

## Some recent research and developments in Swedish tunnel blasting

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### Abstract

This paper describes some recent research activities carried out by the Swedish Detonic Research Foundation, SveDeFo and its sponsoring industries<sup>1</sup>, with the overall goal of improving tunnel blasting. The two vital parts of the tunnel round have received the major attention, the opening cut and the contour.

In the cut part, the breakage mechanism, the matter of detonation failure versus simultaneous detonation and the effect of the time delay have been studied. In the contour blasting, methods that will decrease the damage and overbreak have been investigated. These include notching of the contour holes and precise delay intervals.

A recent large tunneling R&D effort is also described, where 1255 m of tunnels were blasted using new techniques. This has resulted in :

- A new well functioning parallel hole cut for  $\phi 64$  mm blast-holes in long rounds.
- Long rounds, using a drilled depth of 7.8 m, that now produce average advances of 7.0 m, and more if the rock conditions and the drilling precision are good.
- Drilling and contour blasting techniques that decrease the overbreak by 50% and increase the visible number of half-casts by nearly as much.

Finally, the future development of Swedish tunnel blasting is briefly treated.

### Introduction

Modern Swedish rock blasting has well known roots in the works and inventions of Alfred Nobel of the blasting cap, of the dynamite etc. in the 1860 : ies. The monograph by Langefors and Kihlström<sup>2</sup> gives a widely read summary of the development of Swedish rock blasting up to the beginning of the 1960 : ies. It was during this period, in 1953, that the Swedish Detonic Research Foundation (SveDeFo) was founded as a cooperative effort between industry and government agencies.

Since then the development in tunnel blasting has accelerated. The introduction of hydraulic rock drills on drilling jumbos, new carbide qualities, drill bits with button shaped inserts, improved drill rod connectors etc. have revolutionized the drilling. Nonel, a safer and easier to handle nonelectric initiation system, is the leader in many markets. Dynamite explosives have largely been replaced by ANFO and water based emulsions.

A short description of present Swedish tunnel blasting would perhaps be as follows :

1. The drilling of 4 5 m deep rounds with  $\phi 48$  mm diameter blast-holes of larger, using parallel hole cuts with one or two large empty holes.
2. Charging all holes except the contour ones with ANFO whenever possible.
3. Smooth blasting of the contour holes.
4. Initiating the round with the Nonel GT/T series of caps which have a 100 ms delay between the first numbers.
5. Achieving relative advances of 90-95% on a regular basis. Usually values of less than 90% are a cause for redesign of the round.

The monograph by Olofsson<sup>3</sup> gives an up to date description of Swedish rock blasting techniques. It will soon become available in Japanese.

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This paper based on some of the research made by SveDeFo and our sponsoring industries in the last 5-7 years, related to tunnel blasting. Much of this work has been published only in Swedish, see Ouchterlony<sup>1)</sup> for a comprehensive description. The overall aim of SveDeFo's work has been to develop knowledge and techniques so that rock blasting will have an increased competitiveness within mining and construction. High speed filming to visualize cut breakage mechanisms

Since blasting processes seldom develop exactly according to plan, such filming is a valuable method for showing what is actually happening. SveDeFo has used it to study the blasting of parallel hole cuts in Swedish granite quarries<sup>1)</sup>. The cuts had 4,  $\phi 38$  mm blastholes in quadrangle surrounding a  $\phi 89$  mm empty hole with the burden 160 mm. In all 14, 3-4 m deep cuts in the quarry bench walls were blasted either hole by hole or in one sequence. The delay sequence was checked by accelerometer measurements. A filming layout is shown in Figure 1. The two 16 mm high speed cameras covered an area of roughly 1.0 by 1.5 m in front of the cut.

Packaged decoupled dynamite type explosives were used. The standard configuration became a 3 m cut with  $\phi 29$  mm Nabit column charges and a small 175 g primer. The charges were locked in place by wedges. The uncharged hole length was 0.1-0.4 m. The delay time between the holes was varied in the

range 50-125 ms. The results may be shortly summarized as follows :

1. The detonation conditions vary greatly as shown by a muzzle flame character ranging from bright light, plumes of fire or single flames to just black or grey smoke. There was no correlation with the resulting rock breakage however.
2. Many pressurization effects were observed. Gasses entered cracks up to 4 m away. The charge locks could not always contain the charges in the holes. When breakage was unsatisfactory, the ejection of charges from neighboring holes started within 40 ms of initiation and they were thrown 20-40 m. In one case, see Figure 2, a charge from a detonating hole was ejected and detonated part-way into the air!
3. The ejecta consisted mostly of sub 30 mm fines and some large pieces from the collaring region. The measured ejection velocity at the muzzle was roughly less than 120 m/s for 400-500 ms and the flow of ejecta stopped after about 800-1100 ms.
4. An interhole delay of at least 75 ms was required to obtain acceptable advances in the 3m cuts but this was not sufficient in the two 4m cuts.

It is concluded<sup>4)</sup> that parallel hole cuts using cartridge explosives run a large risk of malfunction due to detonation cut offs, caused either by charge separation or dead-pressing effects. Even if the advance is good the initiation sequence may not be working pro-

### Cut Blasting Test Layout in Quarry Positions of cuts and cameras on bench

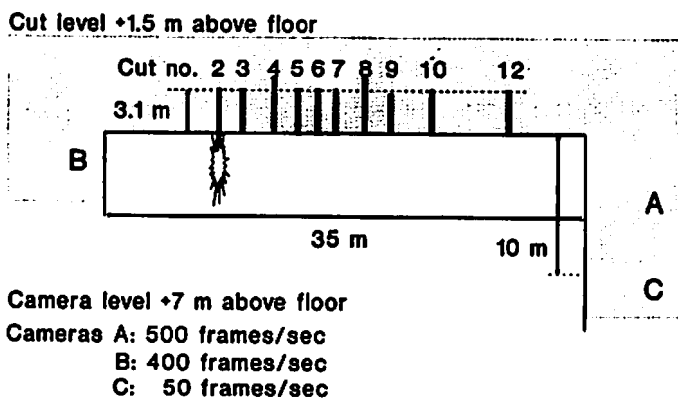


Fig. 1 The layout of the cut blasting and the high speed filming at Kråkemåla quarry.

## Partly Ejected Charge which Detonates

Sketches after high speed filming frames



Two consecutive frames from cut K7 in the Kråkemåla quarry  
 Fig. 2 Charge detonating part-way in the air. Sketch after high speed filming frames.

perly due to simultaneous detonations of closely spaced blast-holes. When new cut blasting tests were made with ANFO in cuts with  $\phi 48$  mm blast-holes recently, a simulated Nonel GT/T initiation with 100 ms delays gave good advances in 4 m cuts. Delays simulating simultaneous detonations resulted in bad breakage however.

### Detonation failure versus simultaneous detonation of blast-holes

The detonation properties of pre-compressed ANFO (Prillit A) have been investigated<sup>5)</sup> in order to assess the risks of detonation failure. Bore hole conditions were simulated using  $\phi 45$ , 60 and 75 mm steel cylinders with precompressed ANFO inserted in between or after sections of ANFO with the normal degree of packing,  $0.95 \text{ g/cm}^3$ . See Figure 3. The critical density for dead-pressing,  $\rho_{crit}$ , and the detonation transmission (flash-over) ability versus density were found by measuring the detonation velocity

(VOD) along the explosive.

For Prillit A,  $\rho_{crit}$  depends on the initiation pressure, the charge diameter and the confinement. These tests gave the result  $\rho_{crit} \approx 1.35, 1.39$  and  $1.43 \text{ g/cm}^3$  respectively for the 0.4-0.5 m test sections with diameters  $\phi 45, 60$  and  $75$  mm. Flash-over occurred for a reaction velocity as low as 600 m/s at the end of the precompressed section, see Figure 4. For lower values the detonation dies out.

The length of ANFO which no longer can transmit a detonation between two charges of normal density,  $L$ , is shown in Figure 5. A general expression which fits the data is

$$L = L_{min} \cdot \sqrt{[(\rho_{max} - \rho_c) / (\rho - \rho_c)]}$$

Here  $\rho_{max} = 1.73 \text{ g/cm}^3$ , the crystalline density of AN, and  $\rho_c = 1.2 \text{ g/cm}^3$ , an estimated highest density that can support a detonation.  $L_{min}$  is a minimum length required to obtain detonation failure. The

## Detonation Flash-over Test in Compressed ANFO

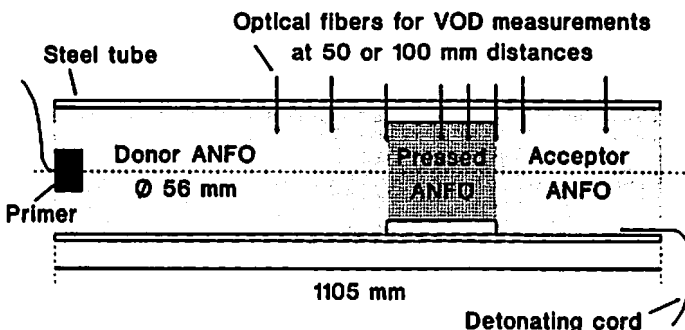


Fig. 3 Set up for detonation flash-over test in compressed ANFO.

## Detonation Velocity in Flash-over Tests on ANFO

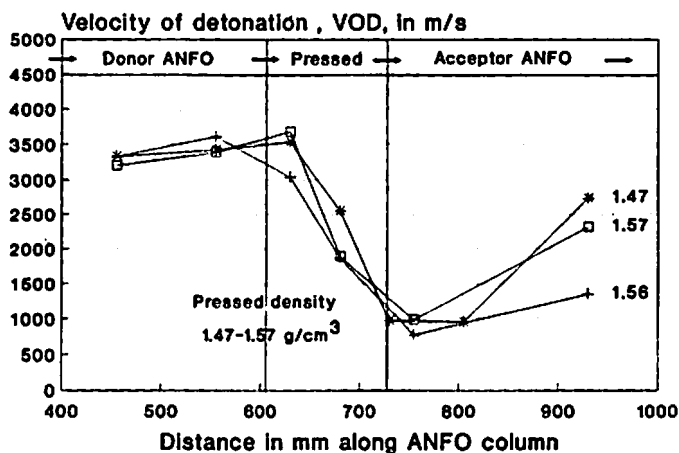


Fig. 4 VOD versus distance in flash-over test.

## Detonation Flash-over in Compressed ANFO

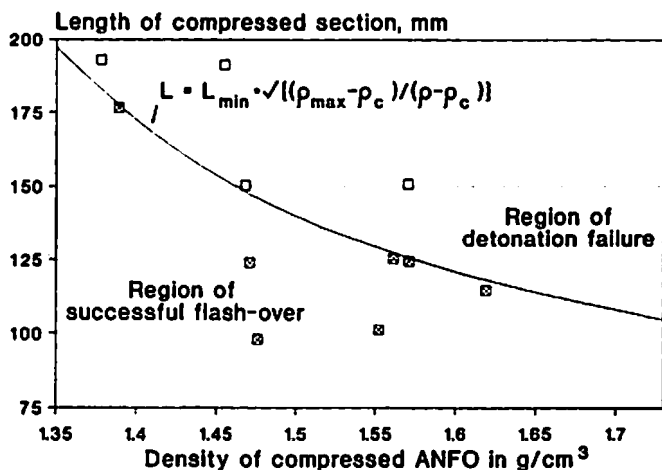


Fig. 5 Detonation flashover data for compressed ANFO in  $\phi 45$  mm.

static compression properties of Prillit A were also determined and computer simulations of dead pressing in blast-holes made. Further some shot-receiver hole tests with Prillit A were made in shale. The results may be summarized as follows :

1. A pressure of 70-100 MPa is sufficient to dead-press prilled ANFO in less than 1-2 ms in common blast-hole diameters. Hence it is hard to avoid such effects in the cut.
2. In bore hole diameters of 45 to 75mm, the flash-over capacity is
  - always larger than 100-140mm in dry ANFO

- larger than 400-500mm in dry ANFO with densities in the range 1.35-1.45 g/cm<sup>3</sup>,
- larger than 500mm in wet sections or in air sections between dry ANFO sections.

3. In neighboring  $\phi 48$ mm blast-holes in shale, the risk of dead-pressing is substantial at a 0.2m distance but nearly nonexistent 0.5m away. The risk of flash-over seems to dominate from about 0.25m and outwards.

Similar work is being conducted with emulsion explosives. Where the granular nature of ANFO tends to give a stemming effect under pressure, an emulsion

works like a liquid plug that transmits the pressure and is ejected. For the emulsions we have further been more worried about dynamic deadpressing effects. For this work we have had to develop our own pressure gauges<sup>6)</sup>, see Figure 6. Such a gauge consists of a  $\phi 3$ mm, 1mm thick piezo ceramic disc at the end of a coaxial cable and surrounded by silicon oil inside a rubber casing. The cable runs inside a  $\phi 6$ mm steel tube, in order to protect it from various pressure effects and to make it possible to insert the gauge into a hole full of explosives. These gauges are quite linear up to 100 MPa and we have used about 100 of them to date.

Field tests with a shot-hole and charged receiver holes have been made with the cap sensitive emulsion explosive Kimulux R<sup>7)</sup>. Four cuts with  $\phi 64$ mm holes

were drilled 2-4m deep in a competent relatively unfractured rock, see Figure 7. In these, 9 shot-holes instrumented with VOD gauges were fired at the various stages of a normal cut excavation sequence, each hole surrounded by 3 receiver holes instrumented with pressure gauges. The interhole distance was between 0.22 and 1.0m.

The holes were inspected for crack communications before blasting by pressurization with water. When such communication existed, the pressure gauge was placed close to the crack. The initiation of the shot-holes was by Nonel GT/T caps no.0 (25 ms) inserted into a 25g TNT primer and the times were measured with a velocity gauge in a drift near by. The receiver holes around shot no.1 were also primed to facilitate the post test excavation. The other receiver

### Pressure Gauge for In-hole Measurements

Based on  $\phi 3$  mm · 1 mm piezoelectric ceramic disc

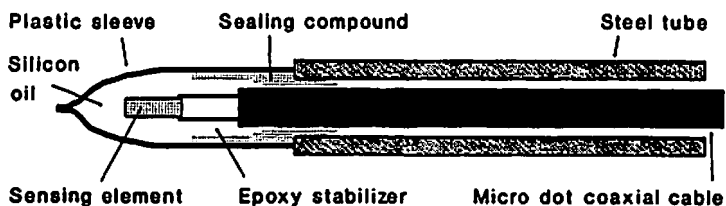


Fig. 6 Pressure gauge for insertion in charged blast-hole.

### Shot-receiver Hole Tests w. Emulsion Explosive

Bold underline shows drift 474 and test no.2

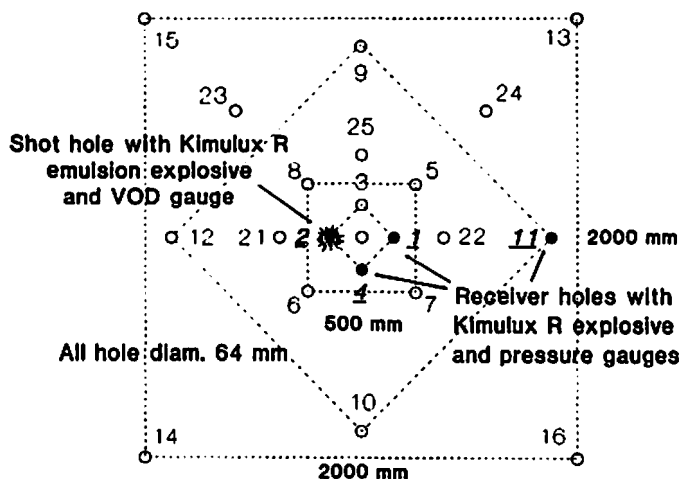


Fig. 7 Layout of shot hole-receiver hole tests in quartz porphyry.

holes were not primed. The main results are summarized as follows :

1. The water injection showed preexisting crack communications in 4 cases of 27, but only for holes within 0.31m of each other.
2. The pressure gauges were ejected from 7 receiver holes, up to 1m away from the shot-hole. Only in one of these cases had a crack communication been detected.
3. For receiver holes within 0.31m of the shot-holes, pressures of 25-50 MPa were measured. According to earlier tests this is sufficient to cause dead-pressing but neither crushed micro spheres nor recrystallization of the emulsion could be detected.
4. Of 5 receiver holes at 0.22m, 3 detonated and from the other 2 the gauges were ejected. Thus for this emulsion explosive, the risk of simultaneous detonations is greater than the risk of detonation failure at spacings smaller than 0.25m.
5. Even when no cracks between the holes exist before the blast, the blasting creates them and penetrating gases may prematurely cut off and eject parts of the charges in the receiver holes.

Contour blasting with detonators with electronic delay circuits

The contour comes next to the cut in importance in tunnel blasting. Minimal damage and overbreak will decrease the scaling and support work, it will decrease

the risk for rock falls and personnel injuries. All of this increases the productive time available at a face. In a recent field test<sup>9)</sup>, detonators with electronic delay circuits (IC caps) were used to try to achieve this and smoother contour than standard contour blasting procedures.

The test site was a road cut provided by the National Swedish Road Authority. The main test comprised six 16-18m long rows with a height of 4-5m. See Figure 8. Each row consisted of 21,  $\phi 42$ mm blast-holes charged according to traditional smooth blasting procedures. The charges were Gurit  $\phi 17$ mm cartridges with 200-250 g of Dynamex M as a bottom primer. The total charged length was 3.4-3.7m.

The test was divided into 12 sets or half-rows with 10-11 holes each. Of these 3 reference sets were blasted using conventional Nonel GT/T detonators no.55 which are the ones normally used in tunnel contours. Their initiation time is  $5500 \pm 150$  ms. This means that each contour hole detonates virtually by itself without any assistance from the others. In the other 9 sets, IC caps were used. They have a scatter well below 1 ms.

Two initiation principles were tried with the IC caps. The first one was simultaneous initiation of all holes in a half-row. In this way there will be stress wave superposition and the row can move out more or less in one piece. The second principle could be called (sequential) zipper blasting. In it a small but precise delay between holes is used so that

### Contour Blasting with Electronic Delay Detonators

Smooth wall test blasts in road cut at Svalbo  
 Hole diam. 42 mm, charge diam. 17 mm  
 Burden 0.9 m, spacing 0.8 m

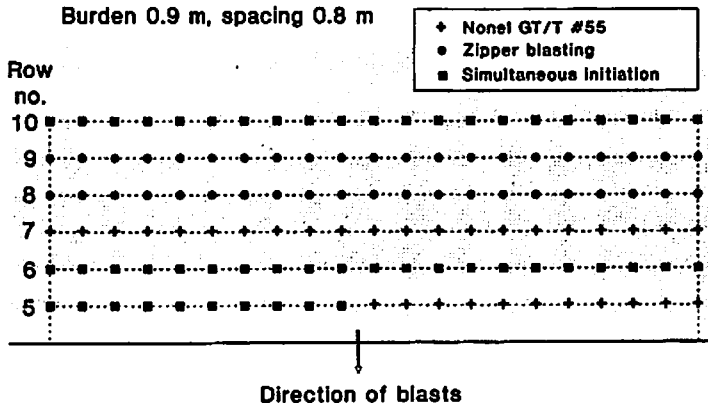


Fig. 8 Layout of contour blasting tests with electronic detonators at Svalbo.

## Half-casts on Bench Face after Blasting (row #7)

Blast hole diam. 42 mm and spacing 0.8 m

Gurit 17 mm diam. charges, Nonel GT/T #55 detonators

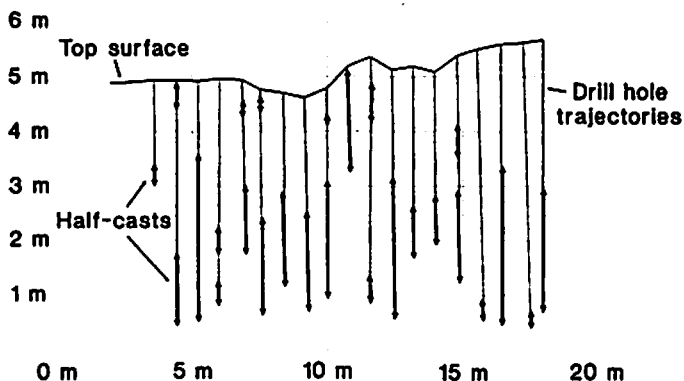


Fig. 9 Visible half casts on Svalbo bench face after blasting of row no.7.

## Roughness of Bench Face after Blasting (row #5)

Surface scanlines and blast-hole positions (•)

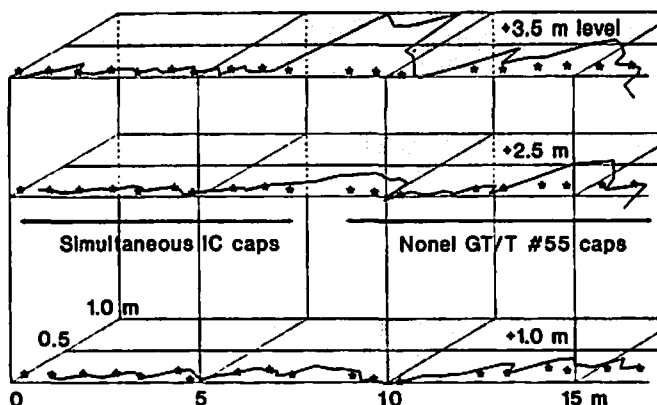


Fig. 10 Scanlines showing surface roughness of Svalbo bench face at different levels.

one gets a continuous crack driving force. Yet the delay is long enough to prevent stress wave superposition effects. In these tests a 2 ms delay was used.

The tests were monitored by standard video, high speed photography and vibration measurements 10m behind a blast. The test results were judged by the lengths of visible half-casts on the bench face relative to actually charged length, the fracture frequency behind the face as measured by optical bore hole logging and core logging before and after blasting and, finally, the roughness of the rock surface as determined from 3 scanlines across the bench face. See Figures 9

and 10.

The photography verified the planned initiation sequences, the Nonel GT/T sequence was random within 200-300 ms, the zipper sets were nicely linear sequences and the simultaneous sets practically speaking mostly truly simultaneous. The logging gave both the in-situ fracture frequency and adepth of 1.5-3.0m for the blast induced fractures.

Some results are shown in Table 1. The surface smoothness percentage relates the length of scanline which lies within  $\pm 4$  cm of a polygonal line through the actual blast hole centers. The MAD denotes the

Table 1 Contour blasting with detonators with electronic delay circuits.  
Results from bench blasting with Ø 42 mm holes<sup>9)</sup>

Type of initiation	Nonel GT/T	Zipper	Simultaneous
No. of half-rows/blast-holes	3/26	4/34	5/42
Initiation time[ms]	5500±150	0.2, 4...	0±0.01
Fracture frequency[1/m]	1.5	1.3	1.4
Visible half-casts[%]	42±19	55±09	79±13
Smooth surface[%]	37±15	55±15	59±07
MAD, all 3 profiles[cm]	9.8	5.0	4.5
MAD, lower 2 profiles[cm]	6.2	2.1	1.4
Max. vibration ampl.[mm/s]	-	24±06	96±18

mean absolute deviation of the rock surface with respect to this polyline. Both these measures were computer evaluated from the digital scanline data. The results may be summarized as follows :

1. A simultaneous initiation of the contour holes gave the fracture surfaces with the least visible damage. The half-cast factor was better and the bench face smoother.
2. The conventional smooth blasting for tunnels gave the visibly poorest results, much worse than simultaneous initiation. In this sense the project goals were reached.
3. The zipper blasting rates between the two other methods in terms of surface smoothness. However it does give 4 times lower vibration amplitudes than the simultaneous initiation, but the fracture logging didn't show significantly fewer blast induced fractures inside the rock mass.
4. A simultaneous initiation of the contour holes can probably use a lower charge concentration without impairing either breakage of smoothness much, and still decrease the blast damage in a tunnel contour.

This ends the exposé of research for the improvement of tunnel blasting. The next section will show how the experience gained has gone into the large Sofia tunnelling R & D project.

The Sofia tunnelling project

The large scale sublevel caving introduced by the LKAB mines limits the number of accessible drift faces and this forces the development work to become more effective too. Rounds with long advances and

reduction of the blasting damage are ways to achieve this.

They were addressed in the Sofia tunnelling project<sup>9)</sup>, which was carried out in the Sofia ore body of the Kiruna mine during the period of late August 1990 to mid-June 1991.

A total of 1255m of 19-28 m<sup>2</sup> tunnels or drifts were driven as a part of a pre-scheduled development operation. The project goals were to achieve

- Low cost, well functioning standard drifting or tunnelling techniques.
- Rounds with long advances and without large empty holes in the cut.
- A safe working environment, less overbreak and lower support costs.

The calculated potential saving are roughly 1, 200 SEK (¥ 25000) per meter of tunnel.

The project was divided into two main parts. Part 1 contained only short 4.4m rounds drilled with an old rig and the goal was to have developed a well functioning ø64mm blasting pattern at the end of it. The use of ø64mm holes was considered necessary to achieve long advances on a routine basis. Part 2 started with short rounds of 4.0m and ended with long rounds with drilled depths of up to 7.8m. In it a newly developed rig, the Atlas Copco Boomer 186S with an automated rod adding system was used. It was equipped with feed beam angle instrumentation and drilling data logging units.

These project parts were then divided into often simultaneous opening cut tests and contour blasting tests. The main follow up consisted of geology and



structure mapping in the drifts, advance measurements and half-cast measurements. In selected rounds, overbreak, blast vibrations, drill hole deviations and blast damage were also measured.

During Part 1 a total of 132 rounds were blasted with an average advance of 3.94 m or 90 %. Of these 27 were reference rounds with a standard LKAB blasting pattern with typically 53,  $\phi 48$ mm blast-holes and parallel hole cut with a  $\phi 102$  empty hole. The charging of these rounds was ANFO in the cut and

stopping holes,  $\phi 22$ mm emulsion (Kimulux 82) pipe charges for smooth blasting in the contour and either ANFO or  $\phi 50$ mm emulsion charges (wet holes) in the lifters. Initiation was by the Nonel GT/T system.

Relatively soon the  $\phi 48$ mm pattern was remade for  $\phi 64$ mm blast-holes with 1 1/2" drill steels. At least 10 blast-holes are eliminated in this way, see Figure 11. Soon a well functioning cut without a large empty hole had been developed, the so called 64T cut in Figure 12. 27 rounds without large empty holes were blasted

Sofia Haulage Drift, 6.0 × 4.5 m and 25 m<sup>2</sup>  
Blast hole diam. 64 mm, empty holes 64 mm

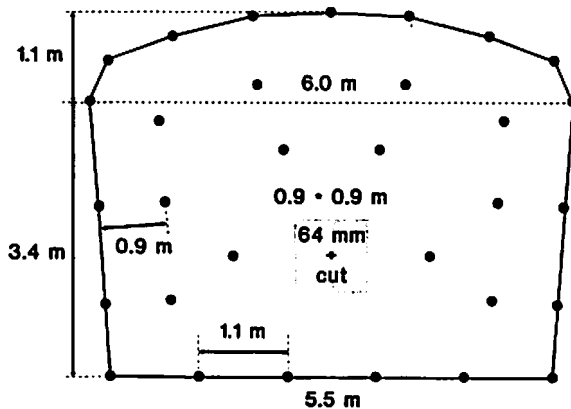


Fig. 11 Drilling pattern for a Sofia haulage drift, using  $\phi 64$ mm blast-holes.

during Part 1. During it, small test series with presplit cuts, spiral cuts and diluted bulk explosives (Emulet 50) were also tried. Part 2 started by drilling short, 4.0 m rounds with the new rig. About 90 of these with  $\phi 64$ mm patterns were blasted before the tests with long rounds started.

A total of 222 short rounds were blasted with a total advance of 840 m. The average advance was 3.78 m of 89 %, including a number of heading and cross cut rounds. The results are shown in Figure 13. The standard  $\phi 48$ mm pattern produced acceptable relative advances of 89 % in the 4.0-4.4 m short rounds but the presplit cut did not. The Emulet 50 results show that a decrease in the charge density of 30 % in the cut may actually improve the breakage. All  $\phi 64$ mm patterns gave satisfactory results with averages well above 90 %. The 64T has the largest basis, 65 rounds but the

64T Cut of Sofia Project  
Blast hole diam. 64 mm, empty holes 64 mm

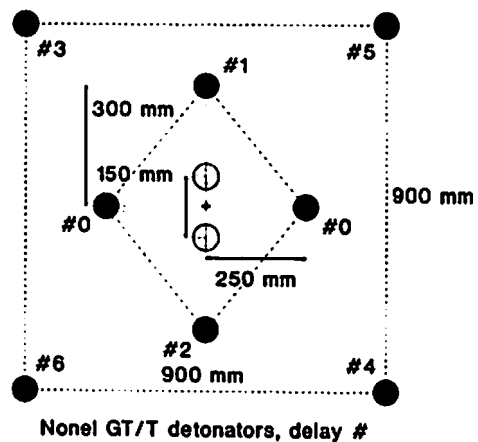


Fig. 12 The 64T cut of the Sofia project, using only  $\phi 64$  mm drill holes.

## Sofia Tunnelling Project

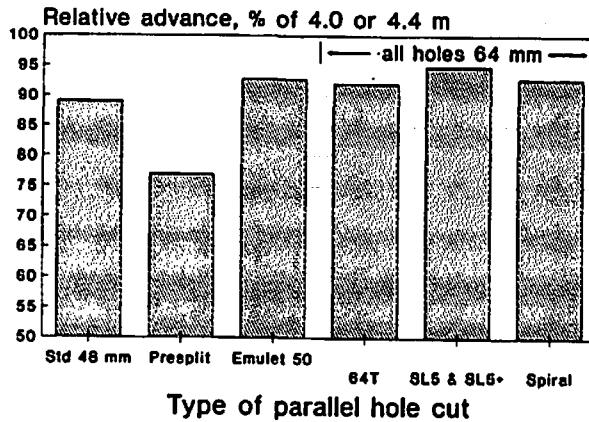


Fig. 13 The relative advance of the short, 4.0m and 4.4m rounds in the Sofia project.

## Sofia Tunnelling Project

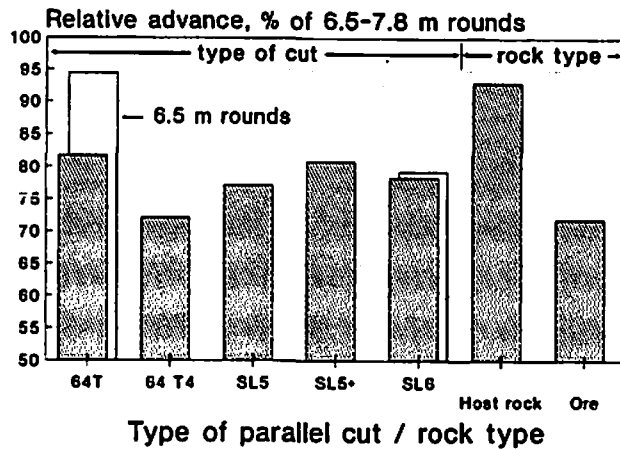


Fig. 14 The relative advance of the long, 6.5-7.8m rounds in the Sofia project.

SL5 cut with 3 empty holes seems to be slightly superior with its 95 % average over 33 rounds. These longer advances correlate with a better functioning blast timing sequence in the cut.

The long phase of Part 2 started with 7.8 m rounds. Since these were not always successful a number of different cuts were tried. The difficulties occurred mainly in the smaller area drifts in the ore. Therefore 6.5 m and 7.2-7.8 m deep rounds were also tried. The advance in the host rock and the breccia finally reached an acceptable level, but not in the ore. The results are summarized in Figure 14. A total of 72

long rounds were blasted with a total advance of 415 m, with an average advance of 3.78 m of 89 %.

The average advance of the 72 long rounds is 5.76 m or 79 %. For different cut types they range between 72 and 82 % and are definitely not satisfactory. The difference between the best and the worst cut is 10 % or about 0.7 m in a long round. The multivariate analysis shows the rock type to be major influence though. In the ore, the average relative advance was only 72 % (22 rounds) but in the host rock it was 93 % (21 rounds). The six 6.5 m rounds with the 64T cut were especially successful, with an average relative

advance of over 94 %.

Large drilling trajectory deviations is one probable reason for the moderate advances. Most rounds were drilled with button bits and a check on one round showed that all holes had deviated more than 250mm from their intended trajectory already after 5-6 m. For two X-bit rounds only 20 % had done this and the remaining 80 % had deviated less than 100mm at full depth. So the use of such bits should increase the advances.

The moderate advances were also accompanied by bad blast timing sequences. On average more than two of the first 8 intervals were either missing or grossly out of sequence. There were many more misfires too, i.e. remaining parts of blast-holes with undetonated ANFO in. The multivariate analysis, however, gives only a 0.2 m longer advance for rounds in which the blast timing sequence in the cut works properly. There is a larger correlation between the minimum distance between charged holes in the cut and the advance. Again this shows the risk of malfunction, due to either simultaneous detonations (flash-overs) or detonation failures, when blast-holes are too closely spaced.

As mentioned above, using  $\phi 22\text{mm}$  emulsion pipe charges is the LKAB contour blasting standard in

rounds with  $\phi 48\text{mm}$  blast-holes. A cheaper method is to use decoupled ANFO. The resulting charge density is roughly 0.4 kg/m in the  $\phi 48\text{mm}$  holes and 0.7 kg/m in the  $\phi 64\text{mm}$  hole. This corresponds to 20-25 % of a filled hole, the same as for single and double  $\phi 22\text{mm}$  charges respectively. The standard initiation is Nonel GT/T.

A part from these conventional contour blasting techniques some new techniques were tried, simultaneous initiation with electronic delay detonators and water jet notched holes made with abrasive cutting technology. A pressure of 33 MPa made 10-15mm deep linear notches along the sides of the contour holes in one pass and the technique was tried in 9 short rounds. The IC-caps were tried in the contours of 27 short rounds. Of these 18 had a simultaneous initiation, with the wall holes going off 8 ms before the roof holes and 9,  $\phi 64\text{mm}$  rounds had zipper blasting with a delay of 1-2 ms between adjacent holes.

There was no standard cartridges suitable for the  $\phi 64\text{mm}$  contour holes when the Sofia project started. Double strings of Kimulux  $\phi 22\text{mm}$  pipe charges were used instead in 33 short rounds but their handing was cumbersome. In 9 rounds Emulet 20, an ANFO emulsion-styropore mixture with the bulk blasting

### Sofia Tunnelling Project

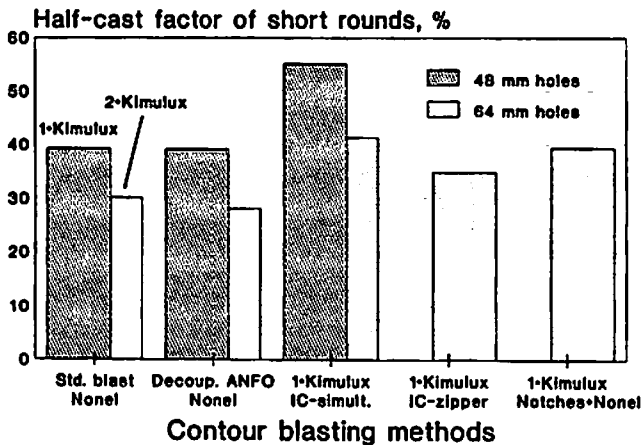


Fig. 15 The half-cast factors of the short rounds in the Sofia project.

strength of 20 % ANFO, was also used.

The short round results are summarized in Figure 15. Standard smooth blasting of  $\phi 48\text{mm}$  blast-holes gave a half cast factor of 39 %, whether single Kimulux  $\phi 22\text{mm}$  charges or decoupled ANFO was used. As expected, substantially better results, 55 %, were obtained when the contour holes were initiated simultaneously. For the rounds with  $\phi 64\text{mm}$  blast-holes a similar tendency turned up but at a lower level. The decrease is probably due to the increase in charge concentration and burden for the larger holes. Water jet notching of the contour holes gave nearly as good a result as a simultaneous initiation and, as in Section 4, zipper blasting was slightly inferior to the latter.

The half-casts were measured in 43 of the 72 long rounds. Of these 13 used the double Kimulux  $\phi 22\text{mm}$  pipe charges, 7 rounds used specially manufactured  $\phi 32\text{mm}$  charges that have a nearly equivalent charge concentration. In 12 rounds, single  $\phi 22\text{mm}$  pipe charges were used but this did not give satisfactory breakage. Decoupled ANFO was used only in 2 rounds and Emulet 20 in 5. In 7 rounds with single Kimulux  $\phi 22\text{mm}$  pipe charges, IC-caps were used but no water jet notched contour holes were tried.

For the long rounds, all of which used  $\phi 64\text{mm}$  blast-holes, the results are slightly better than the corresponding results for short rounds. The best results were again obtained with an simultaneous initiation of

the contour holes. The multivariate analysis showed however that the effect of the rock type was nearly as large. This might account for some of the differences between the  $\phi 48\text{mm}$  hole rounds and  $\phi 64\text{mm}$  hole rounds.

The results of the overbreak measurements in 39 short rounds are seen in Figure 16. The old rig, without either boom direction or laser levelling equipment, produced roughly 23 % overbreak when standard smooth blasting was used. With a simultaneous initiation of the contour holes this value decreased to 19 %. The corresponding figures for the new rig are 15 % and 11 %. This shows the potential of using hole direction equipment. The effect of notching the contour holes was the same as a simultaneous initiation of them.

The main conclusions of the Sofia project may be summarized as follows :

1. Opening-cuts with only  $\phi 64\text{mm}$  holes work well and give advances of 92-95 % for short rounds with 4.0-4.4 m drilled depths.
2. In long rounds they give as good advances in the host rock, 93 %, but not in the ore. Low drilling precision and too closely spaced blast-holes contribute to these results.
3. New contour blasting techniques, with notched holes or electronic delay detonators, give smoother contours with more visible half-casts and less overbreak.

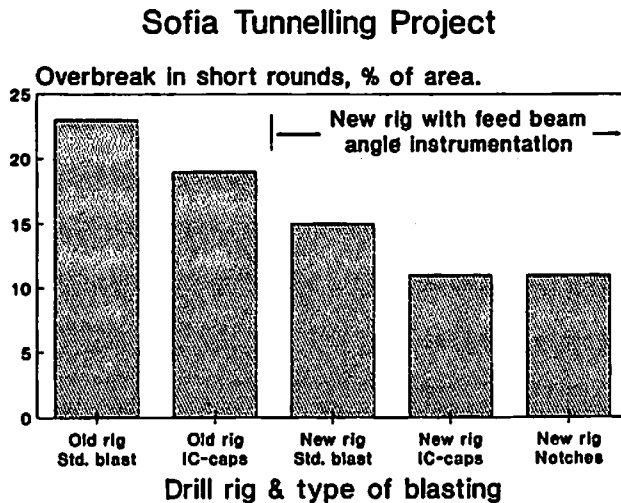


Fig. 16

## Sofia Tunnelling Project

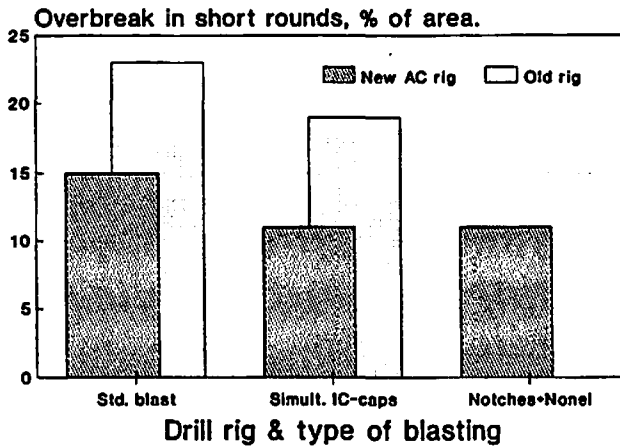


Fig. 16 Overbreak versus drill rig and contour blasting method for short rounds in the Sofia project.

### Further developments of Swedish tunnel blasting

New tests with long rounds have already started at the LKAB mine in Malmberget<sup>10)</sup>. Here 7.8 m rounds were blasted using  $\phi 48$ mm blast-holes and the standard drifting pattern. Tubular drill steels were used in the cut as were X-bits in the cut in ore to improve the drilling precision. The delay between cut holes was also increased to 200 ms. Some results for the 90 round series are shown in Figure 17. The average is now 7.0 m or 90 % and only 20 % of the rounds have shorter advances. The reason for this was nearly always some external disturbance such as heavily fractured rock, much water or a bad drilling precision. The use of short  $\phi 64$ mm rounds without large empty holes is increasing too. The LKAB Kiruna mine use them in some parts and Swedish contractors use them in Saudi Arabia and on Iceland. An increase of the advances will follow, when the rock conditions permit it.

The potential support savings are much larger than the costs of notching the contour holes or initiating the charges in them simultaneously with electronic delay detonators. A new project has been run where these methods were used together in tunnel rounds. With it we hope to establish the limits of extreme smooth blasting.

Large development efforts are also made to improve the drilling rigs. Automated charging equipment that produces explosives with different blasting strengths on site is further being introduced. This firstly

reduces the charging times drastically. Secondly, such trucks with ANFO-emulsion-styropore mixes with ANFO strengths of 20, 50 and 100 % for the contour, helper and stoping/lifter holes respectively will make it possible to balance the blast damage zones in the contour. Furthermore, if a 70 % strength mix were used in the cut, the risks of detonation failure and flash-over would probably decrease, the sensitivity to deadpressing as well and the amount of fines go down.

The detonator is an important part of the system too. Nitro Nobel is now introducing the Nonel NPED detonator, which contains no primary explosives. It is a safer product. Its flash-over distance is 10 times smaller than conventional detonators. In air the maximum distance for serial flash-over between detonators is about 20 mm and the risk of initiation by drilling impact is only 1/3 of that of conventional detonators. Besides, the environment is spared about 0.2 g of lead for each NPED detonator used.

The programmable delay between the interval numbers of the electronic delay detonators add two interesting possibilities. Firstly, if longer delays than 100 ms are needed in the cut part of long rounds these can easily be achieved. Secondly, they can be used to separate interval numbers in the rest of the round to avoid both choking effects in the flow of fragmented rock and overlapping vibration signals. Since their price today is roughly 10 times that of ordinary ones, their use will however for some time to come be only

## Long Drift Rounds in the Malmberget Mine

New test series Aug.-Dec. 1991

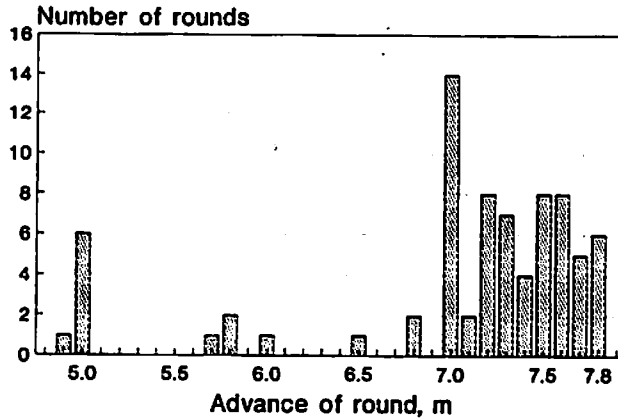


Fig. 17 Histogram of the advances in the recent test series with long rounds in the Malmberget mine.

marginal.

I expect the techniques and methods described above to permeate Sweden fairly rapidly when they have shown their economic potential. If I thus would describe advanced Swedish tunnel blasting 5 years from now it would read something like this

1. The drilling of 7-8 m deep rounds with  $\phi 48-64$ mm diameter blast-holes, using semiautomated positioning techniques and both tubular drill steels and special bits where straight holes are needed.
2. The drilling pattern will have parallel hole cuts, usually without large empty holes.
3. The explosive will mainly be ANFO, but in the contour, in the helpers and possibly also in the cut lower strength ANFO mixtures will be used. The charging will be made using automated equipment that can regulate the blasting strength at will and on site.
4. The contour will be more lightly charged than today, taking advantage of notching and/or simultaneous initiation of the contour holes to produce contours that are smoother, have less over-break and contain less blast damage.
5. The initiation will mainly be made with the Nonel GT/T system with NPED detonators. When especially smooth contours or low vibration levels are required, detonators with electronic delay circuits will be used however.

6. The relative advance will still be 90-95 % on a regular basis.

It would seem that the methods presented above for extreme smooth blasting of tunnel contours would make it possible to blast longer rounds also in weaker rock. Thus I believe that the Swedish experience will be of value also to Japan. The transplantation of Swedish techniques that are suitable in hard and competent rock to weak rock is however by no means trivial. The details of the cut, both geometry, explosive and timing need to be checked closely. It is also quite probable that better methods for rock support have to be developed in order to do this successfully.

I believe finally, that tunnel blasting will be a competitive alternative to mechanical tunnel boring machines for a long time to come. This is mainly the result of a stubborn and goal oriented research and development effort worldwide and this paper has covered recent Swedish contributions to these efforts.

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#### References

1. F. Ouchterlony, "Some Recent Research and Developments in Swedish Tunnel Blasting", SveDeFo Report DS 1992 : 1 (1992). In preparation.
2. U. Langefors and B. Kihlström B, "The Modern Technique of Rock Blasting", (1963), Almqvist & Wiksell, Stockholm (Wiley, N. Y.).
3. S. O. Olofsson, "Applied Explosives Technology for Construction and Mining," (1991), Applex, Årila, Sweden.
4. G. Persson and I. Bergqvist, "Studies of the Function of a Parallel Hole Cut by High Speed Photography," SveDeFo Report DS 1987 : 9 (1987). In Swedish.
5. S. Nie, J. Deng and A. Persson, "The Dead-pressing Phenomenon in an ANFO Explosive," SveDeFo Report DS 1991 : 1 (1991).
6. S. Nie, A. Persson, J. Deng and U. Nyberg, "Measuring Dynamic Pressure in ANFO and Emulsion Explosives-Experiences in Developing a Pressure Gauge Based on Piezo ceramic Material." SveDeFo Report DS 1990 : 1 (1990).
7. S. Nie, A. Nordqvist and J. Oqvist, "Pressurization of an Explosive in a Blast hole," SveDeFo Report DS 1991 : 5G (1991). In Swedish.
8. B. Niklasson and L. Karlsson, "On the Influence of the Delay Time on the Result in Smooth Blasting," SveDeFo Report DS 1991 : 6G (1991). In Swedish.
9. B. Niklasson and M. Keisu, "New Techniques for Drifting and Tunnelling-The Sofia Project," SveDeFo Report DS 1991 : 10 (1991). In Swedish.
10. B. Niklasson and M. Keisu, "The Sofia Project - A Summary of Activities and Results", Proc. Swedish Rock Blasting Committee BK 92, pp. 169-190 (1992).

## スウェーデンにおけるトンネル発破に関する最近の研究開発

Finn Ouchterlony\*

本論文は(財)スウェーデン爆発研究所(SveDeFo)とその出資会社がトンネル発破の改善を総合研究する目的で行った最近の研究活動の一端を紹介するものである。トンネル掘進発破の2つの重要な問題すなわち心抜き発破と周辺孔発破を主に取り上げられた。

心抜き問題に関しては、破壊機構、爆轟中断と斉発性、及び遅延時間の影響の問題が研究された。周辺孔発破に関しては、残壁の破壊や過破砕を減少する工法について研究された。この中には周辺孔にノッチを設けることや遅延秒間を精度よくすることなどが含まれている。

最近行った大規模トンネル掘削の研究開発についても説明する。これは長さ1255mのトンネルを新しい発破技術で掘削し、以下の結果が得られた。

- 64mm径の装薬孔を用いる長孔掘進発破のために開発された新しいパーンカット工法は十分な機能が確認された。
- 7.8mの装薬孔を用いた長孔掘進発破で平均掘進長7.0mが得られ、岩盤条件や削孔精度が良いとさらに長いくっしんが得られた。
- 穿孔技術と周辺孔発破技術により過破砕が50%程度減少し、はっきり分かる穿孔跡の数が50%近く増加した。

最近に、将来のスウェーデンのトンネル発破技術の開発について簡単に説明した。

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