



Flyrock in surface mining–part 4. Adaptation of Gurney model to predict burden velocity, flyrock velocity, and explosive energy partitioning in bench blasting

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Dates:

Received: 12 Mar. 2025
Revised: 11 Nov. 2025
Accepted: 27 Nov. 2025
Published: January 2026

How to cite:

Szendrei, T., Tose, S. 2026. Flyrock in surface mining–part 4. Adaptation of Gurney model to predict burden velocity, flyrock velocity, and explosive energy partitioning in bench blasting. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 126, no. 1, pp. 13–22

DOI ID:

<https://doi.org/10.17159/2411-9717/3690/2026>

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Abstract

The Gurney approach to explosive/inert material interaction was adapted to analyse the face velocity in bench blasting. The model is based on the blasthole diameter, rock and explosive density, burden, spacing, linear charge density, and the Gurney energy constant. It is validated by comparing its predictions with a set of 20 field measurements of face velocities reported by Chiappetta et al. (1983) in an iron ore mine. The Gurney model links the observed large scatter of measured face velocities to the variation of the Gurney energy constant. This in turn is linked to the variability of the gas pressure acting on the burden. These variable pressures are generated when detonation product gases migrate into the extensive and complex fracture network around and between in-row blastholes.

The energy efficiency of burden movement can be derived from the model. It is shown that ~7% of the explosive's chemical energy is available for gas expansion work on the burden; of this quantity, 36% is actually converted to burden kinetic energy. That is, less than 3% of chemical energy is ultimately expended in burden displacement and throw. The model further indicates that the projection of high-velocity (say, 100 m/s) flyrock is possible only when the path of least resistance through the burden has an effective density far less than the host rock. An equation is derived that identifies the combinations of burden and path density that may yield flyrock. These values are specific to a particular baseline blast design.

Keywords

gas expansion work, Gurney energy, burden velocity, flyrock, energy partitioning, rock fracture

Introduction

Szendrei and Tose (2022) demonstrated through aeroballistic calculations of trajectories with air drag resistance being included, that the throw of flyrock beyond the safety zone of a surface mine (500 m) would require high projection velocities that previously postulated sources of flyrock, such as shock and stress wave action and airblast, cannot provide. It is common practice to set mine safety zones at 500 m. This value is based on the South African Health and Safety Act (1996), which stipulates that various actions must be taken by the mine prior to blasting within 500 m of structures of concern. Thus, it is used as a reference when determining flyrock risk zones.

It was further pointed out that high velocities of 100 m/s and more can only be attained by gas piston action following the conversion by detonation of the charge load in the blasthole to a high-pressure gas. Gas expansion work transfers momentum (impulse) and kinetic energy to the fractured rock at three recognised sources of flyrock – movement of burden and possible faceburst, stemming ejection and rifling, and cratering of hole collar. The forward movement of the free face in bench blasting has been the subject of many studies because it provides important information about explosive performance and its interaction with the rock mass (Noren, 1956; Petkof et al., 1961; Lemesh, Pozdnyakov, 1972; Chiappetta et al., 1983; Segarra, 2003; Zhang et al., 2021). While it is well-established that under typical conditions, face velocities are in the range of 2 m/s to 30 m/s, the mechanism of face movement has not been established in quantitative terms that display the underlying physics.

Various attempts have been made to correlate face velocity with particular details of blast design, and explosive and rock properties. A prime example of this empirical approach is the work of Segarra (2004). This study derived correlations of 20 blasting parameters with face velocities measured opposite the blastholes in 8 production blasts. These parameters comprised the geometrical details of the blastholes and drilling patterns, charge load and powder factors, explosion detonation properties, chemical and

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useful energies, and intra-hole timing. Three statistically significant correlations were identified. One was a positive correlation with stemming length (Pearson's $r=0.64$); the other two correlations were based on in-row timing delays. Paradoxically, the strongest correlation ($r=0.86$) indicated that, as the cooperation between blastholes decreases with increasing delay times, the face velocity increases. The difficulty in explaining the influence of stemming length and delay timing on initial velocity led Segarra (2004) to conclude that the derivation of a formula for face velocity based on correlation with known and measurable blast details was not feasible.

A semi-quantitative physical model for face movement was described by Szendrei and Tose (2023). The large variation of the charge-to-rock mass ratio that may arise for various reasons in localised areas of the face was proposed as the underlying cause of high velocity rock ejection from the face. In this study, the details of the proposed burden movement model are mathematically elaborated within the conceptual framework of the Gurney approach. Although this model is primarily intended to provide an interpretation of the displacement and throw velocity of burden rock, it is general enough to allow predictions of flyrock under unusual, but nonetheless plausible, combinations of blasting parameters.

Burden movement

Basic features – field observations

The advent of high speed photography has dispelled the long-held belief that the bench face is blown out immediately upon detonating the shotholes. In fact, there is a distinct time lag after detonation when nothing is visible on the face. Noren (1956) identified this time lag when blasting 15-tonne granite blocks with a single 1.8 m × 32 mm hole, bottom filled to a height of 1 m with cartridge dynamite. Noren (1956) detected face movement opposite the charge column with an electromechanical device that was capable of measuring the outwards movement of the face in increments of 3 mm at first, then in increments of 13 mm up to a maximum distance of approximately 1 m. The measurements revealed two important characteristics of burden movement: (i) the time required for the first movement was approximately seven times longer than the transit time of the shock and seismic waves through the burden; and (ii) the face acquired its final velocity within a displacement of 10 mm–20 mm, irrespective of the amount of burden tested (0.18 m–0.53 m).

Noren's observations were confirmed by Petkof et al. (1961) in full-scale blasting at three quarries (granite, marble, and limestone). Using high-speed photography at 1000 frames per second (fps) in close-up mode on selected small areas of the face, they tracked the movement of the face to a maximum displacement of about 1 m. The results, as presented in the time-distance plots clearly display the two features noted by Noren (1956): First movement was detected at lag times of 12 ms to 41 ms, which are approximately ten times longer than the transit times of seismic waves; thereafter, the face continued to move at a constant velocity.

A comprehensive study of lag time was reported by Lemesh and Pozdnyakov (1972) by performing a kinematic analysis of the lateral displacement of the face based on 1000–2500 frames per second (fps) photography. This study was described in greater detail by Hustrulid (1999) after clarifying the terminology of the Russian source. Measurements were recorded in 14 blasts in an open pit nickel mine with 200 mm diameter holes at 5 m to 9.5 m

spacing and variable burdens of 4.9 m to 11.3 m. There was no visible change on the face for 15 ms to 40 ms after detonation and its surface remained at rest. In no instance was gas venting observed before the burden started to move ahead. Although the widening of existing cracks and the formation of new cracks were observed as the forward movement of the face continued, gas venting was only observed in the case of exceptionally small burdens. The tests were repeated in other areas of the pit in four rock formations with varying degrees of blast resistance. The burden was kept constant at 6.2 m ± 0.5m. The lag times averaged for 7 to 14 tests in each formation decreased with increasing rock resistance and varied from 3.3 ms to 5.3 ms per metre. Following the detection of initial movement, the face velocity remained essentially constant.

Lemesh and Pozdnyakov (1972) noted that the absence of acceleration of the rock mass after its initial movement indicates that there was a rapid drop of gas pressure acting on it. This line of interpretation can be extended to indicate that gas pressure forces were the most active in the quiescent period when the rock mass acquired its initial (and maximum) velocity. Based on this interpretation, the conversion of gas internal energy to burden kinetic energy commences during the quiescent period and goes to completion soon after first movement is detected due to the rapid increase of gas volume as the burden block is displaced ahead.

In a very detailed report, Chiappetta et al. (1983) described the use of motion picture photography at 250 to 500 frames per second as a dynamic tool in surface mines to evaluate, among other uses, explosive efficiencies in relation to burden velocity. Lightweight markers placed on the face were tracked to lateral distances of up to 15 m. From these measurements of displacements at known times the profile of the face could be reconstructed over a range of about 1000 ms. Two important features of burden motion were established:

- The time lags to the first motion were in the range 23 ms – 53 ms and the overall average time delay was 3.3 ms per metre of burden, which was essentially the same as that reported by Lemesh and Pozdnyakov (1972);
- Individual markers on the face remained at a constant velocity for up to 3 m over a time span of approximately 1000 ms.

A further conclusion that can be drawn from the report is that the face and burden blocks moved as a whole despite the often wide differences in the velocities over the face between the crest and grade. Despite the differential movements, wholesale venting of gas was only evident at late times, 700 ms – 1000 ms, when the whole face was obscured by dust, fumes, and broken rock as the burden block fragmented into various sizes.

Conceptualisation of burden movement

As a prelude to the derivation of a predictive model, the process of burden movement can be conceptualised as follows. Following the detonation of the blasthole charge, no response is detected on the face for a period of 15 ms to 60 ms, depending mostly on the burden thickness and much less on the rock mechanical properties. Thereafter, and quite abruptly, the face moves ahead at some velocity, usually in the range of 3 m/s to 30 m/s, with the specific value depending mostly on the burden thickness. No gas venting has been observed at the onset of burden movement. The initial velocity of the face at first detection of movement does not undergo change (acceleration) and remains constant, at least over the first few metres of displacement where velocity is generally measured. The vertical profile of the face remains intact until it fragments into

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various sizes. At this time, and depending on its initial velocity, the face and the whole rock mass may have advanced up to 10 m from their original location on the bench.

The importance of the burden for determining both the duration of the quiescent period and the initial velocity, which is also the maximum velocity, of the face can be understood on the basis that the burden defines the mass per unit area of the face. This mass is acted upon by the gas pressure resulting from the explosion of the charge load and acquires its initial velocity. The fact that it has been almost impossible to detect an acceleration phase—which, if it exists, must occur in the first 50 mm to 100 mm of burden movement as some measurements suggest—indicates that momentum transfer to the burden is accomplished mostly during the quiescent period. This mode of momentum transfer over an extended period of time does not depend on shock and stress wave action. The generation of these waves would occur concurrently with the radial expansion of blastholes, that is, within 1 ms as calculated by Szendrei and Tose (2024). The phase of stress wave action would dissipate long before the commencement of burden motion.

The central problem of any burden movement analysis is, first, to define the amount of explosion energy that is converted to the kinetic energy of the burden and, second, to determine how the details of blast design and rock mechanical properties influence the efficiency of this energy conversion process. A related problem – and the ultimate focus of the present study – is the understanding of how flyrocks with much higher velocities than the bench face may be generated during the forward displacement of the burden.

This study shows that the mass movement of rock can be analysed in terms of the Gurney model of explosive interaction with inert materials when it is suitably adapted to the geometry of the bench. This model is also capable of identifying the combinations of rock and explosive charge that will allow the generation of flyrock from small, localised areas of the face.

Gurney analysis of burden movement

Gurney model for bench blasting

A physical model for the interaction of a quantity of explosive with an inert body in contact with it that is widely utilised in various technological fields is the so-called Gurney concept. The core element of the Gurney approach is that only a certain fraction of the explosive energy that is liberated by detonation can be converted to mechanical work on the inert body. The second key element is that the terminal velocity of the explosive-driven mass can be derived, based on momentum and energy conservation, when the internal energy of the detonation gases is converted by expansion work to the kinetic energy of the driven mass (Jones et al., 1980). The calculated values are accepted as providing excellent engineering approximations within 10% (and often much better) of measurements of the impulse and velocity of projected materials (Kennedy, 1970; Walters, 1986).

The Gurney approach has found widespread application in the explosives and rock mining industries as the cylinder test (Esen et al., 2005; Trzcinski, Cudzilo, 2001) This test measures the conversion of gas internal energy to cylinder wall kinetic energy, and is generally acknowledged as a more accurate measure of the potentially useful energy of explosive compositions than traditional techniques, such as the pond test or various measures of strength. The Gurney energy (E_G) is a characteristic property of every explosive composition and is expressed as a specific energy, MJ/kg.

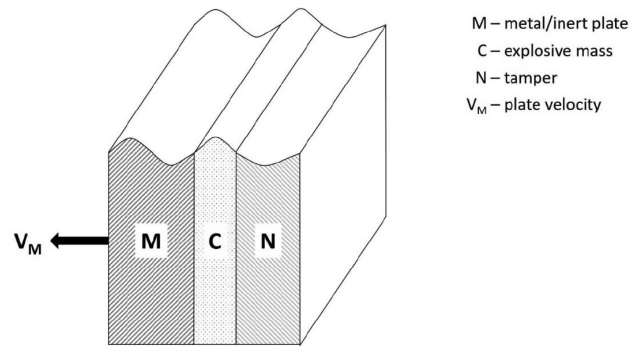


Figure 1—Gurney model of asymmetric sandwich combination of explosive and inert layers

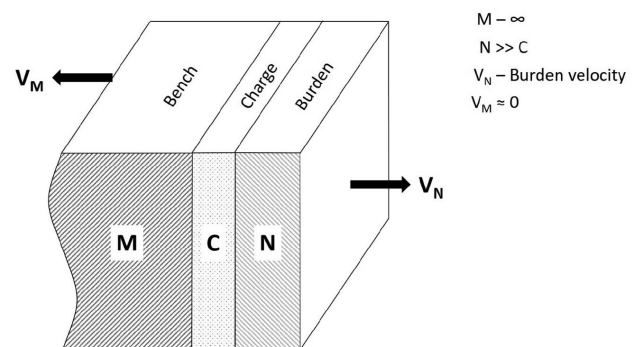


Figure 2—Schematic Gurney model for bench blasting

A related parameter is $(2E_G)^{1/2}$, which has units of velocity (m/s), and is directly related to the projection velocity imparted to inert bodies.

While the Gurney approach can be applied to a large variety of explosive-inert body combinations in planar, cylindrical, and spherical symmetry, the geometrical arrangement that is most relevant to bench blasting and the movement of the burden is the so-called flat asymmetric sandwich. A schematic illustration of such a combination is shown in Figure 1.

The designations C, M, and N as charge mass, plate mass, and tamper mass, respectively, are standard terminology. Conventionally, it is the velocity of the metal plate that is of importance. The tamper N is used for charge confinement in order to enhance momentum transfer to the plate M. It is important to note that in this configuration C, M, and N are defined as mass per unit area.

The Gurney method does not place any limits on the absolute values of M and N that may be associated with a given charge. This allows the re-interpretation of the parameters C, M, and N when applied to surface bench blasting, as illustrated in Figure 2.

The 'plate' M represents the bench of which the mass is effectively infinite and thus, immovable. The forward velocity V_N of the 'tamper' is now of interest; it is identified with the moveable burden mass, which is driven ahead by a row of blastholes containing the charge C.

In the following section we adopt the Gurney model as a working hypothesis, define the appropriate input values for M, C, and N, and examine the predictions of the model.

Gurney prediction of burden velocity

The general equation for 'plate' velocity moving to the left in Figure 1 (Kennedy, 1970; Walters, 1986) is:

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$$V_M = \sqrt{2E_G} \left[\frac{1+A^3}{3(1+A)} + \frac{N}{C} A^2 + \frac{M}{C} \right]^{-\frac{1}{2}} \quad [1]$$

$$A = \frac{1+2\frac{M}{C}}{1+2\frac{N}{C}}$$

This expression can be greatly simplified when M/C tends to infinity and N/C is much greater than 1, as illustrated in Figure 2 (Conner, Quong, 1993; Cooper, 2004):

$$V_N = \sqrt{2E_G} \left[\frac{N}{C} + \frac{1}{3} \right]^{-\frac{1}{2}} \quad [2]$$

When Equation 2 is applied to a bench, the tamper mass N can be replaced with the burden mass M_B , and the velocity V_N with the burden velocity V_B . A further simplification is possible; the factor $\frac{1}{3}$ can be dropped because the burden mass is much larger than the charge mass. Thus,

$$V_B = \sqrt{2E_G} \left[\frac{C}{M_B} \right]^{\frac{1}{2}} \quad [3]$$

Cooper (2004) extensively used Equations 1 and 2 in a theoretical and experimental investigation of explosive-driven propulsion systems. In that study, very large ratios of M_B/C and N/C up to 10^6 and beyond were considered. The mass ratios in conventional surface blasting are well within these limits.

Prediction of momentum transfer to burden

Given the mass of the burden and its velocity, its momentum is simply $M_B \times V_B$. A parameter of greater fundamental interest is the specific momentum, that is, momentum transferred per unit mass of explosive. It is also related to the Gurney energy E_G in the following way:

$$\frac{M_B V_B}{C} = \left(\frac{M_B}{C} \right) \sqrt{2E_G} \left[\frac{C}{M_B} \right]^{\frac{1}{2}} = \sqrt{2E_G} \left[\frac{M_B}{C} \right]^{\frac{1}{2}} \quad [4]$$

Equations 3 and 4 constitute the Gurney model for burden movement. A similar approach was described by Roth (1979) who noted the analogy between the projection of metal plates and fragments by explosives and the throw of burden rock. Roth (1979) was unable to fully develop a predictive model for two reasons. The first was the inability to reconcile the C/M ratio as required by the Gurney model with the more familiar blasting parameter of the powder factor. The issue of defining an appropriate value for the Gurney energy constant was also problematic.

The same problem of defining the appropriate energy value for burden movement was noted by Zhang et al. (2021). These authors based their model on the conversion of explosion energy (ΔH_d) (often called chemical energy or heat of detonation) to burden kinetic energy (E_{KB}). This model is summarised by the following equation:

$$E_{KB} = \frac{1}{2} M_B V_B^2 = \alpha_B C \Delta H_d \quad [5]$$

The burden mass M_B was calculated as the mass of a prismatic volume of rock displaced by the explosion of a single blasthole. The factor α_B is an empirical coefficient lying between 0.02 and 0.12 and defines the fraction of explosion energy converted to rock kinetic energy. This model conceptualises burden movement as a succession of 'facebursts' from grade to stemming, as each blasthole detonates and displaces a prismatic volume of rock, each in isolation from any influence of stress waves and gas action from adjacent holes. This concept is difficult to reconcile with well-documented

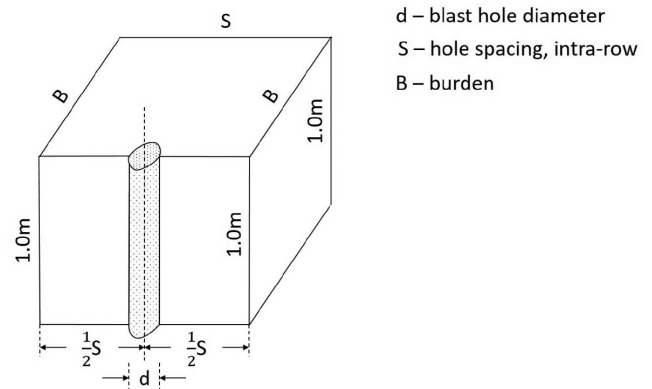


Figure 3—Volume of rock acted upon by a 1 m vertical segment of the blasthole

observations of the forward movement of the whole burden as a coherent mass for times that are much longer (~1 second) than normal intra-hole delay times.

The issue of explosion energy and burden kinetic energy is considered in the following.

Definition of Gurney model input parameters

Rock mass M_B

In the geometry of the flat sandwich shown in Figure 1, M_B and C are mass values per unit area of the face. When applying the Gurney model equations to a bench blast, it is convenient to express M and C in terms of the blast design parameters. Figure 3 defines the volume of rock acted upon by a one-metre segment of a charged blasthole.

The volume of rock ultimately moved by the 1 m segment of charge is represented by the parallelepiped of volume equal to $(S \times B_t) \text{ m}^3$. Here S is the spacing, and B_t is the burden at a specific location on the face where a marker or target has been placed opposite a blasthole. This yields a definition of the 'plate' mass to be used in the Gurney model as:

$$M_B = (S B_t \times 1) \rho_r, \text{ kg} \quad [6]$$

ρ_r is the in situ rock density, which is assumed to be a known constant for the purposes of establishing a baseline Gurney model.

Charge mass

The charge mass associated with the movement of the burden mass is the linear charge density (kg/m). This value may be taken to be equal to the nominal linear charge as defined in the blast design. A more reliable value can be derived from the charge load in a given column height and the hole diameter. The latter is preferable as it is well known that the actual charge load in a hole may deviate significantly from the design value. The above definitions of burden and charge mass recognise the fact that flyrock is projected from specific, small areas of the face and the parameters M_B and C that determine rock projection velocity may vary from place to place on the face on the scale of metres. Therefore, the powder factor, which is conventionally reported as a measure of the total mass of broken rock, is a coarse estimate of C/M_B at any given location on the face and would be incapable of identifying the presence of exceptionally under-burdened areas. A more appropriate definition of the powder factor is to restrict the M_B to the rock mass present between the grade and top of the charge column. This may be referred to as the adjusted powder factor.

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Effective Gurney energy

The magnitude of the energy constant, E_G , appearing in Equations 3 and 4 is not the same as the Gurney energy as defined in the section: *Gurney model for bench blasting*, where it was identified as a certain fraction of the chemical energy released by detonation of the charge. Approximately 50% of this energy is dissipated during the blasthole expansion in the immediate aftermath of detonation (Szendrei, Tose, 2024). At the conclusion of hole expansion (which occurs in less than 1 ms), the remaining fraction of the initial Gurney energy is present as the latent work capacity of the explosion gases that are still contained within the expanded holes. In ways that are not well understood, the trapped gases split the first row of blastholes from the bench as a block and impart sufficient impulse to this block to propel it forward at velocities that have been measured.

In the absence of any clear understanding of how burden movement is initiated, it is not possible to assign a credible value to the effective Gurney energy (denoted as E_{GB} for clarity in the following analysis) responsible for its forward propulsion, except to note that it is expected to be substantially less than the explosive's characteristic Gurney energy E_G , which is approximately 2 MJ/kg across a wide range of blasting agents (Esen et al., 2005). A more accurate estimate of its value can be obtained using the Gurney model to examine the relationship between the face velocity and adjusted powder factor.

Such an analysis was conducted on the face velocity measurements reported by Chiappetta et al. (1983) in an iron ore mine. These authors used a photogrammetric method to determine the displacements of various targets placed on the bench face. An especially useful aspect of the reported results is the wide range of burdens considered (5 m to 26 m) while keeping the hole diameter (381 mm) and hole spacing (8.5 m) constant. The resulting scatter plot of $Y = V_B$ versus $X = \sqrt{\text{adjusted powder factor}}$ is shown in Figure 4, where the X-label refers to the adjusted $\sqrt{C/M}$ calculated according to the definitions given in the above for the blastholes.

Despite the large scatter of velocity values, a distinct trend of increasing velocity with increasing values of $\sqrt{C/M}$ is evident. The Pearson's r -correlation statistics are: $N=20$, $r = 0.8535$, $t_{0.001, 20} = 0.679$, p -value < 0.001 . If the uppermost point at 26.5 m/s is discarded as an outlier, r improves to 0.8803. The p -value indicates that the probability of obtaining the observed correlation coefficient of 0.8535 by chance is less than 0.1%.

Despite the highly significant value of the correlation coefficient, the value of r does not indicate the nature of the relationship between V_B and $\sqrt{C/M_B}$. Pearson's coefficient of determination (r^2) addresses this question by evaluating the correlation based

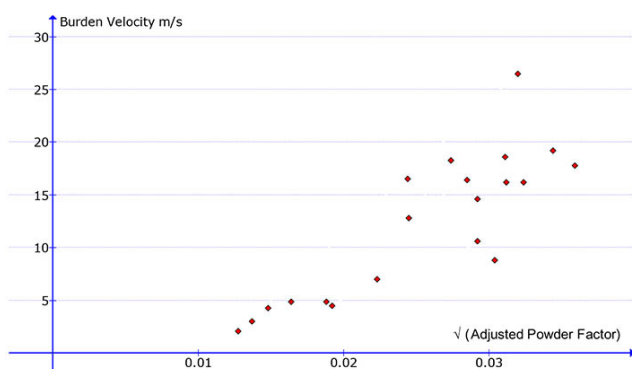


Figure 4—Scatter plot of face velocity vs adjusted powder factor. (Data points sourced from Chiappetta et al., 1983)

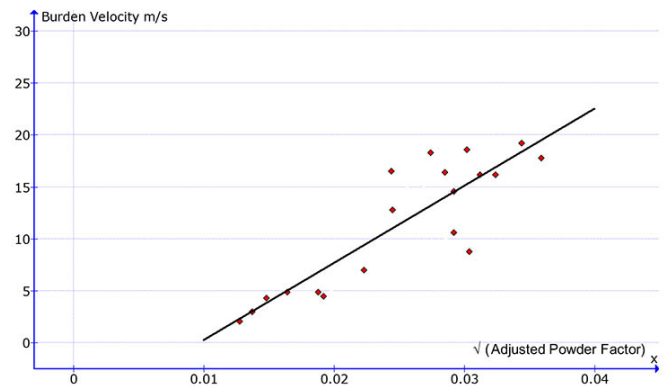


Figure 5—Linear regression line of burden velocity versus root-adjusted powder factor

on a particular functional relationship. The least-squares linear regression line for the data points shown in Figure 4 is displayed in Figure 5. This line is defined by a 2 parameter linear equation based on the slope and the Y-intercept, that is:

$$V_B = 740.74 \sqrt{\frac{C}{M_B}} - 7.17 \quad [7]$$

The top-most point at 26.5 m/s in Figure 4 was removed as an outlier.

The regression statistics are:

$N = 19$

Regression slope = 740.75 m/s

Y-intercept = 7.17 m/s

Coefficient of determination $r^2 = 0.7749$

Standard error of slope = 97.6 m/s.

Formally, r^2 is the fraction of the variation of measured velocities that is removed by the regression model. Given the standard error of the slope, the t -statistic can be calculated by dividing the slope by its standard error. This yields $t = 7.592$. At $N-2 = 17$ degrees of freedom, standard statistical tables yield the following t -values at 95% and 99.1% levels of confidence: $t_{0.05, 17} = 2.110$; $t_{0.001, 17} = 3.965$. Hence, the probability of obtaining a value of t equal to 7.592 by chance is less than 0.001. By convention, probabilities ≤ 0.05 are deemed to be significant. Thus, we may conclude that there is statistically significant evidence that a linear correlation exists between V_B and $\sqrt{C/M_B}$. The plot of the residuals (differences between the measured and predicted velocity values) supports this conclusion. There is no systematic deviation from zero slope, that is, the variations in V_B are evenly distributed above and below the expected values.

The slope of the regression line, 741 m/s, is as expected – it is about half or less of the explosive's Gurney velocity constant, which ranges from 1600 m/s to 2200 m/s for a wide variety of commercial blasting agents (Esen et al., 2004). However, the strong correlation indicated by the r^2 - and t -values does not identify or explain the source of the large scatter of V_B values, which is evident in Figure 5. Assuming that under normal blasting conditions the values of C and M do not vary by more than 10% from the nominal blast design values, the fractional error in V_B is expected to be approximately 14%. This is far less than the dispersion observed in Figure 5. Deviations from expected velocity values are 20% to 40% (the deleted point at $V_B = 26.5$ m/s showed a 53% deviation). To gain physical insight into such large deviations, it is necessary to examine the possible variability of the remaining factor of Equation

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3, namely, the effective Gurney velocity constant $\sqrt{2E_{GB}}$. Using Equation 3, the value of this constant determines the predicted value of V_B at a given value of $\sqrt{C/M}$ and any variation in its value would result in a proportionate change in V_B . The value of $\sqrt{2E_{GB}}$ and its variability are considered in greater detail in the section *Energetics of burden movement*.

Gurney model interpretation of burden movement

Flyrock from the face

It will be noted from Figure 5 that all measured and predicted face velocities are below 20 m/s. When Equation 7 is applied for the prediction of flyrock velocities (greater than 100 m/s, say) with $\sqrt{2E_{GB}} = 741$ m/s face velocity would be attained at a C/M ratio of 0.0209. This is 33-times higher than the average C/M_B value (0.00063) reported by Chiappetta et al. (1983) when blasting iron ore. Substantial deviations of C/M_B values that are known to occur in the field would, at worst, double burden velocities. For instance, when a blasthole intersects a cavity, the linear charge mass could possibly double locally, and the burden mass may halve in similarly localised areas due to the presence of a path of weakness through the burden or to overdigging of the face. Although major, these deviations would increase the face velocity only by a factor of 2, as shown in Equation 3.

It is evident that the blast design value of C/M_B can be increased by a factor of 10 or more only through drastic, and unanticipated, reductions in the burden mass. However, the occurrence of far-flung flyrock requiring a projection velocity of 100 m/s or more from the face, is well documented. This conundrum necessitates a closer examination of the blast parameters that determine the value of C/M_B .

Equation 3, for face velocity, can be expanded to explicitly show the contributions of charge load, blast pattern, and rock density in terms of the following blast parameters:

d	blasthole diameter, m
L_e	charge column height (above grade), m
ρ_e	explosive density, kg/m ³
B_t	burden, m
S	spacing, m
ρ_r	nominal rock density, kg/m ³
$\sqrt{2E_{GB}}$	adjusted Gurney constant, m/s.

Based on these parameters, the charge-to-burden mass ratio can be defined as follows:

$$\frac{C}{M} = \frac{\left(\frac{\pi}{4}d^2L_e\right)\rho_e}{(SB_tL_e)\rho_r} \quad [8]$$

The face velocity associated with any combination of the above parameters is given by the following equation:

$$V_B = \sqrt{2E_{GB}} \sqrt{\frac{\left(\frac{\pi}{4}d^2L_e\right)\rho_e}{(SB_tL_e)\rho_r}} \quad [9]$$

After cancelling out the parameter L_e , the above equation can be rewritten in dimensionless form:

$$\frac{V_B}{\sqrt{2E_{GB}}} = \sqrt{\left(\frac{\pi}{4}\right)\left(\frac{d^2}{B_tS}\right)\left(\frac{\rho_e}{\rho_r}\right)} \quad [10]$$

Equation 10 is derived in System Internationale Units (SI) and the use of customary units such as mm, cm³, litres, calories or pressures quoted as atmospheres, bars, kg/m², MPa, etc., will yield incomprehensible results. Because it is dimensionless, Equation 10 is valid in any consistent set of units. The values of d, S, and ρ_e are more or less constant for a given blast design. In comparison, the parameters B_t and ρ_r are potentially far more variable over a much wider range of values when evaluated over relatively small areas on the face.

By squaring Equation 10 and extracting $B_t \rho_r$, the following expression is obtained:

$$B_t\rho_r = \left(\frac{\sqrt{2E_{GB}}}{V_B}\right)^2 \left(\frac{\pi}{4}\right)\left(\frac{d^2}{S}\right)\rho_e \quad [11]$$

Equation 11 defines the combinations of B_t and ρ_r required to attain a specific Gurney projection velocity, V_B . The combination of B_{tpr} has units of kg/m². It can be interpreted as indicating the mass contained in a path of length B_t through the burden of 1m² cross-sectional area. This interpretation permits the generalisation of both B_t and ρ_r .

Burden is generally defined as the shortest horizontal distance from the face to the nearest part of the explosive column. However, in Equation 11, B_t can be considered as the path of least resistance from the blasthole to the face, which may not necessarily be horizontal, and along which the material density may be far less than the nominal rock density. An effective density may, for instance, arise due to the presence of soft strata, clay, mud, water, or fissures. This interpretation of B_t and ρ_{eff} is particularly useful when conceptualising a faceburst as a source of flyrock – an eruption of rock from a small, localised area of the face, which is particularly underburdened. It is not possible to state what the individual values of B_t and ρ_{eff} are at any particular location on the face, but it is possible to state what combinations of their values would potentially yield flyrock velocities.

Effective burden density kg/m ³	$\sqrt{2E_{GB}}=741$ m/s	
	Maximum burden (m)	Burden/hole diameter ratio
3400	0.25	0.66
3000	0.28	0.74
2500	0.34	0.89
2000*	0.42	1.11
1500**	0.57	1.48
1000***	0.85	2.22
500****	1.69	4.44

*clay ** mud *** water **** fissure

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As an illustrative example, Equation 11 is applied to the prediction of flyrock from blasting iron ore (Chiappetta et al., 1983). The required blast parameters are as follows: $d = 0.381$ m, $S = 8.5$ m, $\rho_r = 3400$ kg/m³, $\rho_e = 1150$ kg/m³, $\sqrt{2E_{GB}} = 741$ m/s. Flyrock velocity to be generated is 100 m/s. The predictions of maximum allowable burden at various effective path densities are listed in Table 1.

Table 1 indicates that the critical or maximum allowable burden increases rapidly when the effective density drops below approximately 1500 kg/m³. This suggests that when the open fissure condition is approached and the material in the path of gas expansion possesses low inertial resistance (mass), the resultant flyrock velocity may attain 100 m/s.

Energetics of burden movement

The slope of the regression line (Figure 5) is 740.75 m/s. According to Equation 7, the slope is equal to $\sqrt{2E_{GB}}$. This equality yields a value of 0.274 MJ/kg for the modified Gurney energy, E_{GB} . As previously mentioned, following the radial expansion of the blasthole, the remaining mechanical energy of detonation product gases would be less than half of its original value (Szendrei, Tose, 20022). The fraction of the explosion chemical energy that is converted through gas expansion to burden kinetic energy has been the object of many studies (Spathis, 1999; Ouchterlony et al., 2003; Segarra, 2004; Zhang et al., 2021). The Gurney model permits the derivation of an explicit algebraic equation that defines the efficiency of this energy conversion. The efficiency may be defined as the ratio of the kinetic energy acquired by the burden to the energy released by the detonation of the column charge, that is:

$$\varepsilon_1 = \frac{1}{2} \frac{M_B V_B^2}{C \Delta H_d} \quad [12]$$

Here M_B is the burden mass acted upon by an explosive charge C possessing a specific chemical energy of ΔH_d (J/kg). As before, both M_B and C are evaluated per unit length of the blasthole. By introducing the Gurney energy present in the expanded blasthole (E_{GB}) as the internal energy of the detonation product gases, Equation 12 can be rearranged as follows:

$$\varepsilon_1 = \frac{1}{2} \frac{M_B V_B^2}{C \Delta H_d} \frac{E_{GB}}{E_{GB}} = \left[\frac{M_B}{C} \left(\frac{V_B}{\sqrt{2E_{GB}}} \right)^2 \right] \frac{E_{GB}}{\Delta H_d} \quad [13]$$

The first term in square brackets is the fraction of the Gurney energy converted to the kinetic energy of the burden. The second term is the ratio of the Gurney to the chemical energy of the explosive. Thus, the efficiency of energy transfer to the burden is determined by two energy constants of the charge – specific chemical energy (ΔH_d) and the specific gas internal energy (E_{GB}), which is available for gas expansion work on the burden.

Based on Figure 5, the required parameters for the evaluation of Equation 13 can be defined as follows:

$\sqrt{2E_{GB}}$ is given by the slope of the regression line, 741
 E_{GB} can be derived by solving the equation $\sqrt{2E_{GB}} = 741$.
 It is 0.2745 MJ/kg

The M_B/C ratio can be identified by noting that a regression line with linear X- and Y-axes always passes through the coordinates (X_{mean} , Y_{mean}). Using the data in Figure 5, with $X = \sqrt{C/M}$ and $Y = V_B$, the respective averages are 0.0251 and 11.45 m/s. By

manipulation of the X_{mean} value, the appropriate burden-to-charge mass ratio M_B/C can be derived as 1587.

The predicted value of energy efficiency ε_1 by Equation 13 is then 0.0258 or 2.6% of the explosive's chemical energy (4 MJ/kg).

A similar value is obtained when energy transfer to the burden is calculated directly from field measurements by making use of Equation 12 to convert measured burden velocities to kinetic energy at each location of a target on the face. Using the velocity measurements of Chiappetta et al. (1983) in combination with blast pattern details, it is possible to define the burden mass (M_{Bt}) and charge mass at 20 target (t) locations. These empirical quantities permit another estimate of the efficiency factor (ε_2) to be defined as:

$$\varepsilon_2 = \frac{1}{20} \sum \frac{1}{2} \frac{M_{Bt} V_{Bt}^2}{C_t \Delta H_d} \quad [14]$$

The summation is taken over 20 targets (t). C_t and M_{Bt} are particular values of charge and burden mass at each target calculated for 1 m of charge column and ε_2 is the energy efficiency averaged over the bench face. Equation 14 yields an efficiency of $\varepsilon_2 = 0.0269$ (2.7% ΔH_d). The individual values of energy conversion ranged from 0.6% to 5.6% with a standard deviation of 1.8%.

The close correspondence between the Gurney model-based and empirical efficiencies indicates that they can provide a reliable estimate of the energy transfer to the burden. An advantage of the Gurney model, Equation 13, is that the parameters M_B and C can be evaluated in terms of the blast design details (Equation 8). This permits the determination of the relative influence of d , ρ_e , ρ_B , S , and B upon energy utilisation in burden movement.

Discussion

Gurney model – mechanics of burden movement

The Gurney model yields a deceptively simple formula (Equation 3) for the velocity of rock thrown from the face, which comprises just 3 parameters, namely: a Gurney constant, $\sqrt{2E_{GB}}$; charge mass, C , and burden mass, M_B . This simplicity is deceptive because, although the mass ratio C/M can be defined in terms of field measurements of the charge load and bench geometry, defining the parameter $\sqrt{2E_{GB}}$ is more problematic. In the Gurney model, $\sqrt{2E_{GB}}$ arises as a measure of the explosion energy that can be converted to rock kinetic energy by gas expansion work. Measurements of the terminal effects of this expansion work – face velocity and burden kinetic energy – show that the energy conversion process is highly variable across the face in any given blast. The ability of the Gurney model to predict burden velocity, and hence momentum, based on the mass of the burden implies that it is predominantly inertia alone, without any other mechanical property, that determines the transmission of momentum and energy to the burden. As the relevant inertia corresponds to the full volume and mass of the rectangular block of burden rock, as illustrated in Figure 3, it may also be concluded that the burden moves as a whole.

The variability of $\sqrt{2E_{GB}}$, which determines both the face velocity and burden momentum, will arise when the pressure forces driving the burden laterally are subject to large variations. In effect, each small area of the face, say, ($S \times 1$) m², as sketched in Figure 3, experiences a different pressure load. It is proposed here that the variable pressure forces are generated in the quiescent period after detonation and before the commencement of any measurable face displacement. In this period, which typically measures 3 ms to 4 ms per metre of burden, explosion product gases migrate from the enlarged blasthole into the extensive fracture network

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that surrounds each blasthole. Following detonation, fracturing is caused by the interaction of reflected and multiply reflected stress waves from the face and from other possible free faces and material interfaces that may be present as geological anomalies in the burden. These stress waves overlap while propagating in different directions throughout the burden and create an unpredictable and complex pattern of fractures through tensile splitting. The propagation velocity of elastic stress waves in rocks is generally higher than typical detonation velocities of blasting charges, and fracture formation by reflected waves goes to completion before the burden mass starts to move.

The details of gas migration and its interaction with the complex network of tight fractures are not known, but in order to set the burden into motion, two processes must first occur. Firstly, the pre-fractured rock must undergo further crack extension and coalescence to ‘split’ the burden away from the bench. This process must clearly expend some energy. Secondly, there must be sufficient gas energy remaining, as measured by the factor $\sqrt{2E_{GB}}$, to impart the velocities and kinetic energy to the burden such as are observed and measured. The transfer of momentum and energy to the burden is a process that ends more or less simultaneously with the onset of burden motion as no distinct period of acceleration has been observed. Thereafter the burden moves ahead at constant velocity, as field measurements have shown. A possible reason for the absence of a detectable period of acceleration is that a small displacement of the burden block, say 100 mm, is sufficient to drop the pressure to ineffective, low values. Such small displacements are at the limit of resolution of photogrammetric and high speed camera measurements.

Scaling of burden velocity

Equation 10 defines a function linking the burden velocity to blast design parameters. On shifting the focus from an energy-based ($\sqrt{2E_{GB}}$) interpretation of the Gurney model to a velocity-based interpretation, it is convenient to explicitly identify $\sqrt{2E_{GB}}$ as a characteristic velocity, V_{GB} , associated with the expansion work imparted to the burden, i.e.,

$\sqrt{2E_{GB}} = V_{GB}$ (m/s). Equation 10 can then be rewritten in dimensionless form as:

$$\frac{V_B}{V_{GB}} = \sqrt{\frac{\pi}{4}} \sqrt{\frac{\rho_e}{\rho_r}} \sqrt{\frac{d^2}{B_t S}} \quad [15]$$

The trend of V_B with particular elements on the right-hand side of Equation 15 can be deduced by inspection:

- (i) The ratio of explosive-to-rock mass density is limited. Generally, ρ_e is in the range of 900 kg/m³ to 1250 kg/m³, and ρ_r in the range 2000 kg/m³–3400 kg/m³. After taking the square root, the range of the density ratio reduces to 0.5 to 0.8. Hence, the first two terms on the right-hand side can be treated as a constant. This is particularly true when blasting is carried out in the same geological formation with the same blasting agent. In this case, the reduced burden velocity is determined by the combination of d , B , and S , as in Equation 15.
- ii) This relationship can be expressed as a proportionality:

$$\frac{V_B}{V_{GB}} \propto \sqrt{\frac{d^2}{B_t S}} \text{ or } \frac{V_B}{V_{GB}} \propto \frac{d}{\sqrt{B_t S}} \quad [16]$$

Replacing V_{GB} with its definition, $\sqrt{2E_{GB}}$, the absolute value of burden velocity scales with the following expression:

$$V_B \propto d \sqrt{\frac{2E_{GB}}{B_t S}} \quad [17]$$

Equation 17 encapsulates the sensitivity of V_B to the blast pattern design. Four particular trends of V_B with details of the blast design are readily apparent:

- For a given blast design, V_B will always increase with increasing hole diameter.
- For a given hole diameter, rock type, and explosive, V_B is inversely proportional to \sqrt{BS} .
- For a given hole diameter and blast pattern ($B_t \times S$), V_B is directly proportional to the adjusted Gurney velocity, $\sqrt{2E_{GB}}$, which varies with the type of blasting agent used.
- Blasthole spacing is generally related to the burden by a factor f such that $1 < f < 1.25$. Hence, $\sqrt{B_t S} = \sqrt{f B_t^2} \approx B_t$, that is, the burden velocity is inversely proportional to the burden (at a given hole diameter). The scaling relationship, Equation 15, then takes a particularly simple form:

$$\frac{V_B}{V_{GB}} = K \frac{d}{B_t} \quad [18]$$

where K is a constant for a given rock and explosive and for a constant burden-to-spacing ratio.

Considering Equation 17, the values of $\sqrt{2E_{GB}}$ across the face are far more variable than field values of burden and spacing, and would dominate the variability of V_B . This is why it has not been possible to identify a simple equation linking burden velocity to usual blast and rock parameters. As Zhang et al. (2021) noted, burden velocities at more or less the same value of burden are highly variable. The difficulty is that the value of $\sqrt{2E_{GB}}$ is not directly related to the specific Gurney energy of the blasting explosive used. Its value at any particular location on the face is determined firstly by the energy loss experienced during blasthole expansion and secondly by a further loss when detonation gases migrate from the blasthole into the highly variable fracture network.

Energy partitioning

Based on the analysis of face velocities measured by Chiappetta et al. (1983), energy partitioning during the displacement of the burden can be summarised, as listed in Table 2.

The above energy partitioning is specific to iron ore blasting, but in broad details other rock types are expected to show similar behaviour. The most striking feature of energy partitioning is that a very small portion of the explosion energy is responsible for moving the burden block forward and casting it in a muckpile. The second striking feature is the large fraction (up to one-third) of the mechanical energy that is not accounted for. This large portion will obviously include the energy lost in ejecting the stemming and gas venting through the collar, bench top swelling, and cratering, as well as air and ground vibrations. Vibration energy losses are known to be relatively minor, not more than a few per cent of the chemical energy. It is unlikely that energy losses in the collar zone are more energy intensive than the kinetic energy of burden movement (ca. 0.1 MJ/kg). For the sake of definiteness, we estimated the consumption of gas internal energy in the quiescent period before burden movement to be ~0.5 MJ/kg-charge.

Flyrock

The Gurney model indicates that the projection of long-range flyrock, that is, rock missiles with velocities exceeding 100 m/s, is

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Energy utilisation	MJ/kg
Initial Gurney specific energy*	2.2
Blasthole expansion energy**	1.2
Gurney energy available for driving burden***	0.275
Gas energy converted to burden kinetic energy***	0.1
Residual Gurney energy at disintegration of burden***	0.175
Mechanical energy unaccounted for****	0.73

* 55% of 4.0 MJ/kg explosive chemical energy

** Calculated for iron ore by the cavity expansion model presented in Szendrei and Tose (2024)

*** As derived in this report

**** By difference from 2.2 MJ/kg.

possible only when the path of least resistance through the burden has an effective density far lower than the nominal density of the massrock. This implies that under normal blasting conditions, the throw of the fractured burden to form a muckpile would not yield flyrock. Such low effective densities may exist in weak strata or in the presence of open fissures. These geological anomalies are not predictable or easy to assess on the bench. The occasional ejection of high-velocity flyrock would carry away a miniscule quantity of the energy of explosion. Attempts to improve rock breakage by suppressing flyrocks, and thereby saving energy, are misplaced.

In summary, it is not overconfinement and excessive energy that leads to flyrock. Rather, it is underconfinement and lack of insufficient inertial resistance through the burden that allows the development of flyrock velocities from the burden.

Conclusion

The Gurney approach to burden movement yields reliable predictions of face velocities, provided the powder factor is suitably adapted to the geometry of the bench. When unplanned deviation of M and C from blast design values are exceptionally large or there are geological defects in the burden that present low inertial resistance to gas expansion, flyrock throw may occur. The model identifies the inertial mass per unit area, that is, $B\rho_r$, as the key parameter that determines the throw velocity of rocks from the burden.

In addition to the prediction of face velocity, the Gurney model yields physical insight into some of the lesser understood aspects of burden movement, such as:

- Conventional powder factor is not a measure of the propensity of a charge load to project flyrock from the bench face.
- The burden moves as a whole at some locally constant initial velocity.
- The initial velocity is acquired by an impulsive process, that is, without a significant, or even detectable period of acceleration.
- The post-detonation lag time to first movement is identified as the period when high pressure gases migrate out of the blastholes into the fractured burden. The Gurney model yields a rough estimate of gas internal energy expended during this process.
- The components of blast energy partitioning and their values relative to the chemical energy or the Gurney energy of the explosive are identified and evaluated.

- The observed large variability of face velocities is due to the random nature of the fracture network around and between the blastholes, which creates variable resistance to gas expansion into the fractured rock matrix and variable transfer of momentum.

Aside from the technical aspects of Gurney that provide a relatively simple and straightforward interpretation of burden movement, it can be used as a tool to manage flyrock risk. Flyrock is often a misunderstood area of blast management until an uncontrolled flyrock event occurs and creates a major impact. The objective of this series of papers has been firstly to focus the industry on the understanding of the root causes and sources of potential flyrock and enable daily management of blasting activities to minimise the potential for these events. The second is to provide a new focus on the risk assessment, providing alternative predictive models to those currently used to challenge the industry around the question: “Are we managing our risk in the best way?”

There are many new blast survey techniques, changes in explosives, and initiating systems that enable us to challenge the current risk assessments to manage the sources of flyrock and improved techniques in minimising the likelihood of such events. This is where the predictions of Gurney can be put into use, to provide better predictions in analysing the potential risk based on the individual mine sites and the conditions they face. Alternative ways of looking at the assessment of the risk have come into sharp focus with the publication of the recently Gazetted Explosives Regulations (Department of Employment and Labour, 2024). Following a potentially life-threatening incident, the risk assessment of the explosive process of concern must be revisited.

References

- Chiappetta, R.F., Bauer A., Dailey, O.J., Burchell, S.J. 1983. The use of high speed motion picture photography in blast evaluation and design. *Proceedings of 9th Annual Conference on Explosives and Blasting Technique*, Dallas, TX, USA. International Society of Explosives Engineers, pp. 258–309.
- Cooper, M.A. 2004. Impulse generation by detonation tubes. *PhD Thesis*. California Institute of Technology, Pasadena, CA, USA.
- Cooper, P.W. 1996. Acceleration, formation and flight of fragments. *Explosives Engineering*. Wiley-VCH, pp. 385–394.
- Conner, M., Quong, A.A. 1993. Velocity of explosively driven liners. *Tactical Missile Warheads*, J. Carleone (ed.) Progress in Astronautics and Aeronautics, AIAA, Washington, DC. vol. 155, pp.199–222.

Flyrock in surface mining–part 4. Adaptation of Gurney model to predict burden velocity

- Department of Employment and Labour. 2024. Explosives Regulations, 2024. *Government Gazette* no. 50960, pp. 29–43, 23 July 2024, Republic of South Africa. <https://www.gpwonline.co.za> (accessed 16 September 2025).
- Esen, S., Nyberg, U., Hiroyuiki, A., Ouchterlony, F. 2005. Determination of the energetic characteristics of commercial explosives using the cylinder expansion test. *Swebrec Report No. 2005:1*. Swedish Blasting Research Centre, Lulea University of Technology, Sweden.
- Hustrilid, W. 1999. *Principles for open pit mining*, vol. 2. Theoretical Foundations. Balkema, Rotterdam, Chap.18, pp. 763–769.
- Jones G.E., Kennedy J.E., Bertholf L.D. 1980. Ballistics Calculations of R.W. Gurney. *American Journal of Physics*, vol.48, no. 4, pp. 264–269.
- Kennedy, E. 1970. Gurney energy of explosives: estimation of velocity and impulse imparted to driven metal. *Report No. SC-RR-70-790*. Sandia National Laboratories, Albuquerque, NM, USA.
- Lemesh, N.I., Pozdnyakov, B.V. 1972. The kinematics of motion of ledge rocks in the zone of fracture during blasting. *Soviet Mining Science*, vol.8, no.4, pp. 388–391.
- Noren, C.H. 1956. Blasting experiments in granite rock. *Quarterly of the Colorado School of Mines*. pp. 213–229.
- Ouchterlony, F., Nyberg, U., Bergkvist, I., Lars G., Grind, H. 2004. Where does the explosive energy of rock blasting rounds go? *Science and Technology of Energetic Materials*, vol. 65, no. 2, pp. 54–63.
- Petkof, B., Atchison, T.C., Duvall, W.I. 1961. Photographic observations of quarry blasting. *Report of Investigations RI 5849*, Bureau of Mines, U.S. Department of Interior.
- Roth, J. 1979. A model for the determination of flyrock range as a function of shot conditions. *Report No. NTIS PB81-222358*, Management Science Associates (MSA), Los Altos, CA, USA.
- Segarra, P. 2004. Experimental analysis of fragmentation, vibration and rock movement in open pit blasting. PhD Thesis, Universidad Politecnica de Madrid–E.T.S.I. Minas, Spain.
- Spathis A.T. 1999. On the energy efficiency of blasting. *Proceedings 6th International Symposium on Rock Fragmentation by Blasting*. Symposium Series S21, South African Institute of Mining and Metallurgy, Johannesburg, pp. 81–90.
- Szendrei, T., Tose, S. 2022. Flyrock in surface mining.–Limitations of current predictive models and a better alternative through modelling the aerodynamics of flyrock trajectory. *Journal of the South African Institute of Mining and Metallurgy*, vol.122, no. 12, pp.725–732. <http://dx.doi.org/10.17159/2411-9717/1873/2022>
- Szendrei, T., Tose, S. 2023. Flyrock in surface mining–Part 2. Causes, sources and mechanisms of rock projection. *Journal of the South African Institute of Mining and Metallurgy*, vol. 123, no. 12, pp. 557–564. <http://dx.doi.org/10.17159/2411-9717/2583/2023>
- Szendrei, T., Tose, S. 2024. Flyrock in surface mining – Part 3. Shock wave, stress wave, blasthole expansion. *Journal of the South African Institute of Mining and Metallurgy*, vol. 124, no. 9, pp. 491–500. <http://dx.doi.org/10.17159/2411-9717/3321/2024>
- Trzcinski, W.A., Cudzilo, S. 2001. The application of cylinder test to determine the energy characteristics of industrial explosives. *Archives of Mining Science*, Vol. 46, no. 3, pp. 291–307.
- Walters, W.P. 1986. Explosive loading of metals and related topics. *Special Publication BRL-SP-56*. U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, USA.
- Zhang, Zong-Xian, Chi, Li-Yuan, Yi, Changping. 2021. An empirical approach for predicting burden velocities in rock blasting. *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 13, pp. 767–773. <https://doi.org/10.1016/j.jrmge.2021.04.004> ◆



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