

## Monitoring of large open cut rounds by VOD, PPV and gas pressure measurements

F.Ouchterlony, S. Nie, U. Nyberg & J. Deng

*Swedish Rock Engineering Research, SveBeFo, Stockholm, Sweden*

**ABSTRACT:** A project with the goal to minimize the blast damage to the remaining pit walls has been carried out at the Aitik open pit mine in North Sweden. Factors like confinement during the blast, blast direction and size of blast holes in the contour were systematically changed. During the blasts VOD in the blast holes plus PPV and gas pressure in gauge holes behind the contour were monitored.

The VOD measurements were used to check the explosive performance, to obtain the real initiation sequence and to identify the sources of the PPV pulses in the composite acceleration records. The PPV levels were used to establish a scaling law for the test area which later was used for blast damage assessments.

The gas pressure measurements show that the ordinary rounds, in which the blast holes are unstemmed, don't force any significant amounts of high pressure blast fumes into the walls. This is probably explained by a shock wave initiated dynamic swelling movement that opens up fracture planes. Those that are connected with the gauge hole increase its volume and reduce its pressure. The measured under-pressures correlate relatively well with the measured residual swell values. Further a shot presplit line didn't transmit direct shock waves or blast fumes into the walls. The presplit blast holes themselves though, despite being unstemmed, did however force pressurized blast fumes into the rock. This may be a source of blast damage.

### 1 INTRODUCTION

The Boliden Mineral AB, Aitik open pit copper mine in North Sweden produces about 15 Mton of 0.4% grade ore annually. The slope conditions are of vital importance to the mine economy, hence the strong requirements to reach the planned inter-ramp and bench face angles. Even if geology determines the stability to some extent, the blast damage may be quite important for the individual bench crests and have large economic consequences.

The mine uses double 15 m benches with a catchment berm every other level. The berm has to be at least 11 m wide over 90% of its length for it to function properly. This was not always so and projects were initiated to deal with it, the first in 1991 (Sognfors 1994). Despite a steepening of the bench angles, the blast damage to the walls still seemed to be large. Thus a more pronounced cautious blasting of the final slope seemed motivated.

Part 2 started in 1993 with Boliden as coordinator and with SveBeFo and Nitro Nobel as partners. Field tests were made during late fall and early winter of 1993.

Two production rounds were divided into smaller rounds while varying the following factors;

- the degree of confinement of the round, i.e. the number of rows fired,
- the direction of mass movement through variations in the drilling and ignition plan, and
- the use of either the larger production holes ( $12\frac{1}{4}" = 311$  mm) or the smaller contour holes ( $5\frac{1}{2}" = 140$  mm) in the last row of the round.

Presplitting of the contour was also tried as a complement to the ordinary smooth blasting.

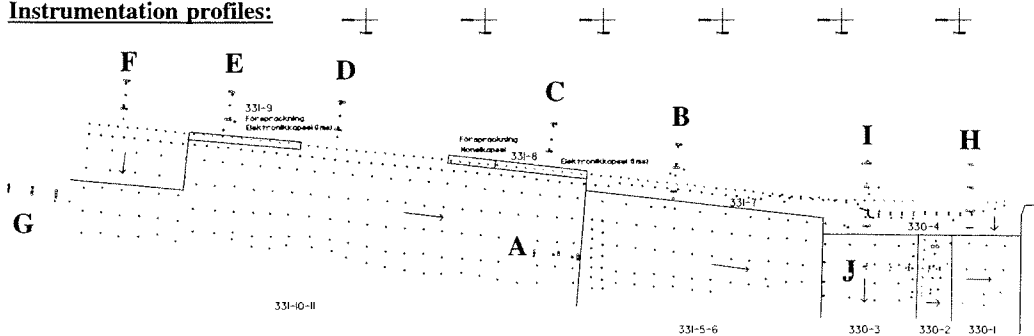
A monitoring program was set up with the purpose of showing how back-break and other forms of blast damage are influenced both by the blasting itself and by the geology. It had three parts;

- careful documentation of drilling, charging and the laying out of the firing lines,
- measurement of VOD, PPV and air pressure in the slope behind the contour holes and
- measurement of the back break and crest profiles in the contour plus the vertical swelling of the bench and the round.

An evaluation of the tests later led to recommendations to the mine how to conduct its contour blasting.

## Project "Cautious Blasting of Final Slope"

### Instrumentation profiles:



### Order of test blasts

330-1:	93-11-23
330-2:	93-11-25
330-3:	93-11-26
330-5+6:	93-11-28
331-8+9:	93-12-02
330-4:	93-12-07
331-7:	93-12-07
331-10+11:	93-12-09

### **Aitik**

Foot wall, -120 m level

Coordinates, Y = 4385-4770 m, 50 m grid

Production rounds 330 and 331

**Figure 1:** Lay out of test blasts and instrumentation profiles in Aitik mine.

This paper focuses on the blast monitoring. Its purpose was to check that the explosive in the blast holes detonates with the correct VOD, in the right sequence and with the proper delay. Furthermore

1. The VOD-records were used to identify which blasthole was the source of what PPV-pulse.
2. The PPV-records were used to construct the site scaling laws needed for damage zone evaluations.
3. The measurement of gas/air pressure in empty bore holes was used both to determine the contribution of the blast fumes to the damage in the remaining bench face and to study the effect of

the presplit crack in protecting the face from PPV pulses and gas penetration. The work by LeJuge et al. (1994) was a very helpful starting point.

Of these the pressure measurements have been presented to an international audience (Ouchterlony, 1995), the VOD and PPV ones only nationally.

## **2 MEASUREMENTS**

### *2.1 Lay-out of test blasts*

The layout of the field tests is shown in Figure 1 and Table 1. Eleven different blasts were fired, using 279 tons of Emulan 7500, a gassed heavy ANFO type emulsion, to break 316200 m<sup>3</sup> of rock.

A typical drilling and charging plan is shown in Figure 2. Note that none of the holes are stemmed. The presplits (331-8 and 331-9) were made with about 90 kg of 10 m long decoupled Emulan charges in Ø 100 mm plastic pipes, initiated partly in a 1 ms sequence by EDD detonators and partly "simultaneously" by Nonel Unidet U 500 detonators.

The initiation system used in the other rounds was Nonel Unidet with U 500 detonators in 0,5 kg bottom primers together with UB 176 surface delay elements between rows and UB 17 elements in the rows. See Figure 3.

**Table 1:** Lay out of test blasts.

Round no	No of holes	Wall-back Ø mm	Confinement/ direction of throw
330-1	11	311-311	free / along wall
330-2	18	311-140	free / along wall
330-3	22	311-311	free / along wall
331-5+6	66	311-140	conf. / along wall
331-8+9	27	140-...	conf. / across wall
330-4	100	140-...	free / across wall
331-7	both		
331-10	199	140-311	conf. / along wall
331-11	both	140-311	conf. / across wall

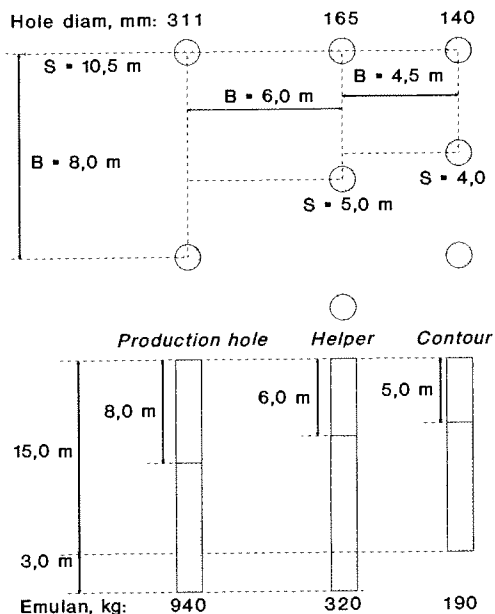


Figure 2: Ordinary drilling and charging pattern.

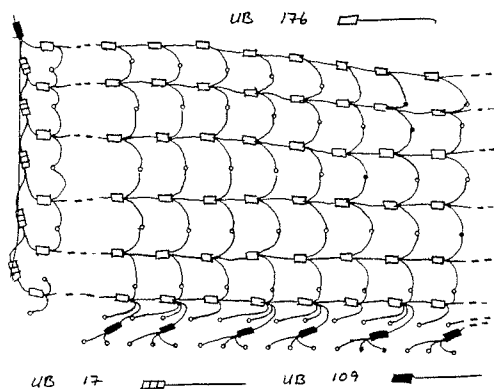


Figure 3: Nonel Unidet initiation on foot wall.

The test site lay in the north and middle parts of the foot wall between the 120-135 m levels. The rock was mainly a biotite gneiss with zones of feldspar and epidote parallel to the foot wall. These zones coincide with the structurally dominating feature, a steeply dipping, about 70°, foliation system which strikes about 10°E from the wall. This anisotropy was considered in the test layout.

The test layout may be described as a number of contour sections, final or temporary, where different contour blasting techniques were tried. In 13 out of 16 test sections an instrumentation profile had been prepared, see Figure 4, where extensometer, PPV and pressure measurements were made.

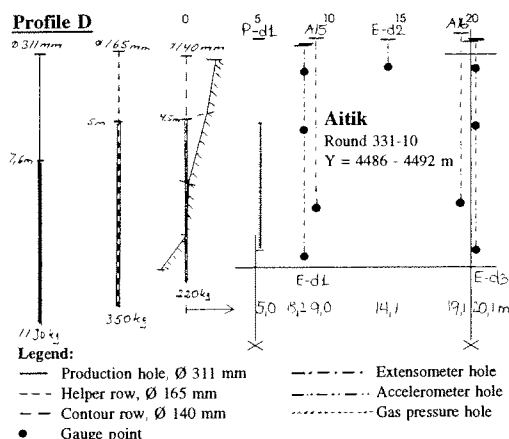


Figure 4: Instrumentation profile D, round 331-10.

## 2.2 VOD measurements

The VOD measurements were made with the VODR-1 instrument from EG&G (Chiappetta 1993). It uses a coaxial cable which runs through the charge. It records the movement of a short circuit caused by the detonation front by sending down a pulse roughly every 10 µs and measuring the travel time for the returning echo. If the initiation sequence is known, the cable can be threaded through several holes and the actual initiation delays measured. There are 2 channels which can record up to 10 holes each.

Figure 5 shows a recording of the position of the detonation front with time. The pigtail part AB is instantaneously shorted by the primer, the slope of part BC gives the VOD in the charge and CD shows the movement of a pressure wave or the blast fumes through the empty unstemmed part of the bore hole.

Figure 6 shows how the instrument was used to measure the relative initiation times of holes in 3 trunk lines and the contour row.

## 2.3 PPV measurements

The relevant part of the ground vibration event is the peak particle velocity at the front of the shock wave which emanates from a detonating charge. This value, the PPV, is often used as an engineering measure of the loading to which the material is subjected and consequently as a means to evaluate the blast damage (Holmberg and Persson 1979).

Close to a blast hole, it is our experience that the frequencies are well above 1 kHz so we prefer to use accelerometers. At Aitik the ground vibrations were measured at the bottom of 12 m deep Ø 165 mm

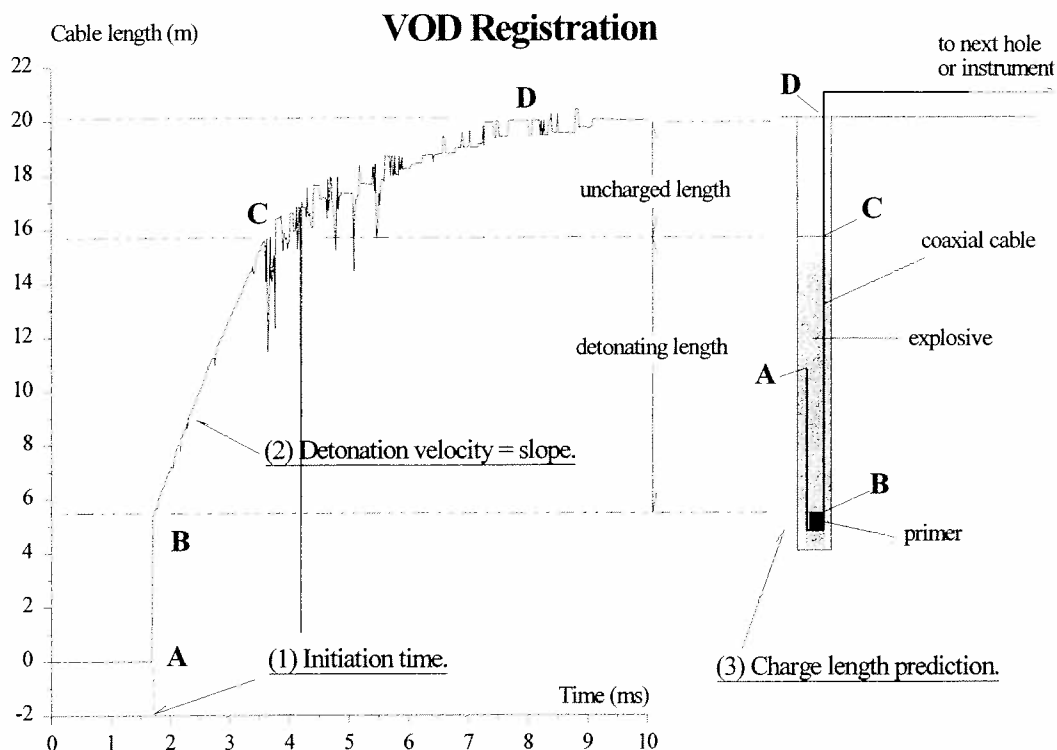


Figure 5: VOD registration, i.e. movement of shorting point for hole 1 in round 330-1.

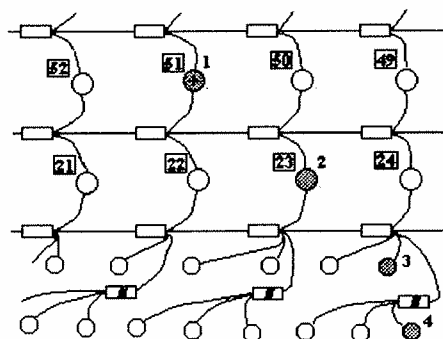


Figure 6: VOD holes in profile D, round 331-10.

holes, approximately at the same level as the center of gravity of the production charges, see Figure 4.

The gauges were mounted on a base plate with a threaded stud, see Figure 7, which was attached to the end of a string of  $\varnothing 63$  mm PVC pipes. Thus we could insert the gauges into the hole before measurements and remove them afterwards while protecting them from moisture. The base plate stud fits into a conical foot which had been securely grouted in place with expanding, quick curing and freeze

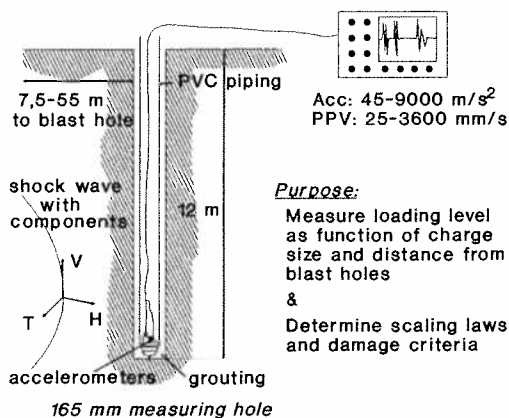


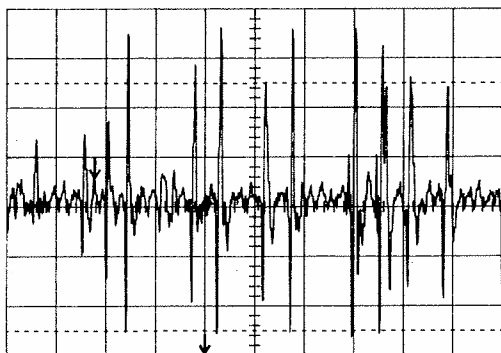
Figure 7: Gauge hole for PPV measurements.

resistant cement. The mount in turn was protected by a PVC pipe sleeve which made it possible to screw the base plate to the mount from the surface.

The measuring system consisted of accelerometers, charge amplifiers and recording units for a maximum of 16 channels. The accelerometers were of type Brüel&Kjaer 2635 or 2626 with a 12,5 kHz

bandwidth. The recording units were one 14 channel FM tape recorder TEAC XR-510 with 20 kHz bandwidth and one 6 channel digital recording unit with a 6 kHz bandwidth and a 10 s storage window. Whenever possible channels were doubled and in each instrumentation profile there were at least two sets of 2 or 3D accelerometers, see Figure 4.

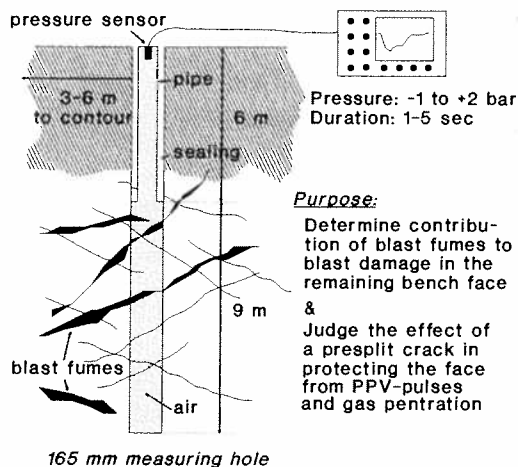
A trace is given in Figure 8. It shows that it may be quite difficult to match each pulse in the round with the correct source. We used both ionization probes and the VOD records to do the matching.



**Figure 8:** Vertical acceleration, hole A-20 in profile G, round 331-10. 100 ms/square.

#### 2.4 Air pressure in bore holes measurements

All air pressure measurement holes except one were vertical, 15 m deep and had  $\varnothing$  165 mm. The damaged upper part was sealed off by a  $\varnothing$  110 mm, 6 m long capped plastic pipe, Figure 9.



**Figure 9:** Sealed holes for gas/air pressure meas.

The gauge was mounted in the cap under extra protection. In the gauge output, a DC level represented atmospheric pressure, so there was no mistaking a nonresponding live gauge for a dead one.

The pressure gauges were of foil strain gauge type, Haenni model ED 517/314.211/075. They had a range of 0-10 bars because we expected mainly overpressures from the pressurized blast fumes that would penetrate the cracks in the slope. The holes were positioned 3-25 m behind the contour. Pressure measurements were made in 9 of the instrumentation profiles, using 1-3 holes. Signals were obtained from 17 out of 18 holes and from all profiles.

### 3 RESULTS AND INTERPRETATIONS

#### 3.1 VOD results

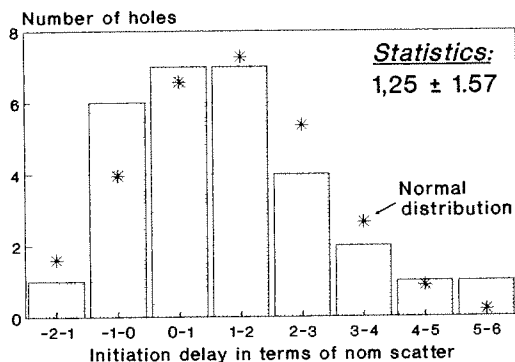
The VODR-1 worked well even in the wet subfreezing conditions. Data are given in Table 2. From 46 instrumented holes, 44 initiation times were obtained and from these 35 good VOD versus time histories were obtained. Four of the missing ones came to the pre-split rounds 331-8+9 where the delay was 1 ms.

The VOD values were as expected, being highest near the primer and decaying towards the top of the holes, as the density of the explosive decreased. The VOD values of the production holes were about 10%

**Table 2:** Summary of VOD-values.

Round no	$\varnothing$ mm + no holes	VOD bottom m/s	VOD top m/s
330-1	311-3	5750-6180	4650-5380
330-2	311-1	6550	5880
	165-2	5530-5800	4250-5090
	140-2	5440-5600	4210-4570
330-3	311-4	6060-6110	4700-5590
331-5+6	311-6	5940-6740	4160-5650
	165-1	5620	3950
	140-1	6320	3580
330-4+	165-1	5810	5170
331-7	140-2	5870-5890	4930-4980
331-8+9	140-2	4930-5130	4200-5160
331-10+11	311-7	5680-6710	4770-5420
	165-3	5420-5690	3600-5560
	140-1	5690	5030
Total	311	6200 $\pm$ 300	5200 $\pm$ 400
	140-165	5600 $\pm$ 300	4600 $\pm$ 600

higher than for the smaller holes. The differences between the VOD values of the Ø 140 and Ø 165 mm holes were however too small to be significant compared to the scatter, which was about 5-10%. This shows that the explosive held a consistent quality during our tests. The VOD recordings could also be used to judge the charge length with acceptable accuracy, but not the uncharged length.

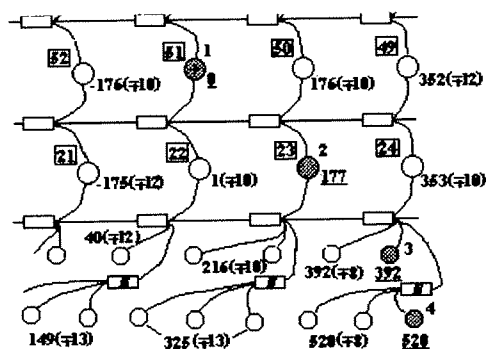


**Figure 10:** Relative delay in initiation of VOD measurement holes in rounds 330 and 331.

Figure 10 shows the relative delay of the initiation time of the holes along a VOD cable with respect to the previous hole, divided by the nominal scatter of the relevant delay elements and caps. The values should simplistically be normally distributed with a standard deviation of 1 around the average 0.

The actual average 1,25 can be explained by the additional 12,5 ms delay of the initiation impulse as it propagates down about 25 m of shock tubing at 2000 m/s. The actual standard deviation 1,57 is probably an RMS build up of individual scatters.

Figure 11 shows the VOD holes outside instru-



**Figure 11:** Measured and predicted initiation times in round 331-10, relative to hole no 51.

mentation profile D. The underlined numbers 177, 392 and 520 show how late after hole no 51 the real initiation occurred. The number 1(±10) for hole no 22 is a back calculation from hole no 23, considering the initiation time scatter of delay element and cap.

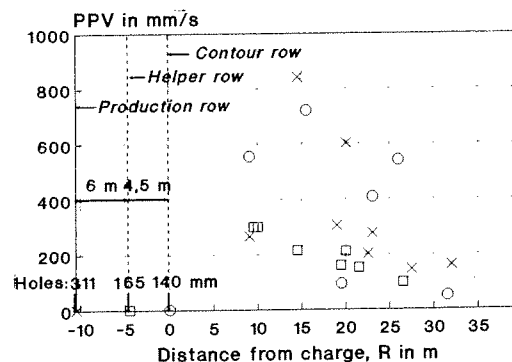
According to Figure 6, hole no 22 should have been initiated 17 ms after no 51 but in reality they were initiated nearly simultaneously. The same then was true for hole pairs 52-21 etc. This shows the difficulty to identify the true sources of the shock wave pulses in a recording like Figure 8, using only the initiation pattern. Despite the example above, there were no specific complaints on the initiation sequences of the test rounds by production people.

### 3.2 PPV results

PPV was measured in 11 of the 16 instrumentation profiles using 2 gage holes each. Three dimensional gauges were used in all rounds except the last one where the vertical and horizontal components along the profile were measured. Signals were obtained from 17 of the 22 gauge holes and from all profiles. The scatter in the amplitudes and the absence of a dominating component made vector evaluation unnecessary so all results refer to velocity components.

These components were plotted in synthetic PPV profiles like the one for instrumentation profile D in Figure 12. Here all identifiable Ø 140 mm sources have been moved to the contour position, all identifiable Ø 160 mm sources to the helper row position 4,5 m out and all Ø 311 mm sources to the first production row another 6 m out.

The quality of the results was sufficient to determine site scaling laws. The swelling in the bench could however not be obtained from the vertical

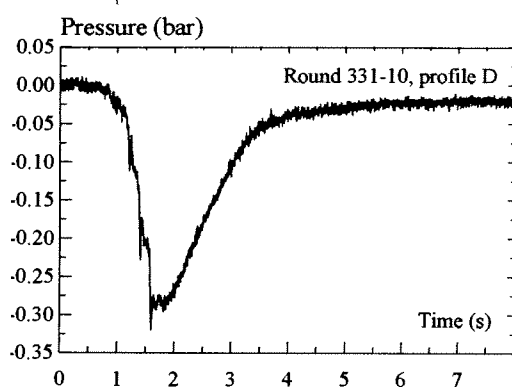


**Figure 12:** Synthetic PPV profile for instrumentation profile D, nominal burdens 4,5 and 6 m.

acceleration through a double integration with sufficient accuracy.

### 3.3 Air pressure results

The air pressure measurements are summarized in Table 3. A clean pressure signal from an ordinary round is shown in Figure 13. Here the pressure usually starts to drop before the closest contour charges detonate. We had expected overpressures to occur but in 10 out of 13 holes there are only underpressures like in the figure. In one case a cable was cut and from the two farthest holes, 22 and 25 m we measured insignificant pressure variations.



**Figure 13:** Air pressure in gauge hole P-d1, 5 m behind contour in round 331-10.

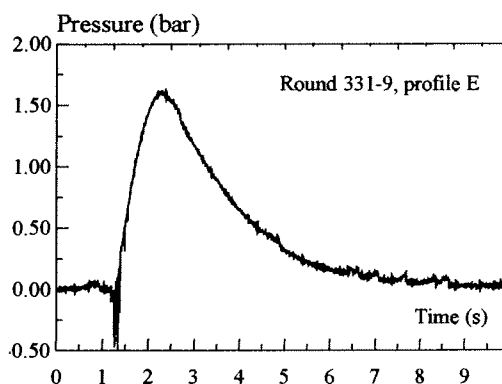
This underpressure is probably caused by the vertical movement in the rock which the shock fronts from the charges initiate and which is amplified by the reflections from the top surface of the bench. This swelling opens up fractures connected to the measuring hole, increasing its effective volume. The pressure drops when the air in the hole is sucked into the fractures. The hole and the fractures behave roughly like an "accordion" together.

The pressure equilibrium is restored as air and maybe blasting fumes flow into the hole. We can not exclude the possibility of the blast fumes from entering the hole, but if so, their pressure effects are negligible. The duration of these pulses are 1-5 s and the maximum underpressure measured was about 0.6 bars 3-4 m behind a charge. This would require a doubling of the original hole volume.

During the presplits two gauge holes at roughly 3 and 6 m behind the charge line were used in each of the profiles C and E. Three of them returned measurable levels, the remaining one a negligible level. All

**Table 3:** Air/gas pressure measurement data; distances, pressures, durations and arrival times.

Round/ profile no	Dist. to hole m	Press. atm	Durat. s	Arriv. ms
330-3/I	11.7	-0.28	3.7	-12
330-3/I	21.8	$\pm 0$	-	-
330-3/I	24.6	$\pm 0$	-	-
330-4/I	2.9	-0.62	1.3	-
330-4/I	5.7	-0.39	2.6	-
330-7/B	4.6	-0.62	1.1	147
330-7/B	2.6	-0.21	>0.5	87
330-7/B	6.3	-0.22	5.3	70
331-8/C	3.0	+1.77	1.3	-3
331-8/C	5.6	$\pm 0$	-	-
331-9/E	2.8	+1.60	4.5	-7
331-9/E	6.4	+0.19	12.2	-9
331-10/D	5.0	-0.31	2.5	2420
331-10/E	5.1	$\pm 0.08$	-	-
331-10/E	7.7	-	-	-
331-10/G	6.1	-0.27	1.3	288
331-10/G	12.3	-0.37	1.2	17
331-11/F	3.5	-0.47	1.8	344



**Figure 14:** Pressure in gauge hole P-e2, 2,8 m behind presplit in presplit round 331-9.

three show the same behavior, see Figure 14. After a short negative pulse (< 0.2 bar except for noise spikes) the pressure rises fast to a substantial overpressure, between 1.6-1.8 bar 3 m behind the split.

What sets the presplit apart from ordinary rounds is the confinement of the surrounding rock and that

the 1 ms delay in charge initiation allows the charges in adjacent holes to cooperate. This appears to be enough to force blast fumes into the remaining rock.

The effect of the presplit was to be judged by 2 holes in profile E but the only signal came from 1 m behind the uncharged presplit or about 5 m behind the charged Ø 165 mm holes.

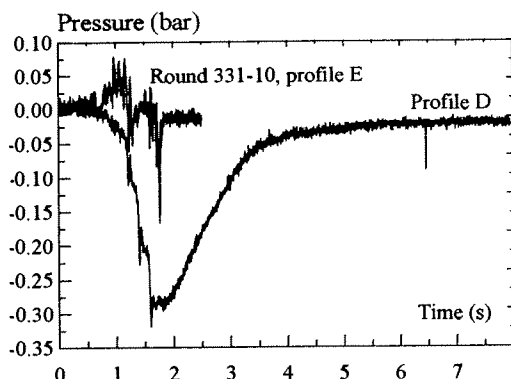


Figure 15: Pressure in gauge hole with (E1) or without a presplit crack covering the charges.

Figure 15 shows that the presplit effectively cuts off the pressure, compared with hole D1 which is situated just as far behind a charged contour row.

The PPV measurements indicated the same effect on the incident shock wave. However, the damage may already be there since pressurized blast fumes have penetrated the rock mass during the presplit.

The vertical swelling,  $h$ , in the bench after blasting can go about 20-25 m in from the blast holes. If we assume that it is due mainly to an irreversible dilation of the fractures during the round we can relate it to the measured underpressures. Since the upper 6 m of the pressure holes were sealed off, it follows that the extensometer readings from the 6 m level are a measure of the fracture widths accumulated below it. The active hole length  $H \approx 9-10$  m.

For simplicity assume that these fractures can be estimated by a number of circular fractures of radius  $R$  and that the air in the hole follows a polytropic gas law. Then it follows that

$$p_{\min} \approx 1/[1+4(R/\emptyset)^2 \cdot (h/H)]^{1.4} - 1. \quad (1)$$

Like the PPV-data, the swelling data scatters much but the envelopes for the two main hole sizes, Ø 140 and 311 mm, give upper limits. The right magnitude for  $2R$  would be somewhat larger than the average distance between fracture planes, 0.9-1.7 m. With  $2R = 1.8$  m we get the results in Table 4 and Figure 16.

Table 4: Estimated underpressures in gauge holes.

Swelling mm	Pressure atm	Distance to Ø 140 m	Distance to Ø 311 m
70	-0.57	3.0	4.5
50	-0.48	5.0	7.1
30	-0.35	8.2	11.5
20	-0.26	11.0	15.1
15	-0.21	13.0	17.2
10	-0.15	15.2	20.1
5	-0.08	18.2	25.0

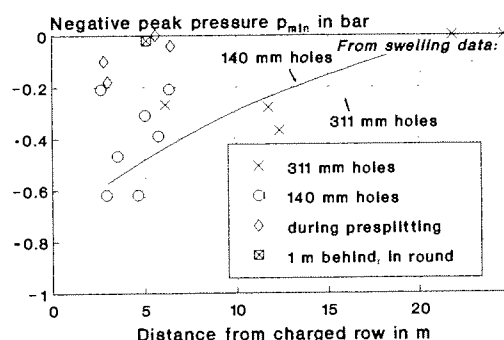


Figure 16: Measured underpressures and estimates based on equation 1 and data in Table 4.

Since swelling envelopes were used, the curves should envelope the measured values. This they do reasonably well so the agreement is acceptable and this supports the hypothesis that the measured underpressures in the holes are due mainly to the opening of fracture planes in the rock mass.

Our observations are largely in agreement with those of LeJuge et al. (1994) from the Rössing mine. They attribute the underpressure to the same mechanism as we and they didn't detect any gas flow across the presplit crack either.

Behind a stemmed presplit blast they measured a signal much like Figure 13 at 2 m, but with a shorter duration. At 4 m the overpressure has decayed substantially and at 6 m the initial negative pulse dominates completely. The difference might be caused by their more lightly charged presplit, about 18 kg per hole vs our 90 kg, and a more fractured rock which both exaggerates the fracture dilation effect and shortens the pressure restoration time.

The pressure record they show from a Ø 381 mm, 15 m deep stemmed production hole is different



from Figure 13 though. At 5 m they recorded a substantial overpressure, something which we never found behind our unstemmed Aitik holes.

We can probably attribute this to the pressure retaining effect of the stemming at Rössing. It then follows that an unstemmed blast hole is important in venting the blast fumes and avoiding gas penetration into the rock mass. For the Aitik mine at least we were able to conclude that the blast fumes from an ordinary unstemmed blast in all probability don't give a significant contribution to the blast damage.

However, it doesn't necessarily follow that;

- the blast damage would be measurably smaller if there were no stemming, or that
- the stemming effect which contains the blast fumes would significantly add to the damage.

Firstly, the swelling goes considerably deeper than the gas penetration and all fracture dilation should be considered as damage once it has reached a certain level, no matter what caused it. Secondly, we have no comparative experiments where the stemming is the only test variable.

### 3.4 The site scaling laws

The synthetic PPV profiles, like in Figure 12, give a good idea of how the measured PPV-values depend on distance R, charge size Q and charge length H. They show how far into the wall waves of a certain amplitude can penetrate. The present Aitik data could be divided into two groups, mainly the foot wall profiles and those parallel to the wall.

A site scaling law was fitted to the complete set of foot wall data,

$$PPV = 160 \cdot (\sqrt{Q/R})^{1.42} \text{ in mm/s.} \quad (2)$$

The prefactor for our profiles varied between 130 and 220. The uncertainty in A could also be expressed through the standard deviation factor 2.03. The equation and some of the data are shown in Figure 17 together with an upper limit line. Previously measured PPV data follow this trend well too.

The different data for instrumentation profiles oriented along and across the foot wall made us estimate the wave propagation velocity parallel and perpendicular to the foot wall. We combined the VOD initiation time and the PPV arrival time data with the distance between source and receiving gauge to obtain a P-wave speed of 4850 m/s independent of direction.

Scaling laws of the form (2) predict the average PPV value as a function of charge size and distance. In estimating the depth of a blast damage zone we

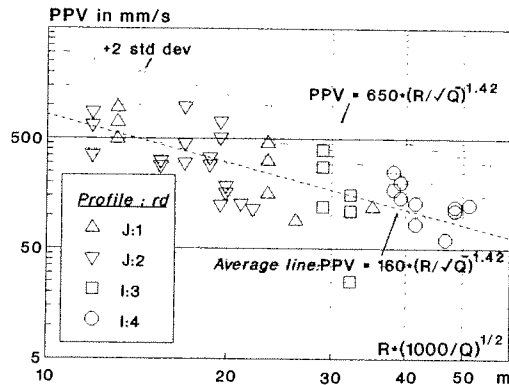


Figure 17: PPV data from profiles I and J.

are perhaps more interested in obtaining engineering estimates of their maximum penetration. Ouchterlony et al. (1993) handled this by using a double deviation factor for A. If the errors are random and normally distributed, 98% of the measured values should fall below this limit.

Close in, only part of the charge is expected to contribute to the PPV value (Holmberg and Persson 1979). Adding this charge length correction to equation 2 we obtained the following limiting curve for the PPV values in the foot wall

$$PPV = 650 \cdot [\sqrt{(fQ)/R}]^{1.42} \text{ in mm/s with} \quad (3a)$$

$$f = [\tan(H/2R)/(H/2R)]. \quad (3b)$$

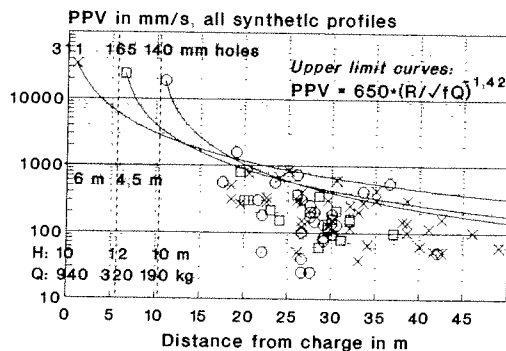


Figure 18: Synthetic PPV profile for foot wall.

In Figure 18 all the foot wall data are shown together with the limiting curves for the different holes. Close to the final wall, the contour holes dominate the loading but already 8-9 m in the production holes start to dominate. The Ø 165 mm holes seem to be relatively harmless though.

## CONCLUSIONS

Based on these monitoring results the following conclusions could be drawn:

- VOD is an excellent means of checking the performance of explosives and initiation system in a blast. At Aitik both of these worked well.
- At Aitik the VOD records were instrumental in pin pointing 10-20 individual PPV pulse sources in each round.
- The charges in ordinary rounds, in which the blast holes are unstemmed, didn't force any significant amounts of high pressure blast fumes into the walls since only subatmospheric pressures were measured.
- A shock wave initiated dynamic swelling movement opens up fracture planes. Those fractures that are connected with the gauge hole increase its volume and reduce its pressure. The measured under-pressures correlate relatively well with the measured residual swell values.
- The shot presplit line didn't transmit direct shock waves or blast fumes into the slope. The presplit holes themselves did however, despite being unstemmed, force pressurized blast fumes into the rock.

Despite their relatively confined conditions, the blast fumes from normal blast holes could thus be eliminated as a direct source of blast damage. This doesn't rule them out as a considerable source of damage if the holes are stemmed so that the blast fumes are prevented from venting axially.

The blast damage assessment could thus focus on the PPV levels. Measurement of back break and swelling made it possible to quantify the blast damage and, through the scaling law, to relate it to the blasting patterns. This has been the basis for suggested designs of cautious blasting that the mine has been trying out. The results of this part of the project will be reported later.

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