APPENDIX 11

OFFICE OF SURFACE MINING
REPORT ON
BLASTING

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OFFICE OF SURFACE MINING (OSM)
REPORT ON
BLASTING

PREPARED IN RESPONSE TO THE OCTOBER 11, 2000,
IMPOUNDMENT BREAKTHROUGH
AT
MARTIN COUNTY COAL CORPORATION (MCCC)
BIG BRANCH SLURRY IMPOUNDMENT

This report was prepared by OSM as a part of its review of the MCCC 2000 breakthrough. This report addresses the blasting conducted by MCCC at the Big Branch Slurry Impoundment during 1995 and its relationship to the 2000 breakthrough. MCCC conducted the blasting in order to obtain spoil material for the construction of a "seepage barrier" over the outcrop barrier of the underground mine in the Coalburg coal seam. Kentucky's Department for Surface Mining Reclamation and Enforcement approved MCCC's blasting plan on December 7, 1994, as part of permit revision number 5. Summit Engineering, Inc., prepared the permit revision.

This review covers:

- Blasting plan adequacy
- Blasting records adequacy
- Powder factors (amount of explosive used to break the rock)
- Vibration levels at the underground mine roof in the area of the 2000 breakthrough
- Vibration levels at the underground mine seals

Wyatt, Tarrant & Combs, on behalf of MCCC, supplied the blasting records covered by this review. The blasting records cover January 4 to July 13, 1995. MCCC blasted near the 2000 breakthrough during April and May 1995. During June and July, the blasting approached the underground mine seals located off the North Mains. These blasting periods are estimated based on the progress of the blasting operation as shown in MCCC's weekly impoundment inspection photographs.

The blasting was conducted in the overburden directly above the Stockton coal seam. The top of the Stockton coal seam is about 100 to 115 feet above the roof of the underground mine in the Coalburg coal seam. MCCC mined the Coalburg coal seam near the 2000 breakthrough during 1981.

1. BLASTING PLAN

The plan only addresses the protection of the underground seals. The plan limits blasting adjacent to the seals to a square root scale distance ($SD^{1/2}$) of 20 ($SD^{1/2} = D \div W^{1/2}$ where D is the distance of blast to the protected structure and W is the weight of explosive per 8 millisecond delay period). To comply with the $SD^{1/2}$ limit, the blasts must have an $SD^{1/2}$ that is equal to or higher than the prescribed limit.

The permit revision application first proposed a $SD^{1/2}$ of 8, but this was changed at the request of DSMRE to a more conservative $SD^{1/2}$ of 20. The blasting plan in the permit revision stated that the blasting would come within 125 feet of the seals. At that distance from the seals, MCCC could use 40 pounds of explosive per delay period ($SD^{1/2} = 20 = 125 \div 40^{1/2}$).

For the 40-pound per delay blasting pattern, the blasting plan calculated that it would have a powder factor (PF) of 0.22 pounds of explosive per cubic yard of rock. The actual PF for that blasting pattern was 0.45. OSM's review of this blasting pattern indicates that it would result in a blast of poor performance because of the following: 1) the explosive would not reach full detonation velocity, 2) the pattern would result in minimal fragmentation, and 3) the pattern would cause excessive ground vibration which is the reverse of the blasting plan's intent to reduce vibrations at the underground mine seals.

The blasting plan did not address the protection of the underground mine roof. Such protection is important in consideration that the blasting was to be conducted as part of a project to prevent the impoundment from breaking through the mine roof into the underground mine. Unless specific safe blasting levels had been established for the mine, it may have been appropriate, for the protection of the mine roof, to establish a $SD^{1/2}$ limit of 20 or a peak particle velocity limit (PPV) limit of 2 inches per second (in/sec). Two in/sec is consider the level at which no damage would occur to mine roofs. Each site is different, and without a thorough monitoring and inspection program, the probability of failure in the areas of concern are only best estimates based on the literature and personnel experience. At the MCCC impoundment, considering the narrow outcrop barrier, and the potential for weathering of the outcrop barrier, a conservative design should have been used to ensure the protection of the underground roof.

The blasting plan stated that the underground mine was abandoned. This was not correct. Portions of the underground mine are active while the remainder of it is inactive. The blasting plan should have addressed the protection of the active and inactive areas with regard to miner safety. A number of steps may have been appropriate to protect the miners, including withdrawing the miners prior to a blast, and the examination of the mine roof and ventilation system, by certified personnel, after each blast.

2. BLASTING RECORDS

OSM reviewed 142 blasting records. Of the 142 blasts, 109 were production blasts, those to shoot and fragment the overburden above the Stockton coal seam; 13 were pre-split blasts, required to assure a stable highwall; 19 were combination pre-split and production blasts; and one blast was to reduce oversized boulders.

Information supplied on the blasting records stated that the material blasted was "sandstone" and the "nearest structure" to be protected was the railroad tracks some

5,000 feet from the blasts. Blast hole diameters were either $5^{1}/_{8}$ inches or $7^{7}/_{8}$ inches and both were used for pre-split or production shots. Millisecond (ms) delays employed in the various blasts were 17 ms, 42 ms, and 100 ms surface delays and 500 ms down-the-hole delays.

The explosive products were manufactured and/or supplied to MCCC by Orica USA, Inc., (East Kentucky Explosives). The initiation systems were Excel shock tube with Excel HTD surface delay connectors and Excel HANDIDET detonators. In addition, Cordtex 25 detonating cord was used to connect pre-split holes together to create a relatively instantaneous multi-hole detonation. In some cases, the pre-split holes were delayed hole-by-hole with the Excel HTDs. The primers used per the blast logs were either an $1^{1}/_{4}$ x 8 inch fixed explosive (ICI-7/D, a permissible emulsion) or Hi-Prime, a cast booster with a cap well. The primary explosives included bagged ANFO and bulk ANFO, PowerAn 500 (minor amounts, seems to be in the form of a cartridge product) a mix of emulsion and ANFO, and a detonator sensitive water gel, under the brand name of Powersplit.

The blasting records also indicated approximate blast hole layout, delay sequence, the number of holes per blast, number of holes per delay (a small number of production shots had two holes per delay period), burden and spacing dimensions, depth of holes, length of stemming (drill cuttings), and the explosive column lengths. The records also indicated total explosive weight of explosive, charge weights per hole, and the maximum charge weight per delay.

All blasting records had the signature, license number, and the certification number of the blaster-in-charge.

The blasting records were deficient in one of the most important aspects related to the evaluation of the blasting effects on the underground mine roof and seals. The records do not give a specific location for the blasts. A third-party reviewer should be able to analyze the records and determine the actual location of a blast. In addition, the elevation at the top of blast holes is not given. Consequently, the distance to the mine roof and seals can only be estimated based on the possible location of the blasts.

3. CALCULATED POWDER FACTORS

The PF is the ratio of the explosive, in pounds, required to break a cubic yard of overburden and is expressed as PF = pound per cubic yard. The PF is based on the burden, spacing, and blast hole depth dimensions on the blast records. The PF can be used to determine the cost of breaking a cubic yard of material and infer the probability of success of the desired blast outcome.

The PF for all of the blasting conducted around the impoundment ranged from 0.30 to 2.48 as follows:

- Burden and spacing of 14 feet by 14 feet.
  Blast hole depth of 23 feet
  Charge weight of 414 pounds
  Volume = 14 x 14 x 23 = 4,508 cubic feet = 167 cubic yards
  PF = 414 / 167 = 2.48 pounds per cubic yard

- Burden and spacing of 15 feet by 15 feet
  Blast hole depth of 10 feet
  Charge weight of 25 pounds
  Volume = 15 x 15 x 10 = 2,225 cubic feet = 83.3 cubic yards
  PF = 25 / 83.3 = 0.30 pounds per cubic yard

The PF of 2.48 shows excessive explosive for the volume of rock blasted. This high PF could result in excessive airblast, rock movement, and ground vibrations. The lower PF of 0.30 shows an under-loaded blast hole, with insufficient explosive for the volume of rock blasted. This could cause cratering and higher than expected vibrations.

During the April and May 1995 blasting near the 2000 breakthrough, the PFs ranged from 0.90 to 2.48 with an average of 1.3. Attachment 1 and Tables 1 and 2 show the PFs for the April and May blasts. The PFs greater than 1.6 are excessive and not typical of surface mine blasting.

4. VIBRATION LEVELS AND DAMAGE POTENTIAL ASSESSMENT AT THE UNDERGROUND MINE ROOF AT THE 2000 BREAKTHROUGH

This review covers the blasting adjacent to the 2000 breakthrough. MCCC conducted the blasting in this area during April and May 1995. The safe blasting levels are discussed in Attachment 2.

The vibration estimates (Attachment 1, Tables 3 and 4) are based on an estimate of the distance of the blasts from the mine limit (i.e., to the outcrop barrier). This distance is a combination of the horizontal distance between the blast holes and the mine limit and the vertical distance between the bottom of the blast holes and the mine roof. A 70-foot wide outcrop barrier, as shown in MCCC's 1994 Impoundment Sealing Plan, was used for the mine limit. Also, it was assumed that the bottom of the blast holes were immediately above the Stockton coal seam (i.e., the lowest blasting bench), and that the blast holes were located as close to the Stockton coal seam cropline as allowed by the drill hole depth. The estimated distances range from 165 to 265 feet.

The vibration estimates were made using the regression formulae contained in the Jenny mine study addressed in Attachment 2. The equations used cube-root scale distance. The equations follow:

- Peak particle velocity, 95 percent confidence level--$PPV_{max} = 1{,}541\ (D/W^{1/3})^{-1.84}$
- Peak particle velocity, 50 percent confidence level--$PPV_{mean} = 592\ (D/W^{1/3})^{-1.84}$

There were 42 blasts with estimated vibrations ranging from 0.3 to 5.6 in/sec. Seven of these blasts were above 5 in/sec. Three of the seven may have been located on a higher blasting bench and; therefore, would have been farther from the mine limit. These three blasts could have had vibrations of 1.4 in/sec to 3.7 in/sec.

The vibration estimates will decrease for shots located to the left or right of the 2000 breakthrough. For example, if the blasts with the highest vibrations (5.6 in/sec) were located 100 feet to the left or right of the breakthrough area, the vibration would have been 4.5 in/sec. In consideration of the size of the blast patterns and the length of the contour bench blasted during the April and May period, it is reasonable to assume that at least one of the blasts in the 5 to 5.6 in/sec range was located immediately adjacent to the 2000 breakthrough. The estimated vibrations at the 5.6 in/sec level are considerably below the 10 to 12 in/sec level where roof damage could occur according to the research.

Based on the spalling radius formulae as addressed in Attachment 2, roof spalling would not occur unless the mine roof is within 47 feet of the blasts. At the closest, the blasts came within 100 feet of the mine roof immediately beneath the blasts and 165 feet from the 2000 breakthrough.

In consideration of the age and weathered nature of the mine at the 2000 breakthrough, the actual safe vibration level may be lower than the 10 to 12 in/sec range. It is possible that the vibrations caused loose roof rock to fall; however, it is possible that such rock would have fallen under their own weight anyway. It is also possible that the vibrations produced micro-fractures and consequently weakened the roof; however, the extent of micro-fracturing and weakening cannot be quantified.

Triad Engineering, Inc. (Triad), under contract to the Mine Safety and Health Administration (MSHA), conducted drilling at the 2000 breakthrough. Except at the breakthrough location, Triad's drilling did not identify any excessive mine height, or rubble on the mine floor, which would be indicative of a roof fall.

5. VIBRATION LEVELS AND DAMAGE POTENTIAL ASSESSMENT AT THE UNDERGROUND MINE ROOF IMMEDIATELY BENEATH THE BLASTS

The PPV estimates (Attachment 1, Tables 5, 6, and 7), except where otherwise noted, are based on the assumption that the bottom of the blast holes was immediately above the Stockton coal seam. There were 42 blasts with estimated vibrations ranging from 1.7 in/sec to 19.2 in/sec. Seventeen of these blasts were above 10 in/sec. Four of the seventeen may have been located on a higher blasting bench; and therefore, would have been farther from the mine room. These four blasts could have had vibrations of 2.5 in/sec to 11.5 in/sec.

Several of the blasts could have exceeded the 10 to 12 in/sec level where roof damage could occur according to the research. However, the fact that the 10 to 12 in/sec level was exceeded cannot be used by itself to conclude that roof damage occurred. For example, the Jenny mine study noted vibrations up to 17.5 in/sec without roof damage. Based on the spalling radius formula, roof spalling would not occur unless the mine roof is within 47 feet of the blasts. At the closest, the blasts came within 100 feet of the mine roof immediately beneath the blasts.

Triad did not drill directly beneath the blasting area. Consequently, Triad's drilling does not provide information concerning any roof falls directly beneath the blasting. However, the Triad drilling adjacent to the 2000 breakthrough did not identify roof falls.

6. $SD^{1/2}$ COMPLIANCE, VIBRATION LEVELS, AND DAMAGE POTENTIAL ASSESSMENT AT THE UNDERGROUND MINE SEALS

Permit revision number 5 required that blasting levels not exceed $SD^{1/2}$ 20 at the seals. This review covers 1) the seals located off the North Mains, and 2) the seal to the entrance of the mine area associated with the 2000 breakthrough. Attachment 1, Tables 8, 9, and 10, contain the $SD^{1/2}$ and vibration estimates for these seals. The vibration estimates are based on formulae discussed in Attachment 2. The seals are constructed of concrete block masonry. Research on dwellings indicates that 3 in/sec is a safe vibration limit for masonry.

Seals to 2000 breakthrough mine area: During April and May, there were 42 blasts, and they were located from about 290 to 850 feet from the seals. The $SD^{1/2}$ for these blasts could have ranged from 10 to 100. During June and July, there were 25 blasts, and they were located about 250 to 800 feet from the seals. The $SD^{1/2}$ for these blasts could have ranged from 12 to 93. This review could not determine whether the blasts were in compliance with the permit's $SD^{1/2}$ requirement of 20 because the actual distance from each blast to the seals could not be determined. The estimated highest vibration at the seals during April and May was 2.7 in/sec. This estimate assumes that all of the blasts were 290 feet from the seals. During June and July, the estimated highest vibration at the seals was 2.6 in/sec. This estimate assumes that all of the blasts were 250 feet from the seals. The worst-case vibration estimate of 2.7 in/sec did not exceed the 3 in/sec safe vibration limit for masonry.

Seals located off the North Mains: During June and July, there were 25 blasts, and they were located from about 180 to 1,400 feet from the seals. The $SD^{1/2}$ for the blasts could have ranged from 8 to 163. This review could not determine whether the blasts were in compliance with the permit's $SD^{1/2}$ requirement of 20 because the actual distance from each blast to the seals could not be determined. The estimated highest vibration at the seals was 4.7 in/sec. This estimate assumes that all of the blasts were 180 feet from the seals. The 4.7 in/sec worst-case vibration estimate exceeds the safe blasting level for masonry, and if that level was actually reached, the vibrations could have cracked the mortar bond between the concrete block. During an interview conducted by MSHA, a contractor was asked about the condition of the seals. The contractor had examined the seals after the blasting and prior to constructing bulkheads against the seals. The contractor did not indicate that the seals were damaged.

7. SUMMARY

In summary, this review found that:

1. The blasting plan did not address the protection of the underground mine, except for the mine seals, and was not designed in a manner to effectively break the rock and minimize ground vibrations. Considering the importance of a stable mine roof, a conservative blasting design was appropriate.

2. The blast records were incomplete. They did not contain information concerning the location of the blasts. Consequently, a third-party reviewer is not able to determine the vibration levels at any particular location within the mine except by making worst-case estimates.

3. The review found that the PFs are generally high, but the majority are acceptable considering the hard sandstone that was blasted. However, there were a number of blasts with PFs of 1.7 to 2.5. These blasts could have resulted in undesirable effects such as excessive airblast, rock movement, and ground vibration.

4. The vibration levels do not appear to have been high enough to have damaged the underground mine roof at the 2000 breakthrough. The vibrations may have caused micro-fractures to form in the mine roof rock and weakened the roof; however, the degree of weakening cannot be quantified.

5. The vibration levels may have been high enough to cause roof falls immediately under the blasts. However, blasting was not conducted immediately above the 2000 breakthrough.

6. The blasting plan may not have been followed with respect to the protection of the underground mine seals. However, the estimated blasting vibrations were not high enough to damage the seals to the 2000 breakthrough area, and a contractor's examination of the seals off the North Mains did indicate that those seals were damaged.

ATTACHMENT 1. TABLES

Table 1. Powder Factors April 1995.

Date of Blast	Burden – Spacing & Depth (feet) BxSxH	Hole Diameter (inches) D_H	Volume (Cubic Yards) Yd^3	Pounds/Hole (Lbs)	Powder Factor Pounds/cubic-yards (Lbs/Yd^3)
4/7/95	12x?x21	7 7/8	NA*	198.0	NA
4/11/95	Pre-split	7 7/8	NA	108.0	NA
4/11/95	Pre-split	7 7/8	NA	108.0	NA
4/13/95	Unknown	7 7/8	NA	216.0	NA
4/26/95	Pre-split	7 7/8	NA	108.0	NA
4/26/95	14x14x23	7 7/8	167.00	414.0	2.48
4/21/95	12x12x26	7 7/8	139.00	324.0	2.33
4/3/95	12x15x30	7 7/8	200.00	396.0	1.98
4/26/95	12x15x30	7 7/8	200.00	378.0	1.89
4/4/95	12x15x26	7 7/8	173.00	306.0	1.77
4/18/95	12x15x21	7 7/8	140.00	234.0	1.67
4/20/95	12x15x21	7 7/8	140.00	234.0	1.67
4/22/95	12x15x21	7 7/8	140.00	234.0	1.67
4/19/95	12x15x20	7 7/8	133.00	216.0	1.62
4/20/95	12x15x20	7 7/8	133.00	216.0	1.62
4/26/95	15x15x29	7 7/8	242.00	360.0	1.49
4/5/95	12x15x25	7 7/8	167.00	238.0	1.43
4/28/95	15x15x20	7 7/8	167.00	216.0	1.29
4/12/95	16x16x22	7 7/8	209.00	254.0	1.22
4/21/95	12x15x12	7 7/8	80.00	72.0	0.90

Total number of blasts for the month of April: 20, with the average PF for the production shots alone being 1.67 lbs/yd^3. Powder factors for pre-split shots are not relevant, and those blasts without burden and/or spacing given cannot be calculated.

* Data Not Available

Table 2. Powder Factors May 1995.

Date of Blast	Burden-Spacing & Depth (feet) BxSxH	Hole Diameter (inches) D_H	Volume (Cubic Yards) Yd^3	Pounds/Hole (Lbs)	Powder Factor Pounds/cubic-yards (Lbs/Yd^3)
5/4/95	12x15x30	7 7/8	200.00	396.0	1.98
5/2/95	12x15x20	7 7/8	133.00	216.0	1.62
5/11/95	12x15x44	7 7/8	293.00	468.0	1.60
5/5/95	12x15x21	7 7/8	140.00	218.0	1.56
5/6/95	15x16x35	7 7/8	311.00	470.0	1.51
5/31/95	15x16x39	7 7/8	347.00	488.0	1.41
5/3/95	14x16x21	7 7/8	174.00	234.0	1.34
5/22/95	15x15x20	7 7/8	167.00	218.0	1.31
5/17/95	16x16x44	7 7/8	417.00	543.0	1.30
5/17/95	15x15x22	7 7/8	183.00	236.0	1.29
5/18/95	15x15x21	7 7/8	175.00	218.0	1.25
5/20/95	15x15x21	7 7/8	175.00	218.0	1.25
5/23/95	15x15x21	7 7/8	175.00	218.0	1.25
5/9/95	16x18x45	7 7/8	480.00	540.0	1.13
5/24/95	16x16x21	7 7/8	199.00	218.0	1.10
5/19/95	15x15x20	7 7/8	167.00	182.0	1.09
5/8/95	12x15x10	7 7/8	67.00	72.0	1.07
5/26/95	16x16x20	7 7/8	190.00	200.0	1.05
5/25/95	16x16x21	7 7/8	199.00	200.0	1.01
5/2/95	18x18x25	7 7/8	300.00	288.0	0.96
5/19/95	15x15x21	7 7/8	175.00	164.0	0.94
5/12/95	Pre-split	7 7/8	Na	101.0	Na

Total number of blasts for May: 22, with an average PF of 1.29 lbs/yd^3.

Table 3. Estimates of blasting vibrations at 2000 breakthrough, April and May 1995 blasts. The estimates assume that the blasting occurred at the lowest blasting bench.

Peak Particle Velocity (PPV) Maximum = 1541(D/W1/3)-1.84						PPV Mean = 592(D/W1/3)-1.84			
Scale Distance (SD) =D/W1/2			Spalling Radius (SR) =5.1 x W1/3						
"Distance" is based on the assumption that the blast holes are located as close to the outside									
bottom edge of the contour cut as allowed by the depth of the blast holes. For example,									
a 10-foot hole can be about 18 feet from the edge and 165 feet from the mine limit (assuming a 70-foot outcrop									
barrier), while a 30-foot hole can be about 55 feet from the edge and 195' feet from the mine limit.									
Date	Hole Depth	Distance	Wt/delay	PPV Max	PPV Mean	SD	SR	PPV Max & Mean Table 4	
4/3/1995	30	195	792	5.6	2.2	7	47		
5/4/1995	30	195	792	5.6	2.2	7	47		
4/26/1995	30	195	756	5.5	2.1	7	46	3.7	1.4
4/21/1995	26	186	648	5.4	2.1	7	44	3.7	1.4
4/4/1995	26	187	612	5.2	2	8	43		
4/5/1995	25	185	576	5.1	2	8	42	3.7	1.4
5/2/1995	25	185	576	5.1	2	8	42		
5/3/1995	21	181	468	4.7	1.8	8	40	3.4	1.3
4/28/1995	20	180	432	4.5	1.7	9	38	3.4	1.3
5/2/1995	20	180	432	4.5	1.7	9	38	3.4	1.3
4/26/1995	23	183	414	4.2	1.6	9	38	3	1.2
5/6/1995	35	205	470	3.7	1.4	9	40		
5/17/1995	44	218	543	3.6	1.4	9	42		
5/9/1995	45	220	540	3.6	1.4	9	41		
5/31/1995	39	209	458	3.5	1.4	10	39		
4/26/1995	29	194	360	3.5	1.3	10	36		
5/11/1995	44	218	468	3.3	1.3	10	40		
4/12/1995	22	182	254	3.2	1.2	11	32	2.3	0.9
4/18/1995	21	181	234	3.1	1.2	12	31	2.2	0.9
4/20/1995	21	181	234	3.1	1.2	12	31	2.2	0.9
4/22/1995	21	181	234	3.1	1.2	12	31	2.2	0.9
5/17/1995	22	182	236	3	1.2	12	31	2.2	0.8
5/22/1995	20	180	218	3	1.1	12	31		
4/13/1995	20	180	216	2.9	1.1	12	31		
4/19/1995	20	180	216	2.9	1.1	12	31		
4/20/1995	20	180	216	2.9	1.1	12	31		
5/5/1995	21	181	218	2.9	1.1	12	31		
5/18/1995	21	181	218	2.9	1.1	12	31		
5/20/1995	21	181	218	2.9	1.1	12	31		
5/23/1995	21	181	218	2.9	1.1	12	31		
5/24/1995	21	181	218	2.9	1.1	12	31		
5/26/1995	20	180	200	2.8	1.1	13	30		
5/25/1995	21	181	200	2.8	1.1	13	30		
4/7/1995	21	181	198	2.8	1.1	13	30		
5/19/1995	20	180	182	2.6	1	13	29		
5/19/1995	21	181	164	2.5	0.9	14	28		
5/8/1995	10	165	72	1.8	0.7	19	21		
4/21/1995	12	167	72	1.7	0.7	20	21		
4/11/1995	45	265	108	0.9	0.4	25	24		
4/11/1995	43	265	108	0.9	0.4	25	24		
4/26/1995	45	265	108	0.9	0.4	25	24		
5/12/1995	45	265	101	0.9	0.3	26	24		
The above blasts are pre-split shots: both shots on 4/11, the 108 wt shot on 4/26, and the 5/25 shot.									

Table 4. Estimates of blasting vibrations at 2000 breakthrough, April and May 1995 blasts. The estimates assume that the blasting occurred at the second lowest blasting bench.

This table does not include the blasts from Table 3 where the PPV Max was less than 3.0 in/sec. Also, this table does not include blasts >3.0 in/sec if the number of blast holes and configuration indicate that the blast occurred on the lowest bench.

"Distance" is based on the assumption that all the blasts were on benches above the lowest blast bench. For example, a 10-foot blast hole could have been drilled at the lowest bench 100 feet above the ug mine and 165 feet from the mine limit, or it could have been drilled 110 feet above the ug mine and about 185 feet from the mine limit.

See Table 3 for formulae.

Date	Hole Depth	Distance	Wt/delay	PPV Max	PPV Mean	SD	SR
4/26/1995	30	240	756	3.7	1.4	9	46
4/21/1995	26	229	648	3.7	1.4	9	44
4/5/1995	25	225	576	3.6	1.4	9	42
5/3/1995	21	214	468	3.4	1.3	10	40
4/28/1995	20	210	432	3.4	1.3	10	38
5/2/1995	20	210	432	3.4	1.3	10	38
4/26/1995	23	221	414	3	1.2	11	38
4/12/1995	22	218	254	2.3	0.9	14	32
4/18/1995	21	214	234	2.2	0.9	14	31
4/20/1995	21	214	234	2.2	0.9	14	31
4/22/1995	21	214	234	2.2	0.9	14	31
5/17/1995	22	218	236	2.2	0.8	14	31

Table 5. Estimate of vibrations at mine roof, directly beneath April and May 1995 blasts. The estimates assume that the blasting occurred at the lowest blasting bench.

"Distance" is based on the assumption that all the blasts were on the lowest blasting bench immediately above the Stockton coal seam.											
See Table 3 for formulae.											
Date	Hole Depth	Distance	Wt/delay	PPV Max	PPV Mean	SD	SR	PPV Max & Mean Table 6		PPV Max & Mean Table7	
5/4/1995	30	100	792	19.2	7.4	4	47				
4/3/1995	30	100	792	19.2	7.4	4	47				
4/26/1995	30	100	756	18.7	7.2	4	46	11.5	4.4	7.9	3
4/21/1995	26	100	648	17	6.5	4	44				
4/4/1995	26	100	612	16.4	6.3	4	43				
5/2/1995	25	100	576	15.8	6.1	4	42				
4/5/1995	25	100	576	15.8	6.1	4	42				
5/17/1995	44	100	543	15.3	5.9	4	42				
5/9/1995	45	100	540	15.2	5.8	4	41				
5/6/1995	35	100	470	14	5.4	5	40				
5/11/1995	44	100	468	13.9	5.4	5	40				
5/3/1995	21	100	468	13.9	5.4	5	40				
5/31/1995	39	100	458	13.7	5.3	5	39				
5/2/1995	20	100	432	13.3	5.1	5	38	9.5	3.6	7.1	2.7
4/28/1995	20	100	432	13.3	5.1	5	38	9.5	3.6	7.1	2.7
4/26/1995	23	100	414	12.9	5	5	38	8.8	3.4	6.4	2.5
4/26/1995	29	100	360	11.9	4.6	5	36				
4/12/1995	22	100	254	9.6	3.7	6	32	6.6	2.6	4.9	1.9
5/17/1995	22	100	236	9.2	3.5	7	31	6.4	2.4	4.7	1.8
4/22/1995	21	100	234	9.1	3.5	7	31	6.4	2.5	4.8	1.8
4/20/1995	21	100	234	9.1	3.5	7	31	6.4	2.5	4.8	1.8
4/18/1995	21	100	234	9.1	3.5	7	31	6.4	2.5	4.8	1.8
5/24/1995	21	100	218	8.7	3.4	7	31				
5/23/1995	21	100	218	8.7	3.4	7	31				
5/22/1995	20	100	218	8.7	3.4	7	31				
5/20/1995	21	100	218	8.7	3.4	7	31				
5/18/1995	21	100	218	8.7	3.4	7	31				
5/5/1995	21	100	218	8.7	3.4	7	31				
4/20/1995	20	100	216	8.7	3.3	7	31	6.2	2.4	4.7	1.8
4/19/1995	20	100	216	8.7	3.3	7	31	6.2	2.4	4.7	1.8
4/13/1995	20	100	216	8.7	3.3	7	31	6.2	2.4	4.7	1.8
5/26/1995	20	100	200	8.3	3.2	7	30				
5/25/1995	21	100	200	8.3	3.2	7	30				
4/7/1995	21	100	198	8.2	3.2	7	30	5.8	2.2	5.8	2.2
5/19/1995	20	100	182	7.8	3	7	29				
5/19/1995	21	100	164	7.3	2.8	8	28	5.2	2	3.8	1.5
4/26/1995	45	100	108	5.7	2.2	10	24	2.9	1.1		
4/11/1995	45	100	108	5.7	2.2	10	24	2.9	1.1		
4/11/1995	43	100	108	5.7	2.2	10	24	2.9	1.1		
5/12/1995	45	100	101	5.4	2.1	10	24	2.8	1.1		
5/8/1995	10	100	72	4.4	1.7	12	21	3.7	1.4	3.2	1.2
4/21/1995	12	100	72	4.4	1.7	12	21	3.6	1.4	3	1.1

Table 6. Estimates of vibrations at mine roof, directly beneath April and May 1995 blasts. The estimates assume that the blasting occurred at the second lowest blasting bench.

This table does not include blasts if the number of blast holes and configuration

Indicates that the blast occurred on the lowest bench.

"Distance" is based on the assumption that all the blasts were on benches above the lowest blast bench, e.g. a 25-foot blast hole could have been drilled at the lowest bench 100 feet above the ug mine, or it could have been drilled 125 feet or 150 feet above the ug mine.

See Table 3 for formulae.

Date	Hole Depth	Distance	Wt/delay	PPV Max	PPV Mean	SD	SR
4/26/1995	30	130	756	11.5	4.4	5	46
5/2/1995	20	120	432	9.5	3.6	6	38
4/28/1995	20	120	432	9.5	3.6	6	38
4/26/1995	23	123	414	8.8	3.4	6	38
4/12/1995	22	122	254	6.6	2.6	8	32
4/22/1995	21	121	234	6.4	2.5	8	31
4/20/1995	21	121	234	6.4	2.5	8	31
4/18/1995	21	121	234	6.4	2.5	8	31
5/17/1995	22	122	236	6.4	2.4	8	31
4/20/1995	20	120	216	6.2	2.4	8	31
4/19/1995	20	120	216	6.2	2.4	8	31
4/13/1995	20	120	216	6.2	2.4	8	31
4/7/1995	21	121	198	5.8	2.2	9	30
5/19/1995	21	121	164	5.2	2	9	28
5/8/1995	10	110	72	3.7	1.4	13	21
4/21/1995	12	112	72	3.6	1.4	13	21
4/11/1995	43	143	108	2.9	1.1	14	24
4/26/1995	45	145	108	2.9	1.1	14	24
4/11/1995	45	145	108	2.9	1.1	14	24
5/12/1995	45	145	101	2.7	1.1	14	24

Table 7. Estimates of vibrations at mine roof, directly beneath April and May 1995 blasts. The estimates assume that the blasting occurred at the third lowest bench.

This table does not include blasts if the number of blast holes and configuration indicate that the blast occurred on the lowest bench.

"Distance" is based on the assumption that all the blasts were on benches above the lowest blast bench, e.g., a 25-foot blast hole could have been drilled at the lowest bench 100 feet above the ug mine, or it could have been drilled 125 feet or 150 feet above the ug mine.

See Table 3 for formulae.

Date	Hole Depth	Distance	Wt/delay	PPV Max	PPV Mean	SD	SR
4/26/1995	30	160	756	7.9	3	6	46
5/2/1995	20	140	432	7.1	2.7	7	38
4/28/1995	20	140	432	7.1	2.7	7	38
4/26/1995	23	146	414	6.4	2.5	7	38
4/7/1995	21	121	198	5.8	2.2	9	30
4/12/1995	22	144	254	4.9	1.9	9	32
4/22/1995	21	142	234	4.8	1.8	9	31
4/20/1995	21	142	234	4.8	1.8	9	31
4/18/1995	21	142	234	4.8	1.8	9	31
5/17/1995	22	144	236	4.7	1.8	9	31
4/20/1995	20	140	216	4.7	1.8	10	31
4/19/1995	20	140	216	4.7	1.8	10	31
4/13/1995	20	140	216	4.7	1.8	10	31
5/19/1995	21	142	164	3.8	1.5	11	28
5/8/1995	10	120	72	3.2	1.2	14	21
4/21/1995	12	124	72	3	1.1	15	21

Table 8. Estimates of vibrations at seals to 2000 breakthrough mine area, April and May 1995 blasts.

"Distance 1" is based on the approximate distance between the contour bench highwall										
at its closest to the seals.										
"Distance 2" is based on the approximate distance between the contour bench highwall										
at its farthest to the seals.										
The 1 and 2 following the headings indicate whether distance 1 or 2 was used.										
See Table 3 for formulae.										
Date	Distance 1	Distance 2	Wt/delay	PPV Max 1	PPV Mean 1	PPV Max 2	PPV Mean 2	SD 1	SD 2
4/3/1995	290	850	792	2.7	1	0.4	0.1	10	30
5/4/1995	290	850	792	2.7	1	0.4	0.1	10	30
4/26/1995	290	850	756	2.6	1	0.4	0.1	11	31
4/21/1995	290	850	648	2.4	0.9	0.3	0.1	11	33
4/4/1995	290	850	612	2.3	0.9	0.3	0.1	12	34
4/5/1995	290	850	576	2.2	0.9	0.3	0.1	12	35
5/2/1995	290	850	576	2.2	0.9	0.3	0.1	12	35
5/17/1995	290	850	543	2.2	0.8	0.3	0.1	12	36
5/9/1995	290	850	540	2.1	0.8	0.3	0.1	12	37
5/3/1995	290	850	468	2	0.8	0.3	0.1	13	39
4/28/1995	290	850	432	1.9	0.7	0.3	0.1	14	41
5/2/1995	290	850	432	1.9	0.7	0.3	0.1	14	41
5/6/1995	290	850	470	2	0.8	0.3	0.1	13	39
5/31/1995	290	850	458	1.9	0.7	0.3	0.1	14	40
5/11/1995	290	850	468	2	0.8	0.3	0.1	13	39
4/26/1995	290	850	414	1.8	0.7	0.3	0.1	14	42
4/26/1995	290	850	360	1.7	0.6	0.2	0.1	15	45
4/12/1995	290	850	254	1.4	0.5	0.2	0.1	18	53
4/18/1995	290	850	234	1.3	0.5	0.2	0.1	19	56
4/20/1995	290	850	234	1.3	0.5	0.2	0.1	19	56
4/22/1995	290	850	234	1.3	0.5	0.2	0.1	19	56
5/17/1995	290	850	236	1.3	0.5	0.2	0.1	19	55
5/22/1995	290	850	218	1.2	0.5	0.2	0.1	20	58
5/5/1995	290	850	218	1.2	0.5	0.2	0.1	20	58
5/18/1995	290	850	218	1.2	0.5	0.2	0.1	20	58
5/20/1995	290	850	218	1.2	0.5	0.2	0.1	20	58
5/23/1995	290	850	218	1.2	0.5	0.2	0.1	20	58
5/24/1995	290	850	218	1.2	0.5	0.2	0.1	20	58
4/13/1995	290	850	216	1.2	0.5	0.2	0.1	20	58
4/19/1995	290	850	216	1.2	0.5	0.2	0.1	20	58
4/20/1995	290	850	216	1.2	0.5	0.2	0.1	20	58
5/26/1995	290	850	200	1.2	0.4	0.2	0.1	21	60
5/25/1995	290	850	200	1.2	0.4	0.2	0.1	21	60
4/7/1995	290	850	198	1.2	0.4	0.2	0.1	21	60
5/19/1995	290	850	182	1.1	0.4	0.2	0.1	21	63
5/19/1995	290	850	164	1	0.4	0.1	0.1	23	66
4/11/1995	290	850	108	0.8	0.3	0.1	0	28	82
4/11/1995	290	850	108	0.8	0.3	0.1	0	28	82
4/26/1995	290	850	108	0.8	0.3	0.1	0	28	82
5/12/1995	290	850	101	0.8	0.3	0.1	0	29	85
5/8/1995	290	850	72	0.6	0.2	0.1	0	34	100
4/21/1995	290	850	72	0.6	0.2	0.1	0	34	100

Table 9. Estimates of vibrations at seals to 2000 breakthrough mine area, June and July 1995 blasts.

"Distance 1" is based on the approximate distance between the contour bench highwall at its closest to the seals.

"Distance 2" is based on the approximate distance between the contour bench highwall at its farthest to the seals.

The 1 and 2 following the headings indicate whether distance 1 or 2 was used.

See Table 3 for formulae.

Date	Distance 1	Distance 2	Wt/delay	PPV Max 1	PPV Mean 1	PPV Max 2	PPV Mean 2	SD 1	SD 2
6/6/1995	250	800	471	2.6	1	0.3	0.1	12	37
6/1/1995	250	800	453	2.5	1	0.3	0.1	12	38
6/5/1995	250	800	453	2.5	1	0.3	0.1	12	38
6/12/1995	250	800	398	2.3	0.9	0.3	0.1	13	40
6/13/1995	250	800	326	2.1	0.8	0.2	0.1	14	44
6/15/1995	250	800	272	1.9	0.7	0.2	0.1	15	49
6/17/1995	250	800	272	1.9	0.7	0.2	0.1	15	49
6/8/1995	250	800	218	1.6	0.6	0.2	0.1	17	54
6/9/1995	250	800	218	1.6	0.6	0.2	0.1	17	54
6/23/1995	250	800	218	1.6	0.6	0.2	0.1	17	54
6/24/1995	250	800	218	1.6	0.6	0.2	0.1	17	54
6/28/1995	250	800	218	1.6	0.6	0.2	0.1	17	54
6/29/1995	250	800	218	1.6	0.6	0.2	0.1	17	54
7/13/1995	250	800	218	1.6	0.6	0.2	0.1	17	54
6/17/1995	250	800	200	1.5	0.6	0.2	0.1	18	57
6/16/1995	250	800	182	1.4	0.6	0.2	0.1	19	59
6/19/1995	250	800	182	1.4	0.6	0.2	0.1	19	59
6/20/1995	250	800	182	1.4	0.6	0.2	0.1	19	59
6/30/1995	250	800	182	1.4	0.6	0.2	0.1	19	59
6/20/1995	250	800	164	1.4	0.5	0.2	0.1	20	62
6/21/1995	250	800	164	1.4	0.5	0.2	0.1	20	62
6/21/1995	250	800	164	1.4	0.5	0.2	0.1	20	62
6/22/1995	250	800	164	1.4	0.5	0.2	0.1	20	62
6/17/1995	250	800	74	0.8	0.3	0.1	0	29	93
6/27/1995	250	800	74	0.8	0.3	0.1	0	29	93

Table 10. Estimates of vibrations at seals off North Mains, June and July 1995 blasts.

"Distance 1" is based on the approximate distance between the contour bench highwall at its closest to the seals off the North Mains.

"Distance 2" is based on the approximate distance between the contour bench highwall at its farthest to the seals off the North Mains.

The 1 and 2 following the headings indicate whether distance 1 or 2 was used.

See Table 3 for formulae.

Date	Distance 1	Distance 2	Wt/delay	PPV Max 1	PPV Mean 1	PPV Max 2	PPV Mean 2	SD 1	SD 2
6/6/1995	180	1400	471	4.7	1.8	0.1	0	8	65
6/1/1995	180	1400	453	4.6	1.8	0.1	0	8	66
6/5/1995	180	1400	453	4.6	1.8	0.1	0	8	66
6/12/1995	180	1400	398	4.3	1.6	0.1	0	9	70
6/13/1995	180	1400	326	3.8	1.5	0.1	0	10	78
6/15/1995	180	1400	272	3.4	1.3	0.1	0	11	85
6/17/1995	180	1400	272	3.4	1.3	0.1	0	11	85
6/8/1995	180	1400	218	3	1.1	0.1	0	12	95
6/9/1995	180	1400	218	3	1.1	0.1	0	12	95
6/23/1995	180	1400	218	3	1.1	0.1	0	12	95
6/24/1995	180	1400	218	3	1.1	0.1	0	12	95
6/28/1995	180	1400	218	3	1.1	0.1	0	12	95
6/29/1995	180	1400	218	3	1.1	0.1	0	12	95
7/13/1995	180	1400	218	3	1.1	0.1	0	12	95
6/17/1995	180	1400	200	2.8	1.1	0.1	0	13	99
6/16/1995	180	1400	182	2.6	1	0.1	0	13	104
6/19/1995	180	1400	182	2.6	1	0.1	0	13	104
6/20/1995	180	1400	182	2.6	1	0.1	0	13	104
6/30/1995	180	1400	182	2.6	1	0.1	0	13	104
6/20/1995	180	1400	164	2.5	1	0.1	0	14	109
6/21/1995	180	1400	164	2.5	1	0.1	0	14	109
6/21/1995	180	1400	164	2.5	1	0.1	0	14	109
6/22/1995	180	1400	164	2.5	1	0.1	0	14	109
6/17/1995	180	1400	74	1.5	0.6	0	0	21	163
6/27/1995	180	1400	74	1.5	0.6	0	0	21	163

ATTACHMENT NUMBER 2. BLASTING RESEARCH

Over the years, a number of papers and technical books have been written by universities and consultants on the effects that surface blasting has on underground mines. The following are those considered most relevant to the concerns at MCCC:

1. "Underground Vibrations from Surface Blasting at Jenny Mine, Kentucky," Woodward-Clyde Consultants, Orange, CA, USBM Open File Report 41-80/Contract No. J0275030, April 1980.

2. "Criteria For the Proximity of Surface Blasting to Underground Coal Mines," Rupert, G.B., and Clark, G. B., USBN Contract No. H0232032, And 18th U.S. Symposium on Rock Mechanics, June 1977.

3. "Use of Seismographs in Quality Control of Surface Mine Blasts Adjacent to underground Mines," Hayatdavoudi, A. and Brown, R. C., S.E.E., February 1980.

4. "Propagation from Surface Mine Blast to the Adjacent Underground Mine," Hayatdavoudi, A. and Brown, R. C., 20th U.S. Symposium on Rock Mechanics, June 1979.

5. "Effects of Field Stresses, Seismometer Coupling and Blast Angle on Wave Propagation from Surface Mine Blast to Underground Mine," Hayatdavoudi, A. and Brown, R. C., 21st U.S. Symposium on Rock Mechanics, May 1980.

6. "Effects of Surface Mine Blasting on Underground Mine Openings," Simpson, T. A. and Phang, M. K., S.E.E. February 1984.

7. "Wave Propagation in a Subsurface Environment Due to Blasting Operations," Clark, D. A. and Cavin R. E., 7th Conference on Explosives and Blasting Technique, January 1981.

8. "The Modern Technique of Rock Blasting," Langefors and Kihlstrom, 2nd edition, John Wiley and Sons, New York, 1973.

9. "Pit Slope Manual," Bauer, A., & Calder, P.N., Chapter 7, 1977.

10. "Open Pit and Blast Seminar," Bauer, A., & Calder, P.N., Course Number 63-321, Kingston, Ontario, Canada: Queen's University Mining Engineering Department, 1978.

11. "Vibrations From Blasting," Siskind, D.E., International Society of Explosive Engineers, 2000.

The Jenny mine study is the primary study considered for the MCCC blasting review, since the location of the Jenny Mine is approximately 15 miles southwest of Inez, Kentucky, in Martin County and thus near MCCC. The Jenny mine was located in the Stockton coal seam, while the surface mining occurred in the Clarion coal seam some 140 to 150 feet above the Stockton coal seam mine roof. This is similar to the blasting at the MCCC impoundment, where the underlying mine is in the Coalburg coal seam and the blasting was above the Stockton coal seam.

The Jenny mine report data supported cubic root scaling [scale distance ($SD^{1/3}$)] for determining the blasting vibrations at the underground mine. The report gives the formula for vibrations in the mine roof as:

- $PPV_{mean} = 592\ (D/W^{1/3})^{-1.84}$

Where:

PPV	= the peak particle velocity, inches per second (in/sec)
D	= the distance from the source (feet)
W	= the weight of the explosive per 8 millisecond delay period (pounds)
1/3	= the scaling exponent on W
592	= the intercept of the regression line at $D/W^{1/3} = 1$
-1.84	= the slope of the regression line

The above formula is the "mean equation," which means that 50 percent of the data points fall either above or below the linear regression line. A more conservative formula, PPV_{max}, follows. It is used to assure protection to underground mine structures is the 95 percent confidence level formula where 95 percent of the data points fall below the regression line.

- $PPV_{max} = 1541\ (D/W^{1/3})^{-1.84}$

The investigators required a 95 percent confidence level for the data presented and stated, "From a strictly statistical viewpoint, therefore, for the data collected at the Jenny mine, it would be appropriate to scale the roof data by the cube root of the maximum delay charge weight."

A total of 30 surface mine blasts were monitored during the Jenny mine study with 74 data pairs for this study, due to multiple monitoring locations on the underground roof, compared to the 141 blasts by MCCC above the Coalburg coal seam.

The Jenny mine was active and ventilated compared to the MCCC works, portions of which were inactive and sealed. These facts should be recognized when reading the Jenny mine report. Also, the Jenny mine report noted:

> "No evidence of damage which could be directly attributed to the blasting was found from any of these studies." The maximum particle velocity recorded by a transducer mounted on the mine roof was 17.5 inches/second."

"It was the opinion of those familiar with the mine that loose rock which fell from the mine roof during the monitoring period would have fallen regardless of the blasting."

"Efforts to quantify roof fall frequency and magnitude were intensified during the final stages of the project. Rigorous logging of entries 3 and 5, as described in Section 3.2.2; however, proved inconclusive due to unexpected termination of the blasting."

In addition to addressing the Jenny mine study, the author(s) also noted on page 59 of the report under a section titled Roof Falls, the following:

"Few references are made in the literature to vibration levels associated with roof failures. Langefors and Kihlstrom cite approximately 12 in/sec as being associated with the fall of stones in galleries and tunnels."

"One substantial case history is presently available . . . When particle velocities reached 5 in/sec, 1 or 2 loose stones fell from an unsupported, unreinforced section of access tunnel. That was the only known rockfall during the 6 years with particle velocities reaching about 10 in/sec. The chamber arch was bolted. The arch rose about 5/8 in. relative to the floor as a result of elastic rebound from excavation of the mountain above the chamber."

The Jenny mine report (pages 62 to 64) noted several modes of damage to mines due to blasting vibrations: crushing, compressive fracturing of confined rock, fracturing or spalling at free surfaces, and roof micro-fracturing due to the addition of dynamic stresses from vibrations to existing static stresses. The first three modes of damage occur in the immediate area of the blast zone, and are expressed as the product of an empirically-determined rock constant and the yield of the explosive source. For sandstone, the rock constants have been determined to be:

For Zone of Crushing	1.3	(crushed zone)
For Zone of Compressive Damage	3.3	(severely fractured zone)
For Zone of Spalling	5.1	(moderately fractured zone)

The explosive source is the cube root of the maximum pounds per delay interval. During the April and May 1995 blasting at MCCC, the largest explosive charge per delay interval was 792 pounds. The zones of concern for this charge weight follow:

Zone of Crushing	$(1.3)\ (792^{1/3}) = (1.3)(9.25) = 12.0$ feet
Zone of Compressive Damage	$(3.3)\ (792^{1/3}) = (3.3)(9.25) = 30.5$ feet
Zone of Spalling	$(5.1)\ (792^{1/3}) = (5.1)(9.25) = 47.2$ feet

The last mode of damage (zone of spalling) is the major concern at the MCCC blast site. Rock under tension fails by spalling. It is in this zone of spalling and beyond, known as the least fractured zone, being a zone were the rock acts as an elastic material, that tensile failure and crack extensions occur. Much of the original energy from the detonation has been consumed in first two zones (crushing and compressive failure); therefore, the compressive stress energy in the seismic wave is well below the compressive strength of the rock. The tangential stress component of the wave is still substantially larger than the tensile strength of the rock. The tensile strength of rock is $^1/_{15}$ to $^1/_{10}$ of the compressive strength, and the wave energy is large enough to cause radial fractures. This energy can result in cracks initiated from micro-fractures and flaws inherent in a typical rock mass or even existing flaws resulting from mining.

The Jenny mine report states the following on the "Addition of Dynamic Stresses," which is the last mode of damage, one that is not as obvious as crushing of a rock mass or even spalling:

> "The design of an underground mine is generally based on consideration of static loads many times greater than expected dynamic stresses. However, if conditions are such that static stresses are near the strength of supporting rock, added dynamic stresses from blast vibrations could cause failure."
>
> "Tincelin and Sinou (24) monitored deterioration of mine roofs near production blasts. They observed that strains larger than those, which could be attributed to increasing static stresses, occurred as blast vibrations passed gage locations. They compared total strains with those in openings driven by continuous mining methods and found the values associated with blasting to be significantly larger. They were able to correlate damage induced by blasting with peak particle velocity and duration of shaking."
>
> "Although techniques have been developed for estimating both static and dynamic stresses, there is not sufficient information about the conditions at Jenny mine to make an accurate estimate of these stresses during the blasting program. The previous work described above **indicates that dynamic stresses may be a critical consideration in estimating potential damage from blasting near underground openings.**" (emphasis added)

The Jenny mine report, while not having any "fixed number" in terms of safe or damaging levels of vibration, did qualify the tests within the RECOMMENDATIONS as follows:

> "The relationship developed from the Jenny mine observations represent a significant first step in defining the impact of surface blasting over underground workings. **However, these relationships are presently not sufficiently well defined to use in general production situations without a <u>high degree of conservatism.</u> Furthermore, it is not presently clear what vibration levels might be associated with undesirable physical effects in the underground mine <u>on a long-term basis.</u>**" (emphasis added)

The Bauer and Calder manual discusses the problem of slabbing or spalling and gives the following formula for estimating PPV:

$$PPV = 1{,}728\ S_T / P_M\ C_L$$

Where:

PPV = peak particle velocity (in/sec)
S_T = dynamic tensile strength of the rock mass in pounds per square inch
P_M = mass density of the rock (lb $sec^2/feet^4$)
C_L = longitudinal wave velocity in the rock (feet/sec)

In addition, Bauer and Calder, at their 1978 seminar, predicted damage criteria for rock masses based on stresses produced by PPV. They presented the following table:

Peak Particle Velocity	**Effects on Rock Mass**
Less than 10	No fracturing of intact rock
10-25	Minor tensile slabbing
25-100	Strong tensile & some radical cracks
Greater than 100	Total failure

During the seminar, two case histories were given that expressed the concern that 'hardrock' operations place on the probability of damage to underground mine operations from surface blasting.

> "At some of the Sudbury Basin mines in Ontario, damage is reported as being visible in the form of tensile slabbing when peak particle velocities (ppv) approach 14 in/sec. In an underground haulage tunnel underneath IOCC's open pit mine in Labrador, the ppv is contained below 10 in/sec at all cost. Since the haulage tunnel is a very important part of the operation, only one hole per delay is fired at a scale distance of no less than 7. A scale distance of 7 relates there to a ppv of 10 in./sec."

The work done by Rupert and Clark confirmed the work at the Jenny mine and the report stated in the summary and conclusions, "Only minor damage of the form of localized thin spalling and possible collapse of portions of previously fractured coal ribs resulted from those shots having associated peak particle velocities in excess of 2 in/sec." The actual levels of particle velocities in excess of 2 in/sec are not given, but the assumption is that levels of vibration 2 in/sec or less are entirely safe, while vibration levels in excess could result in spalling. Rupert and Clark refer to the rib or pillar of coal and not the roof of the room. The roof, not being comprised of coal, is of a stronger rock, since it is normally cleaned or scaled and supported by bolts or cribbing. The degree of threshold failure would also be determined by the conditions of the roof, including its strength and the existing integrity and stability. In most cases, convention would say, the particle velocity would have to exceed 10 in/sec.

The most recent publication is by David E. Siskind, Ph.D., a blast vibration researcher and author with the U.S. Bureau of Mines prior to the bureau's closure in 1995. Chapter 11 "Vibrations in Underground Mines and Tunnels" summarizes the various research. The "summary analysis," Section 11.5, pages 77 and 78 states:

> "There is much variation between the structure and geologic conditions represented by the nine studies (and 12 sites) detailed above. A general observation is that major failure such as roof collapse and pillar failure would require vibrations greater than about 12 in/sec. In some cases, loose pieces were dislodged at lower vibration levels of about 1.2 to 5 in/sec. Low-level vibrations, certainly below 1.0 in/sec, have been found to be totally harmless to underground workings, even active ones where rockfalls are a personnel hazard."

A number of the nine studies referenced by Siskind were also examined for the MCCC review.

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