the percent of potential coal loss can then be determined based on estimates of the stress concentrations.

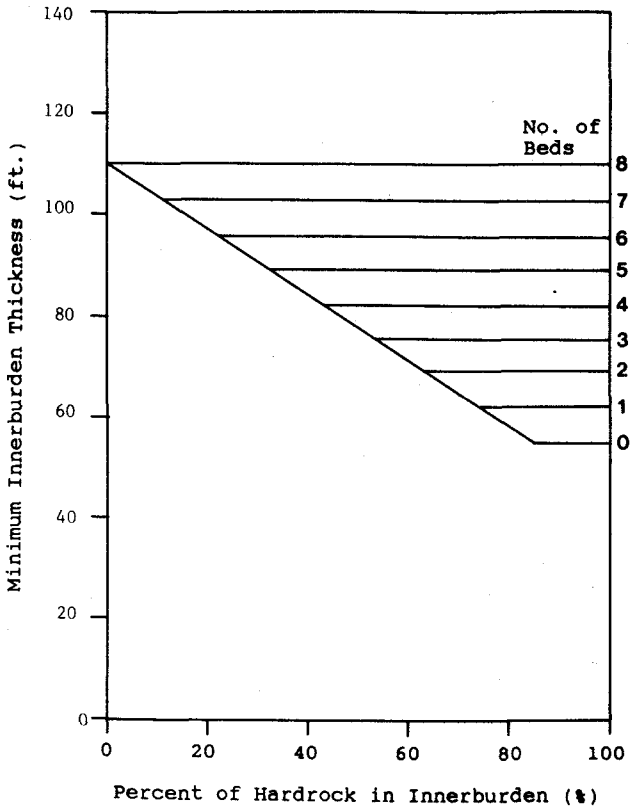


Figure 17. Minimum innerburden requirement forlLower-seam stability.

Figure 18 shows a simplified diagram of the loading condition on a remnant pillar in the upper bed. Assuming that the distributed load on the pillar can be substituted for a concentrated load P, on a foundation of 2B wide, then P is given by the following equations:

Sub-critical condition:

$$P = [(Wp+w)D - \frac{2}{3}dw]\gamma \qquad (30)$$

Super-critical condition:

$$P = [\frac{2}{3}D + - LTD(D)]\gamma = \frac{2}{3}D(1 + - LTD)\gamma \qquad (31)$$

where P = total load on upper bed remnant pillar; Wp = width of remnant pillar; w = width of pressure arch (panel width); d = height of pressure arch; D = overburden depth of upper bed; LTD = Load Transfer Distance; and γ = unit weight of overburden material.

From elasticity and foundation theories, the maximum stress at a vertical distance of h from the distributed load (P over a foundation of width 2B) can be approximated by:

$$\sigma_{max} \approx \frac{3P}{4(B+h)} = \frac{3P}{2(Wp+2h)} \qquad (32)$$

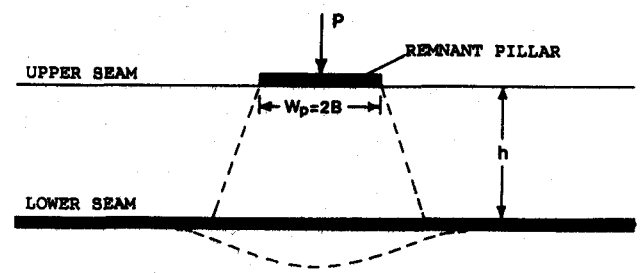


Figure 18. Analysis of lower-seam stress concentration using foundation theory.

where σ_{max} = maximum vertical stress; B = half width of foundation (remnant pillar); B = 1/2Wp; h = vertical distance from foundation (innerburden thickness).

The maximum stress, α_{max}, thus calculated is about 1.5 times the average stress. Therefore, the average stress is given by:

$$\sigma_{avg} = \frac{\sigma_{max}}{1.5} = \frac{P}{Wp+2h} \qquad (33)$$

The original pre-mining stress at the lower bed level is:

$$\sigma_0 = (D+h)\gamma \qquad (34)$$

The average stress concentration will be:

$$S = \frac{\sigma_{avg}}{\sigma_0} = \frac{P}{(D+h)(Wp+2h)\gamma} \qquad (35)$$

Substituting the expressions for P, Equations (30) and (31), yields the following stress concentration expressions for the average stress concentration at the lower seam level:

Sub-critical condition:

$$S = \frac{(Wp+w)D - 2/3dw}{(D+h)(Wp+2h)} \qquad (36)$$

Super-critical condition:

$$S = \frac{D(1 + 2/3LTD)}{(D+h)(Wp+2h)} \qquad (37)$$

CONCLUSIONS AND RECOMMENDATIONS

Methods have been developed for estimating recoverable coal reserves influenced by the mining of a lower bed. In order to facilitate the implementation of the research results, a computer program called MSCOAL has been developed.

Because of the nature of this pilot research project, this report deals with primarily overmining operations where the lower bed has been mined prior to the mining of the upper bed. Although undermining operations (upper bed mined first) have relatively simpler interaction mechanisms, they are equally important to the evaluation of multi-seam coal reserves. It is therefore recommended that studies be carried out on methods for estimating recoverable coal reserves under such mining conditions.

It is also conceivable that many of the coal beds occur in a multi-seam environment where there has been no previous mining. Under such conditions, an estimate of reserves can be made using bore-hole data and an average extraction ratio for the mining method to be used. Sensitivity analyses can be conducted by varying the sequence of mining and mining methods to investigate their effects on recoverable coal reserves.

For wider applications, new options should be added to the MSCOAL program such as the ability to interpolate data (gridding), to draw contour maps of coal loss percentage and tonnage, and to interface with different hardware and currently available geology/reserve programs.

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APPENDIX

MSCOAL AND MULEXT USER GUIDES AND EXAMPLE

CONTENTS

Page
MSCOAL: a multiseam coal reserve evaluation program 17
Program overview 17
Purpose and usage 17
Program features 17
Program installation 17
Software and hardware 17
Making back-up copies 18
Installing MSCOAL 18
Running the Program 18
Starting MSCOAL 18
The main menu 18
Data input/editing 18
MULEXT - a data extraction program 20
Use and purpose of ther program 20
Running the program 20
Example - the Vansant quadrangl;e 20
General description 20
A case study 20

ILLUSTRATIONS

Figure
1. Main menu of MSCOAL 19
2. Summary of data editing commands/function keys. 19
3. Input screen for general information 19
4. Input screen for quick-and-dirty analysis 19
5. Input screen for detailed analysis 19
6. Output of detailed analysis from MSCOAL 22

TABLES

1. Data for Vansant quadrangle 20
2. Summary statistics of drill-log data 21
3. Case study data of mine 10210 from Vansant quadrangle 21

MSCOAL: A MULTISEAM COAL RESERVE EVALUATION PROGRAM

PROGRAM OVERVIEW

MSCOAL is an integrated program which can be used to evaluate coal reserves influenced by multi-seam mining. It was developed based on results of many multiseam research efforts.

The current program handles mining situations where the lower or upper seam has been previously mined or will be mined prior to mining of a second seam when two seams are being planned for mining. Both empirical results and theoretical analyses have been incorporated into the program to provide maximum flexibility in applications.

PURPOSE AND USAGE

The main purpose of MSCOAL is to assist in the evaluation of recoverable coal reserves in multi-seam mining situations where a certain amount of input data allows a more accurate estimation based on empirical rules and rock mechanics analyses. With the wide availibility of personal computers, MSCOAL is a valuable tool in coal reserve evaluation.

The current version of MSCOAL includes both over-mining and under-mining operations. Methods of extraction used for the mined seam are divided into broad types: partial extraction and complete extraction. A partial extraction typically results from the use of the room-and-pillar method with pillars left for support or other purposes. Complete extraction of the lower seam includes longwall operations and room-and-pillar operations with complete recovery of the pillars.

PROGRAM FEATURES

MSCOAL is written in TURBO PASCAL to run on an IBM PC/AT or compatible. It is an interactive, menu-driven program with extensive on-line help on usage of the program and technical details of the program. Anytime the user is in doubt about a command, a particular variable, or an operation, help is available by pressing the function key F1.

Data entry and editing are done through a full-screen editing procedure which provides flexibility in data manipulation. Sensitivity analysis can be easily conducted because data evaluation and data entry are interactive.

Output of results can be in the form of screen display, print-out, or disk file. The default output mode is screen display.

PROGRAM INSTALLATION

SOFTWARE AND HARDWARE

The MSCOAL program disk is supplied as a stand-alone package. No other programs are required to run MSCOAL.

There are a total of 17 files on the program disk. They are:

Program File
MSCOAL.COM

Screen Files

MSCOAL.SRN	MS-HOLE1.SRN
MS-MENU.SRN	MS-AREA.SRN
MS-IN01.SRN	MS-OUT01.SRN
MS-IN02.SRN	MS-OUT02.SRN
MS-PANEL.SRN	MS-OUT03.SRN
MS-HELP.SRN	

Example Data Files
EXAMPLE1.DAT
EXAMPLE2.DAT

MSCOAL will run on any IBM PC/AT or compatibles with a minimum memory of 128K bytes. The program automatically determines the type of monitor installed on the computer system. No special installations are required. Hard-copies of the output can be printed on any printer conected to the computer.

MAKING BACK-UP COPIES

The user should make a back-up copy of the original program disk and use the back-up copy of the program. To do so, follow the following steps.

Two drive system:

Step 1. Insert DOS diskette in drive A.
Step 2. Type "DISKCOPY A:B:"* and hit RETURN.
Step 3. Follow instructions by placing the original program disk in drive a and the blank diskette in drive B and hitting RETURN.

Single drive system:

Step 1. Insert DOS diskette in disk drive (Usually Drive A).
Step 2. Type "DISKCOPY" and hit RETURN.
Step 3. Follow instructions which tell you how and when to swap your original and blank diskettes.

Hard drive system:

If your system is equipped with a hard disk and floppy drive configuration as described above (two-drive or single drive), the above operations can be done by issuing the "DISKCOPY A:B:" or "DISKCOPY" command from the hard drive, usually designated as C.

INSTALLING MSCOAL

If you plan to run **MSCOAL** on a floppy disk, no special installations are necessary. However, if you plan to install **MSCOAL** on the hard disk of your system, the following procedures are recommended:

Step 1. Make the hard drive the default drive. For example, if your hard drive is designated as C drive, you can do so by typing "C:" followed by a RETURN.
Step 2. Create a subdirectory, say \MSCOAL (for any name you prefer), by typing "MD\MSCOAL" followed by a RETURN.
Step 3. Change to the newly created subdirectory by typing "CD\MSCOAL" followed by a RETURN.
Step 4. Insert the program disk in drive A.
Step 5. Copy all files on the program disk onto the subdirectory MSCOAL by typing "COPY A:*.*" followed by a RETURN.

After all the files have been copied onto the hard drive, installation for **MSCOAL** is complete. You should now store your original program diskette in a safe place.

RUNNING THE PROGRAM

STARTING MSCOAL

To run **MSCOAL** from disk drive A:

Step 1. Insert program disk into drive A.
Step 2. Type "MSCOAL" (followed by a RETURN).

To run MSCOAL from a hard disk drive:

Step 1. Type "CD\MSCOAL" (followed by a RETURN).
Step 2. Type "MSCOAL" (followed by a RETURN).

MAIN MENU

Upon invocation, **MSCOAL** will display its logo, followed by the Main Menu after you press a key. The main Menu has eight (8) command options. Figure 1 shows the main menu screen.

Each command is self-explanatory. There is also a help screen explaining each command in more detail. You can choose a command option by typing the corresponding number or by moving the cursor to the command and hitting RETURN.

If you coose Option 2 to retrive data from a disk file, the program will ask you whether the data was created by MSCOAL or raw data, which is created by MULEXT (see last section). Note also that you must run Option 4 before you can print or save the results.

DATA INPUT/EDITING

Data input/editing is done through a full-screen editor. By selecting Command Option 1 from the main menu, you can enter new data or edit current data (which will exist after you retrieve a data file using Option 2).

On the bottom line of the screen, information is displayed about some important command and function keys. For example, if you want to return to the main menu, simply press the ESCape key. The data you have entered or any changes you have made will stay in memory. Figure 2 is a

* All commands appearing in quotes must be typed by the user.

summary of all command and function keys which are used in **MSCOAL** data input/editing.

The first input screen - General Information - is required of all analyses to enter critical variables such as mining sequence, mining method, and evaluation method (Figure 3). Subsequent input screens are dependent on the input to the first screen. If a quick-and-dirty analysis is requested, the input required is as shown in Figure 4. The same screen is also used if extraction of the mined seam is by partial extraction. The input screen for detailed analysis is shown in Figure 5.

When data input is completed, the user can press the ESC key to return to the Main Menu.

```
M S C O A L
A MULTI-SEAM COAL RESERVE EVALUATION PROGRAM

        1. Input/Edit Data
        2. Retrieve Data
        3. Save Data
        4. Run Program
        5. Save Results
        6. Print Results
        7. List Data Files
        8. Exit Program

Input or edit data using screen editor
```

Figure 1. Main menu of MSCOAL.

ESC	- Return to **MAIN MENU** when in **EDITING** mode or output display - Return to **EDITING** mode when in **HELP** mode
F1	- Display **HELP** information; Exit **HELP** session
Arrow keys	- Cursor movement in **EDITING** mode ↕: Move between data cells ↔: Move one character forward or backward within a cell
Home	- Go to beginning of a data cell
End	- Go to end of a data cell
PgUp	- Turn to previous page (in EDITING or HELP mode)
PgDn	- Turn to next page
DEL	- Delete at cursor position
INS	- Turn on/off insert mode; When INSert is on, the word "INSERT" is displayed on the lower right corner in reverse color

Figure 2. Summary of data editing commands/function keys.

```
Page - 1                    General Information

  Project Title

  Name of Lower Seam

  Name of Upper Seam

  Method of Analysis

    1 - Quick-and-dirty evaluation with minimal amount of input data
    2 - Evaluation with known layouts of mined seam

  Method of Extraction in Mined Seam

    1=Partial extraction (RAP)     2=Complete extraction (longwall or RAP)

  Mining Sequence (1=Lower seam first; 2=Upper seam first)

  Number of Panels (or drill holes)

  Number of Coordinate Points Defining Study Area
```

Figure 3. Input screen for general information.

```
Page - 1                    Drill Hole Data                    No.

  Hole ID

  Latitude (or X coordinate)

  Longitude (or Y coordinate)

  Overburden Thickness (ft)

  Percent of Hardrock in Overburden (%)

  Upper-Seam Thickness (inches)

  Innerburden Thickness (ft)

  Percent of Hardrock in Innerburden (%)

  Lower-Seam Thickness (inches)

  Extraction Ratio in Mined Seam (%)
```

Figure 4. Input screen for quick-and-dirty analysis.

```
Page - 1                    Panel Input Data                   No.

  Width of Panel (ft)

  Length of Panel (ft)

  Width of Remnant Pillars in Mined Seam (ft)

  Average Innerburden Thickness (ft)

  Percent of Hardrock in Innerburden (%)

  Overburden Thickness to Upper Seam (ft)

  Lower-Seam Thickness (inches)

  Upper-Seam Thickness (inches)
```

Figure 5. Input screen for detailed analysis.

MULEXT - A DATA EXTRACTION PROGRAM

USE AND PURPOSE OF THE PROGRAM

MULEXT is a program for extracting data relevant to analyses for multi-seam coal reserve evaluations using **MSCOAL**. Input to the program should be in ASCII format and conform to the U.S. Geological Survey National Coal Reserve Data System (NCRDS) standard (see program listing of MULEXT.BAS). If your data file is in a format other than the NCRDS standard, which is quite likely, you must modify program **MULEXT** to conform to your data format. The program is written in Advanced BASIC to run on the IBM PC/AT or computers or compatibles (GWBASIC) so that modification of the data format is easily done because BASIC (or GWBASIC for PC compatibles) is readily available to any PC user.

Using the names of the two seams under consideration, the program extracts the following data for each drill hole:

Hole-Id
Longitude
Latitude
Overburden Thickness
Percent of Hardrock in Overburden
Upper-seam Thickness
Innerburden Thickness
Percent of Hardrock in Innerburden
Lower-seam Thickness

The first record of the output file is the identification "MULEXT," and the second is the header information identifying each data item that follows. The data portion contains the above nine parameters in the order that they are listed (see program listing for data format). This output file can be used directly as input to the **MSCOAL** program as raw data.

RUNING THE PROGRAM

The program MULEXT is supplied in both source file and compiled version. The source file, MULEXT.BAS, must be run with a BASIC Interpreter whereas the compiled version, MULEXT.EXC, can be run as a stand-alone program.

To run MULEXT using BASIC interpreter, type:
"BASICA MULEXT" (Followed by a RETURN).

If you use an IBM compatible computer, you must run the GW BASIC by typing:
"GWBASIC MULEXT" (followed by a RETURN).

To run the compiled version, simply type:
"MULEXT" (followed by a RETURN).

EXAMPLE - THE VANSANT QUADRANGLE

GENERAL DESCRIPTION

The Vansant quadrangle is located in south-central Buchanan County, Virginia. Along with the Prater quadrangle, it lies entirely within the Appalachian Plateaus physiographic province. Both quadrangles are characterized by a gentle northwestward regional dip with steeply sloping ridges and V-shaped valleys (Nolde and Mitchell, 1984). Up to 25 coal beds are found in the Vansant quadrangle with the Pocahontas No. 3 being the dominant in both seam thickness and coal quality.

The two coal beds under study in the Vansant quadrangle are the Pocahontas No. 3 sean and the Little fire Creek seam. Mine maps were available for five mines with the lower Pocahontas No. 3 seam mined first. Table 1 and 2 list, respectively, the extracted data (using **MULEXT**) and a statistical summary of relevant data items. Note that when the upper seam has a thickness of zero, indicating a pinch-out of the coal seam or some other geologic anomaly, the overburden thickness extends to the lower seam. On the orther hand, the innerburden has a thickness of zero when either seam (or both) pinches out.

A CASE STUDY

To demonstrate the application of the computer program **MSCOAL**, data from one of the five mines in the Vansant quadrangle are supplied with the program disk: EXAMPLE.DAT and EXAMPLE2.DAT. EXAMPLE1.DAT contains data for analysis using panel layout information whereas EXAMPLE2.DAT contains data for a quick-and-dirty analyis for the same mine.

The mine has four mined panels in the lower seam using the longwall method. Therefore, the mine is in the category of complete extraction in the lower seam. To maintain confidentiaality for the mine operator, the real name of the mine is not used. It must be noted that, due to the scarcity of the borehole data available for the area, approximations had to be made. Table 3 shows the input information for the case study. The result of the analysis using panel data is shown in Figure 6; two of the four panels showed a loss of coal in the upper seam due to interaction.

Table 1. Data for Vansant quadrangle.

HOLE ID	OBT	PHR	UST	IBT	PHR	LST
L-1	1079.25	14	5.25	0.00	0	0.00
L-2	660.25	4	1.83	446.59	76	4.33
L-8	965.42	7	1.58	365.67	22	4.00
L-5	808.75	5	0.17	329.77	41	4.31
L-7	653.00	5	1.25	449.46	62	4.37
L-10	1113.00	5	1.17	438.85	57	4.81
L-13	1037.58	28	0.00	0.00	0	6.19
L-14	1029.96	6	1.79	430.83	63	5.36
L-23	1366.08	6	1.50	391.42	62	1.35
L-26	1313.81	29	0.00	0.00	0	4.61
L-28	1325.54	5	1.00	0.00	0	0.00

HOLE ID	OBT	PHR	UST	IBT	PHR	LST
L-38	876.33	5	0.25	497.50	48	4.92
L-43	1038.90	42	0.00	0.00	0	4.34
L-46	1024.42	3	1.41	432.53	77	4.35
L-65	883.87	6	1.38	376.75	63	5.33
L-67	1129.67	4	2.08	478.71	54	5.64
L-68	980.00	3	1.17	398.56	60	4.94
L-69	834.58	1	1.25	383.50	12	5.25
L-70	1273.19	2	1.64	455.49	60	4.85
L-71	1236.83	7	0.92	401.08	66	6.16
L-73	1699.00	2	1.96	421.62	52	0.50
L-74	1192.92	5	1.29	388.54	66	5.98
L-75	924.25	2	1.08	396.84	78	5.25
L-77	877.75	9	0.67	417.48	49	5.93
L-79	1138.79	6	1.67	484.69	57	5.27
L-80	1193.00	1	1.58	388.73	60	0.00
L-81	1296.08	4	1.36	407.96	67	6.14
L-82	1287.25	3	0.92	400.65	60	0.07
L-83	909.00	6	2.73	391.16	51	6.11
L-85	1220.17	9	0.42	446.62	80	5.29
L-224	2084.33	26	0.00	0.00	0	4.90
L-228	1602.08	1	1.84	0.00	0	0.00
L-229	1721.25	1	2.92	347.66	49	3.79
L-230	965.17	5	2.58	363.75	64	8.21
L-231	1338.17	7	2.25	434.83	68	3.21
L-232	1285.00	6	1.75	406.58	83	3.00
L-233	1172.00	0	2.25	0.00	0	0.00
L-234	1211.92	9	1.08	445.37	72	5.13
L-236	1143.75	6	4.08	427.71	86	0.88
L-239	1233.29	6	1.46	391.00	58	1.00
L-203	1020.33	10	2.25	396.09	41	4.70
L-202	1272.83	4	1.75	398.84	60	4.70
L-205	1418.75	6	3.17	428.83	49	5.75
L-206	920,75	1	1.58	0.00	0	0.00
L-207	1242.50	4	1.58	410.42	56	6.12
L-208	1358.17	3	1.83	0.00	0	0.00
L-209	1279.67	8	1.37	423.17	56	5.08
L-245	1454.58	1	2.59	333.83	64	4.00
L88	1211.42	7	1.25	423.84	70	5.41
L150	730.25	10	2.08	0.00	0	0.00
L199	1174.08	10	4.17	317.17	47	6.12
L201	1125.33	0	2.50	404.17	57	5.62
L117	1363.13	3	2.20	409.04	48	6.40
L159	1425.50	3	1.83	486.88	72	4.50
L165	1042.75	0	1.42	467.58	95	5.08
L108	1373.00	4	2.42	392.60	52	7.65
IC205	1842.67	0	0.00	0.00	0	4.42
L111	928.00	27	0.00	0.00	0	0.00

OBT - Overburden Thickness (ft) PHR - Percent of Hard-rock
IBT - Innerburden Thickness (ft)
Ust - Upper-Seam Thickness (ft) LST - Lower-Seam Thickness(ft)

Table 2. Summary statistics of drill-log data.

Parameter	Min.	Max.	Average
Total no. of drill holes	—	—	58
Overburden thickness (ft)	653	2084	1178
Percent hardrock (%)	0	42	7
Upper-seam thickness (ft)	0	5.25	1.61
Innerburden thickness (ft)	317	497	411
Percent hardrock (%)	12	95	59
Lower-seam thickness (ft)	0	8.21	3.99

Table 3 Case study data of mine 10210 from Vansant quadrangle.

Drill holes in the vicinity:

	DH-1	DH-2	DH-3
Overburden Thickness (ft)	1220	1211	1139
Percent Hardrock	9	7	6
Upper-Seam Thickness (in)	5	15	20
Innerburden Thickness (ft)	447	424	485
Percent Hardrock	80	70	57
Lower-Seam Thickness (in)	63	65	63

Four (4) Mined Panels:

Panel	Width (ft)	Length (ft)	Remnant (ft)	IBT (ft)	PHR(%)	Rock Type*
1-DEV	600	6400	220	440	75	2
2-DEV	600	6800	220	430	70	2
3-DEV	600	6800	220	420	65	2
4-DEV	750	6600	250	450	60	2

Overburden thickness = 1200 feet for all pannels.
Percent of hardrock in overburden = 10% for all panels.

* See report for definitions.

MSCOAL 1.0 Detailed Analysis - Output Page 2 of 2

Panel No.	Avg L.S. Thickness (inches)	Panel Width (ft)	Panel Length (ft)	Pillar Width (ft)	Coal Loss (%)	Coal Loss (tons)
1	65	600	6400	220	0	0
2	65	600	6800	220	0	0
3	65	600	6800	220	11	130057
4	65	750	6600	250	3	46154

Figure 6. Output of detailed analysis from MSCOAL.