TERROCK
Consulting Engineers

A.B.N. 99 005 784 841

P O Box 829
Eltham Vic 3095

Phone: (03) 9431 0033
Fax: (03) 9431 1810
Email: terrock@terrock.com

Alan B. Richards
B.Sc.(Tech), F.I.E.Aust., F.Aust.I.M.M.,F.I.Q.

Adrian J. Moore
Dip.C.E.,B.E.(Min.), M.Eng.Sc., M.I.E.Aust.

KALGOORLIE CONSOLIDATED GOLD MINES

GOLDEN PIKE CUT-BACK
FLYROCK CONTROL AND CALIBRATION OF A PREDICTIVE MODEL

Adrian J. Moore
Alan B. Richards
30th November 2005

KALGOORLIE CONSOLIDATED GOLD MINES

GOLDEN PIKE CUT-BACK
FLYROCK CONTROL AND CALIBRATION OF A PREDICTIVE MODEL

TABLE OF CONTENTS

TERROCK

Consulting Engineers

A.B.N. 99 005 784 841

P O Box 829
Eltham Vic 3095

Phone: (03) 9431 0033
Fax: (03) 9431 1810
Email: terrock@terrock.com

Alan B. Richards
B.Sc.(Tech), F.I.E.Aust., F.Aust.I.M.M.,F.I.Q.

Adrian J. Moore
Dip.C.E.,B.E.(Min.), M.Eng.Sc., M.I.E.Aust.

KALGOORLIE CONSOLIDATED GOLD MINES

GOLDEN PIKE CUT-BACK
FLYROCK CONTROL AND CALIBRATION OF A PREDICTIVE MODEL

EXECUTIVE SUMMARY

A predictive flyrock model developed by Terrock Consulting Engineers was calibrated for Kalgoorlie Consolidated Gold Mines Super Pit blasting practice by the observation and measurement of flyrock resulting from routine blasting operations.

With current blasting practice, on 72% of occasions the flyrock was less than 50 metres and the maximum observed throw was 95 metres.

The calibrated flyrock model was then used for a critical examination of the 400 metre blast clearance area, and to determine the blasting specifications and loading procedures required to achieve the same level of risk at 200 metres. Current blasting practice achieves a factor of safety of '4' at the 400 metres blast clearance area for blasts at the pit perimeter.

For a 200 metre exclusion zone, flyrock must be limited to 50 metres, thereby maintaining the factor of safety of '4'. To achieve this, the minimum stemming height must be 5 metres in the oxidised zone and 4.1 metres in the sulphide zone. A zone of equivalent risk was identified where blasting conducted using improved loading checks will have the same risk at a 200 metre blast clearance area as current practice at the historically applied 400 metre blast clearance area.

The checks during loading to ensure that the minimum stemming heights are achieved are:

- The depth of each blasthole is measured and recorded.
- The quantity of explosive to fill the hole to design stemming height is determined.
- The metered quantity of explosive is pumped from the bulk truck.
- The depth of the top of the explosive column is measured – excess explosive is either removed, desensitised or additional material is placed over the hole collar.
- The addition of stemming material is monitored to ensure there are no gaps in the stemming column due to bridging.

A similar loading regime was used during the Chaffers West Cut-Back, where there were no reports of flyrock throw exceeding 50 metres.

Secondary breaking in the Golden Pike Cut-Back should only be undertaken by hydraulic impactor or properly designed and implemented blasting practice.

1.   INTRODUCTION

Terrock Consulting Engineers were requested by Kalgoorlie Consolidated Gold Mines to calibrate a predictive flyrock model to provide a basis for flyrock control and the determination of clearance distances for blasting in the Golden Pike Cut-Back.

The Terrock flyrock model has been developed after analysis of flyrock data from blasting in a wide range of rock types that has been acquired over many years. The model is an empirical relationship that permits flyrock distances to be evaluated quickly and effectively.

Inputs to the model are stemming height, burden, charge mass per metre, and a site calibration factor that takes all other variables into account. The model is particularly useful in determining the effect of changes to stemming height, burden, and charge mass per metre and quantifies the tolerance of the variation to the loading specifications to be able to control flyrock to defined limits.

The flyrock model may be used for planning and assessment purposes to predict flyrock distances, and permits all personnel involved in blasthole loading to be aware of the importance of managing the stemming height during loading.

Further information in regard to the development and use of the model is included in the paper attached as **Appendix 1.**

The aim was to use the calibrated flyrock model for a critical examination of the 400 metre blast clearance area and to determine the blasting specifications necessary to achieve the same level of risk at 200 metres from the pit perimeter.

2.   FLYROCK MECHANISMS

Flyrock from blasting can result from three key mechanisms due to lack of confinement of the energy in the explosive column. Flyrock can occur if there is insufficient burden for the hole diameter or a zone of weak rock occurs in the face. An illustration of each mechanism is shown in **Figure 1**.

- Face burst: burden conditions usually control flyrock distances in front of the face.

- Cratering: if the stemming height to hole diameter ratio is too small or the collar rock is weak flyrock can be projected in any direction from a crater at the hole collar.

- Rifling: if the stemming length is adequate to prevent cratering, flyrock at a high trajectory can result from rifling – the ejection of stemming material and loose rocks from the collar if there is insufficient stemming height or inappropriate stemming material is used.
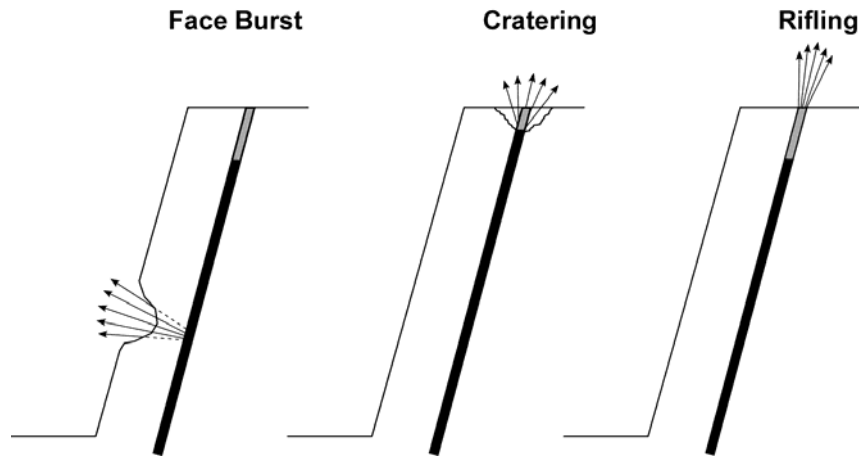
Figure 1 – The three key mechanisms of flyrock

3. METHODOLOGY

Kalgoorlie Consolidated Gold Mines' personnel observed the flyrock from each blast during the period 29th October to 2nd December 2004 and when the flyrock projection exceeded 50 metres, a detailed assessment was conducted. The results of this assessment are summarised in **Table 1**.

The flyrock observations were then used to calibrate the model by inputting maximum flyrock throw, charge mass per metre and design stemming height. The modelling was then used to produce prediction curves, which demonstrate the relationship between stemming height and maximum throw and the sensitivity of stemming height variations.

The flyrock performance in the Chaffers West Cut-Back where there were no reports of flyrock projection over the noise bund was also considered in the modelling.

The 400 metre blast clearance area was then considered and the blasting specifications determined to achieve the same level of risk at 200 metres from the pit perimeter.

Recommendations were made for clearance distances from blasting for equipment and personnel based on current performance, and improved performance similar to that achieved in the Chaffers West Cut-Back.

3.1 Blasting Practice during the Chaffers West Cut-Back

In the Chaffers West Cut-Back the standard blasting method was modified to minimise the effects of vibration in the nearby area of Boulder. It was found that conventional signal tube firing was creating a reinforcement of the primary ground vibration waves by a later arriving reflected wave when a blast lasted longer than 800 ms, which increased the peak vibration levels. The resulting complex vibration also produced low frequencies, which induced a secondary audible response inside some buildings, and was of concern to the occupants.

Limiting blasts to 800 ms duration was essential to control ground vibration. By initiating the blasts with electronic detonators more holes could be fired within the 800 ms timeframe, which resulted in larger blasts being fired with a considerable reduction in ground vibration without adverse frequency content.

Table 1 – Summary of flyrock throw observations

Date	Blast	Maximum Throw (m)	Rock type	Mechanism	Hole Diameter (mm)	Explosive Type	kg/m	k Cratering $\theta = 45^o$	k Rifling $\theta = 75^o$
29/10-29/11/04	23 blasts	<50	sulphide	-	-	-	-	<16.0	-
			trans/oxide	-	-	-	-	<20.6	-
29/10/04	150-1902	80	sulphide	face burst	165	2660	27.8	20.2	-
	100-1306	80	oxide			2640	25.6	27.5	-
	120-2214	60	sulphide		115	ENERGAN	11.7	30.6	-
03/11/04	140-2202	**250-450***	sulphide	cratering	165	2660	-	-	-
05/11/04	110-317	70	oxide	cratering and rifling		ANFO	17.1	33.5	47.4
12/11/04	150-1904	85	sulphide	rifling		2640	25.6	22.0	31.1
17/11/04	140-2201	65		cratering	165	ANFO	23.5	20.2	28.6
24/11/04	140-2203	95					27.8	22.0	32.8
30/11/04	140-2205	30 (50 vertical?)		cratering and face burst		2660	27.8	17.4	17.4
02/12/04	110-1309	90 (80-100 vertical?)		cratering			27.8?	21.4	30.2

*   *secondary breaking toe or boulders – severely overpowered*

To reduce airblast levels in Boulder, the stemming height in the oxidised zone blasts was increased from 4.1 metres to 4.5 metres and then to 5 metres. The blasting in the upper benches of the Chaffers West Cut-Back was more closely controlled than normal, which successfully limited ground vibration, airblast and flyrock, with no reports of rock throw greater than 50 metres.

4.   FLYROCK OBSERVATIONS

In general, the maximum flyrock throw was less than 50 metres. The summary of the flyrock throw observations is shown in **Table 1**. The maximum recorded throw from face burst, cratering or rifling of primary blasts is 95 metres. The observed height reached by flyrock is estimated to be 80-100 metres. The maximum distance for oxide and transition zone blasts is 80 metres, which is similar to the sulphide zone maximum. The maximum throw distance of 95 metres is used in this section of the assessment.

All blasts, except the secondary breaking blast (140-2202), were primary blasts. A reported throw of 250-450 metres resulted from secondary breaking, which was obviously overpowered through lack of confinement and presents a special case. This practice should only be conducted with an awareness of the confinement conditions necessary to control flyrock. This is discussed in greater detail in Section 6.

The maximum throw of 95 metres may have resulted from a 45$^\text{o}$ launch angle (from cratering or face burst), or a high angle emission from rifling – a launch angle of 75$^\text{o}$ to the horizontal appears consistent with observations. It is assumed that the 95 metres throw is to a point at the same elevation as the blast collar. The trajectory paths for each case are shown in **Figure 2**.
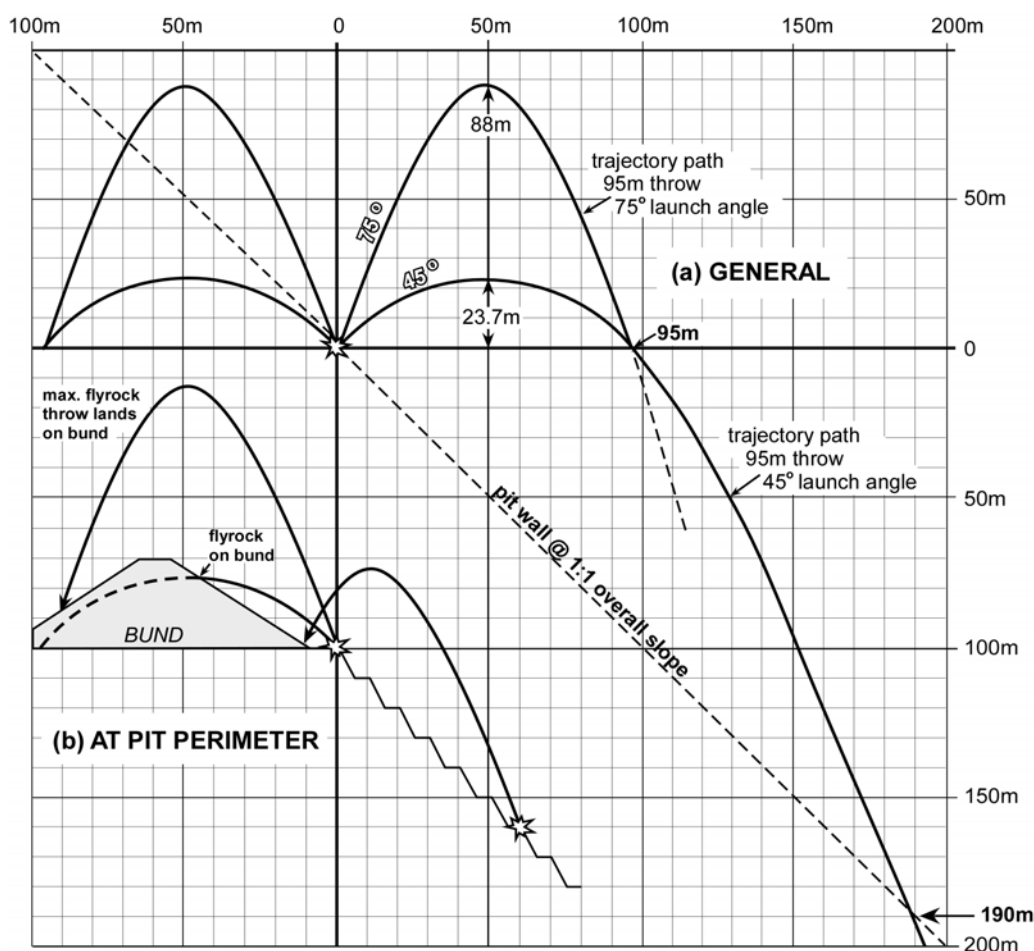

Figure 2 – Possible trajectory paths from current blasting practice

The maximum height reached for the 45° launch angle is 23.7 metres. The maximum height reached for the 75° launch angle is 88 metres, which is consistent with observations and suggests that the maximum throw of 95 metres resulted from rifling.

The observations reported in the flyrock assessment forms have been checked by reviewing video records of the blasts.

5. FLYROCK MODEL AND CALIBRATION

The flyrock model developed by Terrock for choke blasting is:

$$L = \frac{k^2}{9.8} \left(\frac{\sqrt{m}}{S.H.}\right)^{2.6} Sin\, 2\theta \qquad [1]$$

where:
- L = maximum throw (m)
- m = charge mass per delay (kg)
- S.H. = stemming height (m)
- θ = launch angle from horizontal
- k = a constant

L is a maximum when θ = 45°, ie. $L_{max} = \frac{k^2}{9.8} \left(\frac{\sqrt{m}}{S.H.}\right)^{2.6}$ \qquad [2]

The explosives used range from ANFO (an s.g. of 0.8 g/cc) to 2660 emulsion (an s.g. of 1.3 g/cc). The common explosives used in wet blastholes is ENERGAN with an s.g. of 1.15 g/cc. The charge mass per metre for a 165 mm diameter hole ranges from 17.1 kg to 27.8 kg. The stemming heights used are 5.0 metres for oxide zone blasts and 4.1 metres for sulphide zone blasts.

For 72% of primary blasts the maximum throw is less than 50 metres, with the resulting k factor less than the range 15.9 to 22.1 for sulphide zone blasts and less than the range 20.6 to 28.3 for oxide zone blasts. For ENERGAN explosives (s.g. 1.15) with a charge mass of 24.6 kg, the k factors are <17.2 for sulphide zone blasts and <22.3 for oxide zone blasts. For ANFO blasts, the k factors are 21.9 for sulphide zone blasts and 28.3 for oxide zone blasts.

The predictive models, therefore, become:

1. ENERGAN

- **Oxidised zone:** $L_{max} = \frac{(22.3)^2}{9.8} \cdot \left(\frac{\sqrt{m}}{S.H.}\right)^{2.6}$ \qquad [3]

- **Sulphide zone:** $L_{max} = \frac{(17.2)^2}{9.8} \cdot \left(\frac{\sqrt{m}}{S.H.}\right)^{2.6}$ \qquad [4]

2. ANFO

- **Oxidised zone:** $L_{max} = \frac{(28.3)^2}{9.8} \cdot \left(\frac{\sqrt{m}}{S.H.}\right)^{2.6}$ \qquad [5]

- **Sulphide zone:** $L_{max} = \frac{(21.9)^2}{9.8} \cdot \left(\frac{\sqrt{m}}{S.H.}\right)^{2.6}$ \qquad [6]

The fact that the flyrock was in the range 50-95 metres for 28% of blasts indicated that the stemming performance had been downgraded by ground conditions or loading practice. By back-calculating from the maximum throw and using appropriate k factors, an evaluation of the effective confinement and stemming heights was obtained.

For the maximum throw of 95 metres in the sulphide zone, the minimum effective stemming height was calculated to be 3.2 metres (compared with a design stemming height of 4.1 metres) and for the maximum throw of 80 metres in the oxide zone, the effective stemming height was calculated to be 4.2 metres (compared with a design stemming height of 5.0 metres). This indicated that current loading practice and collar rock conditions is achieving a variance in the effective stemming height of up to 0.9 metres less than the design stemming height.

Subsequent measurements of stemming heights confirmed this variance, (15% of blastholes had stemming heights 0.9 metres less than design), and showed the need for improvement in the accuracy of stemming height control in the Golden Pike Cut-back area if a maximum throw of 50 metres was to be achieved.

A maximum flyrock throw of 50 metres from the blast, similar to that reported in the Chaffers West Cut-Back, is achievable in the oxide zone of the Golden Pike Cut-Back by more accurate loading and Q.A. procedures than are currently used for general blasting in the super pit.

The use of the model permitted the curves shown in **Figures 3a** and **3b** to be produced. For two different explosives (ANFO with an s.g. of 0.8 (**Figure 3a**) and ENERGAN with an s.g. of 1.15 (**Figure 3b**)), these curves show the relationship between stemming height and flyrock distance for sulphide and oxide blasts. The curves show the effect of controlling stemming heights to design (72% of blasts) and the effect of stemming heights 0.9 metres less than design. Loading procedures in the Golden Pike Cut-Back must be put in place to ensure that the minimum stemming height is achieved.
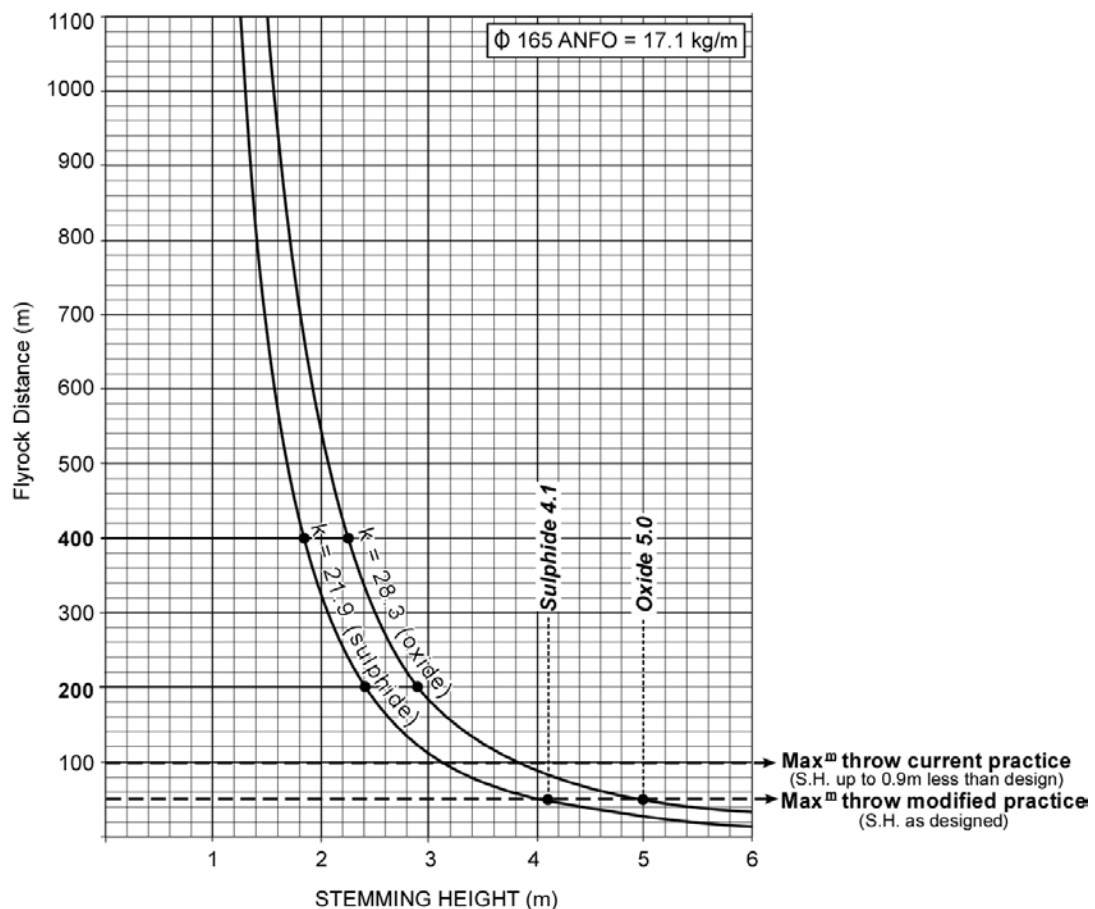

Figure 3a – Relationship between flyrock distance and stemming height – ANFO
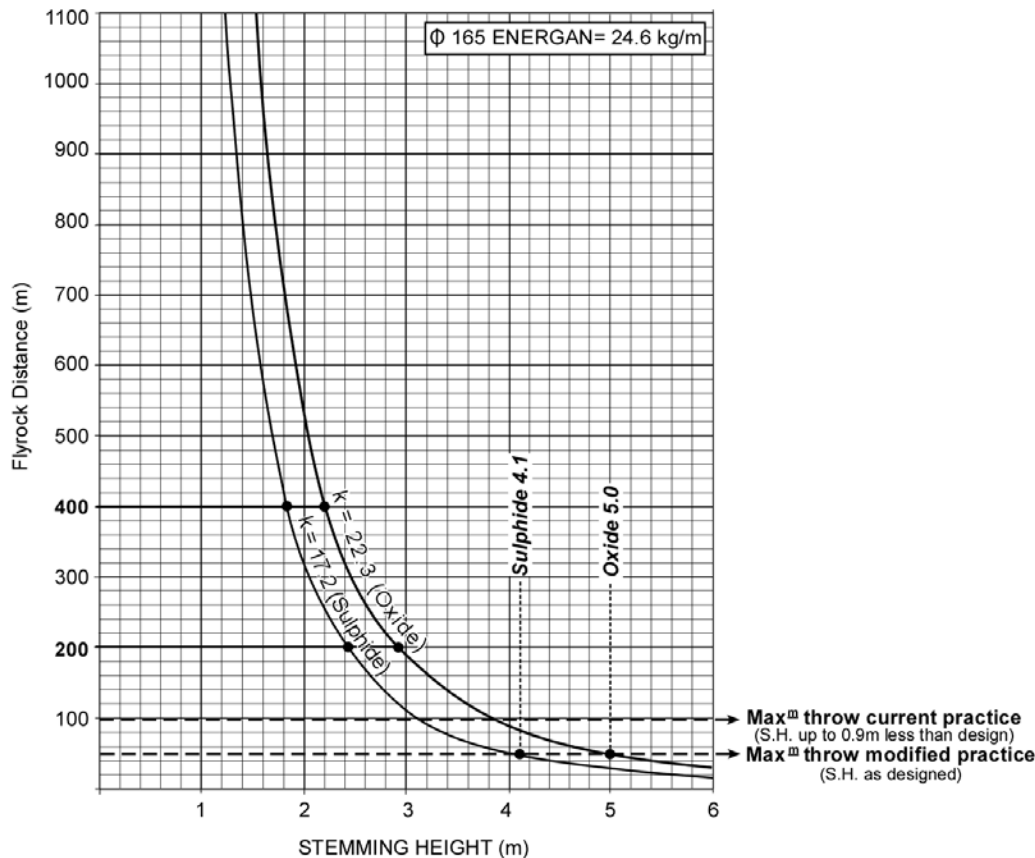
Figure 3b - Relationship between flyrock distance and stemming height – ENERGAN

6. CLEARANCE DISTANCES

6.1 Current Blasting Practice

With current practice for routine production blasting in the sulphide, oxide and transition zones, flyrock is contained within 95 metres of the blast. If the accuracy of stemming height control can be improved, flyrock distances will be limited to 50 metres.

Worst-case flyrock distances can be determined by using the calibrated flyrock model. Inputs into the flyrock model are charge mass per lineal metre, stemming height and/or burden, and a site constant that takes account of all other factors, including rock conditions.

In the case of a situation where the flyrock model predicts a maximum flyrock distance of 95 metres, the average rock throw will be less than 50 metres. This variation is due to the effects of rock conditions and all other factors except charge mass per lineal metre, stemming height, and burden

Weak rock conditions can result in increases in blasthole diameter (and hence charge mass per lineal metre) at the top of the explosives column (ie. at the base of the stemming column).

Improved control of flyrock distances will result from improved control and evaluation of charge mass per lineal metre loaded into the blasthole.

Substantial reduction in the designed stemming height or charge concentrations due to increases in blasthole diameter can result in flyrock being thrown distances far in excess of 95 metres. Flyrock will not be thrown excessive distances if stemming heights are controlled to within an acceptable range, as shown in **Figures 3a** and **3b**.

The calculations are consistent with pit experience. Flyrock has been contained within the outside perimeter bund from all blasts on previous cutbacks. The maximum throw from blasting on the surface at the pit perimeter is predicted to land on the outer face batter.

The above clearance distances are to points at the same elevation as the blast for current blasting practice. To points below the blast the distance is greater as the flyrock can travel further downwards into the pit, as demonstrated in **Figure 2**. The recommended clearance zone for current practice is, therefore, 'egg' shaped. The distance behind the face is based on the throw distance to a point at the same elevation as the blast. The distance in front of the blast is greatest for blasts on the edge of the internal pit batter, as shown in **Figure 2**.

Using the factors of safety specified above, the recommended clearance zone for current general blasting practice in the Super Pit is shown in **Figure 4**.

From the flyrock model **Figure 3a**, for an ANFO blast, the 5 metres design stemming height must be reduced to 3.1 metres to limit the throw to 190 metres and to 2.3 metres to limit the throw to 380 metres.

From **Figure 3b**, for ENERGAN in the sulphide zone, the 4.1 metres design stemming height must be reduced to 2.5 metres to limit the throw to 190 metres and to 1.9 metres to limit the throw to 380 metres. These stemming height reductions are for the 45° launch angle case resulting from cratering or face burst. The stemming height reductions are greater for the 75° launch angle case resulting from rifling.

If cratering is not possible then flyrock can only be projected from rifling. If the stemming height was inadvertently reduced to 2.3 metres, the throw would not exceed 190 metres and if the stemming height was inadvertently reduced to 1.75 metres, the throw would not exceed 380 metres for both ANFO and ENERGAN.

The recommended clearance distance incorporating factors of safety of '2' and '4' therefore allow for a considerable reduction in stemming height before safety is compromised.

The checks in the blasting practice to ensure there is no inadvertent reduction in stemming height from the levels required to compromise safety are:

- The hole depths are measured before loading.

- The quantity of explosives to fill each hole to achieve the design stemming heights are determined.

- The metered quantity of explosives is pumped from the delivery truck.

- The depth to the top of the explosive column is measured to ensure the minimum stemming height prevails. Excess explosive is either removed or additional fill material is placed over the hole collar.

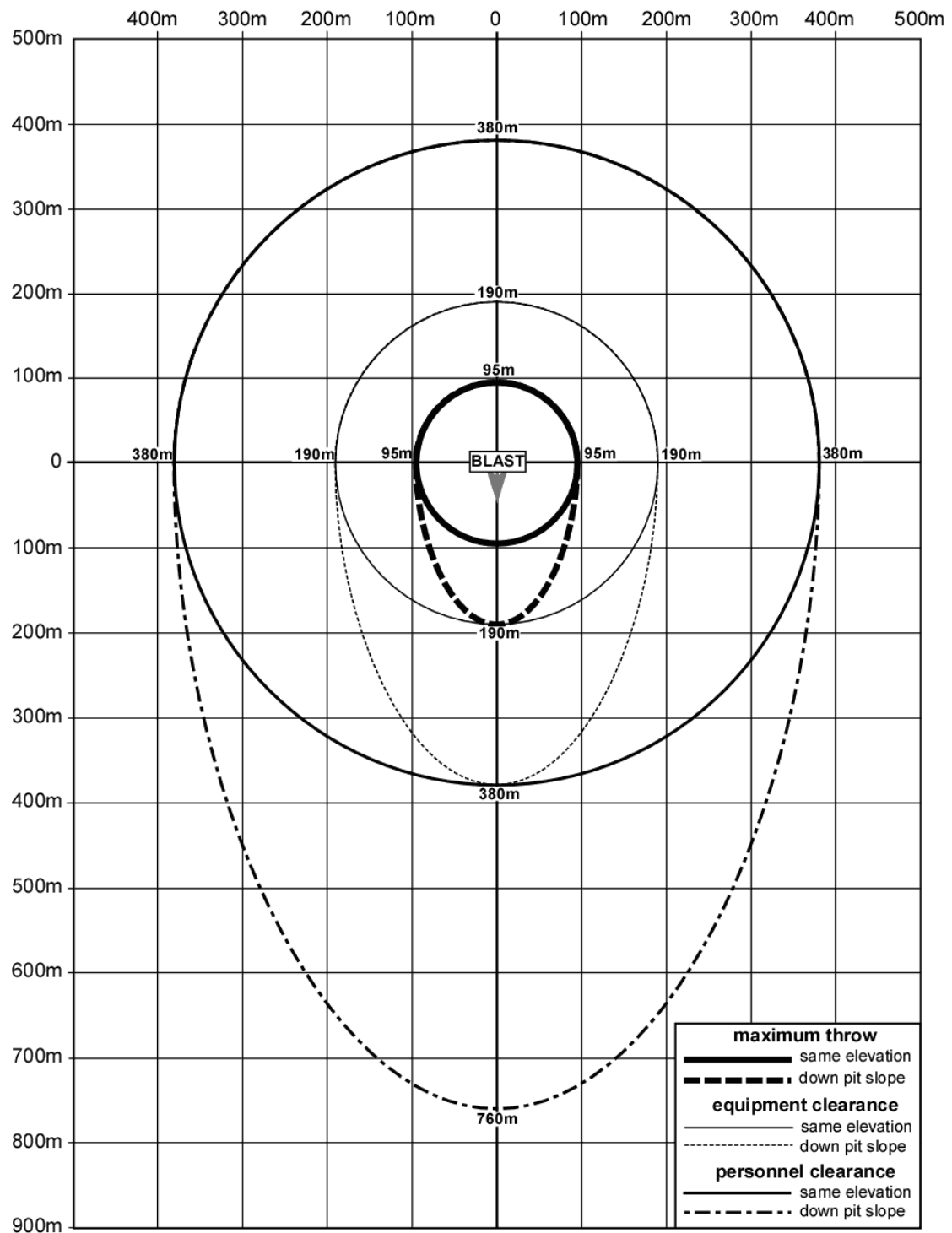- The addition of stemming material is monitored to ensure there are no gaps in the stemming column due to bridging.

Figure 4 – Maximum throw and recommended clearance distance for current blasting practice (without perimeter noise bund)

6.2   Modified Blasting Practice

Experience during the Chaffers West Cut-Back showed that with more efficient confinement of the explosives, the maximum flyrock throw distance can be substantially reduced to 50 metres, and a smaller clearance zone can be justified. The minimum confinement conditions to limit the throw to 50 metres can be quantified by the calibrating of the Terrock flyrock model in Section 4.

The recommended clearance distances for modified blasting practice (proposed for the zone of modified blasting practice shown in **Figure 9**) that limits flyrock throw to 50 metres are shown in **Figure 5**.

This modified blasting practice is based on current practice used in the Super Pit, modified practice used in the Chaffers West Cut-Back, and analysis of data obtained during this investigation.

The most important features of the modified blasting practice will be a minimum stemming height of 5.0 metres for production holes (which may be increased to 5.5 metres as required to control airblast overpressure levels), strict control of stemming heights (to within +/- 0.1 metre of design), and control of the charge concentration in the top metre of the explosive column.
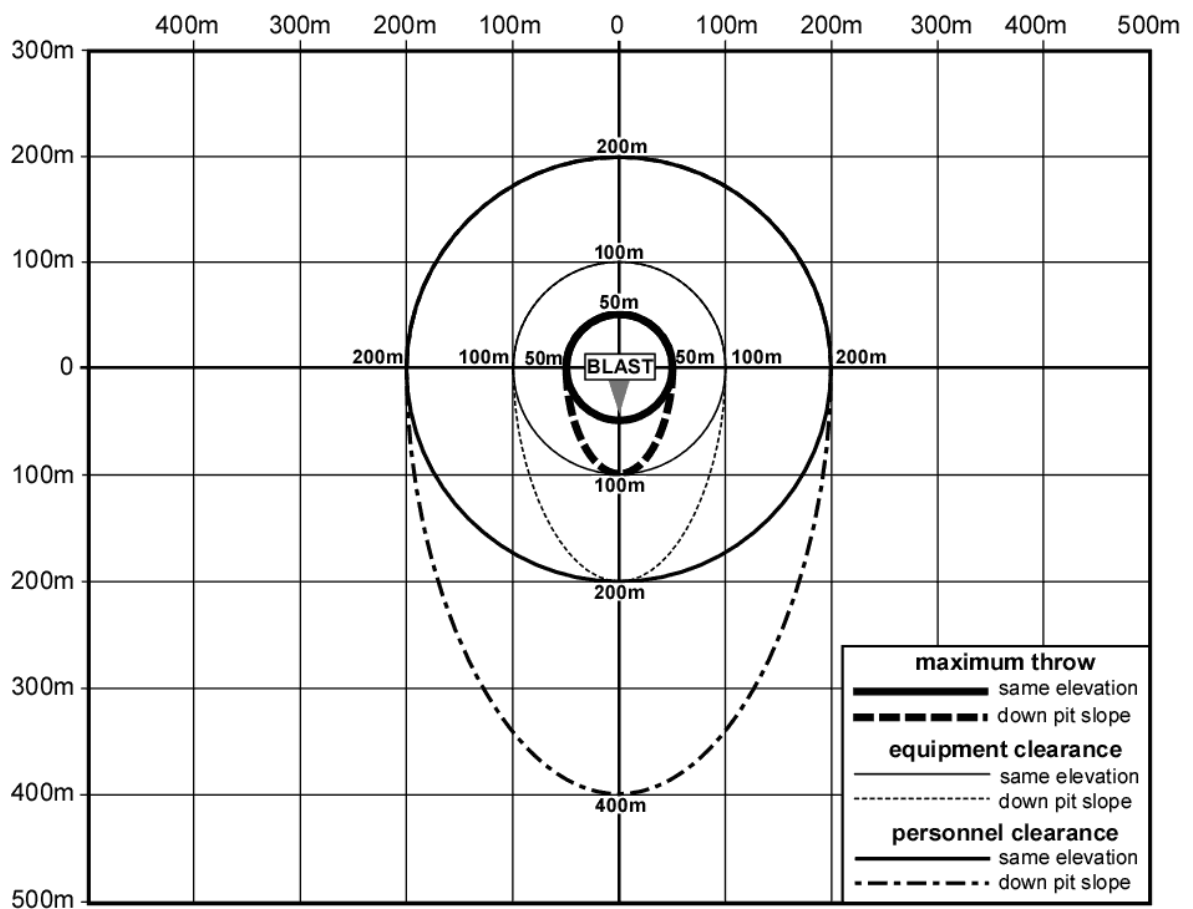

Figure 5 – Recommended clearance distance with improved loading control (without perimeter noise bund)

6.3 The Effect of the Pit Outline on Flyrock Throw from Blasting near the Pit Perimeter

The flyrock throw distance may be reduced to points at a higher elevation than the blast, as demonstrated in **Figure 6.** There are two possibilities for flyrock to be limited by points at a higher elevation, one on the way up and the other coming down.

If blasting is conducted at levels below the pit perimeter, the horizontal throw is reduced by the pit wall. The construction of the perimeter noise bund will also provide similar benefits to reducing horizontal throw. The factors of safety used to define the recommended clearance distances are further increased by the pit wall and the perimeter noise bund.

At a certain depth below the perimeter, flyrock will not clear the noise bund and at greater depths will not clear the pit perimeter. The depths at which this occurs can be determined from the application of basic trajectory formula.
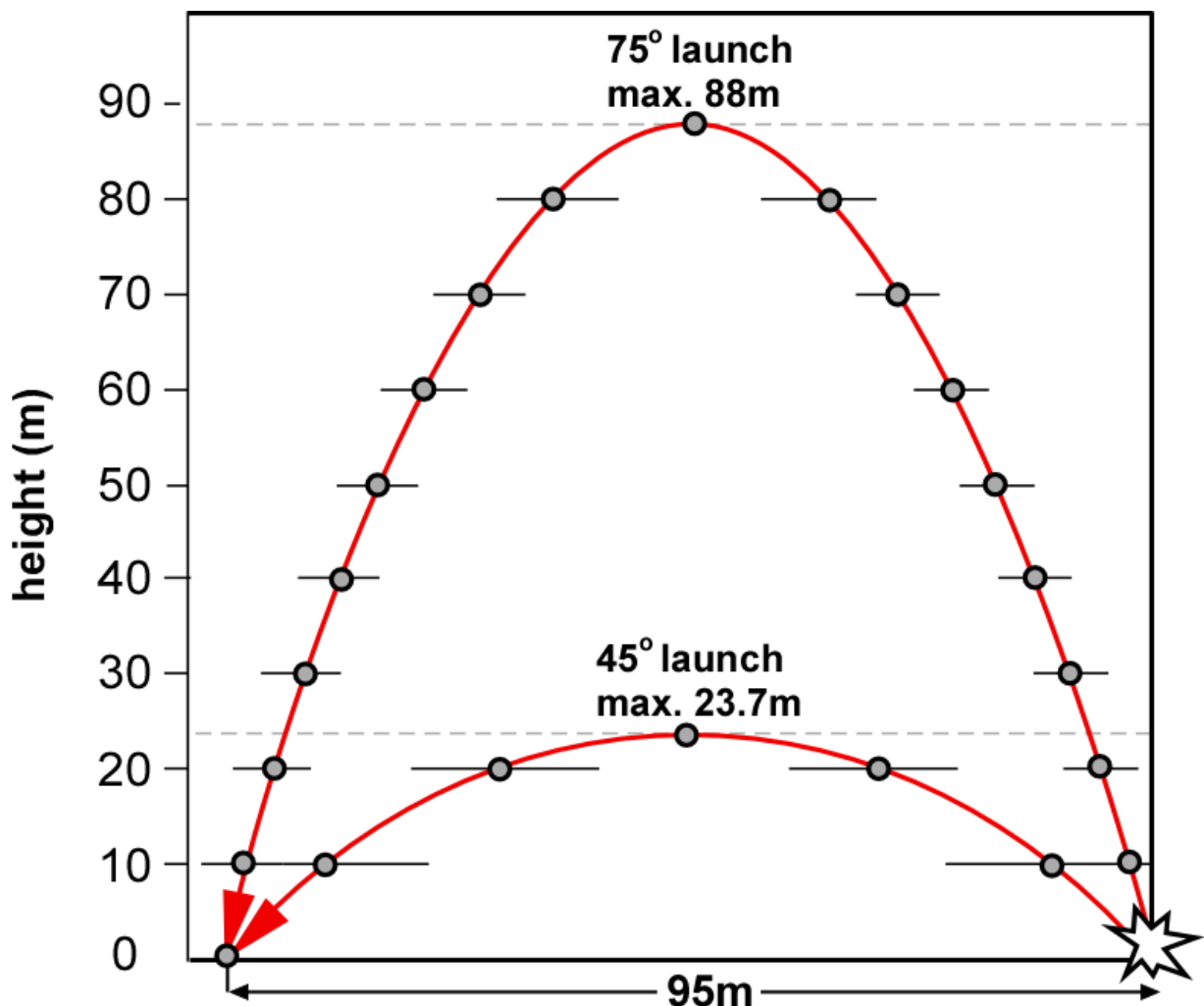

Figure 6 – Possible intersections at a point above a blast

The horizontal throw 'L' reached by flyrock to a point 'H' meters above the launch site is determined from:

$$L = V_o \; Cos \, \theta \left(\frac{V_o \; Sin \, \theta + \sqrt{(V_o \; Sin \, \theta)^2 - 2 \, gH}}{g} \right) \qquad [7]$$

where:
- V_o = launch velocity (m/s)
- θ = launch angle (from horizontal)
- g = gravitational constant
- L = horizontal throw

The launch velocity can be determined from:

$$V_o = k \left(\frac{\sqrt{m}}{S.H.} \right)^{1.3} Sin \, 2\theta \qquad [8]$$

$$or \quad \sqrt{\frac{Lg}{Sin \, 2\theta}} \qquad [9]$$

The maximum height reached by flyrock at the top of its trajectory is:

$$H = \frac{V_o^2 \; Sin^2 \theta}{2g} \qquad [10]$$

6.4 Current Practice

By substituting in formula [7] for the worst case maximum throw observed of 95 metres, at a 45° launch angle, the required velocity is 30.5 m/s and at a 75° launch angle, the velocity is 43.1 m/s.

By substituting for V_o in formula [8], the maximum height flyrock reaches is 23.7 metres at 45° launch angle and 88.4 metres at 75° launch angle (see **Figure 2**).

For the above launch angles and launch velocities, the horizontal throw to a landing point at different heights above a blast can be determined by substituting in formula [5]. The horizontal throw distances are listed in **Table 2** and illustrated in **Figure 6**.

Table 2 - Horizontal throw distances and landing heights for a 95 metres maximum throw

Landing Height above Blast (m)	Maximum Horizontal Throw @ 45° Launch Angle Current 95m max. (m)	Landing Height above Blast (m)	Maximum Horizontal Throw @ 75° Launch Angle Current 95m max. (m)
0	95	0	95
10	81.6	10	92
20	63.9	30	86
23.7*	47.5-	40	82
* maximum height		50	79
		60	74
		70	69
		80	62
		88.3*	47.5

When the trajectory paths are drawn on a cross-section of the pit perimeter, at a 45° and 75° launch angle at the limit of extraction for each bench, the landing sites were determined as shown in **Figure 7**. The description of landing sites for blasts at the extraction limits of benches 0-90 are summarised in **Table 3**.

Table 3 – Description of landing sites for current blasts at the extraction limit

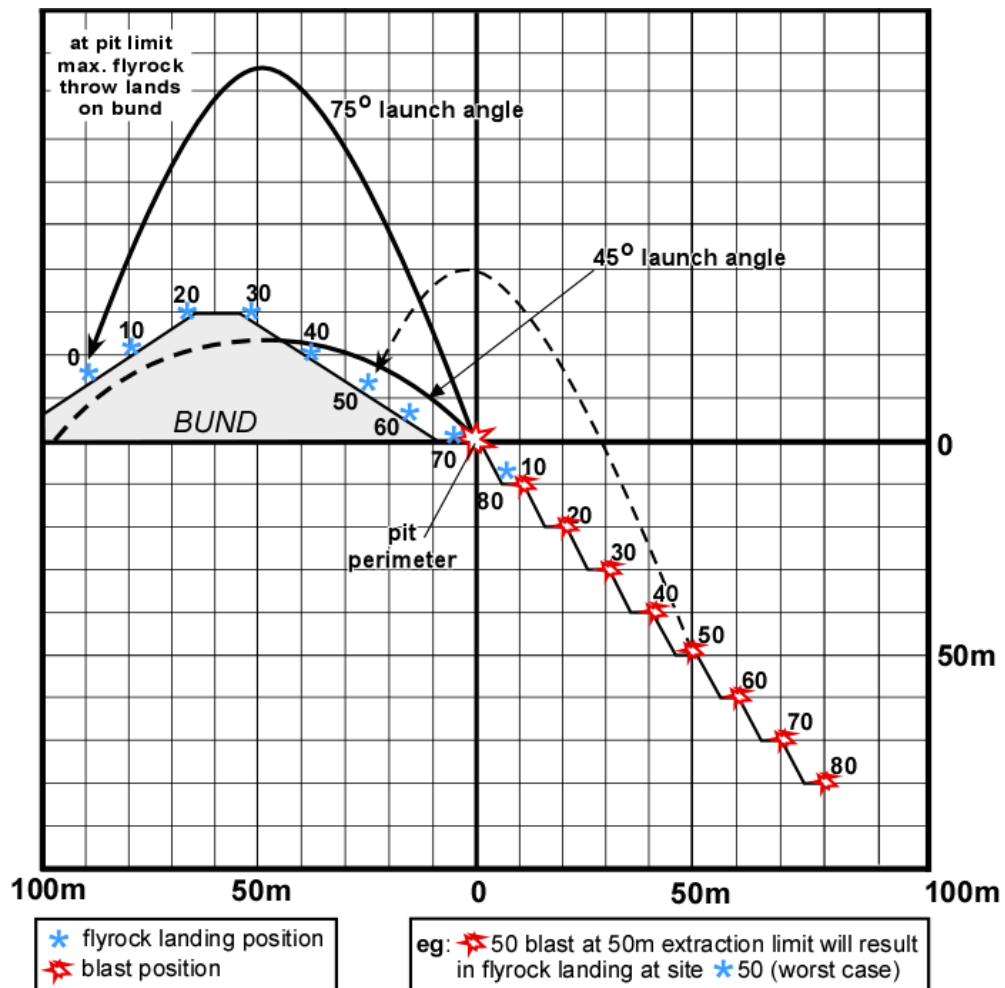| Blast at Extraction Limit of Bench (m)	Landing Site at 45° Launch Angle	Distance from Pit Perimeter (m)	Landing Site at 75° Launch Angle	Distance from Pit Perimeter (m)
0	internal face of bund	45	external face of bund	90
10				80
20			top of bund	65
30				50
40	within pit perimeter	-	internal face of bund	40
50				25
60				15
70				5
80			within pit perimeter	-
90				-

Figure 7 – Flyrock projection at extraction limit with current practice – maximum 95 metres throw

At a 45° launch angle at the pit perimeter, flyrock will land on the internal face of the bund. At the 10 metre bench, flyrock will not clear the pit perimeter. At a 75° launch angle, blasts at 20 metres below the pit perimeter will land on top of the bund and at 70 metres below the perimeter will not clear the pit perimeter.

The calculations are consistent with pit experience. Flyrock has been contained within the outside perimeter bund from all blasts on previous cutbacks. The maximum throw from blasting on the surface at the pit perimeter is predicted to land on the outer face batter.

With current practice, the flyrock from blasting, even on the surface at the pit perimeter, will not clear a 100 metre wide noise bund. The noise bund is designed as 100-300 metres wide at the base.

6.5 Modified Practice

Tighter control of the loading operation as implemented during the Chaffers West Cut-Back showed that the maximum flyrock distance could be limited to 50 metres. For a 50 metres throw, the required launch velocities are 22.1 m/s for a 45° launch angle and 31.3 m/s for a 75° launch angle.

The horizontal throw distances are listed in **Table 4**, and illustrated in **Figure 8** with reference to blasting at the pit perimeter. The description of the landing sites for blasts are summarised in **Table 5**.

The maximum elevation reached by flyrock is 12.4 metres and 46.6 metres, respectively. Again, from cratering (45° launch angle), flyrock does not clear the bund. From high angled rifling (75° launch angle), flyrock also does not clear the bund and at depths greater than 35 metres does not clear the pit perimeter.

Table 4 - Horizontal throw distances and landing heights for a 50 metres maximum throw

Landing Height above Blast (m)	Maximum Horizontal Throw @ 45° Launch Angle (m)	Landing Height above Blast (m)	Maximum Horizontal Throw @ 75° Launch Angle (m)
0	50	0	50
10	36	10	47.1
12.4*	25	20	43.8
maximum height		46.6*	25

Table 5 – Description of landing sites for modified blasting at the extraction limit

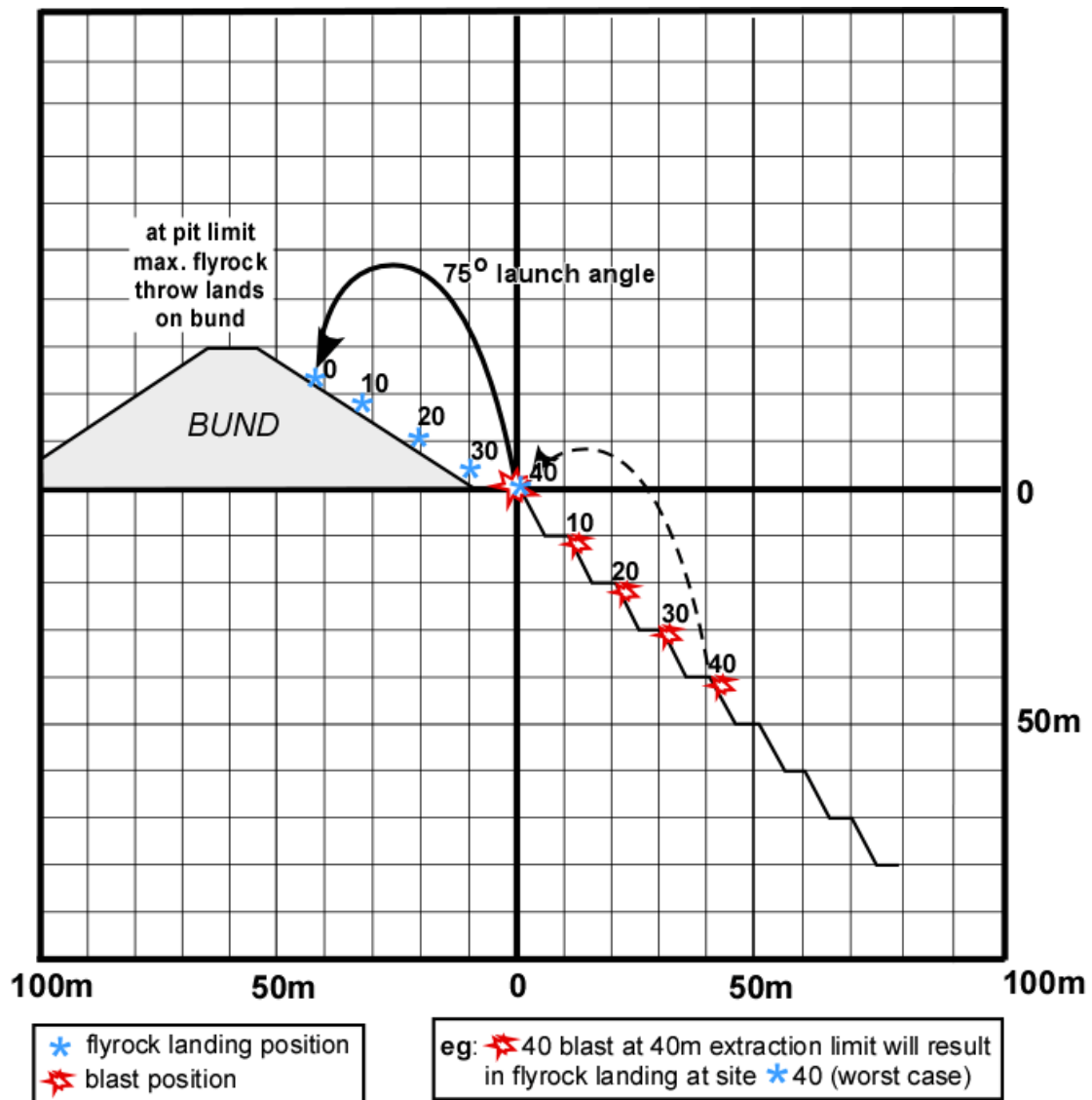| Blast at Extraction Limit of Bench (m)	Landing Site at 45° Launch Angle	Distance from Pit Perimeter (m)	Landing Site at 75° Launch Angle	Distance from Pit Perimeter (m)
0	internal face of bund	18		42
10	within pit perimeter	-	internal face of bund	32
20				20
30				10
40			at pit perimeter	-
50			within pit perimeter	-

Figure 8 – Flyrock projection at the extraction limit with modified practice – maximum 50 metres throw

6.6 Blast Clearance Area Examination

Sections 5.5 and 5.6 clearly demonstrate the effects that the noise bund and pit wall have on the potential throw of flyrock and introduce an additional safety margin for preventing flyrock from blasts in the upper benches extending beyond the mining area.

With current practice and a maximum throw of 95 metres, flyrock will either land on the noise bund or within the pit, regardless of the launch angle and depth of the blast. The simple application of the 'rule of thumb' safety factors ('2' for equipment and '4' for personnel) produces the recommended clearance shown in **Figure 4**. Application of the factors of safety allows for unanticipated events, such as inadvertent lapses in maintaining the design stemming height during loading and for collar rock weakened by previous over-drilling, geological structures, deep weathering or voids from old workings. The factor of safety of '4' to the current maximum throw of 95 metres gives a clearance distance of 380 metres, which is in accordance with the historically applied 400 metre blast clearance area.

The possible reduction of the 400 metre blast clearance area to 200 metres while maintaining the same level of risk is examined below in more detail. A cross-section at the pit perimeter is shown in **Figure 9**, with the 400 metre safety exclusion zone delineated.
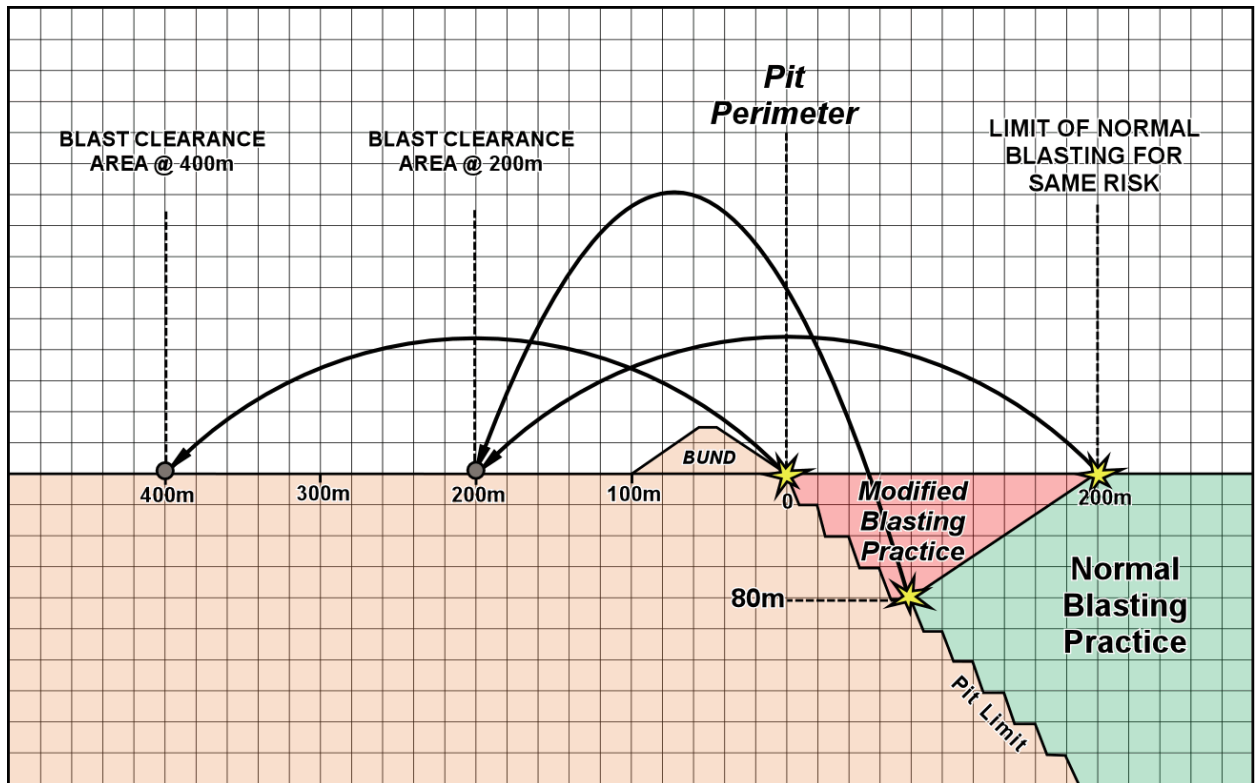

Figure 9 – Cross-section at the perimeter pit

The noise bund dimensions are small in relation to the 400 metre blast clearance area. The conditions under which flyrock will travel 400 metres are quite exceptional, so it will be conservatively assumed that the bund will afford no additional protection from exceptional blasts near the pit perimeter.

The risk of injury or damage from flyrock from blasts at the pit perimeter was evidently considered to be acceptable when the blast clearance area was set at 400 metres. A blast within the pit, located 200 metres from the pit perimeter, will have the same equivalent risk to a person standing 200 metres beyond the pit perimeter. In other words, current normal blasting practice at 200 metres from the pit perimeter poses the same risk to a person 200 metres beyond the pit perimeter as current blasting at the pit perimeter does to a person at the edge of the historically applied 400 metre blast clearance area.

Further, at lower benches within the pit, the current risk is maintained at a blasting distance closer than 200 metres because flyrock throw is limited by the wall profile and possible flyrock trajectory, as shown in **Figure 9**. The distance below the pit perimeter, where the same risk applies, is 80 metres below the perimeter. If the two points of equivalent risk are joined, a zone is defined where the extent of blasting with current practice may be conducted and maintain the 400 metre risk equivalence at a 200 metres distance from the pit perimeter. There is further conservatism with this approach because only high angled projections can clear the pit permitter and bund wall from blasts near the pit perimeter.

To blast closer to the pit perimeter than this limit of equivalent risk, the blasting practice must be modified to limit flyrock to 50 metres. Reference to **Figures 3a** and 3**b** shows that the minimum stemming height to achieve the 50 metre throw is 5 metres for the oxide zone and 4.1 metres for the sulphide zone.

In other words, the loading process in the zone requiring modified blasting practice must have sufficient checks and balances to ensure that the design stemming height is achieved for every hole in every blast within the zone.

With loading procedures similar to those adopted during the Chaffers West Cut-Back, which ensure that minimum stemming heights are achieved, if the blast clearance area was reduced to 200 metres, there would be the equivalent risk to that applying at the edge of the current 400 metre blast clearance area.

7.   SECONDARY BREAKING

Secondary breaking of toe and oversized rock may be achieved by blasting or by the use of mechanical impactors, especially in circumstances where the use of blasting methods are not practical or desirable.

To limit flyrock from secondary breaking (toe and popping oversize), the same principles of explosive confinement as those used for primary blasting apply.

Blastholes must be accurately positioned, and correctly loaded with an explosive charge that depends on rock type and structure, burden, stemming height, fragmentation requirements, and safety and environmental constraints.

The possibilities for excessive flyrock throw from secondary blasting are greater in circumstances where the positioning of blastholes and the accuracy of loading procedures are made more difficult by the presence of voids. Such circumstances exist in parts of the Fimiston Open Pit, and on occasions result in flyrock such as the reported throw of 250-450 metres for the blast of 3rd November 2004. The video of this blast showed excessive explosive force was used to shatter the boulders.

Circumstances in the Golden Pike Cut-Back are more favourable than those in the general open pit area due the absence of voids, and in these circumstances a greater degree of control is possible. It is possible that secondary breaking operations in the Golden Pike Cut-Back will be undertaken by the use of mechanical impactors.

If it becomes necessary to use secondary blasting in the Golden Pike Cut-Back area, design and loading procedures will be required to be specified and implemented to ensure that rock throw does not exceed 50 metres.

For a charge of one metre or more of explosive in a 165 mm diameter blasthole, the minimum distance to a free face burden or stemming must be as per the blasting specifications, eg. 4.1 metres for sulphide and 5 metres for oxide.

If the burden or stemming height is less than that specified because of shallower hole depths or boulder dimensions, the charge mass and, thereby, charge lengths must be reduced accordingly, as indicated in **Table 8**.

The minimum confinement conditions to limit throw to 50 metres for 89 mm and 165 mm diameter blastholes are also shown in **Table 8**. Popping of oversize boulders can be conducted to limit flyrock only if smaller diameter blastholes are used.

Table 8 – Charge masses, hole depths and minimum stemming/burden

| Charge mass per metre = 24.6 kg   k = 20 | | | | Charge mass per metre = 7.1 kg   k = 20 | | | |
| Hole diameter = 165 mm Maximum throw = 50 metres | | | | Hole diameter = 89 mm Maximum throw = 50 metres | | | |
Hole Depth (m)	Charge Length (m)	Charge Mass (kg)	Minimum Stemming/Burden (m)	Hole Depth (m)	Charge Length (m)	Charge Mass (kg)	Minimum Stemming/Burden (m)
5.6	1.0	24.6	4.6	4.2	1.0	11.7	3.2
4.9	0.8	19.7	4.1	3.6	0.8	9.4	2.8
4.2	0.6	14.8	3.6	3.0	0.6	7.0	2.4
3.7	0.5	12.3	3.2	2.7	0.5	5.9	2.2
3.3	0.4	9.8	2.9	2.4	0.4	4.7	2.0
2.8	0.3	7.4	2.5	2.0	0.3	3.5	1.7

7.1   Examples

7.1.1 Popping (throw limited to 50 metres)

- Boulder diameter: 4.0 metres
- Minimum burden: 2.0 metres

Charge to limit throw to 50 metres is 4.7 kg in an 89 mm diameter hole with a charge length of 0.4 metres.

7.1.2 Toe Holes (throw limited to 50 metres)

- minimum hole depth for 1.0 metre charge: 5.6 metres (4.6 + 1.0)
- maximum charge length: 1.0 metres
- maximum charge: 24.6 kg

- minimum hole depth of 0.5 metre charge: 3.7 metres (3.2 + 0.5)
- maximum charge: 12.3 kg

8.   CONCLUSIONS

- Current primary blasting practice limits flyrock to 50 metres for 72% of blasts and 95 metres for 100% of blasts.

- The clearance distance must be increased if the flyrock can land at a lower elevation than the blast.

- Current practice at Kalgoorlie Consolidated Gold Mines for primary blasting is suitable for personnel clearance distances of 380 metres to the same elevation as the blast with a factor of safety of '4'. This is in accordance with the 400 metre blast clearance area. A clearance distance of 190 metres distance is appropriate for equipment with a factor of safety of '2'.

- Analysis using the Terrock flyrock model shows that when current primary blast loading practice achieved design stemming height (72% of blasts) flyrock was limited to 50 metres, but when the stemming height was reduced by up to 0.9 metres, flyrock was thrown up to 95 metres.

- The maximum flyrock throw distance can be reduced to 50 metres by adopting procedures during loading to ensure that the **minimum** stemming height is 5 metres in the zone of modified blasting practice shown in **Figure 9.**

- Procedures were used during the Chaffers West cut-back showed that flyrock could be limited to 50 metres. The procedures proposed for the zone of modified blasting practice shown in Figure 9 are based on current practice used in the Super Pit, modified practice used in the Chaffers West cut-back, and analysis of data obtained during this investigation.

- Current blasting practice has an acceptable risk from flyrock at the historically applied 400 metre blast clearance area for blasts at the pit perimeter.

- The same acceptable risk exists at 200 metres outside the pit perimeter for blasts located inside the pit at surface level 200 metres from the pit perimeter. The same risk applies at the pit limit at a depth of 80 metres. These distances define a zone which limits the distance that current blasting practice may be conducted from the final pit outline.

- For blasts within the zone of modified blasting practice closer to the pit perimeter, improved loading practice must be exercised to limit flyrock throw to 50 metres, thereby maintaining the factor of safety of '4'. This is achieved by limiting the stemming height to an absolute minimum of 5 metres in the zone of modified blasting practice shown in **Figure 9.**

- Secondary breaking operations in the Golden Pike Cut-Back should be undertaken by either the use of mechanical impactors or by secondary blasting only when design and loading procedures are specified and implemented to ensure that rock throw does not exceed 50 metres.

Adrian J. Moore
Alan B. Richards
30th November 2005

APPENDICES

APPENDIX 1 – PAPER PRESENTED AT ISEE CONFERENCE – NEW ORLEANS, 2002

Flyrock Control – By Chance or Design

Alan B. Richards and Adrian J. Moore, Terrock Consulting Engineers Pty Ltd

Abstract

Responsible blasting requires that rock throw be controlled to ensure that no danger will result to people and property. This paper describes the development and testing of empirical field calibrated formulae that can be used to evaluate rock throw, provide an early warning of when reduced burden will endanger people and property, and prevent flyrock incidents.

Inputs to the formulae are charge mass, burden or stemming height, and a site constant that lies within a general range that can be tightened by site calibration. The output is the distance that rock will be thrown, and this 'design your own flyrock' quantification can be used to establish both safe clearance distances, and the critical range of burdens and stemming heights where the situation changes rapidly from safe to hazardous.

Examples are given of the use of the model to control flyrock in open-pit mining and quarry operations, in situations which are controlled by both burden and stemming height.

INTRODUCTION

To an old time shotfiring acquaintance there were four simple rules of blast clearance:

1. Always stand behind a tree or substantial object (*Note: this practice has its own hazards*).

2. If there are no trees, always stand with your back to the sun – it's hard work dodging goolies with the sun in your eyes.

3. Never face your vehicle towards the blast – it's a long cold trip home in the dark with the windscreen missing.

4. You can never stand back far enough.

Rule 4 begs the question, 'how far is far enough?'

The opportunity has been taken to quantify the conditions under which flyrock may result and the blasting practice necessary to control it. Efficient blasting practice results in broken rock being left in the rock pile, but the possibility of flyrock and its effective control must always be considered. The public, personnel and nearby infrastructure must be adequately protected from possible flyrock from blasting operations. The distinction must be made between 'flyrock' being the normal projection of broken rock from a blast and 'wild flyrock', the unplanned and unexpected violent projection of rock fragments at a great velocity from a blast that is the subject of this paper.

Flyrock can be an emotive subject and there is the possibility that flyrock can be projected large distances. However, the fact remains that thousands of blasts are conducted each year, often within 50 metres (165 ft) of roads and houses, without incident.

Flyrock occurs when the explosive in the blasthole is excessive or poorly confined, and energy in the form of high-pressure gas is available to throw broken rock fragments into the air, accompanied by excessive airblast. If there is insufficient stemming height, or poor quality stemming material is used (eg. drill cuttings in wet blastholes), material may be projected from the collar region of the blasthole at a high trajectory into the air around the blast site. If the blasthole has insufficient burden in front of the blasthole, flyrock may be projected at a somewhat flatter trajectory in front of the face.

Our recent flyrock investigations, combined with authoritative research by Lundborg (1981), Workman et al (1994) and St George et al (2001), has permitted the further development of a methodology for quantification of flyrock distances relative to explosive confinement conditions. The establishment of maximum throw distances is then used to determine minimum clearance distances from blasting and personnel, based on the application of appropriate safety factors. The method can also be used to design blasts close to sensitive infrastructure to limit the possibility of damage. It can also be used to indicate to shotfiring personnel the degree of control that must be exercised during surveying and loading to achieve minimum confinement conditions and the consequences of inadvertent lapses in standards.

THROW DISTANCE IN FRONT OF A FREE FACE

From research at the Swedish Detonic Research Foundation (Sve De Fo), Lundborg developed semi-empirical formulae for the prediction of maximum throw and optimum projectile size of flyrock. His formulae, based on experimentation and field observations, are listed below.

For a specific charge (powder factor) ≤ 0.2 kg/m^3, the maximum throw is expressed by:

$$L = 143 \ d \ (q - 0.2) \tag{1}$$

where:
- L = maximum throw (m)
- q = specific charge kg/m^3
- d = hole diameter (ins)

The optimum size of the rock thrown is given by:

$$\phi = 0.1 \ d^{2/3} \tag{2}$$

where:
- ϕ = boulder diameter (m)
- d = hole diameter (ins)

This introduces the concept that the distance that a boulder is thrown depends on momentum (rock size and density) and aerodynamic principles (rock shape, smoothness, air resistance), and that a certain spheroidal size (most aerodynamic) has optimal momentum and air resistance characteristics. In an underburdened or understemmed blasthole, the optimum sized boulder would be thrown a maximum distance of:

$$L_{max} = 260 \ d^{2/3} \tag{3}$$

This maximum distance is the distance beyond which the probability of flyrock of the optimum size from a blast of one million such boulders landing in a square metre is less than one in ten million, or less than the risk of being killed by lightning in ten years, ie. 'safe'. Flyrock may be projected further than this but it serves as a practical maximum throw for our purposes.

The maximum throw and throw of boulders at sizes other than the optimum can be determined from Figure 1.
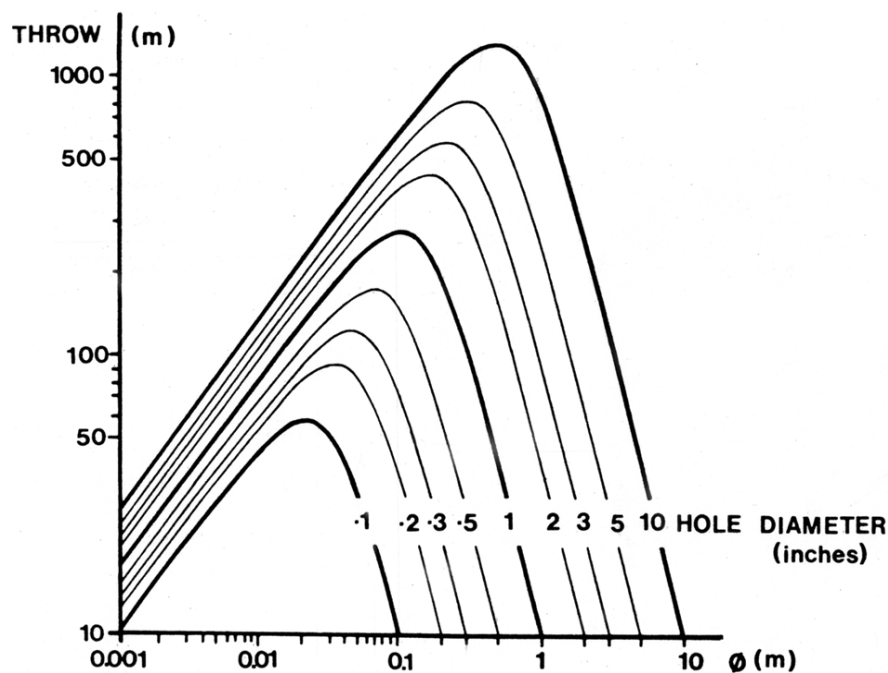

Figure 1 – Maximum throw of boulders (Lundborg, 1981)

The work of Lundborg is useful in demonstrating the distances that flyrock can be projected from totally uncontrolled blasting operations and as a reminder of the importance of proper control procedures during all stages of face survey, blast design and loading. If our friend wanted to be safe he could stand back the appropriate distance for the size blasthole from Figure 1. However, thousands of controlled blasts are conducted every year and the flyrock is limited to distances that are a fraction of Lundborg's maximum distances.

The methodology of Workman et al has proven useful when combined with general trajectory theory to determine the maximum throw based on specific confinement conditions. Our investigation of recent flyrock incidents has permitted further application of the Workman et al model.

The general trajectory formula for the prediction of the maximum horizontal throw of a projectile to a point at the same elevation is:

$$L = \frac{V_o^2 \ Sin \ 2 \ \theta_o}{g} \qquad [4]$$

where:
$\quad V_o$ = launch velocity (m/s)
$\quad \theta_o$ = launch angle (degrees)
$\quad L$ = horizontal throw (m)
$\quad g$ = gravitational constant (9.8 m/s/s)

The throw is a maximum when $2 \ \theta_o = 1$ or $\theta_o = 45^o$, ie $L_{max} = \dfrac{V_o^2}{g}$ $\qquad [5]$

If the ground rises from the launch site, the throw will be less. If the ground drops below the launch site, the throw will be greater, as illustrated in Figure 2.
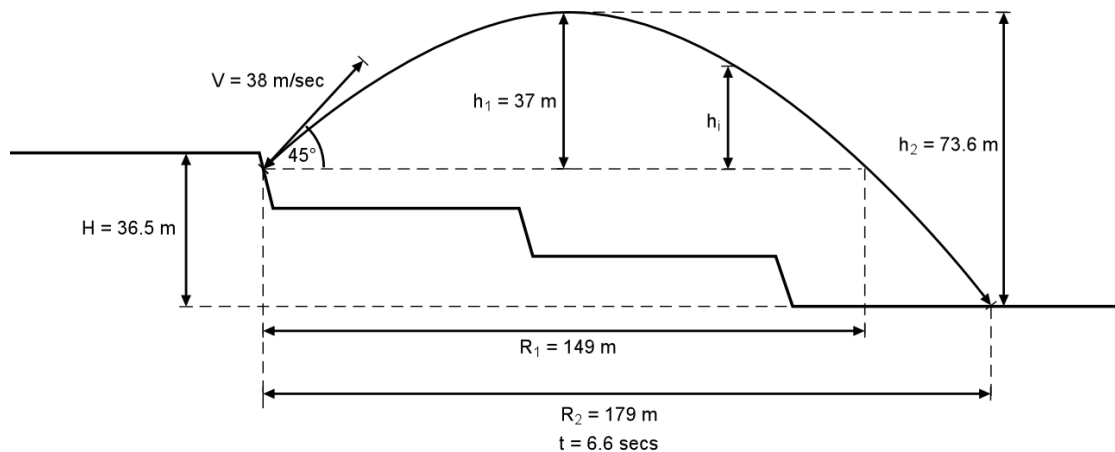

Figure 2 – Projectile path for V_o = 38 m/s (125 ft/s) (after Workman et al, 1994)

More complex formulae are available for determining the throw to points of different elevation but the simple case is accurate enough for our purpose. The general trajectory theory ignores factors such as rock dimension and shape, density, air resistance and wind, but is accurate enough for this methodology at distances up to Lundborg's 'safe' distance. As the work of Lundborg demonstrates, at distances beyond 200-300 metres (600-900 ft), the rock size and shape becomes increasingly important to the maximum throw as momentum and air resistance becomes more significant in how far a rock will travel.

Workman et al introduces the concept of throw being a function of face velocity and scaled burden, ie. burden divided by the square root of the explosive weight per unit length. The Workman et al paper includes a figure from previously published data (see Figure 3), accredited to Bauer, Burchell and Crosby (1982).
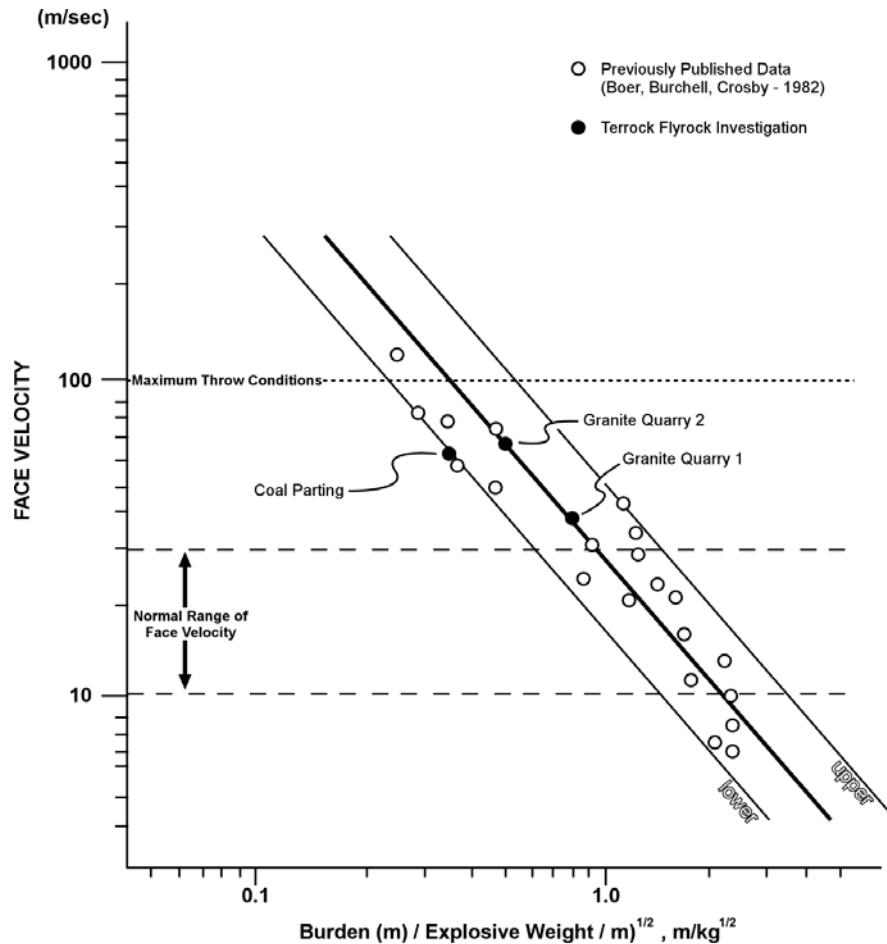

Figure 3 – Scaled burden versus face velocity (after Workman et al, 1994)

The normal range of face velocity for production blasting is 10-30 m/s (32-100 ft/s). With the most severe flyrock incidents, the velocity is 100 m/s (330 ft/s) or more.

The face velocity and scaled burden are related by the formula:

$$V_o = k \left(\frac{\sqrt{m}}{B} \right)^{1.3} \qquad [6]$$

where:
B = burden (m)
m = charge mass/metre (kg)
k = a constant

Equations No. 5 and No. 6 can be combined to give:

$$L_{max} = \frac{k^2}{9.8} \left(\frac{\sqrt{m}}{B} \right)^{2.6} \qquad [7]$$

The mean regression line from the Workman et al data corresponds to a k factor of 27 and the range of k factors to encompass all the data is 15 to 37. The scaled burden/face velocity plots for flyrock incidents recently investigated gave some more data points involving granite quarries and coal overburden were added to Workman et al data and k factors corresponding to 27 and 13.5 were determined. These investigations were conducted with the benefit of accurate survey and face profile information, which has often not been available to earlier flyrock investigations. A summary of the blast confinement conditions resulting in the flyrock incidents is shown in Table 1.

Table 1 – Summary of flyrock incident confinement conditions

Rock Type	Hole Diameter		Burden		Actual Burden		Charge Mass/m		Stemming Height		Hole Depth		Maximum Throw		k Factor
	(in)	(mm)	(ft)	(m)	(ft)	(m)	(lb)	(kg)	(ft)	(m)	(ft)	(m)	(ft)	(m)	
Granite 1	4	102	9.8	3.0	8.5	2.6	24	11	16.4	5.0	54	16.5	460	140	27
Granite 2	3.5	89	9.2	2.8	4.7	1.43	17.8	8.1	9.8	3.0	57	17.5	1440	440	27
Coal (Parting)	8	203	16.4	5.0			78.3	35.6	5.2	1.6	7.2	2.2	968	295	13.5

These incidents have given us confidence in the model and have provided a practical range for common rock types, ie. 13.5 for softer competent rocks and 27 for harder competent rocks. The circumstances under which the k factor of 37 would apply have still to be determined. The relationships of k factor in Equation No. 7 permit graphs, such as shown in Figure 4, to be produced. This clearly shows the relationship between burden and maximum throw for 102 mm (4 ins) diameter blastholes with an explosive with a density of 1.35 g/cm^3. It also shows the minimum burden conditions that will result in Lundborg's 'safe' distance, ie. 0.8 metres (2.6 ft) for softer rocks and 1.4 metres (4.6 ft) for hard rocks.

As the burden/diameter ratio decreases below 20-30, the throw distance increases greatly with small burden reductions and Lundborg's maximum distance is reached when the burden/diameter ratio is about 9-13.
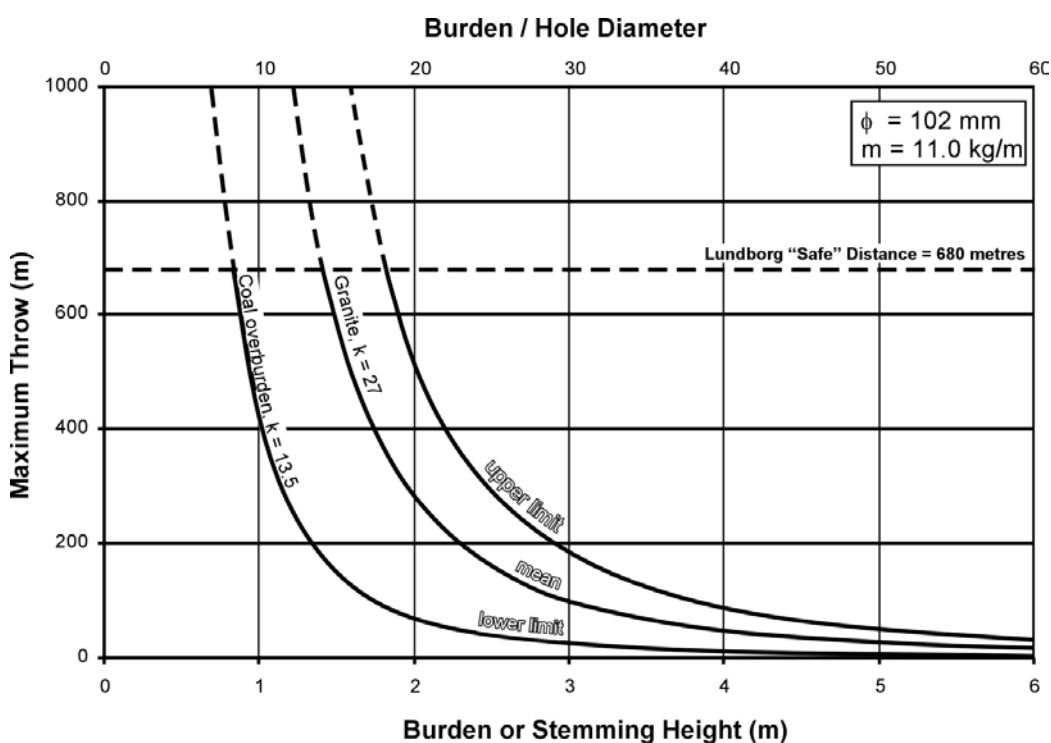

Figure 4 – Maximum throw versus burden – 102 mm (4 ins) ϕ holes; explosive 1.35 g/cm^3

Another graph which expresses the relationship between maximum throw and burden/hole diameter ratio can also be produced, as shown in Figure 5. This is for an explosive density of 1.2 g/cm^3 with at least one metre (3.3 ft) of explosive. The maximum throw distances are achieved when the burden is reduced below 10-15 hole diameters.
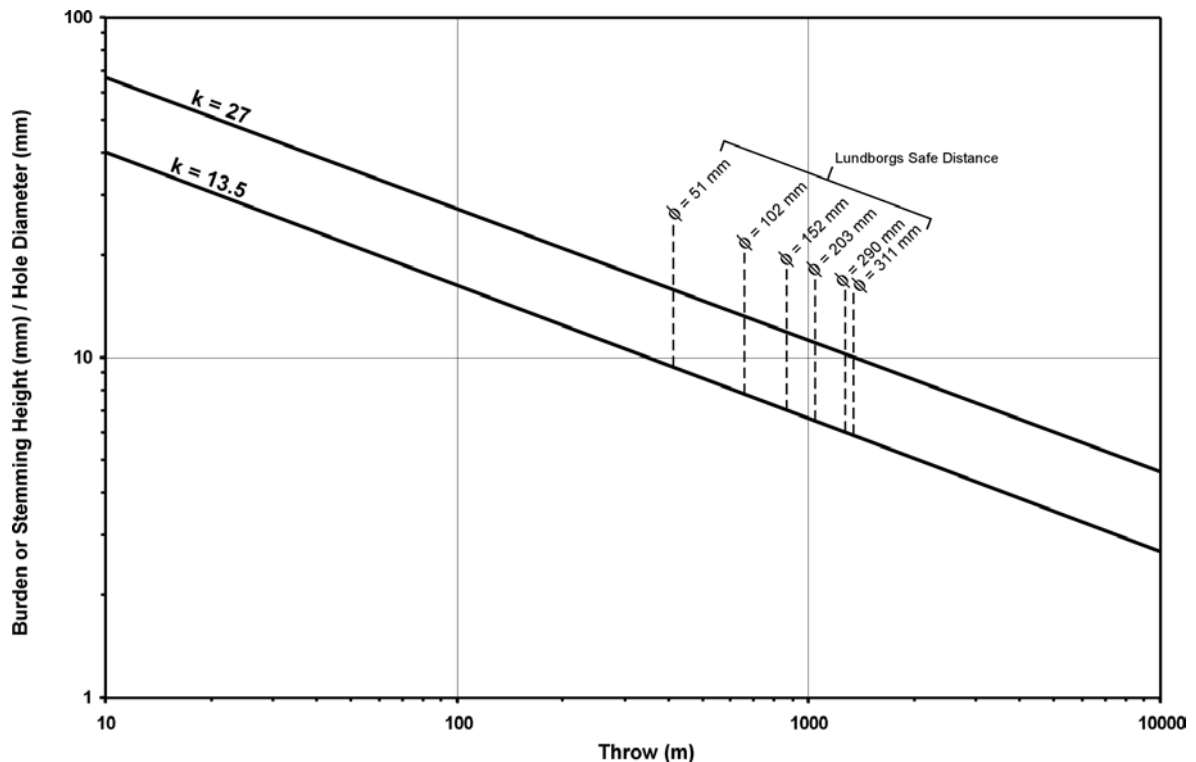

Figure 5 – Maximum throw versus burden/hole diameter ratio

To ensure that flyrock is not projected the maximum distance, the face survey, design and loading checks must ensure that holes or sections of hole that are seriously underburdened must be identified and dealt with appropriately by such measures are light loading with packaged explosives, decking or re-drilling.

The principles outlined can be used to introduce flyrock throw and clearance distances into blast design, as demonstrated in the section of this paper headed 'Clearance Distance Design'.

THROW DISTANCES BEHIND A FREE FACE

In bench and cast blasting, the throw distances behind the face, providing the stemming performs adequately and the collar rock is sound, is less than in front of the face. Similarly in choke blasting and paddock blasting, where there is no free face, the performance of the stemming material and the possibility of cratering will determine the maximum throw distance, and it can be in any direction.

The two possible means of producing flyrock behind the face, in face blasts and stemming controlled blasts are cratering and stemming ejection (gun barrelling or rifling).

CRATERING

If the stemming height is insufficient or the rock in the collar of the hole is weak, cratering can occur and the maximum throw can be in any direction. The 'safest' blast clearance is when Lundborg's maximum distance applied all around a blast but, in most cases, this will prove ultra-conservative.

Experience shows that in bench blasting the incidence of throw behind a face is substantially less than that in front of the face because stemming height is more readily measured and controlled than face burden. The only circumstances by which optimum size flyrock can be thrown the maximum distance behind the face is if the explosive column is bought dangerously close to the collar or the stemming material bridges over too close to the collar in weakened rock and cratering occurs, as illustrated in Figure 6.

The circumstance of cratering will be examined more closely using the specific charge approach of Lundborg. By combining the maximum throw from Equation No. 3 with Equation No. 1, the maximum throw of 658 metres (2158 ft) occurs at a specific charge of 1.35 kg/m^3 (2.27 lb/yd^3) for 102 mm (4 ins) blastholes and 1.11 kg/m^3 (1.87 lb/yd^3) for 203 mm (8 ins) diameter blastholes.

The circumstances under which the maximum throw conditions occur is when the cone of material removed by the portion of the explosive (e) has a specific charge greater than 1.35 kg/m^3 (2.27 lb/yd^3) or 1.11 kg/m^3 (1.87 lb/yd^3) and assuming a 90° crater (see **Figure 6**).
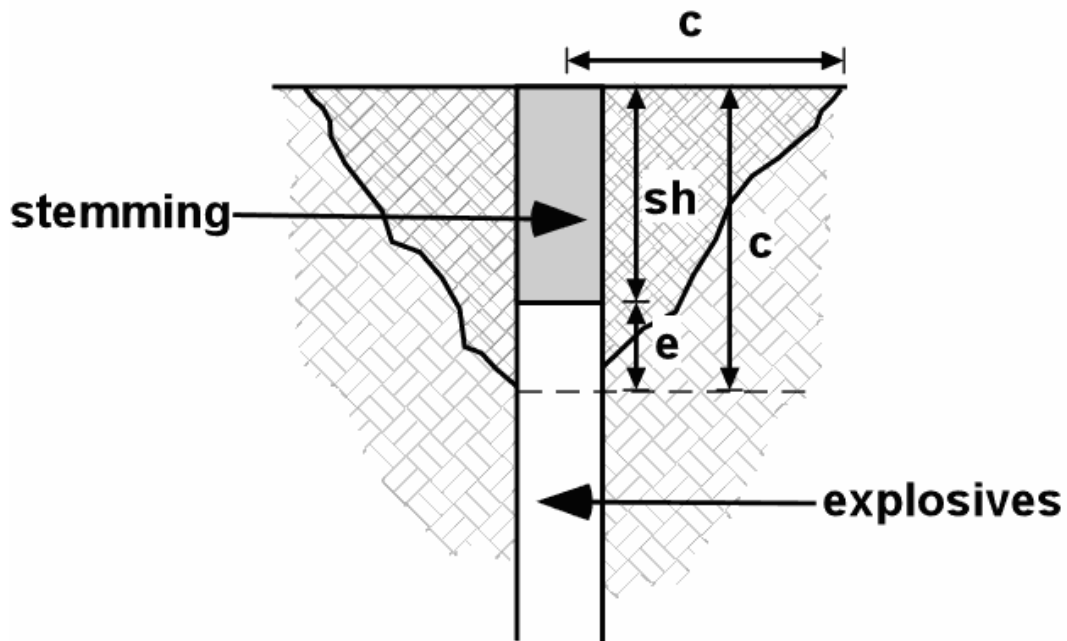

Figure 6 – Cratering conditions dimensions

$$\text{ie. specific charge} \quad = \quad \frac{e \times W}{\frac{1}{3} \times \pi \times c^2 \times c}$$

where: e   =   explosive height (m)
           W   =   explosive mass/m (kg/m)
           c   =   crater radius and height (45°)

For 102 mm (4 ins) diameter blastholes with a charge mass per metre of 9.8 kg (6.5 lb/ft), the crater dimension that matches the necessary loading condition is 1.91 metres (6.3 ft) and the stemming height is thereby 1.91 – 1.0 = 0.91 metres (6.3 – 3.3 = 3 ft) (9.0 hole diameters), ie the stemming height of 0.91 metres (3 ft) or less will create conditions whereby flyrock can be thrown the maximum distance of 658 metres (2158 ft). For 203 mm (8 ins) diameter blastholes with a charge mass of 39 kg (85.8 lb) per metre (26.1 lb/ft), the crater dimension is 3.2 metres (10.5 ft) and the stemming height is thereby 3.2 – 1.0 = 2.2 metres (7.2 ft) (10.8 hole diameters).

The burden/diameter ratios resulting in the maximum throw from this approach are similar to the values determined in Figure 4 from the scaled burden approach. It would appear to be an acceptable approximation to have burden and stemming height as interchangeable variables in Figure 4 for cratering conditions where the explosive column is at least one metre (3.3 ft). As the stemming height is increased, the probability of cratering is reduced and, at some point yet to be determined, would become negligible (from experience, this is probably in the order 20-30 hole diameters).

This methodology can also be used for designing shallow blasts where the explosive column is less than one metre (3.3 ft) by using the actual charge mass in Equations No. 1 and No. 2. In a surface coal mine, parting blasts were to be conducted within 50 metres (165 ft) of an overhead powerline, which had to be protected from flyrock. The hole diameter was 203 mm (8 ins), explosive density was 1.2 gm/cm^3 or 38.8 kg/m (26.0 lb/ft) the powder factor was to be maintained at 0.4 kg/m^3 (0.67 lb/yd^3) where possible and the spacing had to be maintained at 5 metres (16.4 ft) for loading access.

The design procedure is as follows:

1. Determine the minimum stemming height for one metre (3.3 ft) of explosive from Equation No. 7b:

$$50 \quad = \quad \frac{13.5^2}{9.8} \quad \left(\frac{\sqrt{21.1}}{SH} \right)^{2.6} \quad \therefore \quad SH \ = \ 4.3 \text{ metres (14.1 ft)}$$

    The minimum stemming height for seam thicknesses down to 5.3 metres (17.3 ft) is 4.3 metres (14.1 ft) to limit flyrock to 50 metres (165 ft).

2. For seam thickness less than 5.3 metres (17.3 ft), calculate the charge mass and drilling pattern to achieve the powder factor and balance the explosive column and stemming height to limit the throw to 50 metres (165 ft) using Equations No. 7 and No. 8.

    For shallower seams, the stemming height and explosives column must both reduce. Typical blasting specifications to achieve the design criteria are listed in Table 3.
    The minimum seam thickness that can be blasted with this size drill is 2 metres (6.5 ft), corresponding to a 0.15 metre (6 ins) explosive column (enough to cover the booster) and a compromised powder factor to accommodate the access requirement is required for seam thicknesses less than 5 metres (16.4 ft).

Table 3 – Recommended blasting specifications for reduced seam thicknesses - 1.2 g/cc explosive density

Seam Thickness		Stemming Height		Stemming Height/ Diameter	Explosive Column		Explosive Charge		Drilling Pattern S = 1.43 B				Powder Factor	
									S		B			
(ft)	(m)	(ft)	(m)		(ft)	(m)	(lb)	(kg)	(ft)	(m)	(ft)	(m)	(lb/yd³)	(kg/m³)
21.3	6.5	14.1	4.3	21.1	7.2	2.2	187	85	21.3	6.5	16.4	5.0	0.67	0.4
19.7	6.0	14.1	4.3	21.1	5.6	1.7	145	66	19.4	5.9	15.1	4.6	0.67	0.4
18.0	5.5	14.1	4.3	21.1	3.9	1.2	103	47	17.0	5.2	13.1	4.0	0.67	0.4
16.4	5.0	13.5	4.1	20.2	3.0	0.9	77	35	16.4	5.0*	11.5	3.5	0.67	0.4
14.8	4.5	12.3	3.75	18.2	2.5	0.75	64	29	16.4	5.0*	11.5	3.5	0.62	0.37
13.1	4.0	11.0	3.35	16.5	2.1	0.65	55	25.2	16.4	5.0*	11.5	3.5*	0.61	0.36
11.5	3.5	9.8	3.0	14.7	1.6	0.5	43	19.4	16.4	5.0*	11.5	3.5*	0.54	0.32
9.8	3.0	8.7	2.65	13.0	1.1	0.35	30	13.6	16.4	5.0*	11.5	3.5*	0.44	0.26
8.2	2.5	7.4	2.25	11.0	0.8	0.25	21	9.7	16.4	5.0*	11.5	3.5*	0.37	0.22
6.6	2.0	6.1	1.85	9.1	0.5	0.15	13	5.8	16.4	5.0*	11.5	3.5*	0.29	0.17

* *minimum access requirement 5.0 metres (16.4 ft) – minimum burden 3.5 metres (11.5 ft)*

STEMMING EJECTION

If stemming practice is adequate to prevent cratering (ie. sufficient stemming length), there is still the possibility of stemming ejection (gun barrelling) to consider, as schematically shown in Figure 7. sufficient stemming height, poor quality materials or stemming material bridging across a hole may cause the projection of stemming material and loose rocks at the sides and collars of the blastholes into the air as flyrock.
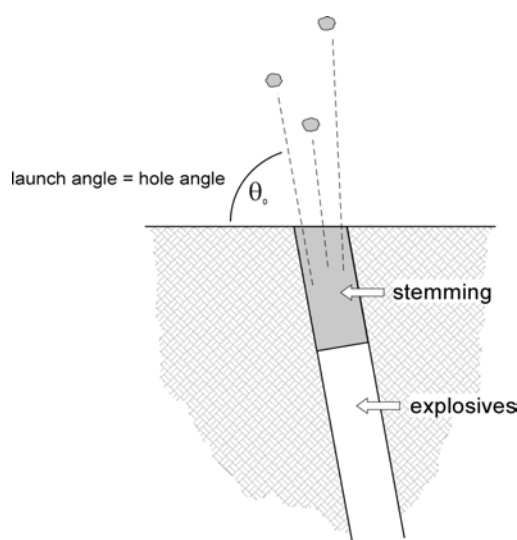

Figure 7 – Stemming ejection from an inclined hole

In this case, the throw angle is the hole angle. The maximum throw can be determined from Equation No. 7 multiplied by Sin $2\theta_o$. For a 100 mm (4 ins) diameter hole in hard rock with 3.0 metres (9.8 ft) stemming height and explosive density 1.35 g/cm^3, the maximum throw is:

$$\frac{27^2}{9.8} \left(\frac{\sqrt{11}}{3.0}\right)^{2.6} \text{Sin } 2\theta_o = 96.5 \text{ Sin } 2\theta$$

The maximum throw behind the face for angled holes is shown in Table 4.

Table 4 – Maximum throw behind the face – stemming ejection

96.5 metre throw		
Hole (launch) Angle (degrees)	Maximum throw	
	(ft)	(m)
0*	0	0
5	56	17
10	108	33
15	157	48
20	203	62
25	242	74
30	275	84
40	312	95
45	317	96.5

*   *vertical holes require an adjustment because stemming can be launched at a
    flatter incident angle from the collar by deflection off the walls.*

CLEARANCE DISTANCE DESIGN

The previous sections have established that the maximum flyrock throw from a blast can be
predicted from:

Face burst:
$$L_{max} = \frac{k^2}{g} \cdot \left(\frac{\sqrt{m}}{B}\right)^{2.6} \qquad [7a]$$

Cratering:
$$L_{max} = \frac{k^2}{g} \cdot \left(\frac{\sqrt{m}}{SH}\right)^{2.6} \qquad [7b]$$

Stemming ejection:
$$L_{max} = \frac{k^2}{g} \cdot \left(\frac{\sqrt{m}}{SH}\right)^{2.6} \, Sin\, 2\theta_o \qquad [7c]$$

where:
θ = drillhole angle
L = maximum throw (m)
m = charge mass/m (kg/m)
B = burden (m)
SH = stemming height (m)
g = gravitational constant

The maximum throw of Lundborg occurs when the stemming is less than about 9-12 hole
diameters. The empirically determined k factor range is 13.5 for soft competent rock, such as
coal overburden, and 27 for hard competent rock, such as basalt or granite. A higher k factor
may be applicable in circumstances yet to be determined.

Behind the face in cratering conditions where the stemming height is less than about 20-30 hole
diameters, the maximum throw can be predicted from the above equations. Where the stemming
height is adequate to prevent cratering, there is still the possibility of stemming ejection and
sufficient clearance must be allowed for this.

The k factors have been determined empirically. If the minimum burdens and stemming heights are accurately controlled by face profiling and loading practice, the range of maximum throw distances can be determined with reasonable accuracy, however, they have no safety margin. Site specific calibration investigations could be conducted to more accurately define the model for any site. Another approach is to apply suitable safety factors.

Because the throw distance increases greatly with small changes to burden or stemming height, it is considered reasonable that the maximum throw distances be doubled to determine the minimum clearance distances to plant and equipment and this be doubled again to determine minimum clearance distances for personnel.

The clearance distance to the sides of a blast face should also be considered. The flyrock from a face is most likely to be projected perpendicular to the face and most unlikely to be projected parallel to the face. If we accept that the maximum throw is most likely to occur within a 90° arc commencing at 45° from the face, the shape of the recommended clearance zone is shown in Figure 8.

This allows for maximum throw at 45° from the face with decreasing potential throw distances past 45° which join up with a tangent to the behind the face clearance. The blast specifications on which this shape is based on are θ = 102 mm (4 ins); B = 3.0 (9.8 ft); SH = 4.0 metres (13.1 ft); hole angle = 10°; explosive density 1.35 g/cm^3 hard rock; k = 27.

Using a totally different approach, St George et al developed a model and used Monte Carlo simulation to produce the plot of flyrock loading locations shown in Figure 9 for 100 mm (4 ins) diameter blastholes.
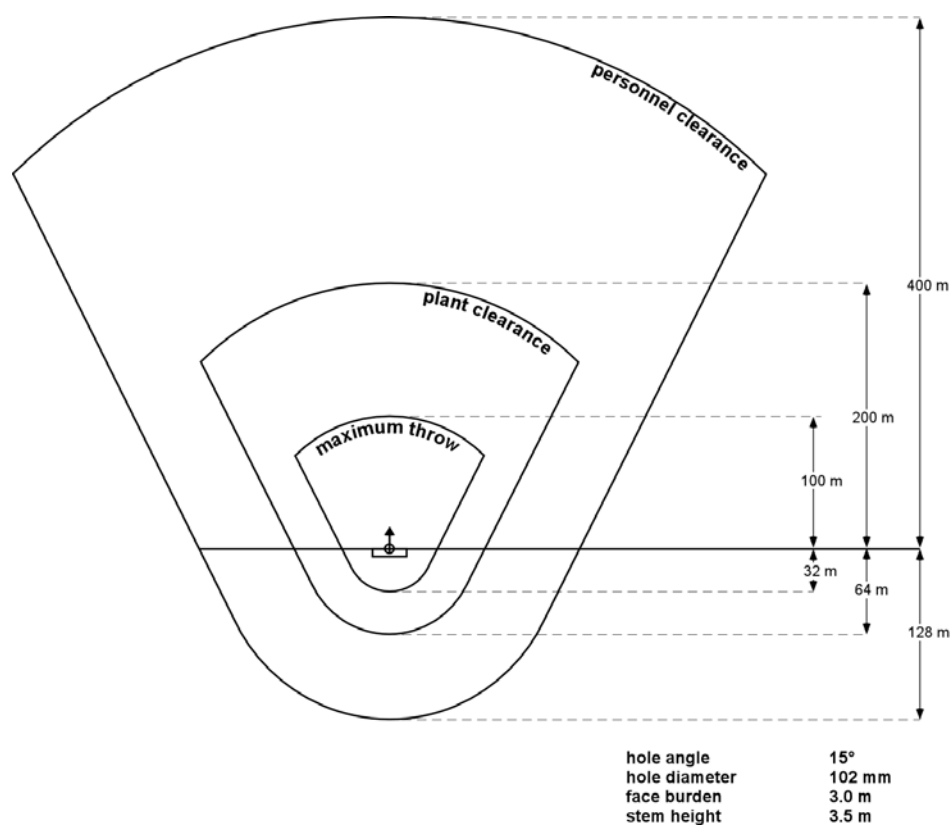

hole angle	15°
hole diameter	102 mm
face burden	3.0 m
stem height	3.5 m

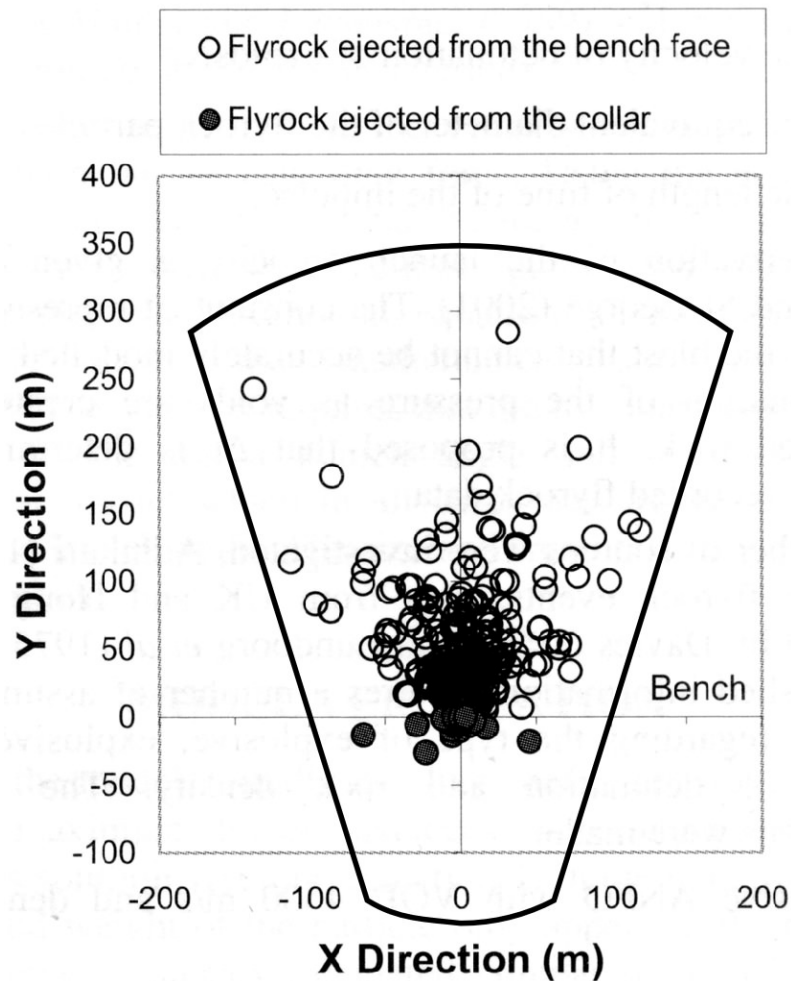**Figure 8 – Recommended minimum clearance zone – 102 mm (4 ins) blastholes**

Figure 9 – Maximum throw determined from 1000 St George et al Monte Carlo simulations (after St George et al)

From 1000 simulations, St George et al determined the maximum throw distances to be 350 metres (1150 ft) in front of the face and 150 metres (490 ft) behind the face, that are not dissimilar from our recommended clearance distances. The outline shown in Figure 9 is our interpretation of the St George et al determinations. St George et al assumed the standard deviation for launch angle was 15.3° and standard deviation for the angle in front of the face to be 25°, which are slightly different to our assumptions.

MINIMUM CONFINEMENT CONDITION DESIGN

As well as predicting maximum throw, the models previously developed can also be used to determine the minimum confinement conditions that must be achieved during drilling and loading to limit flyrock to protect property and personnel. Consider, for example, a blast facing towards the screen house at a distance of 100 metres (330 ft). The maximum throw should be limited to 50 metres (165 ft) if personnel are cleared at the blast time. From Figure 4, the minimum burden and stemming height for the blast is 3.8 metres (12.5 ft). Holes with less burden than 3.8 metres (12.5 ft) must be redrilled, light loaded with packaged explosive or be decked through the underburdened section of face.

The minimum burden conditions can be used in loading design to limit the possibility of flyrock and to determine if personnel must be evacuated before firing or additional confinement, such as blasting mats or the placing of artificial burden material is required.

CONCLUSIONS

By utilising the efforts of previous researchers and the application of our own experience and observations, a methodology has been developed to permit flyrock distances to be determined based on confinement conditions; a 'design your own flyrock' approach.

There is no reason why flyrock design cannot become part of the environmental design of blasts together with ground vibration and airblast design. Like all empirical models, it requires further refinement and testing, especially by the investigation of flyrock incidents where accurate hole profile data is available, but by the application of conservative safety factors already in a useable form.

It is with increasing confidence that in relation to blasting clearance distances we will be able to say to our shotfiring friend 'stop looking for that tree, this is far enough!'

REFERENCES

Bauer A, Burchell S L, & Crosby W A, 1982: 'Use of High Speed Photography in Open Pit Blasting', Mining Resource Engineering Ltd, Kingston, Ontario, Canada.

Lundborg N, 1981: 'The Probability of Flyrock', Sve De Fo Report, DS 1981.

St George J D & Gibson M F L, 2001: 'Estimation of Flyrock Travel Distances: A Probabilistic Approach', Explo 2001, Hunter Valley, New South Wales, Australia.

Workman J L and Calder P N, 1994: 'Flyrock Prediction and Control in Surface Mine Blasting' in the Proceedings of the 20th Conference ISEE, Austin, Texas, USA.