Wind blasts in longwall panels in underground coalmines

by P. Sharma* and J.C.W. Fowler†

Synopsis

Longwall panels facing wind blasts have been investigated at both Newstan and Moonee Collieries in the Newcastle Coalfield under the Wind Blast Project of the School of Mining Engineering, The University of New South Wales. The fluid mechanics involved in the compression and expulsion of air during wind blasts have been defined and the overpressure and air velocity time histories utilized to determine the wind blast parameters and define the relationship between them. The characteristics of wind blasts pressure pulses in mine roadways show some similarity with transient phenomenon like air blasts from explosives and shock waves from the failure of pressurized vessels. The peak wind velocities in roadways, however, exhibit marked deviations from theoretical predictions based on compressible fluid flow and Rankine-Hugoniot relationships applied to goaf air displacement and panel geometry. Peak overpressures and wind velocities have shown a positive correlation with the areas of goaf falls, with the values peaking off for larger areas. The field investigations have helped the mine management in risk assessment and in evaluating the success of induced caving by hydrofracturing to mitigate the hazard.

Introduction

Wind blast in coalmines and its equivalent, air blast, in metalliferous mines have been of concern to the Australian underground mining industry. Collieries in the Newcastle Coalfield, especially those mining the West Borehole seam under massive channel conglomerates to the north west of Lake Macquaire and those collieries south of Lake Macquarie which mine the Great Northern seam under the Teralba Conglomerate, face the wind blast hazard. Although the most recent fatality due to wind blast in a coal mine took place in 1976 at Eastern Main Colliery, incidents involving serious personal injury continue to occur. In metalliferous mines, the history of fatal air blasts spans the period from the 1895 incident, which resulted in the deaths of nine miners at Broken Hill South Mine, to the multiple fatality at Northparkes Mine in 1999. Historically some of the most severe wind blasts in underground coalmines have been associated with violent pillar failures, for example those at Muswellbrook No. 2 Colliery in the Hunter Coalfield of NSW and at Coalbrook North Colliery, South Africa. The high incidence of wind blasts in the Newcastle Coalfield of New South Wales is due to the particular geology of the coalfield, a dominant feature of which is the presence of massive, strong conglomerate beds whose basal sections often lie in close proximity to the coal-seams. According to Bocking, Howes and Weber[1], the conglomerates, in common with the other clastic sediments, show considerable variation in both their lateral and vertical extents throughout the coalfield. They have been proven to extend over areas in excess of 200 square kilometres in irregular lenticular sheets, several discontinuous lenses often occurring on one stratigraphic horizon. Fowler[2] reports that the Wallarah, Myuna, Cooranbong and Endeavour Collieries in the Newcastle Coalfield have experienced significant wind blasts. Fowler and Torabi[3] and Fowler and Sharma[4,5] have monitored the more recent wind blasts at the Newstan and Moonee Collieries, respectively. Anderson[7] reported that at Endeavour Colliery, a significant wind blast associated with a major goaf fall preceded an explosion.

Moonee Colliery, owned and operated by Coal Operations Australia Limited, mine the Great Northern seam by the longwall retreat system of mining. The Colliery is located on the New South Wales coast at Catherine Hill Bay, approximately 20 kilometres south of Newcastle and 100 km north of Sydney, within the Lake Macquaire district of the Newcastle Coalfield. Many significant wind blasts have occurred at Moonee Colliery since January 1998, during the mining of the first five longwall panels. Edwards[6] describes the wind blast prediction at Moonee using microseismic monitoring. The mine management introduced

* *Department of Mining Engineering, NIT Rourkela.*

† *School of Mining Engineering, UNSW, Sydney*

 SA ISSN 0038–223X/3.00 + 0.00. Paper received Feb. 2004; revised paper received Sep. 2004.

hydraulic fracturing in Longwall no. 3 panel for 'caving on demand' as discussed by Mills, Jaffrey and Jones[8] and Wischusen[9]. However, the wind blast hazard still remained and the strategy of the mine management was to control rather than eliminate the hazard as, due to prior development, it was committed to the longwall layout.

Wind blast monitoring

An extensive programme of monitoring was undertaken at Moonee Colliery during the mining of longwall panels utilizing a wind blast monitoring system (WBMS) during 1998 to 2001. Prior to Moonee Colliery, significant wind blasts had been monitored at longwall panels only in Newstan Colliery during 1995 and 1997 by Fowler and Torabi[3]. Out of the 23 events recorded in the 4 panels monitored, only eight were classified as significant wind blasts, i.e. of sufficient intensity to pose a risk of personal injury or of damage to the mine ventilation system.

The WBMS is certified and approved for use in hazardous locations in underground coal mines in both Queensland and New South Wales. Its principal, operational parameters are as follows.

- Support for four sensor pods
- An absolute pressure range of 0-206.8 kPa (0–30.0 psi)
- A dynamic pressure range of ±13.79 kPa (±2.0 psi), which corresponds to an air velocity range of ±150.0 m/s (at STP)
  (The original dynamic pressure range of ±996 Pa (±4.0 inches water gauge) which corresponds to an air velocity range of ±40.3 m/s (at STP) had proven to be inadequate.)
- A sampling frequency of 1 000 scans per second
- A fixed recording time for each event of eight seconds with two seconds pre-trigger
- Storage for up to 16 events in non-volatile memory
- Eight-bit resolution
- Battery back-up, which powers the WBMS for 16 hours or more in the event of interruption to the reticulated power supply.

An intrinsically safe handheld interface unit is employed to both program the WBMS and transfer data to a personal computer for further processing.

The configuration of longwall panel no. 3 and nearby workings and location of the WBMS sensor pods are shown in Figure 1. Pod no. 2 was mounted on an element of the longwall equipment at a distance of 11 metres from the face and moved outbye as the face retreated. Pod no.4 in the maingate was located as far outbye as possible. Pod no. 3 was located in the tailgate outbye of the face.

Data analysis

Data files were further processed and graphical output produced using macros written in WaveMetrics Igor Pro version 3.13. Standard graphical output includes, for each measuring location, the overpressure time history together with its integral and differential from which the impulse and rates of rise (and fall) of overpressure are obtained. Also included in the output is the wind velocity time history together with its integral and differential from which the excursion and rates of rise (and fall) of velocity are obtained. The excursion is the distance travelled by the flow of air past the sensor pod. The maximum integrated overpressure is defined as the impulse. The time histories may be smoothed as appropriate. Other graphical output, such as the differential pressure time history and its derivatives, are generated as required and, when necessary, a fast Fourier transform (FFT) algorithm is employed to transform time histories into the frequency domain for further study. Further data analysis utilizes Microsoft Excel version 8.0 and SPSS DeltaGraph version 4.5.

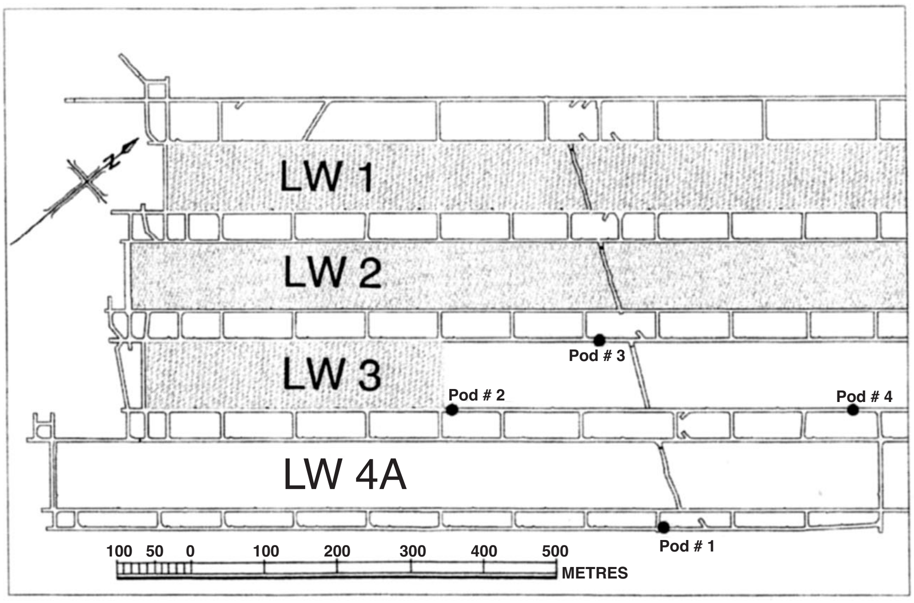

Figure 1—Configuration of longwall panel no. 3 and nearby workings and location of the WBMS sensor pods

Wind blast characteristics and fluid-dynamic aspects

A wind blast comprises a rapid rise in absolute pressure to a maximum (positive compression phase), followed by a similarly rapid fall to below ambient atmospheric pressure (expansion phase 'suck back'). After decreasing to a minimum value, the absolute pressure gradually increases until it becomes equal to ambient atmospheric pressure. At around the same time, although not necessarily in phase with the overpressure, the wind velocity also rises rapidly to a maximum and then exhibits a sudden reversal into the 'suck back' phase. Each event usually lasts for a few seconds. Typical overpressure and wind velocity time histories are shown in Figure 2 and Figure 3, respectively.

From wind blast monitoring and the recorded overpressure and wind velocity time histories, it has been observed that:

- There is no acoustic precursor to the event. Consequently people in the working place will receive no warning of the wind blast before it strikes them unless they hear 'roof talk' or a wind blast warning system is in place
- The onset of the event is very sudden, both overpressure and air velocity exhibiting a rapid rise
- The intensity of the wind blast phase can be very severe, comprising a very large overpressure and corresponding high wind velocity

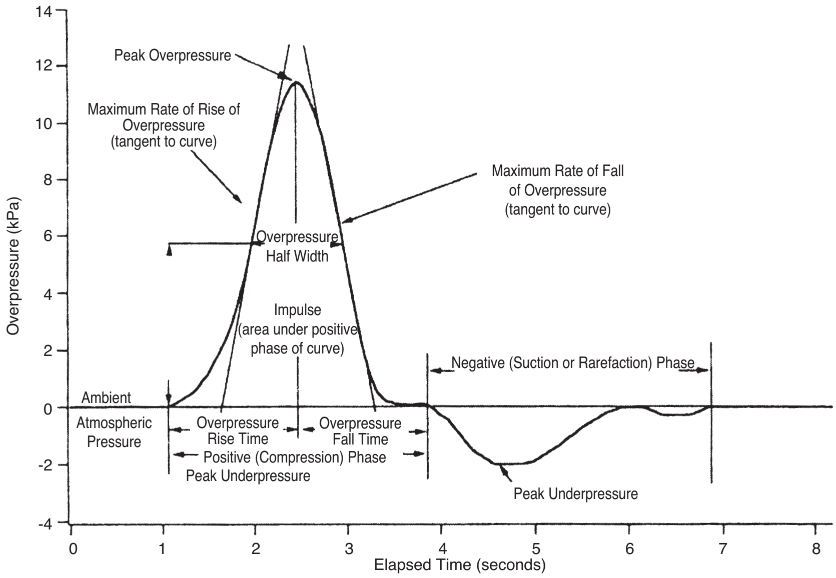

Figure 2—Typical overpressure time histories

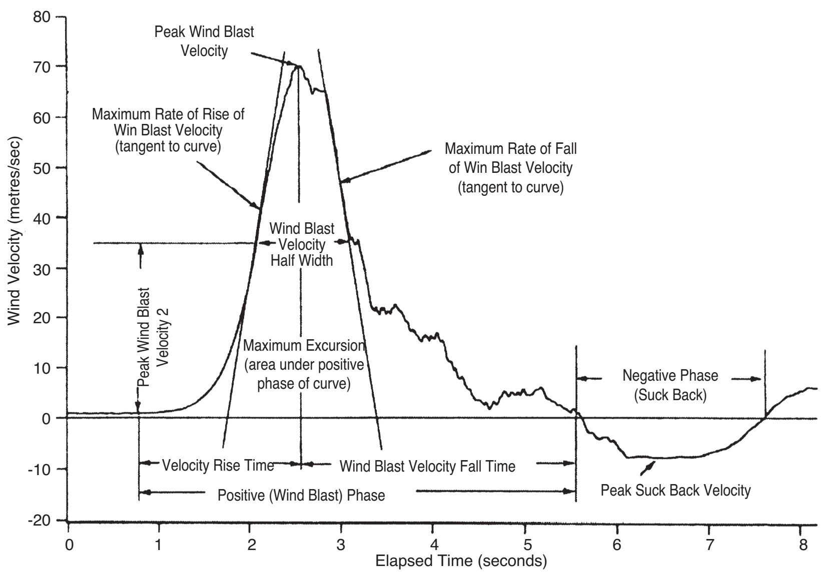

Figure 3—Typical wind velocity time histories

- The peak overpressure is always greater than the peak underpressure. Overpressure time histories are similar, but not identical, for equivalent locations in both gateroads in the near field close to the face ends
- The overpressure pulse in the maingate attenuates with distance as it propagates outbye. The attenuation is predominantly as a result of air viscosity, although other factors, such as flow through cut-throughs (spreading) contribute
- The duration of the positive overpressure phase increases slightly as the pressure pulse propagates outbye due, perhaps, to dispersion, i.e. the tendency for different frequencies to travel at slightly different velocities. Duration also increases with intensity of the event and could be related to the caving mechanism, interaction of the roof element with the air below, the panel and goaf geometry
- From arrival times of the overpressure pulse at the measuring locations in the maingate near to the face and at the outbye location, the celerity or the rate of propagation of the event may be calculated. For weak shocks or pressure pulses the celerity equals the speed of sound
- There appears to be an upper bound to peak overpressure with increasing goaf/fall area
- Wind velocity time histories also follow the same overall shape as the overpressure time histories, with rapid rise to a maximum and then a sudden reversal into the suck back phase
- Peak air velocity in the direction away from the fall is always greater than the peak 'suck back' velocity
- Wind blasts with peak wind velocities greater than 20 m/s are considered significant as they can result in injuries to mine personnel according to Fowler and Torabi[3]. Hurricane level wind speeds have been monitored in mine roadways but not exceeding Mach one values, excluding the possibility of normal shock conditions developing in roadways
- While the overpressure time histories for wind blast events show a resemblance to characteristics of weak shock waves, the wind velocities monitored are often much higher than predicted values based on the Rankine–Hugoniot relationship between peak particle velocity and overpressures. Departure from theoretical values is higher for locations nearer to the goaf. However, possibility of shock conditions developing in the goaf cannot be ruled out
- Occasionally, the suck back phase with negative velocities (towards goaf) has not been recorded. This could be due to blockage of air return paths to the goaf, truncation of the velocity record prior to the event being over, flow being affected by sequential falls and associated pressure pulses, and also orientation of the velocity pods not suitable for reverse flow monitoring
- The wind blast parameters associated with significant wind blast events at Newstan are only a third of the values compared to those at Moonee as shown in Table I.[3–5]
- Empirical scaling laws for wind blasts, based on explosive equivalency, could not be well defined due to the unpredictability and the variability associated with the roof fall, the caving mechanism in the goaf and the geotechnical properties of the coal measures involved in the caving process.

Relationship between overpressure and wind velocity time histories

In the case of an ideal explosive shock front, the relationship between peak particle velocity 'blast wind' and peak overpressure can be derived from the Rankine-Hugoniot equations. As stated in Kinney[10] the relationship for low overpressures is effectively linear and can be stated by the following equation for explosive shock in dry air at 21 °C at sea level:

$$\text{Peak particle velocity (in m/s)} = 2.17 \times \text{peak over pressure (in kPa)} \quad [1]$$

The parameters show a tentative linear relationship at Pod no. 4 location, outbye in maingate, for Class M falls, as shown in Figure 4 with the following equation:

$$\text{Peak particle velocity (in m/s)} = 3.75 \times \text{peak overpressure (in kPa)} \quad [2]$$

At Pod no. 2 location the relationship as shown in Figure 5 is given by the following equation:

$$\text{Peak particle velocity (in m/s)} = 4.11 \times \text{peak overpressure (in kPa)} \quad [3]$$

It may be noted that at Pod no. 2 location the roadway cross–section is constricted due to the mining equipment, including the DCB cover over which the Pod was mounted.

Comparison of wind blasts at Newstan Colliery with Moonee Colliery

The wind blast events at Newstan were localized and confined to where the massive strata were within twice the extraction thickness and bridged the panel. In contrast, at Moonee, incidence of large goaf falls and associated wind blasts continued for virtually the whole length of the longwall panels other than a few localized faulted zones where 'regular caving' took place. The wind blast parameters associated with significant wind blast events at Newstan are nearly a third in magnitude when compared to those at Moonee. The relationships between the wind blast parameters exhibit similar trends at both collieries. Although

Table I

Wind blast parameters at Newstan and Moonee Collieries

Parameter	Maximum value	
	Newstan	Moonee
Peak air velocity	40 m/s	123 m/s
Rate of rise of velocity	50 m/s/s	138 m/s/s
Peak over pressure	10 kPa	34.5 kPa
Rate of rise of pressure	25 kPa/s	36.4 kPa/s
Impulse	20 kPa.s	89 kPa.s
Maximum Excursion (air flow distance)	67.2 m	184 m

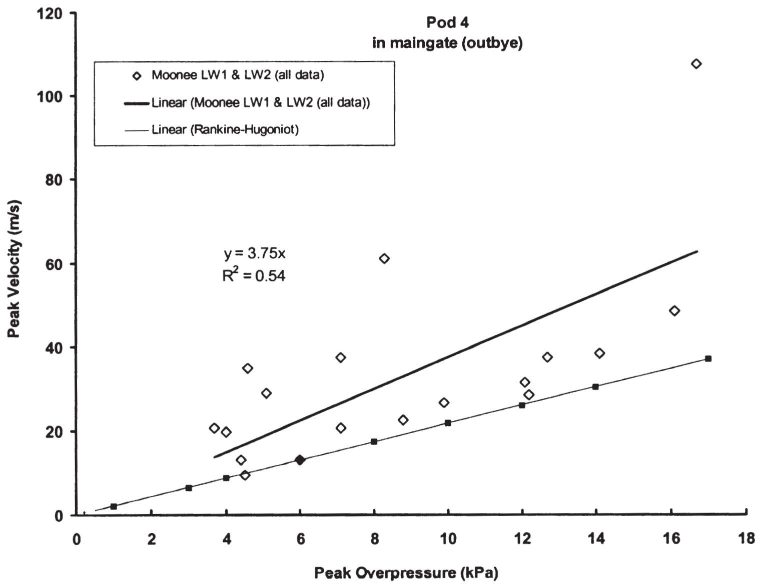

Figure 4—Relationship between peak velocity and peak overpressure

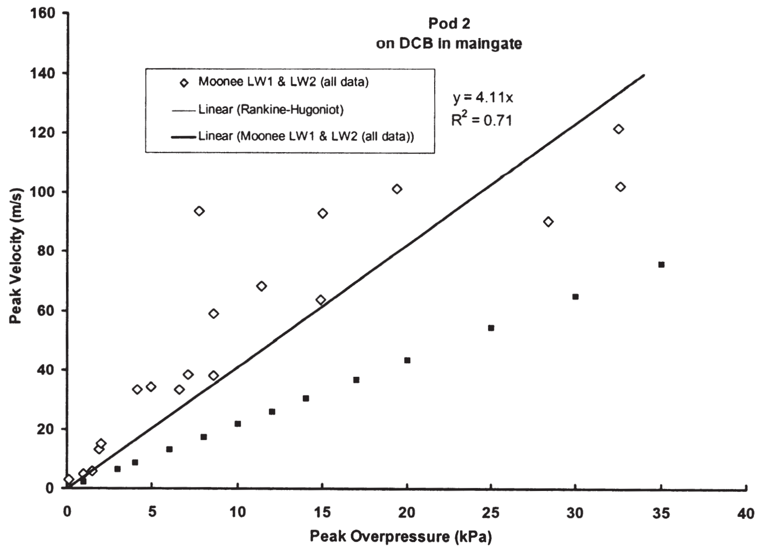

Figure 5—Relationship between peak velocity and peak overpressure near to the longwall face

the goaf at Newstan was not accessible due to the caving of the immediate roof, the spacing of the events, especially at LW8 panel, suggests that like Moonee, large spans of roof were involved. The lower magnitude of the wind blast parameters are consequently due to the following facts: the fall of the roof element was cushioned by the caved immediate roof, lesser volume of air being displaced from the void and also the higher resistance to flow due to partial packing of the goaf by the prior caving of immediate roof.

Impact of hydrofracturing on wind blasts

The Moonee field trials have also allowed the effect upon wind blast intensity of hydrofracturing, including the impact of the resulting reduced caving area, to be quantified. The goaf falls may be divided into three classes:

- Falls solely attributed to mining (Class M)
- Falls induced by hydrofracturing an area of the standing goaf (Class F)
- Falls induced by further mining after hydrofracturing an area of standing goaf (Class C).

The areas of standing goaf that fell during the mining of longwall panels nos. 1 to 4 B varied widely up to a maximum of 31, 560 square metres. The apparent overall area of the fallen roof was determined by inspection several hours after the fall or falls had occurred. In the case of a single, simple wind blast event, the roof may be inferred to have fallen as a 'monolithic piston', and the overall fall area has been assigned in the analysis to the appropriate event. However, wind blast and microseismic evidence suggest that on occasion, the roof failed in a sequential or progressive mode or even in a sequence of separate simple falls. In this case the overall fall area has, of necessity, been assigned to the event with the highest recorded wind blast intensity. Only in a few events was there evidence of the height of falling roof element, and so the thickness of the falling roof element is not included in the analysis as the data was insufficient. The analysis could not take into account the mode of failure of the roof rocks. Another shortcoming has to do with the plan geometry of the fall with respect to the workings with further potential pathways for wind blast over the goaf in an inbye direction. On many occasions, maingate and tailgate cut-throughs intersected the goaf at the time of the fall. As a result of the variations in geometry, the intensity of wind blast in maingate at Pod no. 2 location was not always a good descriptor of the magnitude of the wind blast.

Figure 6 illustrates the relationship between peak overpressure and overall roof fall area for the three classes of falls. The data is restricted to those roof falls for which the area was less than 10000 square metres. Consequently, although all data from class F subset is utilized, for Classes M and C selected data is used. Only Class M subset reveals a high positive correlation. It should be noted, however, that the scatter of the data is such that the maximum peak overpressure is of the order of twice the mean. McPherson[11] proposed an analytical model for determining peak overpressures in the goaf, taking into account the air leakage through leakage paths connected to the goaf. The rate at which the air mass will be displaced will depend on the pressure difference, and the total resistance of the leakage paths. Based on the square law the equation can be stated as:

$$\frac{dm_a}{dt} = \left[\frac{(P - P_o)}{R_t}\rho_a\right]^{0.5} \qquad [4]$$

where,

P, P_o = air pressure below and over the falling block, respectively (Pa)

ρ_a = air density, (kg/m^3)

m_a = air mass, (kg)

R_t = total resistance, (m^{-4}).

The loss of air would lead to a corresponding loss of pressure following general gas laws:

$$dP = dm_a \frac{RT}{v} \qquad [5]$$

where,

R = gas constant (287.04 J/Kg°C for air),

v = volume of space beneath the falling block, (m^3).

The numerical solution of the above equations by McPherson[11] using a time stepping procedure revealed that the thicker the falling block, the higher the peak pressure values. In the goaf, the pressure reaches a peak and then converges to a value corresponding to the weight of the falling block ($\rho_r g h_r$). However, the temperature, after an initial slow rate of rise, escalates rapidly towards the end of the descent of the block (towards the last 0.1 metre). This is due to more work being done against a decreasing mass of air under the descending roof. Another interesting outcome of the simulation was that initial peak pressures and rate of temperature rise tend to increase with decreasing roof dimensions. The explanation lies in the fact that air escapes more readily from beneath the falling roof in smaller plan areas, resulting in a higher rate of descent. However, the simulation was unstable for smaller plan areas. Even at Moonee Colliery there is also some evidence that for some falls of small plan area, of the order of a few hundred square metres, the peak overpressure may be several times the mean.

Figure 7 illustrates the relationship between impulse and overall roof fall area for all three classes of fall. All of the data from all three subsets is utilized. Again, as in previous figure, the regression line for Class M subset reveals a high correlation. Again, it should be noted that for Class F and Class C falls the scatter of data is such that the maximum impulse is of the order of three times the mean.

Figure 8 illustrates the relationships between peak wind blast velocity and overall roof fall area for the three classes of fall. The data is restricted to those roof falls for which the area was less than 10000 square metres. Consequently,

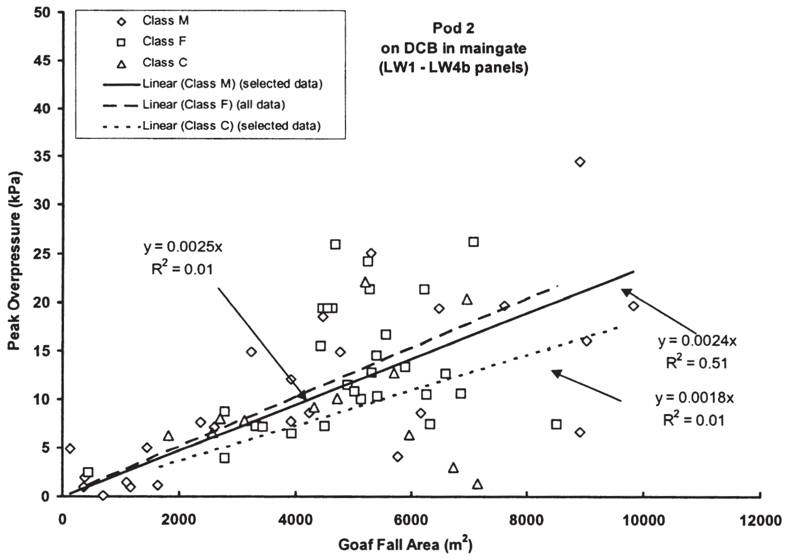

Figure 6—Relationship between peak overpressure and goaf fall area

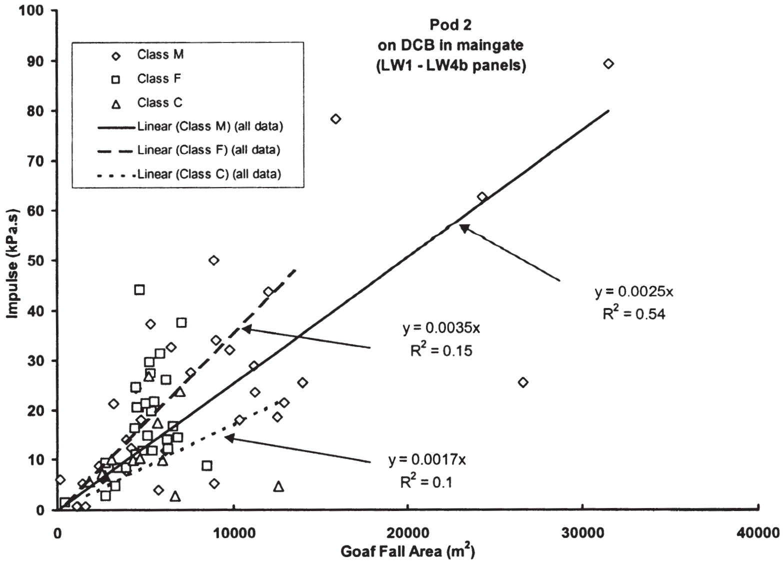

Figure 7—Relationship between impulse and goaf fall area

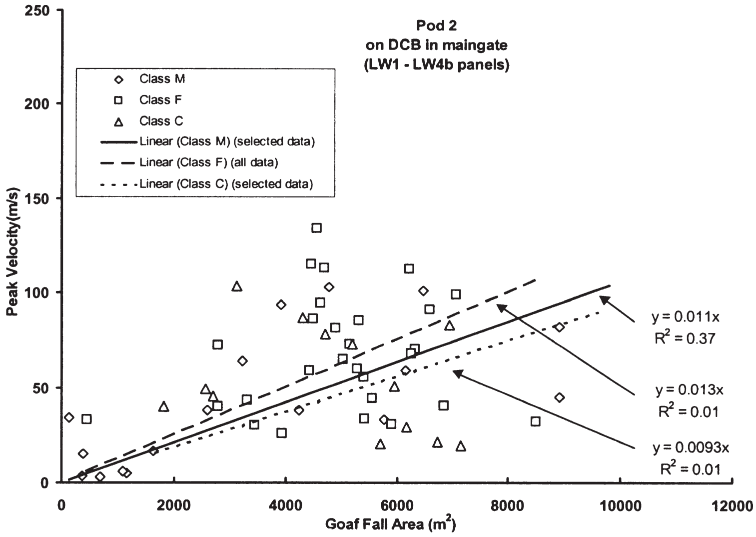

Figure 8—Relationship between peak velocity and goaf fall area

although all data from the Class F subset is utilized, for Classes M and C selected data is used. Although the data in Figure 7 are positively correlated, only the regression line for the Class M subset reveals a 'fair' correlation. It should be noted, however, that the scatter of data is such that the maximum peak wind blast velocity is of the order of three times the mean. There is also some evidence that for falls of small plan area, of the order of a few hundred square metres, the peak wind blast velocity may be several times the mean. Again, it should be noted that for Class F and Class C falls the scatter of data is such that the maximum peak wind blast velocity is more than twice the mean.

Figure 9 illustrates the relationship between maximum excursion and overall roof fall area for all three classes of fall. All the data from all three subsets is utilized. The regression line for all the subsets reveals only a 'weak' correlation. It should be noted, however, that the scatter of data is such that the maximum value of the maximum excursion is of the order of five times the mean. There is also some evidence that for falls of small plan area, of the order of a few hundred square metres, the maximum excursion may be several times that indicated by the regression equation.

Table II summarizes the relationships between the mean normalized values of each of the four key parameters that are considered to be of significance in characterizing wind blast intensity for each of the three classes of roof fall. It is seen that after the values of the four parameters that characterize wind blast intensity have been normalized with respect to overall roof fall area, their means still differ. Comparing Class M and Class F roof falls, the differences between the mean normalized values of peak overpressure and peak wind blast velocity are small and probably not significant. However, the differences between the values of impulse and maximum excursion for the two classes of fall are greater and may be of

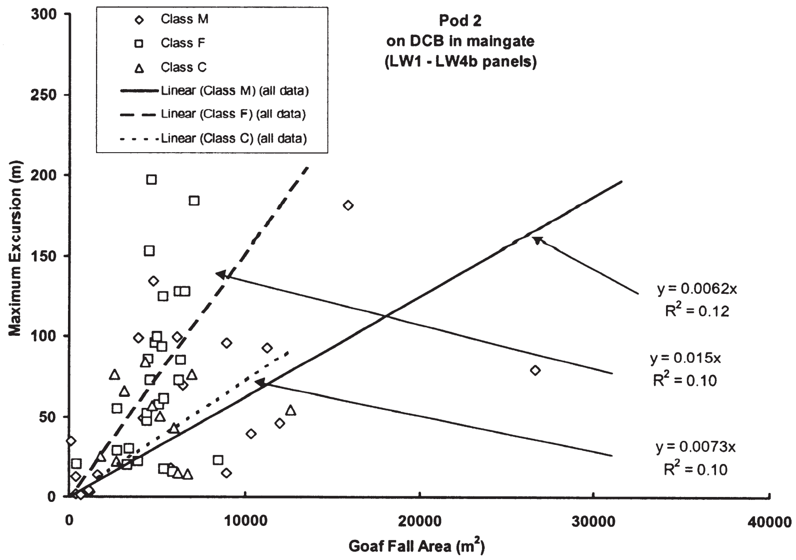

Figure 9—Relationship between maximum excursion and goaf fall area

Table II

Comparison of mean normalized values of key wind blast parameters for each class of roof fall

Wind blast parameter	Class of roof fall			Comments
	M	F	C	
Mean normalized peak overpressure (kPa/1 000 m²)	2.4	2.5	1.8	Utilizes data for all falls of less than 10000 m²
Mean normalized impulse (kPa.s/1000 m²)	2.5	3.5	1.7	Utilizes all data
Mean normalized peak wind blast velocity (m/s/1 000 m²)	11	13	9.3	Utilizes data for all falls of less than 10000 m²
Mean normalized maximum excursion (m/1 000 m²)	6.2	15	7.3	Utilizes all data

significance. Taking all four parameters into account, the data suggests that, for a given overall area of standing goaf, roof falls induced by hydrofracturing possibly give rise to more intense wind blasts, on average, than do falls solely attributable to mining. Comparing Class M and Class C roof falls, the differences between the mean normalized values of peak wind blast velocity and maximum excursion are small and probably not significant. However, the differences between the values of peak overpressure and impulse for the two classes of fall are much greater and are probably of significance. Taking all four parameters into account, the data suggests that, for a given overall area of standing goaf, roof falls induced by further mining after hydrofracturing probably give rise to less intense wind blasts, on average, than do falls solely attributable to mining.

Conclusions about the role of hydrofracturing in wind blast hazard mitigation

According to Wischusen[9] the primary reason for implementing a programme of hydrofracturing in wind blast prone coalmines is to induce 'caving on demand', i.e. to cause an area of standing goaf to collapse at a time determined by mine management rather than by the vagaries of nature. This enables the wind blast hazard to be reduced or eliminated by ensuring that all personnel are outside the zone of wind blast influence at the time of the roof fall. The extent of the zone of influence may be determined by a programme of measurement of wind blast intensity. The extensive programme of monitoring at Moonee Colliery has revealed, for example, that wind blast intensity is approximately halved every 500 metres along the maingate (belt road) and companion roadway (travelling road). For an overall area of 6 000 square metres, typical of a hydrofracturing induced goaf fall, the mean peak wind blast velocity in the maingate near to the face line is predicted to be approximately 80 metres per second. Consequently, neglecting scatter in the data, the zone of influence may be calculated to extend of the order of 1 000 metres outbye. A second effect of hydrofracturing is to reduce the overall area of standing goaf that may fail and, consequently, induce a wind blast. The effect of reducing the area is to reduce wind blast intensity. It may be calculated that, in the particular case of longwall panels nos. 1 to 4B at Moonee Colliery, the effect of a reduction in overall fall area from 30000 square metres, the approximate area of the largest mining induced goaf fall, to 6 000 square metres, the area of a typical hydrofracturing induced goaf fall, would be to reduce mean wind blast intensity by more than half. The mean overall mining induced roof fall area, which corresponds to a peak wind blast velocity of 20 metres per second, i.e a significant wind blast, is of the order of 2 000 square metres. It should be noted, however, that scatter in the data there may be particular circumstances where the threshold area is much less than 2 000 square metres. There are tentative indications that this may apply, in the particular case of Moonee Colliery, to wind blasts generated by the eventual failure of triangular areas of roof which have sometimes 'hung up' near the face ends after large area falls. For, this reason, the Moonee Colliery wind blast management plan regards such triangles as a potential wind blast hazard when their area exceeds 500 square metres. There are also tentative indications from the programme of monitoring at Moonee Colliery of a decrease in intensity per unit area for wind blasts resulting from roof falls induced by further mining after hydrofracturing when compared with those solely attributable to mining. It has been demonstrated, during the mining of longwall panels nos. 3, 4A and 4B at Moonee Colliery, that hydrofracturing is an effective intervention procedure.

Acknowledgments

The authors acknowledge the help and facilities extended by Prof. J.M. Galvin and Prof. Bruce Hebblewhite of the School of Mining Engineering, UNSW, the staff and management of Moonee Colliery and Australian Coal Research Limited for providing financial support for the project as part of the Australian Coal Association Research Programme.

References

1. BOCKING, M., HOWES, M., and WEBER, C. 1988, Palaeochannel development in the Moon Island Beach Sub-Group of the Newcastle Coal Measures' *Advances in the Study of the Sydney Basin, Proc. 22nd Newcastle Symposium*, Newcastle, NSW, 15-17 April ,publ. Newcastle: University of Newcastle. 1988. pp. 37–45.
2. FOWLER, J.C.W. *The Dynamics of Wind Blasts in Underground Coal Mines, Phase 1—Interim Project Report.* The University of New South Wales School of Mines, Sydney, ISBN 0 7334 1550 4. 1977.
3. FOWLER, J.C.W. and TORABI, S.R. *The Dynamics of Wind Blasts in Underground Coal Mines, Phase 3*—Project Report. The University of New South Wales School of Mines, Sydney, ISBN 0 7334 1551 2. 1997.
4. FOWLER, J.C.W. and SHARMA, P. *The Dynamics of Wind Blasts in Underground Coal Mines, Final Project Repor.* The University of New South Wales School of Mining Engineering, Sydney, ISBN 0 7334 0700 5. 2000.
5. FOWLER, J.C.W. and SHARMA, P. *Reducing the Hazard of Wind Blast in Underground Coal Mines—Final Project Report*. The University of New South Wales, School of Mining Engineering, Sydney, ISBN 0 7334 1817 1. 2001.
6. EDWARDS, J.L. Seismic monitoring for wind blast prediction, *Seminar on Mine Seismicity and Rockburst Management in Underground Mines*, Australian Centre for Geomechanics, 3–4 September 1998, Section 12, 1998. pp. 1–4.
7. ANDERSON, I. Endeavour Colliery explosion investigation, *Minfo*, no. 54, 1997. pp. 12–14.
8. Jeffrey, R.G. and Mills, K.W. Hydraulic fracturing applied to inducing longwall coal mine goaf falls, *Proc. 4th North American Rock Mechanics Symposium*, 31 July–3 August 2000, Rotterdam, Balkema. 2000. pp. 45–50.
9. WISCHUSEN, R. Strategy leads to caving on demand, *Australia's Longwalls*, September, 1999. p. 28.
10. KINNEY, G.L. *Explosive shocks in air*, The Macmillan Company, New York, 1962. 198 pp.
11. MCPHERSON, M.J., WU, X.L., and KARFAKIS, M.G. 1995, The compression of air under large falls of roof, *Proc. 26th International Conference of Safety in Mines Research Institutes*, Katowice, Poland, Sept 1995. Central Mining Institute. 1995. pp. 1455–159. ◆