The paper utilizes case histories of blasting in Australian open pit mines to demonstrate techniques that have been used to control airblast to applicable limits.

INTRODUCTION

For many years Australian regulatory authorities have enforced some of the world's strictest environmental airblast limits. With substantial penalties being applied for exceedences, considerable research has been conducted to understand the causes of airblast and the development of control techniques to ensure compliance.

In most Australian states, airblast levels at houses and other sensitive sites, such as hospitals and schools, are not to exceed 115 dBL for 95% of blasts in a 12 month period and not to exceed 120 dBL for any blast. Blasting operations must, therefore, be closely controlled during all facets of design, drilling and loading.

Compliance with the airblast limits is equally challenging for:
- Quarries in urban areas with houses closer than 200 metres.
- Open cut coal mines in semi-rural areas cast blasting 70 metres high faces with houses closer than 2 km.

This paper discusses some of the techniques that have been developed and how they have been used to control airblast. The techniques are used in:
- Analysis.
- Design.
- Loading.

THE NATURE OF AIRBLAST

Airblast is energy that results from blasting that is in the form of Compressional waves travelling through the air at the speed of sound. The airblast from a single blasthole has a characteristic ‘N’ wave form, consisting of an initial positive phase followed by a negative phase and then several minor fluctuations which, for practical effect, may be ignored (see Figure 1).
The 'N' wave shape varies depending on whether it is recorded in front of a free vertical face or behind a free face. Characteristically the negative phase has lower pressure than the positive phase but has a longer duration. For the purposes of understanding airblast, the 'N' wave may be synthesised and considers only the first cycle (see Figure 2).

The airblast signal from a multi-holed blast results from the combining of the waves from individual blastholes in time and/or distance.

**FACTORS EFFECTING AIRBLAST**

The airblast resulting from a blast is influenced by the following factors:

- Charge mass - airblast increases with charge mass increase.
- Confinement - burden, stemming height and stemming material - airblast reduces with increased confinement.
- Distance and direction relative to blast faces - airblast is higher in front of a free face.
- Hole diameter and face height - hole diameter and face height determine charge mass.
- Drilling design, burden, spacing and initiation sequence and direction.
- Topographic shielding.
- Meteorological conditions.
Diagnostic Wavetrace Examination

The simplest analysis that can be conducted in order to have an understanding of airblast is an examination of the wavetrace. Detailed examination will show:

- If the peak airblast statement is due to wind, a blast or some other event.
- Where in the blast the peak occurs, i.e. beginning, middle or end of the wavetrace.
- If the peak is from positive or negative pressure.

A series of wavetraces have been included to demonstrate how some common observations can lead to probable conclusions:

(a) Wind event for entire recording time covering airblast arrival.
(b) Wind event unrelated to blasting.
(c) Wind event mimicking airblast.
(d) Airblast positive peak at beginning of blast.
(e) Airblast positive peak in middle of blast.
(f) Airblast negative peak at finish of blast.
(g) Airblast - wavefront reinforcement (cast blast).
(h) Airblast - unstemmed pre-split blast.
(i) Airblast - multi rowed (choke) blast.

Wind event for entire recording time covering airblast arrival

A wavetrace that continues for the entire recording time or for longer than the blast duration is indicative of wind (see Figure 3a). The microphone responds to the change of pressure and cannot distinguish between changes of pressure due to the passing of Compressional waves or to the movement of air particles by the wind. The actual airblast arrival period during a wind event can be determined from wave arrival analysis, which equates the relative arrival times from distance and characteristic wave velocities.

Wind event unrelated to blasting

If an airblast trigger is used to record the vibration, the wind may exceed the trigger setting. Figure 3b shows such an event where the peak airblast was 134 dBL. This can be distinguished from airblast because the wind characteristically begins with a negative phase (but not always. This is easily distinguishable from a blast event if the time the event was recorded was not the blast firing time.

Wind event mimicking airblast

Figure 3c shows a wavetrace with a peak level of 133 dBL that was a wind event with characteristics of airblast, i.e. positive initial pulse. Comparison of recording time and blast firing time is useful for discounting such events.

Airblast positive peak at beginning of blast

The peak airblast occurring at the very beginning of the blast (see Figure 3d) is an indication of:

- A relatively under-confined blasthole at the initiation point.
- Blastholes are uniformly confined but, after the initial wavefronts positively reinforce, the positive and negative pressure phases cancel (see section on 'Seed Waveform Modelling').
- Wavefront reinforcement (see later section).

Airblast positive peak in middle of blast

The peak airblast occurring during the blast event (see Figure 3e) is an indication that one (or more) blastholes has been under-confined (stemming or burden) and the emission has greatly
exceeded the remainder of the blast. This occurrence is often visible on video replays as a high velocity white emission that may only be present for a few frames. Lower velocity grey or black emissions may look impressive but do not necessarily result in high airblast levels.

**Airblast negative peak at finish of blast**

Peak airblast results from a negative trough either during the wavetrace or at the end (see Figure 3f). The reason for this is demonstrated by the seed waveform model and results if the positive pressure from holes firing ceases too quickly and the negative pressures build up to become the peak. The solution to this problem if the trough exceeds permitted levels too often is to decelerate the control row for the last 4-6 holes, ie. if the control row delay is 17 ms, towards the end of the row use 25 ms for 2 holes and then 42 ms for the last 2-4 holes.

![Figure 3a – Wind event for entire recording time covering airblast arrival](image)

![Figure 3b – Typical wind event unrelated to blasting](image)

![Figure 3c – Wind event mimicking airblast](image)
Airblast – unstemmed pre-split blast

It is standard practise at some remote coal mines to fire pre-split holes without stemming. The resulting airblast is almost the equivalent to unconfined surface charges. The practice is unsuitable in closely settled areas when compliance with airblast limits is required. Figure 3g is characteristic of airblast with a peak of 119.0 dBL measured at a distance of 10.25 km. The waveform is an 'N' wave similar to that from a single hole.
Airblast – multi-rowed (choke) blast

In multi-rowed choked blasts, such as inter-burden and coal blasts, where the blast is fired row by row with detonating cord and an inter-row delay, the resulting airblast from each row may be identified, as shown in Figure 3h.

Basic Airblast Emission Models

Terrock have developed a model that introduces ‘confinement’ and has proven useful for the analysis and prediction of airblast by relating it to charge mass, distance, hole diameter and burden (for burden controlled blasts) or stemming height (for stemming controlled blasts).

If the airblast from explosions enters the atmosphere through a vertical face, then burden conditions are the controlling factor (burden controlled blasts) or, alternatively, if the energy enters the atmosphere through the collar region, then stemming conditions are the controlling factor (stemming controlled blasts). Burden controlled blasts produce higher airblast in front of the face than behind the face. Stemming controlled blasts produce equal airblast in all directions.

The model in its simple form is:

Burden controlled:

\[ D_{120} = \left( \frac{k_b \times d}{B} \right)^{2.5} \cdot \frac{3}{\sqrt{m}} \]

Stemming controlled:

\[ D_{120} = \left( \frac{k_s \times d}{SH} \right)^{2.5} \cdot \frac{3}{\sqrt{m}} \]

where:

- \( D_{120} \) = distance to the 120 dBL contour
- \( d \) = hole diameter (mm)
- \( B \) = burden (mm)
- \( SH \) = stemming height (mm)
- \( m \) = charge mass per delay (kg)
- \( k_b \) = a calibration factor typically ranging from 150-250
- \( k_s \) = a calibration factor typically ranging from 80-180

The calibration factors are determined by site measurement. A typical directional range of \( k_b \) for burden controlled blasts is shown in Figure 4. The limit to either model is the scaled distance formula for unconfined charges.

ie.

\[ P = 185 \left( \frac{D}{\sqrt{m}} \right)^{-1.2} \]

where:

- \( P \) = pressure (kPa)
- \( D \) = distance from the blast (m)
Airblast is a function of the cube root of the charge mass. Control of airblast by reducing the charge mass is not very efficient. Increasing confinement is usually much more effective. This is demonstrated in Figure 5, a graph we have found useful for demonstrating how airblast can be dramatically increased by lapses during loading and can also be used for environmental blast design.

Figure 5 – The effect of changes to the basic airblast emission directly in front of a blast for quarry blasts (102 mm diameter and 110 kg) and coal overburden blasts (270 mm diameter and 1000 kg)
Wave Arrival (P, S, R, A) Analysis

In interpreting a wavetrace, the actual airblast arrival may be masked by wind or the peak air vibration reading may be due to wind. It is often useful to be able to separate airblast from wind. If the distance to the blast is known, the relative velocities of the P, S and R waves and airblast waves may be used to determine the arrival times of each on a wavetrace. On the macro scale, we have found that the following velocities are useful for determining the comparative arrivals:

- V Compressional: 2200 m/s
- V Shear: 1200 m/s
- V Raleigh: 750 m/s
- V Air: 340 m/s

The wave types separate with distance and frequently confirmation of the wave velocities is shown by a change of wave motion at the arrival of a different wave type (see Figure 6).

![Figure 6 - Typical reinforcement wavefront diagram – 3919 metres from blast – 118.5 dBL](image)

Wavefront Reinforcement Modelling

If the delay between adjacent blastholes is not sufficiently greater than the airblast travel time between them, then airblast levels will be increased by wavefront reinforcement. The direction of the reinforcement depends on the drilling pattern, the time delay and initiation sequence.

A typical reinforcement wavefront diagram is shown in Figure 7 For burden controlled blasts, the front row only needs to be considered. For stemming controlled blasts, the back rows also need to be considered. Wavefront reinforcement can increase airblast levels by 20 dBL or more.
Airblast - wavefront reinforcement (cast blast)

The wavetrace recorded in the direction of reinforcement is an 'N' wave with a long tail (see Figure 8). This is characteristic airblast wavetrace from a throw blast in a zone of major reinforcement. In burden controlled conditions, the airblast from successive rows may be insignificant because the energy is absorbed within the moving rock mass. The reinforcement diagram shows the relative wavefront arrivals.

By reversing the direction of initiation, the airblast can often be steered away from airblast sensitive sites. If this technique will increase airblast at another sensitive site, the direction of the reinforcement can be adjusted by using a different control row delay, e.g. 25 ms or 42 ms delay instead of 17 ms delay.

Seed waveform analysis

Seed waveform techniques coupled with wavefront modelling are useful for understanding particular wavetraces that require interpretation.
Figure 9a shows a synthetic wave. Figure 9b shows the waveform that results from combining 10 seed waves at 17 ms separation. After 5 waves, the positive phase of the 'N' waves are cancelled by the negative phase until the conclusion when the negative phases combine to form a large trough.

Figure 9c shows the waveform that results from combining 30 seed waves at 17 ms separation. The ends of the waveform are similar but the mid signal near '0' Pascals has been extended.

Figure 9d shows the comparison between a synthetic seed waveform and an actual wavetrace. The negative trough at the end is sometimes the peak airblast. The airblast from the second and third rows does not contribute significantly to airblast levels.

Figures 9e and 9f show that the magnitude of the negative trough can be reduced by a longer
delay sequence, that is especially effective at the end of the front row (slow finish).

Figure 9e - Combining 10 seed waveforms @ 25 ms apart

Figure 9f - Combining 10 seed waveforms @ 34 ms apart

Regression analysis

Airblast attenuates at 9 dBL with doubling of distance. Plotting of the airblast measurements on a log normal array indicates the relativity at different distances. The peak air vibration levels recorded from a blast are shown in Table 1.

<table>
<thead>
<tr>
<th>Station</th>
<th>Distance (m)</th>
<th>Peak Air Vibration (dBL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>1651</td>
<td>102.8</td>
</tr>
<tr>
<td>B</td>
<td>2488</td>
<td>104.2</td>
</tr>
<tr>
<td>H</td>
<td>4121</td>
<td>92.9</td>
</tr>
<tr>
<td>N</td>
<td>4407</td>
<td>98.6</td>
</tr>
<tr>
<td>P</td>
<td>4433</td>
<td>95.1</td>
</tr>
</tbody>
</table>

The regression analysis for this data is shown in Figure 10. The 8 dBL wide data envelope reflects the variation in airblast that would be expected because of variations in topography (shielding) and minor directional variation from the initiation sequence in a paddock blast (no free face).
Topography

The topography of the area surrounding a blast can provide shielding, which effectively reduces airblast levels. The shielding terminology is demonstrated in Figure 11 and the quantification we have determined is shown in Figure 12.

![Figure 11 - Shielding terminology](image1)

![Figure 12 – Secondary shielding relationships](image2)

BLAST DESIGN TECHNIQUES

Techniques to control airblast levels include:

- Soft start.
- Slow finish.
- Confinement design – minimum burden and stemming height.
- Initiation sequence.
- Meteorological assessment.
**Soft start**

If the wavetraces at a sensitive site show that the peak airblast consistently occurs at the beginning of the wavetrace, as shown in Figure 3d, and a non-reinforcing initiation pattern is used, then 'soft start' will assist in lowering airblast levels. As demonstrated by the seed waveform analysis (Figure 9d), the initial peak can be reduced by increasing the confinement of the first holes fired. This can be achieved by:

- Deliberately increasing the burden.
- Reducing the charge mass per length of blasthole by the use of either packed explosive or a less dense product, eg. ANFO instead of slurry. The object is to reduce the initial peak to the level of the remainder of the blast so that even airblast wavetrace is achieved (see Figure 13).

![Figure 13 – Airblast wavetrace taken 350 metres in front of a well managed quarry blast. Pressure pulses correspond closely to nominal front row firing times. Trough at finish may be reduced by slow finish.](image)

**Slow finish**

If the peak airblast is consistently from a negative trough at the end of the blast, as shown in Figure 3f, the timing at the end of the blast may require decelerating, ie. slow down the timing at the end of the blast. This has had the added benefit of reducing the damage to the resulting end wall.

**Environmental airblast design**

If the empirical models are calibrated for particular sites, the minimum burdens (or stemming heights) to achieve environmental airblast limits can be determined and included in the loading specifications. this is particularly useful if hole profiles produced from face surveying and bore-tracking are available. Decks and light loading can be designed and specified through underburdened sections of blasthole.

**Initiation sequence**

In sensitive blasting locations, it is essential that a non-reinforcing initiation sequence is designed and specified. The 8 millisecond time window limit criteria will give no protection against reinforcement and resulting high airblast levels. In fact, there is evidence that some blasts designed with an 8 millisecond time window criteria will actually result in increased airblast (ref. Richards, A B and Moore, A J (2003). The Eight Millisecond Time Window Myth, presented at The 5th Large Open Pit Conference (The Australasian Institute of Mining and Metallurgy: Kalgoorlie, Australia).
**Meteorological assessment**

When a blast is fired, the airblast travels as Compressional waves outwards from the blast at the speed of sound. The speed of the wavefront is then affected by atmospheric conditions. The effect of wind and air temperature can be demonstrated if the airblast is considered as a series of sound 'rays' radiating from the blast. The airblast level at the surface is increased if higher trajectory sound rays are refracted back towards the surface and are coincident with the arrival of lower trajectory rays. Airblast levels in excess of 20 dBL higher than the normal airblast levels have been recorded due to meteorological reinforcement.

The meteorological conditions that may result in reinforcement are:

- Wind velocity increasing with altitude.
- Temperature inversion – a layer of warmer air.
- The combination of previous two.

The effect of meteorology can be accurately modelled using the Perkins model from the Bureau of Acoustic Research if the wind speed, direction and air temperature at altitudes up to about 1000 metres are known near blast time. Usually the altitudinal data is a 'best guess' interpretation of surface and regional meteorology. A current study, funded by the Australian Coal Association Research Project (ACARP), Project No. C9040, 'Structure Response to Blast Vibration', will improve the quality of data.

**LOADING TECHNIQUES**

Blasts may be designed to achieve environmental airblast limits and the required specifications and performance standards conveyed to the loading crew. **Figure 5** clearly shows the dramatic increase in airblast that may result from inadvertent lapses during loading. It is most important to measure and record data such as charge mass loaded, stemming height, holes blocked or lost, deviations from blast design and initiation for future reference or to enable detailed analysis if high airblast levels result. We also recommend video recording of all blasts. Slow motion replays are invaluable for real time comparison of the blast and face movement with the resulting wave when look for under-burdening, cratering and rifling.

The co-operation of the loading crew is essential in controlling airblast levels. Incorrect loading of only one blasthole can be all it takes to compromise hundreds of holes loaded correctly and to exceed airblast levels. The importance of the loading job should be continually reinforced to the shotfiring crew in sensitive blasting situations.

**CASE HISTORIES**

A series of case histories are presented to demonstrate how the different techniques may be used to gain an understanding of what is happening and what can be used to control airblast from future blasts.
Case History No. 1

Table 2 - Peak air vibration readings

<table>
<thead>
<tr>
<th>Station</th>
<th>Distance (m)</th>
<th>Peak Air Vibration (dBL)</th>
<th>Conclusions following Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>1967</td>
<td>111.8</td>
<td>airblast</td>
</tr>
<tr>
<td>C</td>
<td>3498</td>
<td>114.7</td>
<td>wind</td>
</tr>
<tr>
<td>H</td>
<td>4335</td>
<td>104.5</td>
<td>airblast</td>
</tr>
<tr>
<td>K</td>
<td>4566</td>
<td>124.3*</td>
<td>wind</td>
</tr>
<tr>
<td>T</td>
<td>5459</td>
<td>106.2</td>
<td>wind</td>
</tr>
<tr>
<td>M</td>
<td>6119</td>
<td>95.1</td>
<td>wind</td>
</tr>
<tr>
<td>A</td>
<td>6879</td>
<td>110.4</td>
<td>wind</td>
</tr>
</tbody>
</table>

* in excess of environmental licence condition of 115 dBL

Figure 14 – Location plan

Figure 15 - P, S, R, A analysis – station K
Comment

Elevated air vibration reading at station K was due to wind. The estimated airblast was estimated to be 101 dBL.

Case History No. 2

Table 3 - Peak air vibration readings

<table>
<thead>
<tr>
<th>Station</th>
<th>Distance (m)</th>
<th>Peak Air Vibration (dBL)</th>
<th>Conclusions following Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>2167</td>
<td>116.2</td>
<td>airblast</td>
</tr>
<tr>
<td>C</td>
<td>3766</td>
<td>107.7</td>
<td>airblast</td>
</tr>
<tr>
<td>H</td>
<td>4640</td>
<td>104.7</td>
<td>airblast</td>
</tr>
<tr>
<td>K</td>
<td>4877</td>
<td>115.4*</td>
<td>wind</td>
</tr>
<tr>
<td>T</td>
<td>5524</td>
<td>95.1</td>
<td>airblast (shielded)</td>
</tr>
<tr>
<td>M</td>
<td>6062</td>
<td>101.0</td>
<td>airblast</td>
</tr>
<tr>
<td>S</td>
<td>6769</td>
<td>97.5</td>
<td>airblast (shielded)</td>
</tr>
<tr>
<td>A</td>
<td>7124</td>
<td>116.7*</td>
<td>wind</td>
</tr>
</tbody>
</table>

* in excess of environmental licence condition of 115 dBL.
Comment

Elevated air vibration reading at stations K and A was due to wind. The estimated airblast at station K was 104 dBL and 99 dBL at station A.

Case History No. 3

Table 4 - Peak air vibration readings

<table>
<thead>
<tr>
<th>Station</th>
<th>Distance (m)</th>
<th>Peak Air Vibration (dBL)</th>
<th>Conclusions following Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>1358</td>
<td>126.8</td>
<td>airblast</td>
</tr>
<tr>
<td>B</td>
<td>1793</td>
<td>120.0</td>
<td>airblast</td>
</tr>
<tr>
<td>H</td>
<td>3833</td>
<td>117.5*</td>
<td>airblast and meteorology</td>
</tr>
<tr>
<td>N</td>
<td>4249</td>
<td>128.6*</td>
<td>airblast and meteorology</td>
</tr>
<tr>
<td>P</td>
<td>4482</td>
<td>120.5*</td>
<td>airblast and meteorology</td>
</tr>
</tbody>
</table>

* off lease exceedence
Figure 22a – Wavetrace – station H

Figure 22b – Wavetrace – station D

Figure 22c – Wavetrace – station P

Figure 22d – Wavetrace – station N

Figure 23 – Wavefront reinforcement analysis – no significant reinforcement
Table 5 – Atmospheric profile data

<table>
<thead>
<tr>
<th>Level</th>
<th>Altitude (metres)</th>
<th>Temperature (Celsius)</th>
<th>Windbearing (degrees)</th>
<th>Windspeed (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>16.0</td>
<td>270</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>15.0</td>
<td>240</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>15.0</td>
<td>240</td>
<td>20.0</td>
</tr>
<tr>
<td>4</td>
<td>180</td>
<td>15.0</td>
<td>240</td>
<td>20.0</td>
</tr>
<tr>
<td>5</td>
<td>270</td>
<td>15.0</td>
<td>200</td>
<td>20.0</td>
</tr>
<tr>
<td>6</td>
<td>300</td>
<td>15.0</td>
<td>200</td>
<td>18.0</td>
</tr>
<tr>
<td>7</td>
<td>600</td>
<td>13.0</td>
<td>180</td>
<td>20.0</td>
</tr>
<tr>
<td>8</td>
<td>900</td>
<td>10.0</td>
<td>180</td>
<td>30.0</td>
</tr>
</tbody>
</table>

Comment

The basic airblast levels from the blast were elevated due to the under-stemming of one blasthole. Even with the increase of about 10 dBL due to the under-stemming, the airblast levels at stations H, N and P would have been less than 115 dBL without the meteorological reinforcement. The meteorological reinforcement was caused by wind speed increasing at an altitude above 90 metres with a slowly reducing temperature gradient.

CONCLUSIONS

Airblast can be controlled to environmental limits by first of all understanding the causes and factors contributing to airblast and then using the techniques that have been developed to eliminate the causes. Airblast wavetraces can be analysed and the shape diagnosed to give an understanding of the processes involved in their creation. Importantly, airblast can be controlled to environmental limits if the factors contributing to airblast are recognised and quantified by appropriate models. Techniques have been developed to overcome some of the causes of high airblast levels but the importance of controlling the loading process to achieve the design specification cannot be emphasised enough.