INSTITUTE OF QUARRYING

DEFINING NON-IDEAL PERFORMANCE FOR COMMERCIAL EXPLOSIVES

By

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"Defining non-ideal performance for commercial explosives"

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Claude Cunningham is the Consulting Mining Engineer for AEL, which provides a broad range of continually evolving explosives systems and services to mining operations throughout Africa. He focuses on developing blast design capabilities to achieve specific breaking outcomes, harnessing theory and measurement so as to grow understanding of the rockbreaking process. This is applied to continual improvement processes, both in the company's products, and in how they are used in the field.

Claude graduated from the Royal School of Mines, and completed a Masters Degree at the University of the Witwatersrand before entering the mining industry. He spent four years on production, gaining his Mine Managers Certificate of Competency in South Africa, and working in Zimbabwe, before joining African Explosives, where he has worked on blasting technology for 30 years. He founded the company's Blast Consult group in 1985, and now works closely with this group, reporting to AEL's Technical Director. He has published in excess of 50 technical papers, and is internationally known as the creator of the Kuz-Ram fragmentation model. Amongst many other technologies with which he has been closely involved are the modelling of detonation, the introduction of Electronic Detonator systems, the optical analysis of fragmentation, the development of software for efficient blasting design and the concept of Threshold Blasting. For the past four years he has been building the Vixen suite of detonation codes with International consultants.

Claude Cunningham is on the International Organising Committee of the Fragblast organisation, and serves on the Advisory Board of the Journal. He is on the management team of the Hybrid Stress Blasting Model project, which is a global initiative launched in 2002 by De Beers, AEL, Itasca, and the JKMRC. It is co-sponsored by Rio Tinto, Placer Dome, Codelco, Dyno Explosives and Sandvik Tamrock. In the past four years he has given presentations at international conferences in Beijing, Brisbane, Cambridge, Denver, Hunter Valley, Johannesburg, Las Vegas, Munich, Orlando, Oxford, Prague, New Orleans and Perth, and has been directing a technical investigation with the Russian Academy of Science near Moscow.

1.2 Introduction

Blasting is a key technique for extending civilisation, enabling large volumes of otherwise intractable rock to be

- converted to building material,
- processed for the extraction of valuable minerals, or
- removed, either to gain access to minerals, or to provide thoroughfare or space for storage.

A key issue is the extent to which blast results are sensitive to blast design. If the type of explosive, and the way in which it is used, affect the recovery of mineral, the life of downstream rock-handling equipment, the energy required to process the rock and the investment required to achieve the required throughput, then serious attention must be given to these outcomes rather than to the obvious aspects of explosive cost and convenience.

There are of course limits as to how precisely blasting technique can determine the final condition of the rock. Also, satisfactory evidence of any linked effect in a mining environment is dogged by statistical difficulties, but this should not be allowed to derail advancement, since even small improvements tend to have economic repercussions well beyond the costs. In general, the harder the rock type, the more critical will be the effect of the blast design, but even in weak rocks it can play a key role, for example in limiting losses to fines or reducing the cost of overbreak. It is common to hear that “the explosive should be matched to the rock”, but in practice there is little ability to grapple meaningfully with the concept. This is largely because of the difficulty of defining explosives behaviour in other than simplistic terms.

In arriving at effective blast designs, the most basic relationship assumed is that the greater the mass of explosive, the more will be the energy release in the rock, leading to finer fragmentation and more movement. This leads directly to the powder factor concept of blast design (kg of explosive per cubic metre or ton of rock), which quickly and simply derives a drilling pattern for a required result in a given rock. The powder factor is sometimes disguised, for example by deriving layouts as dimensions scaled by charge masses (Bauer, 1978). However, a scaled distance (D_s) is simply an expression of the form

$D_s = (L/M^{0.3})$,
where L is a distance to a free face,
M is the mass of explosive.

When cubed and inverted, scaled distance returns to (M/L^3), which is the form and units of powder factor (some scaled distances used $L^{0.5}$, but so do some powder factors use L^2). The equations are simply saying that, empirically and without any rigorous definition of the rock, the explosive or the end effect, a certain quantity of rock needs a given mass of explosive.

An unfortunate effect of using powder factor is its close association with the cost of explosives, which results in it being viewed as a key control on operational costs. If the blasting crew are assessed by their ability to contain powder factor, and not by the consequences of blasting, it is highly likely that they will starve the rockbreaking of energy in order to avoid personal penalties, but the cost to the operation in terms of reduced productivity and increased maintenance costs may be very high. This is perhaps the best reason for rather using scaled dimensions.

An advance on the powder factor approach is to assign a result to the layout and adopt design by energy rather than explosive mass. This is behind the Kuz-Ram model (Cunningham 1983, 1987) which predicts fragmentation from blast layout. While the model oversimplifies, it has the merit of focussing blast design on the desired fragmentation size range, which greatly elevates the level of engineering and debate.

A challenge for any energy-based blast design, is how to determine the explosive energy released to rock. "Weight Strength" relative to ANFO is normally used, but different values can be derived for one formulation and one energy value cannot express the complex processes which transform an intact rock mass into a pliable muck pile. The rest of this paper discusses the derivation of useful detonation energy and how effort is progressing toward improving capability for modelling blasting results.

1.3 Ideal Detonation

Since the turn of the 19th century theoretically available explosives energy has been estimated using the Chapman-Jouguet (CJ) concept of Ideal Detonation. This uses a simplification of the detonation process to derive the following detonation state parameters: wave and particle velocity, temperature, pressure, the nature of the explosive gases and their internal energy. Tracking the transformation of the states of the products of detonation during isentropic expansion then leads to the available energy. Unfortunately, while this works quite well for gaseous explosives, it is exceptionally challenging for condensed explosives, and only recently have good solutions evolved for these.

The rapid evolution of computers enabled ever better Ideal Detonation codes to be developed, the core engine of a code being its Equation of State (EOS). Good Equations of State enable the accurate prediction of detonation velocity of molecular explosives which are very close to Ideal in their mode of detonation. It will also show good correlation with the available shock Hugoniot data showing pressure-volume measurements for various fluids (Braithwaite et al, 1996).

In the simplest terms, a detonation code does the following:

- For the chemical formulations involved and at the density of use, determines the heat of reaction for the explosive.
- Determines the equilibrium products of reaction at the detonation state, the ideal detonation pressure and velocity, the particle flow velocity and the expansion kinetics
- Calculates the energy release as pressure falls with expansion, down to some pressure at which it is agreed that little extra useful energy is likely to be released to the confinement.

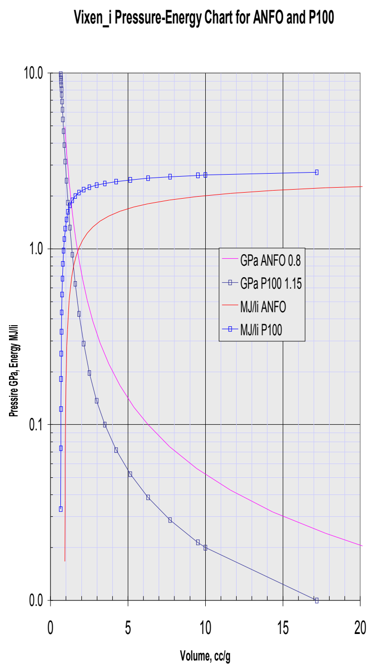


Figure 1: Ideal detonation performance chart.

Thus for ANFO and an AEL pumped emulsion explosive, P100, the pressure-volume-energy plot from AEL's Vixen_i Ideal detonation code is as shown in **Figure 1**.

The significance of this kind of plot was described in Cunningham 2002. Basically it indicates that the pure emulsion delivers its energy more quickly than ANFO, but has little sustained pressure after the passing of the detonation wave. It transmits more shock than the ANFO, but not necessarily more energy. In fact, by the time expansion is 8 times original volume, the ANFO is delivering about 80% more energy for each unit of expansion than the P100, whereas at 50% expansion the energy delivery of the P100 is 65% more than that of the ANFO.

The above gives useful insight into the different effects of these explosives, which are generally acknowledged to be opposites in the spectrum of energy delivery. ANFO tends to create longer cracks and more movement, while emulsion tends to generate less movement and more softening of rock. However, the model is extremely limited, because there is no concept of time or distance in the physics: that is why it is known as an "Ideal" detonation.

Since sensitivity is largely determined by time and space issues, Ideal detonation has no ability to:

- know whether or not a formulation will in fact detonate,
- identify with the fact that VoD decreases with diameter and weak confinement, or
- determine the critical diameter below which detonation cannot take place.

If these things cannot be modelled, it is difficult to define how well-suited an explosive is to real operating requirements.

1.4 Non-Ideal Detonation

Reaction rates determine the behaviour of an explosive in the field, and the rates are commonly defined in Ignition and Growth models. For every formulation there are limits to sensitivity, and the early and late reaction phases may take place in stages which range from fast to slow, as conditions change.

Since the 1950's attempts have been made to move to Non-Ideal detonation theory, in which reactivity, time and dimension are taken into account. The objective of the work has been to understand, predict and therefore control both the sensitivity of explosives in various conditions, and the way in which such explosives affect and are in turn affected by their confining media.

In the case of ANFO at density 0.8 g/cc, AEL's ideal detonation code Vixen_i provides an estimate of 4.84 km/s for detonation velocity. This assumes that total reaction takes place between the shock front and the so-called CJ plane, with a detonation pressure estimated at 4.965 GPa. In practice, ANFO detonates at VoD's seldom higher than 4.3 km/s, and sometimes below 2 km/s. Also, while it will not detonate readily in diameters of less than 75mm in weak confinement, it detonates in strong rock types at diameters of less than 50mm. To model rock-breaking seriously such variation in explosive behaviour itself needs to be modelled.

As computer speeds increased during the 1980's, several major thrusts were undertaken to develop non-ideal models of detonation. These have been described in a masterful summary of the topic by Byers Brown (2002), who demonstrates that the enormity of the task is still challenging for even the fastest of computers. However, work by the ICI group in the 1980's (Kirby and Leiper, 1985) provided a good starting point for commercial explosives. Work building on the published basis for this eventually led to the development of AEL's Vixen_n non-Ideal detonation code. Papers describing this are in preparation.

1.4.1 Differences in Ideal and Non-Ideal Detonation theory

At this point it is necessary to describe briefly the vital elements of Ideal and Non-Ideal detonation. **Figure 2** shows the simplicity of the former, which is one-dimensional and knows nothing of the surroundings or of the reaction rate of the explosive. In CJ calculations, no reference at all is made to the reaction rate of the explosive or to the conditions between shock front and CJ plane. This is more appropriately named the "Sonic Plane", as it defines the point at which the flow rate becomes supersonic relative to the shock front.

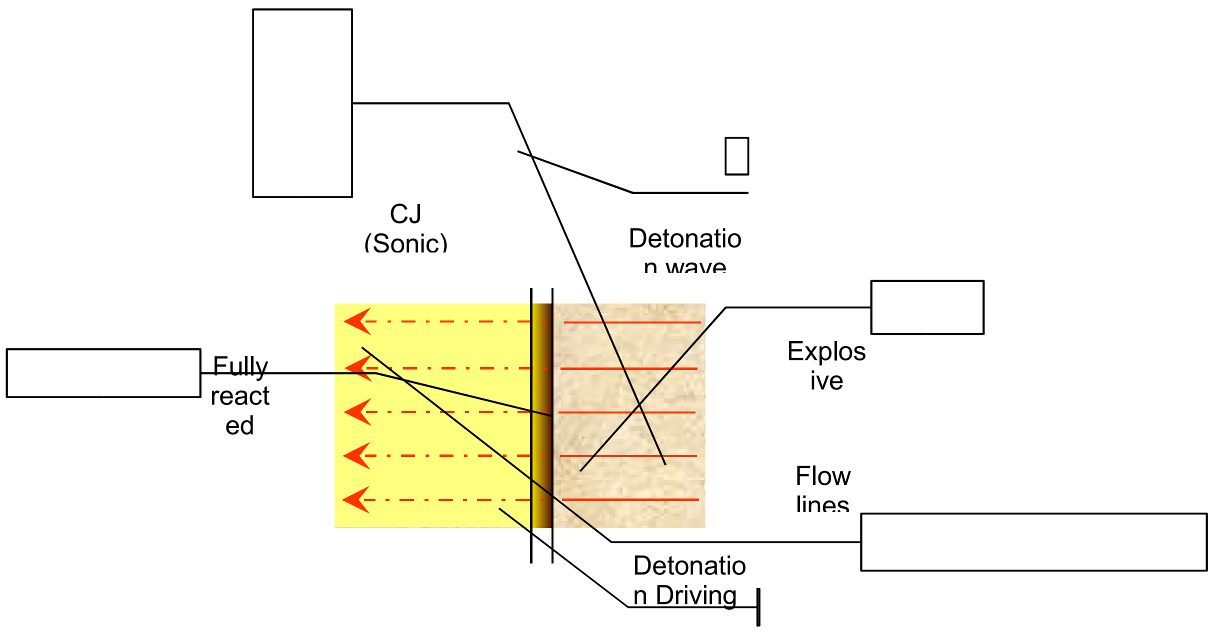
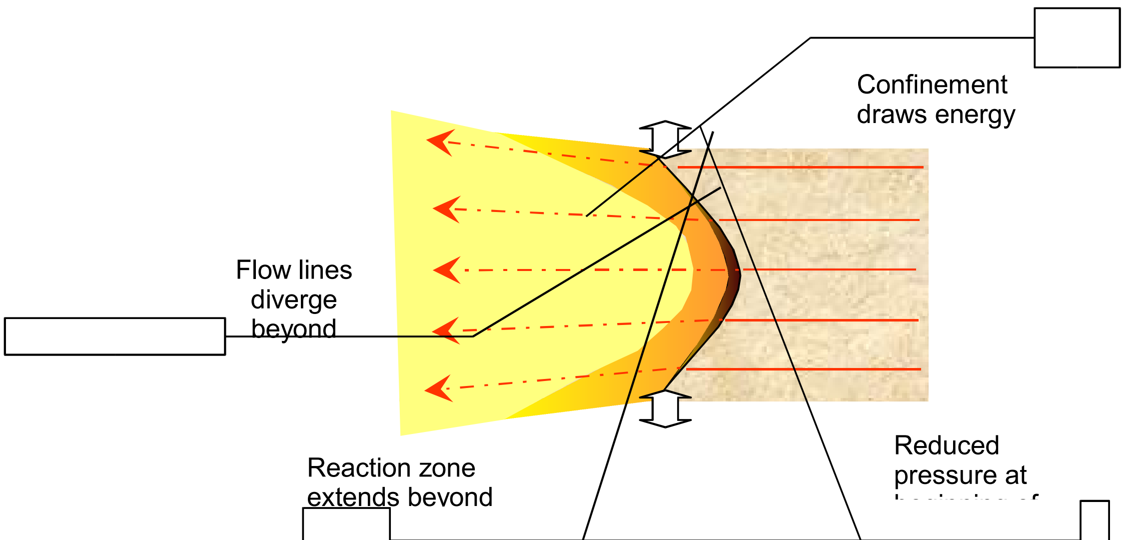


Figure 2: **Ideal detonation.** One dimensional, perpendicular shock



3: **Non-Ideal detonation.** Two dimensional, shock wave is assumed stationary with explosive moving into it with detonation velocity D. Note divergent flow of products.

Figure 3 shows that when the reaction rate and diameter of the explosive are finite, some of the energy in the DDZ (Detonation Driving Zone) leaks sideways, reducing the pressure behind the shock front, which drops both the VoD and the reaction rate. This means that reaction is not complete at the sonic plane, further depriving the DDZ of energy. Where pressure loss is greatest along the side, the shock front weakens and lags behind the axis of the charge where it is thickest. The extent of lateral loss and curvature of the shock front is determined by the rate of reaction, the resistance of the confinement, and the diameter of the charge. Clearly, the detonation velocity is a direct indication of the extent of reaction in the DDZ, and if this amounted to 100%, then the shock front would have no curvature and the measured VoD would be the Ideal value.

The huge increase in complexity of Non-Ideal detonation arises from having to model the process within the DDZ, which means looking at the shock physics, reaction rates and geometric affects. On top of this the nature of the confinement and its dynamic reaction to the impact of the detonation wave becomes a critical input. With so many challenging processes to take into account, simplifications have had to be made, including adoption of pseudo-1D Wood-Kirkwood and other theory. The aim has been to preserve a valid structure upon which to build improvements as technology advances.

The indications are that the Vixen_n code provides a good interim tool for examining Non-Ideality in detonation, and the following is a description of some of the mechanisms addressed and results of the modelling.

Table 1: Unconfined data set for DF56

Diameter, mm	Inverse Dia 1/mm	VoD, km/s
(Vixen_i)	0	6.09
75	0.01333	4.64
50	0.02000	4.25
7	0.02703	4.04
32	0.03125	3.88
25	0.04000	3.77
22	0.04545	3.50

1.4.2 Calibrating Field Data for Vixen_n

The physical states of the explosive ingredients are critical to the sensitivity of the explosive, and the only way to calibrate an ignition and burn rate model is from field tests. For a given explosive density, the Ideal VoD is defined by Vixen_i and represents the maximum attainable value, which would pertain at infinite charge diameter in the strongest rock type. This provides one end of the performance curve, the other being the VoD at critical diameter. VoD tests use different diameters of thin cardboard pipes (which approximate to the worst case situation of unconfined detonation) to define the intermediate sensitivity.
The following set of VoD data is a case in point (**Table 1, Figure 4**).

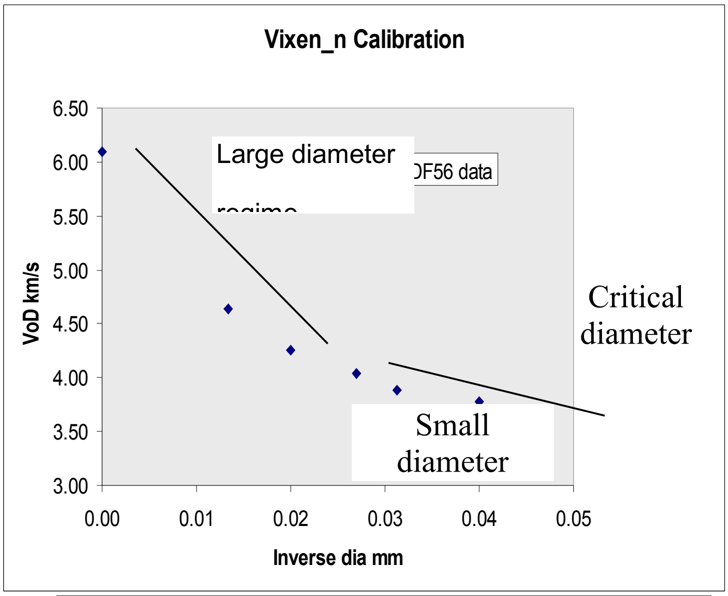


Figure 4: Performance curve for doped emulsion DF56

This unconfined data set indicates a critical diameter of 22mm, with two regimes of sensitivity: at small diameter a sensitive component carries the detonation, with much of the reaction taking place after the DDZ. When the diameter exceeds 37mm, the DDZ is sufficiently large for the rest of the explosive to be participating in the reaction and boosting the VoD.

1.4.3 Mass Fractions

The explosive is in fact an emulsion containing 30% Ammonium Nitrate (AN) prill by mass, and the early reacting component is free emulsion. Key energy and physics data is given by the Ideal detonation code, while knowledge of the components of the emulsion guide choice in the thirteen other parameters needed for defining the energetics of ignition in the DDZ. These parameters address three possible mass fractions, namely the early Hotspot fraction, a Medium rate fraction and the late Slow fraction, which is normally, but not always, associated with solids like Aluminium and AN.

The mass fractions can be derived as a first approximation from the composition and density of the explosive, and from the shape of the inverse diameter graph. **Figure 5** shows the mass fractions used for the DF56 explosive above. This indicates that the emulsion component is driving the hotspot fraction, and that 30% of the emulsion/AN prill mixture is igniting later. The question is, how much later? This brings us to the rate factors for the mass fractions.

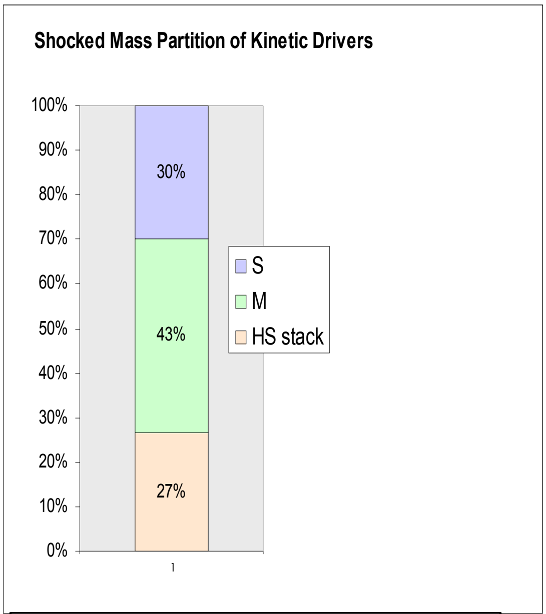


Figure 5: Determined mass fractions for explosive DF56

1.4.4 Critical Hotspot Pressure and Rate Factors

The first consideration is the minimum pressure needed to ignite reaction in the hotspot, and since pressure impacts on velocity of detonation, a low critical hotspot pressure (Ph) results in a low velocity at critical diameter. In the case of DF56, the critical velocity is 3.5km/s, which is a little low relative to the Ideal VoD of 6.09, and a Ph value of 1.5 GPa was used. Typical values range between 0.03 and 12 GPa.

Key guidelines for the rate factors of the mass fractions are given by the shape of the VoD/ inverse diameter plot. The shapes range from concave, as in the case of DF56, to convex. Concave curves indicate that the hotspot mass ignites early, with the remaining fractions relatively slow to pick up from it. Their rate factors are thus longer than that of the hotspot factor. For DF56 the fitted values were 2, 14 and 25 microseconds, resulting in the fit shown in **Figure 6.**

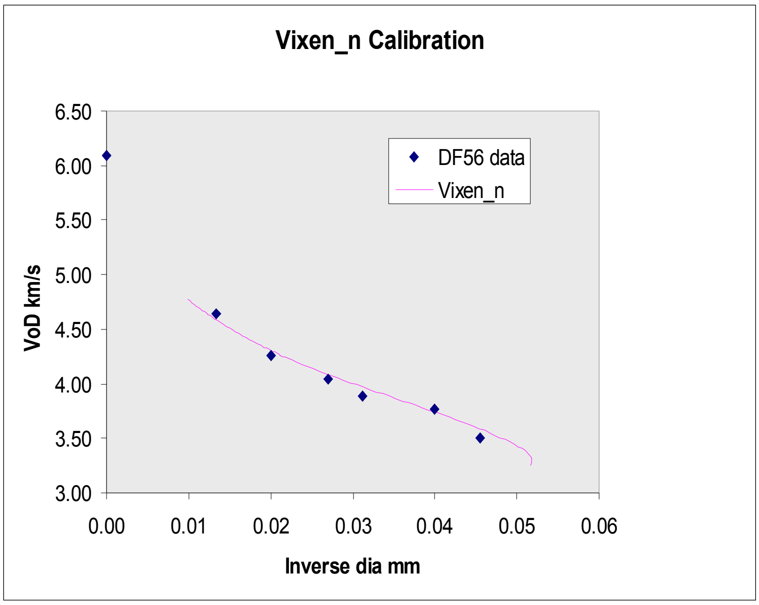
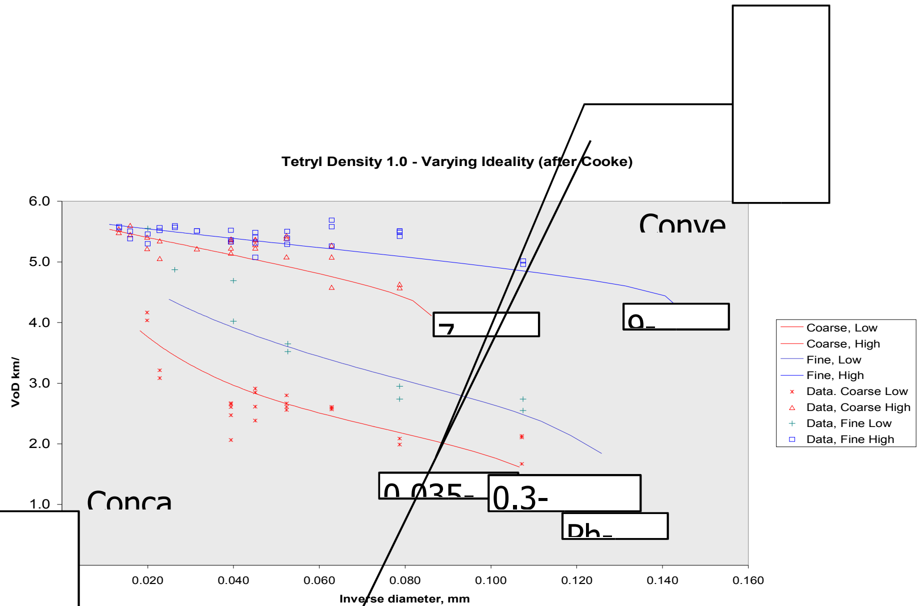


Figure 6: Complete non-ideal fit for explosive DF56

Figure 7 displays an interesting data set from Cooke (1957), showing four curves for one explosive type and density, but two different size gradings. In each, the smaller diameter shots displayed low order VoD when initiated with a detonator, but high order VoD when using a primer.



7: Detonation behaviour in coarse and fine Tetryl. Low order concave curves at bottom show low critical velocity and Ph, late ignition rates Ts slower than early rate Th. High order convex curves at top show high critical

Modelling the four VoD sets provides insight into the significance of ignition parameters. Values for critical pressure and rate factors for Hotspot and Slow fractions are shown with each curve (no Medium fraction for this powdered military explosive, Tetryl).
The Low Order detonations are concave, with low critical pressure resulting in low VoD at small diameter; as is the case with DF56, late phase ignition is slower than the hotspot ignition rate. The finer material is less convex than the coarse material, and has a bigger critical diameter.

The High Order detonations are convex, characterised by late phase ignition rates faster than the hotspot rates. This indicates that the late phase of detonation is quick once the hotspot has ignited. The high velocity at the critical point indicates a high critical hotspot pressure, finer material having a higher detonation velocity at the critical condition. However, all curves indicate that the detonation velocities will converge on the Ideal value of 5.77 km/s as diameters increase.

In this case, there is a degree of interpretation required, as the Low Order detonations in some case were unstable and switched to High Order, providing two VoD's from one reading. The scatter is typical for this kind of work.

1.4.5 Significance of curve shape

The modelled behaviour enables useful information to be derived for the explosive under different conditions. The key information at each diameter is the extent of reaction at the sonic zone, which defines energy released in the DDZ.

For the DF56 data of **Figure 6**, **Figure 8** shows key output required for blast modelling. The distinct "kick-in" of the P_{cj} (pressure at sonic plane) above 32mm shows where the slower reacting material begins to participate in the DDZ. The extent of reaction at this diameter is about 45%.
It is often implied that VoD is a definitive measure of explosive efficiency, but these curves show quite clearly that it is not. What it measures is the energy released in the DDZ to drive the shock wave. Reaction after the sonic plane has no effect on the VoD, but it releases chemical energy nevertheless, and provided the reaction proceeds to completion within the timescale of rock breaking mechanisms, it will affect the outcome.

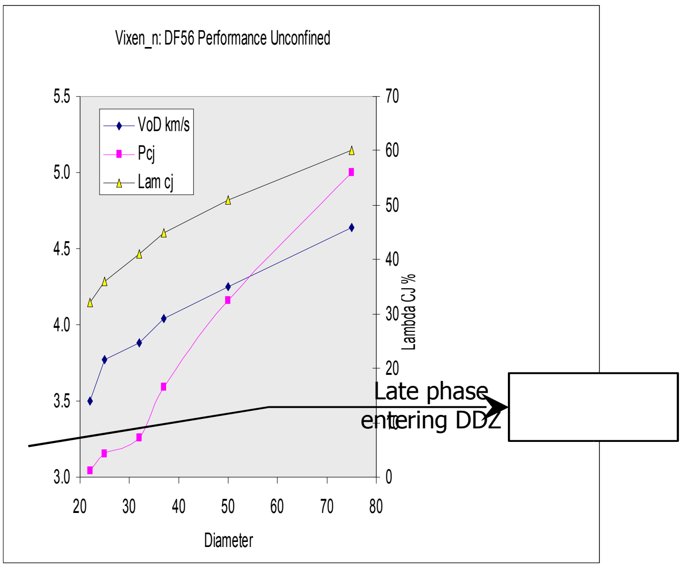


Figure 8: Energy specifics for DF56 at Sonic plane, against charge diameter.

VoD is only a measure of performance where there is evidence to suggest that reaction is not going to completion after the DDZ, or where there are important technical reasons to sustain the detonation pressure at a particular level, whether high or low.

1.4.6 Effect of Confinement

The characterisation of explosives is normally undertaken in unconfined conditions. However, use in confined conditions significantly alters the energy flow in the DDZ. Thus, having calibrated the kinetic model in unconfined conditions, Vixen_n must be run for specific rock confinements. The basis for doing this is somewhat tenuous, since it involves estimating the interaction of the exceptionally dynamic pressure wave of the DDZ with rock in regimes well beyond normal test capabilities. While improved methods are under development, a sensible correlation has been assumed between the curvature of the shock front and the sonic velocity of the rock in question. This induces a correction to the DDZ related to rock strength, and **Figure 9** shows the effect of weak and strong rock types compared to unconfined detonation for DF56.

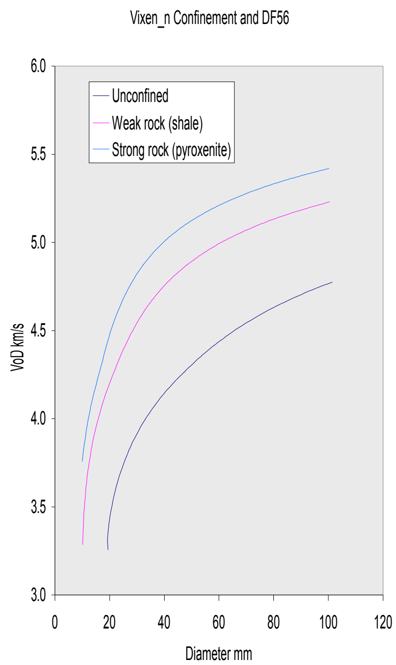


Figure 9: Confinement reduces critical diameter and increases VoD in Non-Ideal domain.

The higher velocities in confinement indicate that there is a greater degree of reaction within the DDZ. **Table 2** below compares the thickness of the DDZ and Lambda CJ for the above conditions of confinement, as given by Vixen_n.
As this table indicates, strengthening the confinement pushes the Sonic degree of reaction up from 41% to 68% and increases detonation pressure from 3.26 to 5.94 GPa. Note that the simple rule of thumb for detonation pressure,

$$Pcj = 0.25 \cdot Density \cdot VoD^2,$$

yields pressures 30 percent higher than are actually achieved.
This modelling reveals the counter-intuitive fact that, for this explosive in this hole diameter, the mode of detonation adjusts to the rock conditions and automatically presents lower pressure to a weaker rock, leaving a greater portion of the reaction to take place at lower pressure beyond the sonic plane.
The weakness of the Non-Ideal modelling on its own, is that the rock provides important feedback to the detonation process, and the simple elastic behaviour assumed in the past

needs to be addressed. It is anticipated that this will be an outcome with the evolution of the HSBM.

Parameter	**32mm DF56**		
Confinement	Nil	Weak	Strong
VoD km/s	3.97	4.61	4.87
Pcj GPa	3.26	5.03	5.94
Lambda CJ %	41.1	61.1	67.7
DDZ length mm	2.2	11.8	14.4
Simplified Pcj GPa	4.5	6.1	6.8

Table 2: Dynamics of confinement for 32mm DF56 explosive.

1.5 Full Blast Modelling – the HSBM

While AEL was building the Vixen detonation codes, the De Beers group was seeking ways to model the dynamic processes close to a blasthole, in order to understand better the implications for diamond breakage from blasting. Work with the University of Queensland and Itasca Consulting Group (ICG) indicated that it would be possible to draw together the resources from these parties to create a rock blasting model which could track energy release from explosive formulation through to detonation, propagation, rock response, fragmentation and motion.

In due course sufficient interest was garnered from international sponsors to assemble a consortium which is building the model, named the “Hybrid Stress Blasting Model”, or HSBM. The current sponsors for the HSBM are, de Beers, AEL, Codelco, Dyno Nobel, Placer Dome, Rio Tinto, Anglo American Base Metals, and Sandvik Tamrock. The project consultants include global experts from Cranfield University, Swebrec (Luleå College of Technology) and Cambridge Cavendish Laboratory, while management and some of the design technology is provided by the JKMRC of Queensland University.

AEL’s Vixen detonation codes, Vixen_i and Vixen_n are a core resource in this. The material model is an evolved development of ICG’s PFC3D code, and the first phase of the project will draw to a close during 2005 after three years of intense development and research.

1.6 Conclusion

Non-Ideal detonation modelling provides a quantum leap for appreciating the energetics of blasting, since it introduces the aspect of sensitivity. In terms of energy “partitioning”, if the reaction is largely complete within the DDZ then the highest peak pressure will be applied to the blasthole wall. This does not necessarily mean that the rock will receive less energy if the reaction is partial and the VoD is lower, but the mode of delivery of the energy could result in different end effects.

The importance of a first rate Ideal Detonation model such as Vixen_i must not be overshadowed by the huge step forward of the Non-Ideal model, because the purity of the science in Ideal detonation is key to providing a good starting point for the Non-Ideal. Few commercial explosives are able to approach their Ideal detonation velocities in the available test conditions, so the only source for this key information is the Ideal code. The gamma constants are also key to determining Non-Ideal behaviour, so if the Ideal code is less than good, the starting point for Non-Ideal modelling is compromised. The vital next step is the merging of a good Non-Ideal detonation model with a good material model, which will be the outcome of the HSBM.

The application of the Vixen detonation codes to rock modelling brings fresh insight to rockbreaking, but the learning curve is still very steep, and significant development lies ahead.

1.7 Acknowledgements

The management of AEL have sponsored the work behind the Vixen detonation codes for several years and given every encouragement in the evolution of improved understanding of rockbreaking, including permission to publish this paper. The sponsors and members of the HSBM group are providing additional input and funding for developing and broadening the vital knowledge and skills required to take blast modelling to a radically new level, and this paper hardly touches what is being achieved and shared, and which should begin to be published and demonstrated in the months ahead.

Finally, the author pays tribute to the outstanding contributions of Prof. Martin Braithwaite of Cranfield Royal College of Military Science and Dr Ian Parker of Cheshire, who have given not only immense dedication but also superb handling of the intricate science and mathematics behind the Vixen detonation models. Their patient teaching and coaching has been invaluable in bringing the models to a state of practical application.

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