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A comparison of the theoretical and measured velocities of detonation for selected explosives

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SYNOPSIS

Two detonation models, IDeX for ideal VOD and CPeX for non-ideal VOD, were used to predict the velocities of detonation (VOD) of five explosives: ANFO, a bulk emulsion, and three repumpable emulsions (R100 Gold, R100 Diamond, and R105).

The theoretical VODs were compared with the in-hole VODs of the explosives, and the predicted and actual values were found to be within experimental error for ANFO and the bulk emulsion. The results were not consistent for the repumpable emulsions. The discrepancies can be explained as being due to variations in mining and loading practices.

The results show that the detonation models can be effective tools in predicting the behaviour of explosives in different diameters and rock confinements, provided that the user is aware of the factors that can affect the optimal usage of explosives and equipment.

SAMEVATTING

Twee detoneermodelle, IDeX vir 'n ideale detoneersnelheid, en CPeX vir 'n nie-ideale detoneersnelheid, is gebruik om die detoneersnelheid van vyf springstowwe te ondersoek: ANFO, 'n massa-emulsie, en drie herpompbare emulsies (R100 Goud, R100 Diamant en R105).

Die teoretiese detoneersnelhede is vergelyk met die detoneersnelhede van die springstowwe in 'n gat, en daar is bevind dat die voorspelde en werklike waardes vir ANFO en die massa-emulsie binne die eksperimentele foutgrens val. Die resultate vir die herpompbare emulsies was nie konstant nie maar die verskille kan aan mynbou- en laaipraktyke toegeskryf word.

Die resultate toon dat die detonasiemodelle doeltreffende hulpmiddels kan wees vir die voorspelling van die gedrag van springstowwe vir verskillende diameters en rotsinsluitings, mits die gebruiker bewus is van die faktore wat die optimale gebruik van springstowwe en toerusting kan beïnvloed.

INTRODUCTION

Over the years, major efforts have been made to optimize the performance of commercial explosives and to improve blasting practices, demanding increasingly more accurate theoretical predictions and physical measurements of the effects of explosives. For this reason, a range of increasingly more sophisticated computer models and experimental instrumentation has been developed. Velocity of detonation can now be measured accurately and reliably in South African mines, by means of a variety of systems such as the Diode system and the commercially available VODR-1 and VODEX-100. In addition, other instruments have been utilized in the field to measure ground vibration, sound velocities, and face velocities. However, the amount of information collected is constrained by time and by the high costs of instrumentation.

To supplement experimentation, predictive computer-modelling packages have been developed by various companies. Examples of computer codes for the modelling of ideal detonation are BLEND, an empirical code developed for commercial explosives, and TIGER, developed with military explosives in mind. Two specific codes have been used in recent years in South Africa: the ideal detonation code IDeX (Ideal Detonation of Explosives[1]) and the non-ideal detonation code CPeX (Commercial Performance of Explosives[2].

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BACKGROUND

Predictions of the velocity of detonation (VOD) based on ideal detonation theory match the experimental VOD measurements of most commercial explosives at large diameters. Predictions deviate markedly from measurements for explosives that have degraded as a result of mishandling or excessively long storage, for chemically sensitized explosives (at even the largest diameters in which these explosives are used commercially), and for explosives in small diameters and weak confinement. To predict VODs in the latter two cases one must turn to a model based on a non-ideal, two-dimensional theory.

Non-ideal (Real) Detonation

In finite diameters, detonation becomes non-ideal because of radial energy flow and reduced rates of chemical reaction. A significant fraction of chemical energy can be released behind the sonic Chapman–Jouguet (C–J) surface. Because only the energy released in the primary reaction zone (the zone between the shock front and the sonic surface) supports the shock front, the VOD and shock energy are reduced in non-ideal detonation. However, reaction in the 'secondary zone' contributes to rock breakage since the gases work on the rock as they escape to the atmosphere. In soft rock, a non-ideal explosive can give better performance than an ideal explosive of the same total energy.

The 'edge' effects described are most pronounced in charges of small diameter because the reactions in the secondary zone consume a large percentage of the total material used. Consequently, the VOD of mining explosives decreases as the diameter decreases. Factors that affect the degree of non-ideal behaviour are the charge diameter, coupling ratio, degree of confinement, particle size, and degree of intimacy of the contact between fuel and oxidizer. Although the VODs of military explosives decrease only marginally as the diameter decreases, the VODs of commercial explosives can drop appreciably.

For commercial explosives at blasthole diameters, confinement plays a significant role. As the stiffness of the confinement increases, lateral expansion near the primary zone is inhibited. This maintains the pressure and temperature at greater levels, and so increases the extent of combustion in the primary reaction zone. This explains why mining explosives can detonate with a significantly higher VOD in rock than in air. Particle size and intimacy of mixing of the constituents exercise strong control over the combustion rate. For instance, large particles, a few millimetres in size, such as ammonium nitrate prills, react relatively slowly. It is mainly these particle-size effects that are responsible for the vast differences between ideal VOD and performance and between actual VOD and performance, especially when the explosives are used in smaller-diameter holes.

IDeX (Ideal Detonation of Explosives)

Detonation models have been used worldwide for many years, originally in military applications, and later commercially. Military models such as TIGER BKW, TIGER JCZ3[3], and FORTRAN BKW, and early commercial models such as BLEND[4], and later IDeX JCZ3[5], are well known.

These models are based on empirical or semi-empirical equations of state. The new IDeX IMP (InterMolecular Potential[6]) model, based on statistical mechanics and an intermolecular potential equation of state, is a fundamental model, deriving ideal characteristics from first principles. IDeX IMP has been found to provide better predictions of detonation velocities and pressures than empirical or semi-empirical models like IDeX, JCZ3, and BLEND[7].

- Input required for IDeX IMP[5]:
  Chemical composition
  Density
- Output obtained from IDeX IMP[7]:
  Detonation velocity
  Detonation pressure
  Heat of reaction
  Detonation products
  Effective energies at different cut-off pressures (expressed as strength relative to ANFO).

Because ideal theory is the launching point for non-ideal theory, IDeX provides the necessary input for CPeX, the AECI non-ideal code.

CPeX

Many attempts have been made to generalize the ZND theory (Zeldovich–Von Neumann–Doring theory of detonation, extension to finite reaction-rate chemistry), and there are many theories of non-ideal detonation[8]. In a particular attempt to generalize one-dimensional ZND theory, Wood and Kirkwood examined a cylindrically symmetric system, assuming, to a first approximation, only slight departure from one-dimensional flow. The work of Chan, and later Kirby and Leiper, is based on their development, and has been encoded in CPeX (Commercial Performance of Explosives)[9].

- Input required for CPeX:
  Selected output from IDeX, including ideal VOD and heat of reaction; and either
  reaction rates, or
  unconfined VOD–diameter data (obtained from experimental testing).

CPeX provides a wealth of information, including values, in different diameters and different confinements, for

- shock energy
- gas energy
- VOD
- failure diameter
- pressure history
- reaction rate and extent of reaction histories
- particle velocity history
- density history.

As an interpretive tool, CPeX can be used to aid the user in selecting an explosive with the correct behaviour. The further the explosive deviates from ideal, the lower will be the shock energy, and the greater the gas energy[10].

It should be noted that CPeX predicts only steady-state values, and does not predict any variation of VODs due to run up (or, in the case of over-boostering, run down). Although it is possible to use CPeX to estimate the variation of VODs within a borehole due to a variation in explosive density, it is not a simple exercise, since it requires multiple simulations at different densities.

IN-HOLE VOD-MEASUREMENT SYSTEMS

VOD represents explosive performance, and its measurement is used as a quality-control tool. The precision with which one can measure VOD depends on the inherent properties of the measuring system and how accurately these can be determined. In any measurement made, there is an estimated experimental error that should be given for each system.

In a point-to-point system the distance between measuring points must be known very accurately. The probe must be placed straight in the hole, and kinks must be avoided. For example, if the distance between measuring points is out by 1 cm over 1 m, and kinks in the probe caused the actual length along the hole to be 2 cm shorter than the probe length along a 1 m length of probe, the measured VOD can be incorrect by between 2 and 3 per cent. In this example, an explosive with a nominal VOD of 4000 m/s, where the time taken over 1 m would be 250 μs, could be measured to be detonating at 3880 m/s:

$[(1 - 0{,}03\ \text{m}) / 250\ \mu\text{s}]$.

In a continuous system, the most important factor to consider is the accuracy with which one can specify the way the particular known chosen characteristic of the probe varies with time. It is essential to put the probe as straight as possible down the hole, avoiding kinks.

The following is an overview of the methods available for the measurement of VODs.

Discrete (Point-to-point) Measurement

The discrete approach (point-to-point) involves measurement of the position of the detonation shock front of the explosive over a measured distance. From the time recorded between two discrete-point sensors or probes of known separation, an average velocity can be calculated. Three basic devices can be placed on or in the explosive column to sense the arrival of the shock-wave front: resistive, optical, and electrical devices.

Diode In-hole VOD System[11]

This system comprises a probe connected by cable to a battery-driven data-capture box. The data-capture box is interfaced to any IBM-compatible computer subsequent to the blast for the collection and analysis of data. The probe consists of flexible copper wire, a diode chain, and a trigger wire. The diode chain consists of six diodes spaced at known intervals.

When the diode chain has been connected to the capture box, a constant current is passed through the diode-chain circuit, and the voltage of this circuit and of the trigger circuit is monitored. The probe is inserted into a borehole that has been primed. The probe relies on a highly charged plasma generated within the explosive front to complete the circuit. On detonation of the explosive column, the trigger is destroyed, causing a drop in the voltage of the circuit, which triggers the data-capture box. The voltage of the diode-chain circuit is recorded as a function of time. These voltage readings have step changes corresponding to the destruction of successive diodes on the probe. The software graphically displays the change in voltage that has been recorded, and the capture times could vary between 800 μs and 8 ms.

VODEX[12]

This is an intelligent eight-channel high-speed timer that records time intervals between the channels and converts these to VODs. The timer relies on the highly charged plasma generated within the explosive detonation front to sequentially short-circuit a series of wire pairs terminating at a desired position in the charge. Ribbon cable is normally used as a sensor cable, with individual pairs cut back to the desired sensor positions. Up to 50 VOD shots can be recorded at a resolution of approximately 0,1 μs by the unit without erasing previous data.

Continuous VOD Measurement

The main disadvantage of the discrete-point techniques is that the calculated VOD is only the average velocity of the explosive between two points. Any change in velocity in the measured region, such as during the run-up to detonation or even the onset of a failure, will not be evident. A continuous method for the measurement of VOD provides more information, and thus gives a deeper insight into the reaction front.

VODR[13] In-hole VOD Measurement System

The VODR-l continuous VOD recorder is a commercial version of the CORRTEX system (Continuous Reflectometry for Radar versus Time). The VODR-l is a repetitive time-domain reflectometer (TDR) with recording capability. The principle of operation is similar to that of radar. However, instead of transmitting bursts of radio waves in the atmosphere, single fast-rise-time electrical pulses are transmitted down a coaxial electrical cable.

These pulses are reflected at discontinuities in the cable, the nature of these reflections depending upon the discontinuity and the cable impedance. For the VODR-l, the major discontinuities are an open or short circuit.

The VODR-l measures the time between the transmission of each pulse and the reception of its reflection. This time is called the Two-Way Transit Time (TWTT). Since the velocity of propagation of electromagnetic waves in the coaxial cables can be calculated, the VODR-l can convert the two-way transit time to distance. When the single-pulse measurement is repeated and the TWTT of each transmitted pulse is recorded, a time history of the cable length is created. The data are used by the VODR-l to generate processed data. When the VODR-l is used to measure the VOD, the coaxial cable is run alongside or in the explosive. The shock wave from the detonated explosive severs or crushes the coaxial cable as it runs alongside it. These cable terminations, either an open or a short circuit, generate reflected waveforms that are used by the VODR-l to stop the timing process. The sampling rate is between 5 and 200 μs.

RESULTS

The Diode, VODEX, and VODR-l systems were calibrated against one another under controlled conditions. The three systems were then used, in mines where the explosives are used on a regular basis, to record VODs for ANFO; Powergel^R P115, a bulk emulsion; R100G and R100D; and R105, a repumpable emulsion with ferrosilicon. The results are listed in Tables I to IV, and illustrated in Figures 1 to 7.

The explosive used for the results of Table I was bulk Powergel P115^R emulsion. The 4 m blasthole was primed with a 150 g Pentolite booster at PPC Slurry Mine in A and B. The 15 m deep borehole was primed with two 60 g Pentolite boosters at Anglo Alpha Limestone Mine in C and D.

For E in Table II, the explosive that was used was R100G (repumpable emulsion used in gold mines). The 3 m holes were primed with two 32 mm Dynagel^R 60 cartridges (a nitroglycerine product). The VOD probe was placed in the first blasthole in the cut, at Cook One underground mine near Johannesburg.

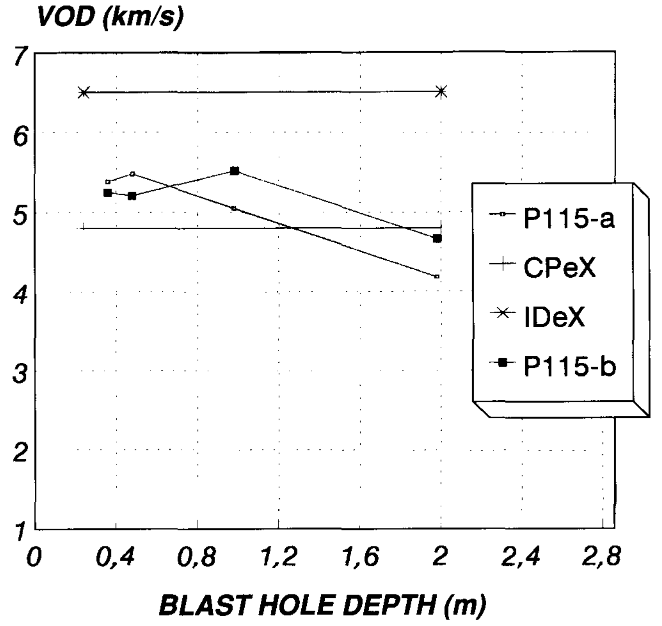
The explosive that was used for F of Table II was R105 (repumpable emulsion with ferrosilicon). The 3 m blasthole was primed with one 32 mm Dynagel 60 cartridge. The VOD probe was placed in the cut at Cook One underground mine.

For G of Table II, the explosive was R100G. The blasthole was drilled at 65 degrees, and the 71 m deep blasthole was primed with ten 150 g Pentolite boosters at Koffiefontein Diamond Mine.

The explosive that was used for H of Table II was R100D (repumpable emulsion of high viscosity used in diamond mines for up-hole loading). The 3 m development-end blasthole was primed with one 60 g Pentolite booster at Koffiefontein Diamond Mine.

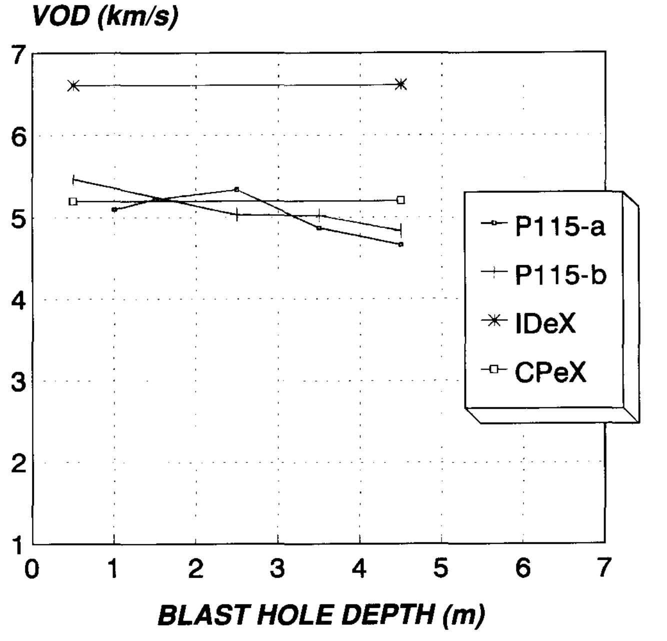
For I, J, M, N, and O of Tables III and IV, the explosive was ANFO (94 per cent ammonium nitrate and 6 per cent fuel oil). The blasthole depth for I and J was 17 m, and for M, N, and O it was 30 m. The blast at Middelburg Colliery (I, J) and the blast at Kleikopje Colliery (M, N, O) were all primed with one 'optimum booster' (46 x 400 Pentolite booster).

The explosive featuring in K and L of Table III was ANFO. The 20 m blasthole was primed with two 400 g Pentolite boosters at Middelburg Colliery. The probes were placed in the back row, near the start of the blast.



a = blast hole one
b = blast hole two
Record A & B

Figure 1—In-hole VOD versus IDeX and CPeX VOD (bulk Powergel, hole dia. 70 mm in limestone)



a = blast hole one
b = blast hole two
Record C & D

Figure 2—In-hole VOD versus IDeX and CPeX VOD (bulk Powergel P115, hole dia. 115 mm in norite)

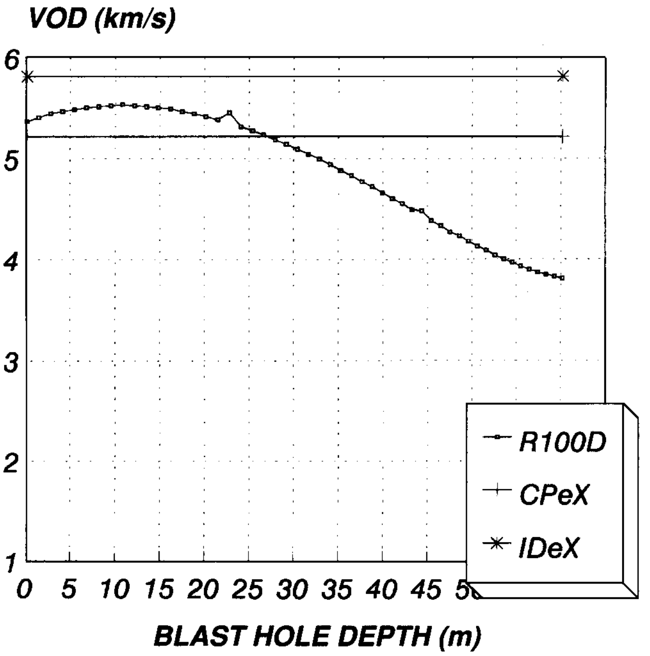
Table I
Records A to D

Record	A (Figure 1)	B (Figure 1)	C (Figure 2)	D (Figure 2)
Explosive	P115	P115	P115	P115
VOD system	Diode system	Diode system	Diode system	Diode system
Recorded VODs km/s	6,40* 5,39 5,49 5,05 4,18 3,81*	6,08* 5,25 5,21 5,53 4,66 3,75*	6,09* 5,10 5,22 5,34 4,87 4,66	5,47 – – 5,03 5,03 4,83
Hole dia. mm	70	70	115	115
^A^Av. VOD km/s	5,03	5,16	5,04	5,09
Std deviation	0,60	0,36	0,49	0,27
IDeX VOD km/s	6,51	6,51	6,51	6,51
Rock confinement	Limestone	Limestone	Norite	Norite
^B^CPeX VOD km/s	4,80	4,80	5,20	5,20
% difference A & B	4,57	6,98	3,1	2,1

* VODs that were omitted in the calculation of the average (results obtained near the booster or at the end of the explosive column where explosive and stemming could have become mixed)

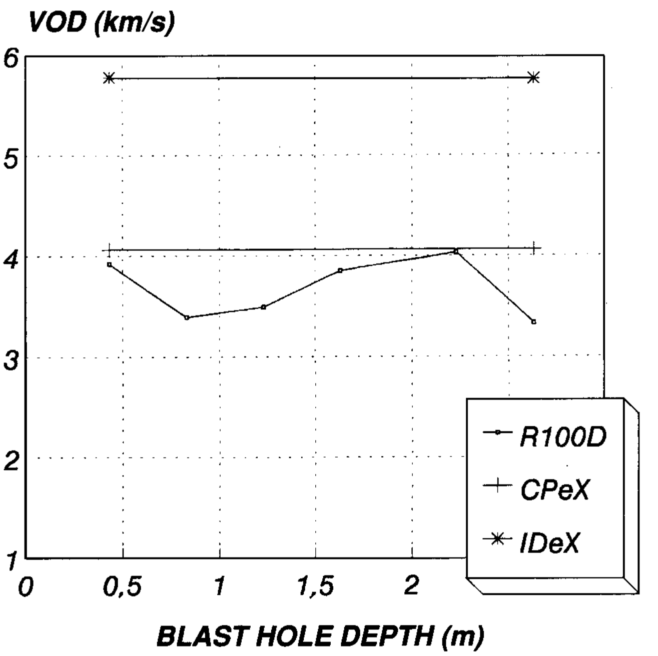
Table II
Records E to H

Record	E	F	G (Figure 3)	H (Figure 4)
Explosive	R100G	R105	R100G	R100D
VOD system	VODEX-100	VODEX-100	VODR-1	Diode system
Recorded VODs km/s	– – 2,08 – – –	3,14 2,98 2,86 4,06 3,60 2,88	VOD on every 1,34 m in a 60 m hole	3,92 3,39 3,49 3,85 4,03 3,33
Hole dia. mm	45	48	165	45
^A^Av. VOD km/s		3,25	4,92	3,67
Std deviation		0,48	–	0,30
IDeX VOD km/s	5,81	5,46	5,81	5,75
Rock confinement	Quartzite	Quartzite	Kimberlite	Kimberlite
^B^CPeX VOD km/s	4,90	4,77	5,21	4,06
% difference A & B		32,0	5,6	9,6



a = blast hole one
Record G

Figure 3—In-hole VOD versus IDeX and CPeX VOD (R100 GOLD, hole dia. 165 mm in kimberlite)



a = blast hole one
Record H

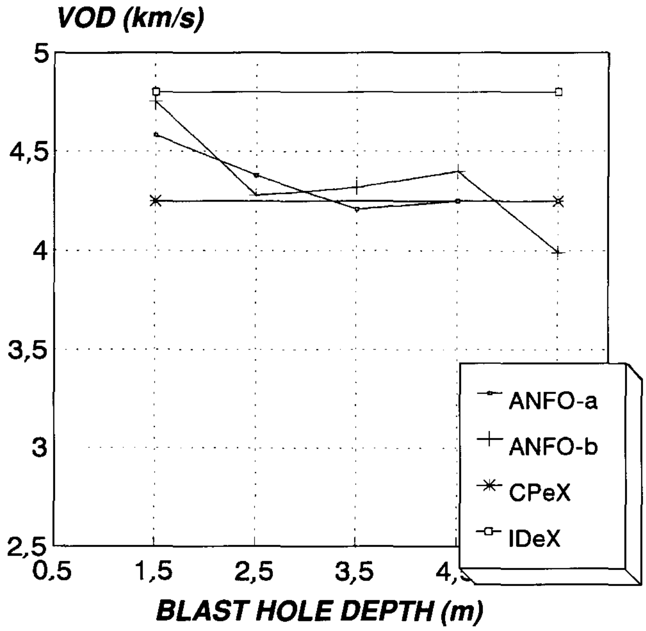
Figure 4—In-hole VOD versus IDeX and CPeX VOD (R100 DIAMOND, hole dia. 45 mm in kimberlite)

Table III
Records I to L

Record	I (Figure 5)	J (Figure 5)	K (Figure 6)	L (Figure 6)
Explosive	ANFO	ANFO	ANFO	ANFO
VOD system	Diode system	Diode system	Diode system	Diode system
Recorded VODs km/s	4,58 4,30 4,21 4,25 4,25	4,75 4,28 4,32 4,40 3,99	4,78 4,58 4,60 4,51 4,46 4,40	– 4,42 4,58 4,31 4,46 4,19
Hole dia. mm	250	250	260	260
AAv. VOD km/s	4,32	4,35	4,55	4,39
Std deviation	0,15	0,28	0,13	0,15
IDeX VOD km/s	4,80	4,80	4,80	4,80
Rock confinement	Sandstone	Sandstone	Sandstone	Sandstone
BCPeX VOD km/s	4,25	4,25	4,27	4,27
% difference A & B	1,5	2,2	6,2	2,7

Table IV
Records M to O

Record	M (Figure 7)	N (Figure 7)	O (Figure 7)
Explosive	ANFO	ANFO	ANFO
VOD system	VODEX-100	VODEX-100	VODEX-100
Recorded VODs km/s	4,66 4,24 3,81 3,98 4,13 4,58 3,94	4,66 4,30 3,75 3,93 4,21 4,38 4,04	4,33 4,36 4,11 4,33 4,40 4,41 4,85
Hole dia. mm	300	300	300
AAv. VOD km/s	4,19	4,18	4,39
Std deviation	0,32	0,30	0,22
IDeX VOD km/s	4,80	4,80	4,80
Rock confinement	Sandstone	Sandstone	Sandstone
BCPeX VOD km/s	4,33	4,33	4,33
% difference A & B	3,2	3,5	1,4

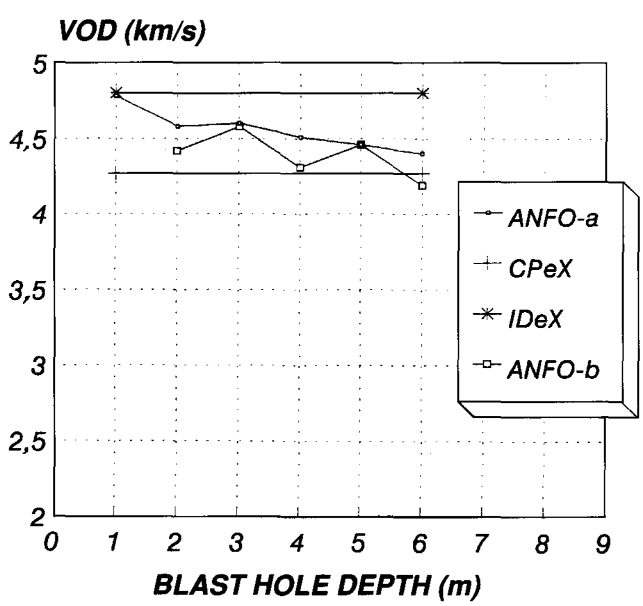


a = blast hole one
b = blast hole two
Record I & J

Figure 5—In-hole VOD versus IDeX and CPeX VOD (ANFO, hole dia. 250 mm in sandstone)

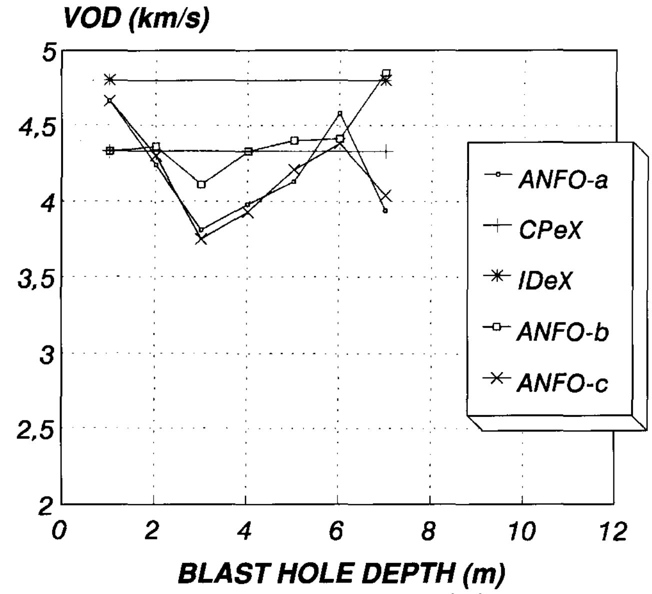
DISCUSSION

Overall, the match between theoretical prediction and experimental results was excellent (Figure 8). For eleven of the fifteen blasts, the CPeX-predicted VOD was within 1 standard deviation of the measured VOD, and for an additional blast, H, it was within 1,3 standard deviations. For blasts A, B, C, D, G, I, J, L, M, N, and O, the mining conditions, as well as the weather and loading practices, were ideal, and very few problems were therefore experienced.



a = blast hole one
b = blast hole two
Record K & L

Figure 6—In-hole VOD versus IDeX and CPeX VOD (ANFO, hole dia. 260 mm in sandstone)



a = blast hole one
b = blast hole two
c = blast hole three

Figure 7—In-hole VOD versus IDeX and CPeX VOD (ANFO, hole dia. 300 mm in sandstone)

As can be seen from E of Table II, only one VOD reading was obtained, and that was much lower than had been expected. It was suspected that there was an air gap within the explosive because the loading procedure had been interrupted. In addition, a single measurement in the Dynagel^R primer cartridge showed the VOD there to be fairly low, indicating that the explosive was initiated poorly.

For F of Table II, all the VOD readings were much lower than had been expected. The discrepancy between the theoretical and the measured results could be explained by a long run-up, which would result if the explosive in F had been boosted insufficiently, as was the case in E.

The measured VOD for blast K (Table III) was more than two standard deviations higher than the predicted value. Because this is the only ANFO blast out of the seven that shows a large discrepancy, it is suspected that the actual rock confinement may have been stronger than was assumed. Rock is notoriously variable in its properties, even over relatively small distances .

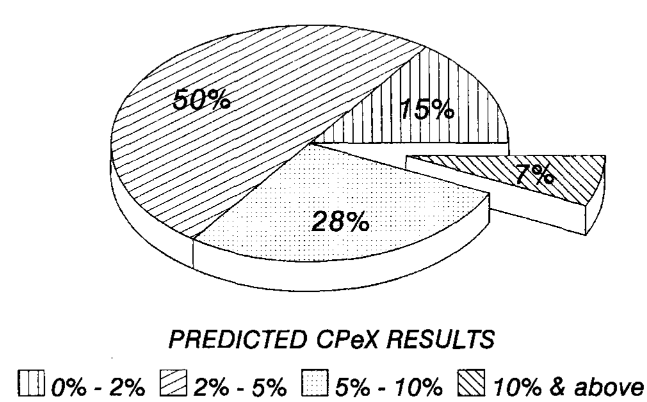


Figure 8—Predicted versus measured VOD

CONCLUSION

CPeX and IDeX have shown themselves to be excellent predictors of the VOD of a commercial explosive in the field, at a given diameter and under a known confinement, provided the explosive is initiated under good blasting conditions.

As accurate predictive tools, these models can be used with discretion in the optimization of explosive performance.

ACKNOWLEDGEMENT

We thank Mr D. Anthony for his perseverance in helping with the physical field work.

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BOOK Review

Mineral-processing technology

Reviewer: R.V.R. Handfield-Jones

Mineral Processing Technology, by Barry A. Wills. New York, Pergamon Press, 5th ed., 1993 (Hard cover: R75. Flexicover: R29,95).

This, the latest edition of the well-known volume on 'mineral dressing', has been updated, enlarged, and altered from previous editions. It is thicker and heavier than the 1988 edition, most of this increase being attributable to the larger type used in the printing, which makes it easier to read, with far less eye strain. The remainder of the increase is due to extensions of the text and the addition of a new appendix (IV).

The chapter layout remains as for previous editions, whilst the references are now presented according to their chronological base as distinct from the previous text numeric base.

Chapters 2, 4, 5, 8, 9, 13, and 14 are the same as before apart from the references.

Acknowledgement that hydrometallurgy can intrude into mineral processing is given by the recognition in Chapter 1 that biotechnology has value in the treatment of refractory ores; and also in Chapter 16, where reference is made to the contamination of heavy metals by dilute acid effluents from residue deposits.

In the case of new equipment, reference is made in Chapter 6 (comminution) to the BARMAC DUOPACTOR; in Chapter 10 (gravity separation) to centrifugal concentrators, mentioning the KNELSON and the (MGS) MULTI-GRAVITY SEPARATOR from the Mozley stable; and in Chapter 15 to the tube press as a drying mechanism.

Chapter 12 (flotation) has undergone the most alteration and addition, with the mention of reagent development, sulphidizing floats, selective gangue depressants, column flotation, sequential flotation, clay flotation in the form of kaolin, and industrial flotation control.

Chapter 3 makes reference to the increasing range of computer applications, which is also mentioned in Chapter 11, along with an economic evaluation of HMS/DMS. (I suspect that users would already have paid attention to this.)

As a reference source to an extraction metallurgist, the volume's value has certainly been enhanced by the addition of Appendix IV, which gives a listing of recent references on mineral beneficiation according to metal or to mineral for the non-metallics. The limited equipment development reported in the volume implies that computer-aided optimization of existing processes has a potential for giving a greater return upon investment , and that the industry is following this approach.