STIFTELSEN SVENSK BERGTEKNISK FORSKNING
SWEDISH ROCK ENGINEERING RESEARCH

THE DIAMETER EFFECT ON DETONATION PROPERTIES OF CYLINDER TEST EXPERIMENTS WITH EMULSION E682

Diameterns inverkan på detonationsegenskaperna hos emulsionssprängämne E682 i cylinderprovet

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SveBeFo Report 66

Stockholm 2004
ISSN 1104-1773

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ISRN SVEBEFO-R--66--SE

Förord

I SveBeFos tidigare arbete för att förstå sprängämnens verkan i berg har en brinnmodell tagits fram, som beskriver det fysikaliska förloppet bakom detonationsfronten i en laddning. I en serie experiment visades hur olika sammansättning av sprängämnet påverkar detonationsförloppet, bland annat för ett emulsionssprängämne, kallat E682, framtaget i samarbete med Dyno Nobel och Kimit och som liknar dagens gängse sprängämnen. Undersökningarna genomfördes av Shulin Nie tillsammans med Junhua Deng och Ulf Nyberg, och de gjorde också inledande försök i form av cylinderexpansionstester för att bestämma arbetsförmågan hos blandningar av emulsion och ANFO i samarbete med FOI.

Det påbörjade arbetet har kompletterats och därmed fullföljts av Ioannis Arvanitidis tillsammans med Finn Ouchterlony och Ulf Nyberg genom ytterligare försök på ren emulsion (E682) och på samma emulsion uppblandad med 20 % ANFO. Cylinderexpansionsproven sker i 1 m långa kopparrör där man mäter detonationshastigheten och volymexpansionen och därmed kan räkna fram den s k Gurneyenergin, som ett mått på sprängämnets arbetsförmåga. Resultaten visar att arbetsförmågan varit i stort sett oberoende av aktuella laddningsdiametrar och att verkningsgraden varit omkring 58 % för ren E682 och 53 % i den med ANFO uppblandade matrisen.

Arbetet som ingått i SveBeFos forskningsprogram FP 2000 har också kunnat integrerats med det pågående EU-projektet ”Less Fines”, som syftar till att kontrollera fragmenteringsförloppet i bergtäkter för ballast och mineralproduktion med syftet att minska den som regel överflödiga finandel som uppkommer vid sprängningen. Kunskaperna om sprängämnets arbetsförmåga har där använts i analysen av genomförda fältförsök.

Denna rapport är den sista i den serie som redovisar de detonikforskningsprojekt som ingått i FP 2000. Fortsatt forskning inom sprängningstekniken sker nu främst hos Swebrec, där de tidigare vid SveBeFo anställda forskarna inom sprängteknik verkar sedan februari 2003.

Stockholm i februari 2004

Tomas Franzén

Summary

Cylinder expansions tests with 4 different diameters ranging from 40 to 100 mm have been conducted on the generic emulsion explosive E682, both pure and with 20 % ANFO content. The work capacity is expressed in terms of the Gurney energy E_G, which equals the sum of the kinetic energy of the copper tube and the radial kinetic energy of the gases. The purpose was to study the effect of charge diameter on the explosive's work capacity expressed as the Gurney energy and to supplement earlier work done by Nie (2001). The radial expansion has been measured as well as the velocity of detonation in 11 copper tubes.

The effect of ANFO granules were tested by making a mixture of E682 with 20% ANFO. The ANFO used in the present study is Anolit from Dyno Nobel, which basically is the same product as the Prillit A used by Nie. The average density of pure E682 was 1130 kg/m^3 and that of E682 with 20% ANFO 1200 kg/m^3.

The results from the new batch of E682 show similarities with the old batch regarding VOD as function of inverse charge diameter but the trend of the Gurney energy is different from the first experiments carried out by Nie. This could be due to previous tolerance variations in the tube dimensions.

The Gurney energy seems to be independent of the charge diameter between 40-100 mm in the new experiments. The measured Gurney energy for pure E682 was 1.77 ± 0.06 MJ/kg and that of E682 with 20% ANFO 1.71 ± 0.07 MJ/kg which is somewhat lower. The use of 20% ANFO in E682 results in the same volume based Gurney energy as for pure E682 however. The overall average is 2.02 ± 0.02 MJ/dm^3.

The energy utilisation ratio is 0.58 ± 0.03 for pure E682 and 0.53 ± 0.03 for E682 with 20% ANFO. This is slightly lower than for the Titan 6000 series gassed bulk emulsion but higher than for pure ANFO.

The detonation pressure decreases with the charge diameter however and this indicates that a smaller hole diameter in rock blasting leads to a lower detonation pressure without loosing work energy when keeping the powder factor constant.

Utökad sammanfattning

Cylindertest har genomförts på emulsionssprängämne 682 (E682) i syfte att undersöka hur arbetsförmågan varierar med laddningsdiametern inom intervallet 40-100 mm.

Två satser syrebalanserad emulsion undersöktes, ren E682 och E682 med 20% ANFO. Receptet till E682 är framtaget tillsammans med Dyno Nobel och Kimit AB. Denna experiment emulsion har undersökts tidigare, bl.a. finns en brinnmodell. Emulsionen är syrebalanserad. När det gäller den volymbaserade explosionsenergin så ligger ren E682 något lägre än E682 med 20% ANFO, 3.47 MJ/dm^3 respektive 3.85 MJ/dm^3.

Mjukglödgade 1 m långa kopparrör med inner/ytter diametrar 40/44, 60/66, 80/88 och 100/110 (mm/mm) har använts. Försöksuppställningen består av ett vertikalt monterat kopparrör fyllt med E682. Laddningsdensiteten var ca 1130 och 1200 kg/m^3 för ren E682 respektive E682 med 20% ANFO. Initieringen sker ovanifrån med sprängdeg varvid detonationsfronten går nedåt genom laddningen i röret. Detonationsfrontens hastighet (VOD) mäts med resistansprob som monterats längs rörets mittlinje. Den radiella expansionen mäts med 10 kontaktpinnar ca 65 cm nedåt på röret ifrån initieringspunkten. Expansionen mäts från 0.5 mm från rörväggen till en total volymexpansion om 6-9ggr.

Med hjälp av VOD och expansionsdata kan man räkna fram kopparväggens rörelse och den kinetiska slutenergin kallad ”Gurneyenergin” som är ett mått på sprängämnets arbetsförmåga. Genom att jämföra Gurneyenergin med explosionsenergin kan man få fram en verkningsgrad. Gurneyenergin, som mäts i MJ/kg sprängämne, var oberoende av laddningsdiametern. Följden blir att även verkningsgraden är oberoende av laddningsdiametern inom det studerade intervallet 40-100 mm.

För ren emulsion låg kopparväggens sluthastighet runt 1280 ± 20 m/s och Gurneyenergin 1.77 ± 0.06 MJ/kg. Vad gäller E682 med 20 % ANFO blev hastigheten något högre, 1290 ± 20 m/s samt Gurneyenergin 1.71 ± 0.07 MJ/kg. Verkningsgraden för ren E682 är 58 ± 3 % och för E682 med 20 % ANFO 53 ± 3% av tillgänglig energi. Den något lägre verkningsgraden för E682 med 20 % ANFO kan förklaras med att ANFO i sig har en lägre verkningsgrad ca 40-50 %.

En tidigare försöksserie av Nie (2001) visade förvånansvärt nog verkningsgraden hos försöken med 80/88 rören var markant högre än hos 40/44 och 100/110 rören. I jämförelse med denna studie så verkar sluthastigheterna i Nie’s försök med 80/88 rören vara onormalt höga vilket kan tänkas bero på materialfel eller dimensionsfel hos rören.

Man kan tydligt se att kopparväggens acceleration ökar med minskande rördiameter. Detta är en naturlig följd av att massan som ska accelereras minskar mycket snabbare med minskande laddningsdiameter än vad detonationstrycket gör.

Sammanfattningsvis kan man säga att verkningsgraden minskar något för E682 då man tillsätter ANFO men att den är oberoende av laddningsdiametern. Om man jämför Gurneyenergin på volymbasis så ligger däremot ren E682 obetydligt lägre än E682 med 20% ANFO, ca 2%.

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1 Introduction

Today, the work capacity of non-ideal explosives used in production blasting is usually expressed in terms of weight strength. Many manufacturers report a weight strength based on the computed explosion energy or a lower value based on the assumption that the gases stop doing useful work at some pressure, e.g. 1000 atm. Langefors' older weight strength concept (Persson et al. 1994) is hardly used anymore.

A new independent measure of the relative work capacity of civil explosives has been developed by Nie (2001) and Nyberg et al. (2003). The so-called cylinder expansion test uses soft annealed copper tubes filled with explosives which are shot and the explosive VOD and the expansion velocity of the tube wall are measured.

The work capacity is expressed in terms of the Gurney energy E_G, which equals the sum of the kinetic energy of the copper tube and the radial kinetic energy of the gases. This test has its origin in military work on high explosives, see e.g. Souers et al. (1994), Helte et al. (1999). It has also been used for small charges of industrial explosives, Trzciński and Cudziło (2001).

In the earlier work at SveBeFo, the generic, micro-sphere sensitised emulsion explosive E682 was tested, both pure and with a 20 % content of ANFO (Nie et al. 2000, Nie 2001), as were three pure ANFO's, one ANFO with aluminum additive and a gassed bulk emulsion from Dyno Nobel, the Titan 6000 series at different densities (Nyberg et al. 2003). Both the pure emulsion, Titan 6000 and one with a 20 % content of AN prills, Titan 6080, were tested

The latter work was done as part of the EU-financed project *"Less fines production in aggregate and industrial minerals industry"*, project no. GRD-2000-25224, together with Nordkalk and Dyno Nobel. "Less Fines" has other partners too, Montan-universität Leoben and aggregate manufacturer Hengl Bitustein in Austria, the CGES & CGI departments of the Ecole de Mines in Paris, France and Universidad Politécnica de Madrid (UPM) with explosives manufacturer UEE and cement manufacturer Cementos Portland from Spain.

The most important conclusion from this testing is that Titan 6080, despite the lower weight strength value given by Dyno, 3,3/4,0 = 84 %, performs more work than ANFO because the E_G-value is larger for Titan 6080 at a normal loading density of 1150 kg/m^3. The relative work capacity for the Titan series of explosives is 60-70 % but only 40-50 % for ANFO.

The work capacity of the Titan series of explosives increases with an increasing density despite that the VOD starts to drop when the density approaches 1300 kg/m^3. The consequence is that the VOD-value may not be a good measure of the work capacity of an explosive.

Adding AN seems to have little influence on the work capacity of the Titan emulsions, except at the lowest densities, 800-900 kg/m^3. Adding aluminum raises the work capacity of ANFO though.

The ANFO and Titan tests were all made in Ø 100/110 mm (inner/outer diameter) tubes, and the question is how the charge diameter influences the work capacity of the explosives. Nie (2001) tested tubes of 40/44, 80/88 and 100/110 mm diameter with emulsion E682. He found that the Gurney Energy does not increase with the tube diameter, it rather shows an unex-

pected maximum at 80-mm diameter. This suspect result could be caused by experimental conditions like dimension error in the copper tubes. A new batch of E682 was prepared in 2003 and tests were made at Ø 40/44, 60/66, 80/88 and 100/110-mm diameter in order to verify or falsify these results.

This work was started under SveBeFo's research program FP2000 and as of 2003-02-01 continued under Swebrec at Luleå University of Technology. It was also decided to share the work and the information with the Less Fines project.

The E682 was manufactured by Hans Perlid and Linda Johansson at Dyno Nobel after the same recipe used by Nie (2001). The addition of ANFO was advised by Hans Karlström, Kimit AB, and the explosion energies for the emulsion was calculated by Lars Granlund, Dyno Nobel. The recipe was developed by SveBeFo, Dyno Nobel and Kimit. 50 kg of E682 with 20% Anolit ANFO and 90 kg pure E682 was produced in the pilot mixing plant at Gyttorp.

2 Experiments

2.1 Test set-up

The cylinder expansion method was developed at Lawrence Livermore National Laboratory in order to find the Equation of state for military explosives (Souers et al. 1994). We rely on a set up used by FOI, the Swedish Defence Research (Helte et al. 1999). Soft annealed oxygen free copper DIN 1754 tubes with a fixed ratio between the inner diameter and the wall thickness are mounted in disposable rigs according to Figure 1 below.

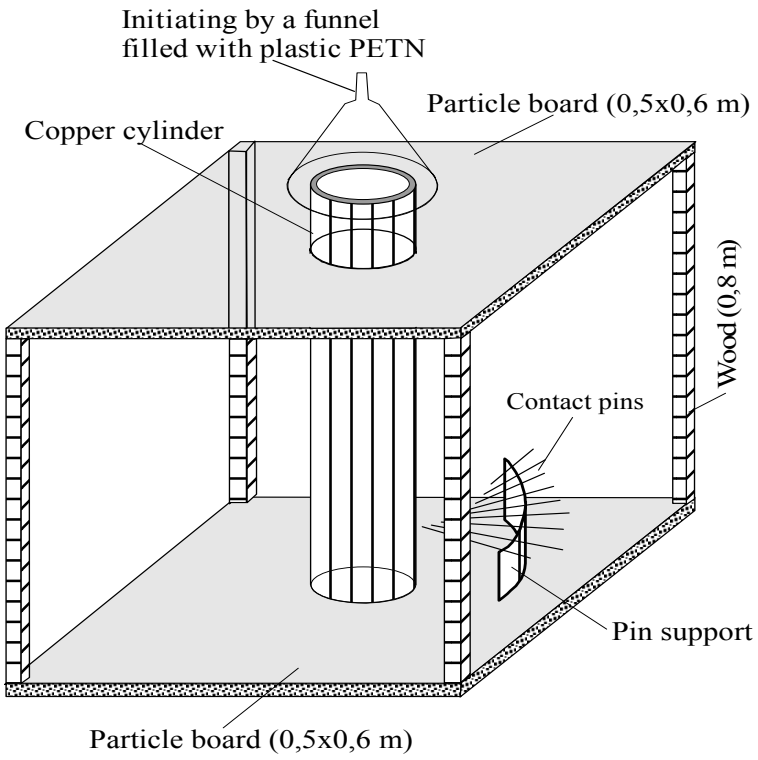


Figure 1. The disposable rig with copper tube and contact pins.

The copper tubes were filled with explosive and primed at the upper end. The onset of the detonation of the main charge inside the copper tube was carried out by initiating with a hexotol booster or plastic PETN, as a substitute for a plane wave lens. The tube wall expansion and the VOD were measured simultaneously.

The copper tubes were filled with the emulsion explosive by creating a weak vacuum at one end and dipping the other end into the container with emulsion explosive. Densities of the charges were regularly calculated in order to check for air pockets inside the charge. The tubes were weighed before and after filling. Contact pins CA 1041-C, made by Dynasen Inc, were connected to a pulse box which sends a 7-volt pulse each time a contact pin is short-circuited. A set of 10 pins were mounted in a PVC block with the radial equidistance of 5.0-9.4 ± 0.05 mm between the pin tips, starting with a small distance, δ, of 0.45-0.50 ± 0.05 mm from the tube wall. The distances from the original tube wall surface were then (mm):

δ + [0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0]	∅ 40/44 mm
δ + [0.0 6.2 12.4 18.6 24.8 31.0 37.2 43.4 49.6 55.8]	∅ 60/66 mm
δ + [0.0 7.4 14.8 22.2 29.6 37.0 44.4 51.8 59.2 66.6]	∅ 80/88 mm
δ + [0.0 9.4 18.8 28.2 37.6 47.0 56.4 65.8 75.2 84.6]	∅ 100/110 mm

Figure 2 shows a photo of the contact pin set up:

Figure 2. Photo of the mounted contact pins with gauge jig.

The pulses were sampled at 200 MS/s by a LeCroy 9354A 500 MHz oscilloscope with a single sample rate capacity up to 2 GS/s. The VOD was measured by inserting a VOD probe concentrically inside the copper tube. The VOD probe was connected to a continuous VOD recorder, MiniTrap, from MREL. For details of the test rig, gauge jigs etc see the report by Nie (2001).

2.2 Explosives

The experimental E682 emulsion was tested both with and without Anolit (Dyno 2003) ANFO prills mixed in. It is sensitized by glass micro-balloons. The E682 recipe is shown in Table 1 below:

Table 1. Composition of pure E682 emulsion.

Component	Ingredient	Composition (weight-%)
Salt solution	Water	14.52
	Sodium Nitrate (SN)	10.88
	Ammonium Nitrate (AN)	65.31
Emulsifier	Lubrizol 2724[1)]	1.50
Oil	Whiterex E 309[2)]	4.51
Micro balloon	3M K20[3)]	3.28

Notes:
1. Figures from the manufacturer Lubrizol Limited: Chemical formula = $C_{6,8}H_{13,9}N_{0,5}O_2$, density at 15.6 °C = 916 kg/m^3 and heat of formation at liquid state = -2500 kJ/kg.
2. According to Mobil Oil: density at 20 °C = 850 kg/m^3, heat of combustion = 45.6 MJ/kg and viscosity at 40 and 100°C is 16 and 3.5 cSt respectively.
3. Produced by 3M Co.

Table 2. Properties of Anolit. Dyno Nobel (2003).

Explosive	Producer	Nominal density (kg/m^3)	Explosion energy, E_0 (MJ/kg)	Gas volume NTP (ℓ/kg)	VOD steel tube (m/s)
Anolit	Dyno Nobel	850	4.0	970	2200

Table 3. Emulsion explosives from Dyno Nobel, values calculated with Tiger.

E682	Density (kg/m^3)	Explosion energy (MJ/kg)	Gas volume (l/kg) NTP	VOD (m/s)
Pure E682	1150[1)]	3.07	905	5475
20% Anolit	1200[2)]	3.21	918	5885

Notes:
1. Manufactured density
2. Average density according to Table 4.

The charge density for Anolit is 850 kg/m^3 but with an approximate 65% degree of packing, the ANFO granules have a density about 1300 kg/m^3. The density for 20% Anolit in E682 should through a simple calculation be 0.2·1300 + 0.8·1150 = 1180 kg/m^3 which is somewhat lower than the density for the E682 with 20% Anolit given in Table 3.

Table 4 shows the % ANFO, VOD, charge diameter, charge density and metal mass to explosive mass charge ratio, M/C, for all present tests. The density was calculated from the weight of explosive filled in the copper tube divided by the inner volume of the copper tube occupied by explosive. The copper tubes follow the DIN 1754 norm according to the supplier Metallvaruhuset, Sweden. The DIN 1754 norm guaranties a dimension error of maximum 5% of the nominal tube wall thickness, for example the thickness of the 80/88 tube wall should lie within 4 ± 0.10 mm.

Table 4. Basic E682 shot data.

Test	ANFO %	Charge diameter (mm)	Charge density (kg/m^3)	M/C ($m_{Cu}/m_{expl.}$)	VOD (m/s)
139	0	80	1148	1.63	5699
140	0	100	1130	1.66	-
141	0	60	1120	1.67	5609
142	0	80	1140	1.64	-
143	0	60	1137	1.65	5670
144	0	40	1120	1.67	5675
145	0	60	1130	1.66	5700
146	20	100	1203	1.56	5617
147	20	60	1195	1.57	5369
148	20	40	1200	1.56	5254
149	20	100	1207	1.55	5523
150	20	60	1195	1.57	-

3 Experimental results and data analysis

The experimental results from the cylinder expansion tests are presented as the radial change of the confining copper cylinder wall as function of time. The radial change is perpendicular to the length axis of the copper tube, note that the true radial motion is about 7° off from the perpendicular measured radial change. Also, the acceleration is calculated from the perpendicular radial change and presented as function of time.

In order to evaluate the kinetic data of the expanding cylinder, the velocity of the copper has to be calculated at the centre radius of the tube, r_m, which could be estimated under the assumption of incompressible deformation and no material flow in the length direction of the copper tube, see Hornberg and Volk (1989). Under these conditions, the position of the centre or mid-wall radius, r_m, is calculated through the half cross sectional surface area as:

$$\pi\left(r_y^2 - r_m^2\right) = \pi\left(r_m^2 - r_i^2\right) = \frac{1}{2}\pi\left(R_y^2 - R_i^2\right) \quad (1)$$

Here r_y and r_i are the measured outer and inner radii, R_i and R_y are the initial inner and outer radii, see Figure 3 below. The radial change of the centre radius, Δr_m, is given by Equation 2.

$$\Delta r_m = r_m - R_m = \sqrt{r_y^2 + \frac{R_i^2 - R_y^2}{2}} - \sqrt{R_y^2 + \frac{R_i^2 - R_y^2}{2}} \qquad (2)$$

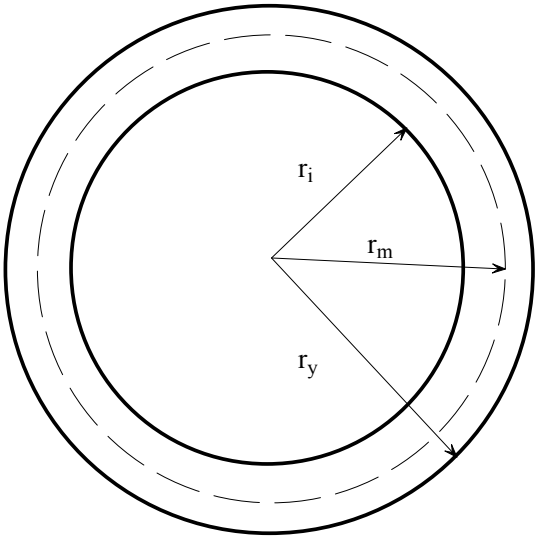


Figure 3. The positions of the radii. Size scale is not proportional.

By using the contact pins, r_y is measured as function of time. An example is given in Figure 4.

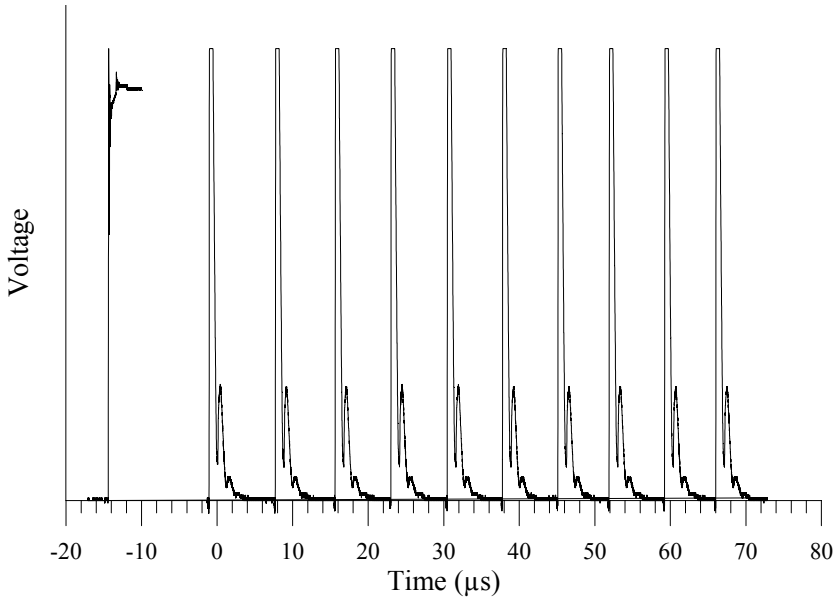


Figure 4. Contact signals vs time during cylinder expansion.

The voltage peak reaches 7.0 volts and the accuracy of reading the contact time is less than ± 5 ns. The measured results from the cylinder expansion tests are given in Tables 5-7.

These Tables give the measured change in position or expansion of the outer wall surface, Δr_y (mm), as function of time (μs). Some entries in the Tables are missing. This is caused by an individual pin failing to deliver a signal despite that its short circuiting capacity was found to function by testing before the firing of the shot.

Table 5. Time versus radial expansion of outer tube wall for pure E682.

139 ∅80/88 VOD = 5699 m/s 2003-05-26		140 ∅100/110 VOD = - 2003-05-28		141 ∅60/66 VOD = 5609 m/s 2003-05-28		142 ∅80/88 VOD = - 2003-06-17	
T (μs)	Δr_y (mm)	t (μs)	Δr_y (mm)	t (μs)	Δr_y (mm)	t (μs)	Δr_y (mm)
-1.10	0.5	-1.16	0.5	-1.16	0.5	-1.85	0.5
9.38	7.9	10.7	9.9	6.80	6.7	8.04	7.9
17.2	15.3	19.4	19.3	12.7	12.9	15.1	15.3
24.5	22.7	27.4	28.7	17.8	19.1	21.8	22.7
30.8	30.1	35.0	38.1	23.3	25.3	27.6	30.1
37.1	37.5	42.6	47.5	28.2	31.5	33.1	37.5
43.3	44.9	50.0	56.9	32.9	37.7	39.1	44.9
49.3	52.3	56.9	66.3	37.7	43.9	45.1	52.3
55.1	59.7	64.7	75.7	42.4	50.1	50.6	59.7
61.0	67.1	71.9	85.1	46.9	56.3	56.1	67.1

Table 6. Time vs. radial expansion of outer tube wall for E682 emulsions.

143 ∅60/66 0% ANFO VOD = 5670 m/s 2003-09-02		144 ∅40/44 0% ANFO VOD = 5675 m/s 2003-09-05		145 ∅60/66 0% ANFO VOD = 5700 m/s 2003-09-19		146 ∅100/110 20% ANFO VOD = 5617 m/s 2003-10-07	
t (μs)	Δr_y (mm)	t (μs)	Δr_y (mm)	t (μs)	Δr_y (mm)	t (μs)	Δr_y (mm)
-1.82	0.45	-1.83	0.5	-1.82	0.45	-1.85	0.45
6.49	6.65	4.17	5.5	7.02	6.65	10.9	9.85
12.5	12.85	8.52	10.5	13.1	12.85	19.7	19.25
17.8	19.05	12.3	15.5	18.8	19.05	27.5	28.65
22.8	25.25	16.9	20.5	24.0	25.25	35.3	38.05
27.9	31.45	20.5	25.5	29.0	31.45	42.6	47.45
(31.7)	37.65	24.5	30.5	34.4	37.65	49.3	56.85
36.8	43.85	28.3	35.5	39.1	43.85	56.3	66.25
41.4	50.05	32.0	40.5	43.8	50.05	63.3	75.65
(45.2)	56.25	35.7	45.5	48.0	56.25	71.2	85.05

Table 7. Time versus radial expansion of outer tube wall for E682 with 20% ANFO.

147 ∅60/66 VOD = 5369 m/s 2003-10-16		148 ∅40/44 VOD = 5254 m/s 2003-10-21		149 ∅100/110 VOD = 5523 m/s 2003-10-28		150 ∅60/66 VOD = - 2003-11-07	
t (μs)	Δr_y (mm)	t (μs)	Δr_y (mm)	t (μs)	Δr_y (mm)	t (μs)	Δr_y (mm)
-1.82	0.5	-1.83	0.5	-0.99	0.45	-0.95	0.5
6.49	6.7	4.02	5.5	12.4	9.85	6.61	6.7
12.5	12.9	8.66	10.5	21.9	19.25	12.7	12.9
17.8	19.1	12.9	15.5	29.9	28.65	(13.5)	19.1
22.8	25.3	16.9	20.5	37.8	38.05	-	25.3
27.9	31.5	21.0	25.5	45.6	47.45	27.1	31.5
31.7	37.7	24.5	30.5	52.3	56.85	31.5	37.7
36.8	43.9	-	35.5	59.7	66.25	-	43.9
41.4	50.1	-	40.5	66.2	75.65	41.7	50.1
45.2	56.3	35.9	45.5	74.2	85.05	46.9	56.3

Note: Data within ( ) are suspect and are not used.

The radial expansion, Δr_m, as function of time is plotted for pure E682 in Figure 5 below. It is seen, with some exceptions, that the initial expansion rate decreases with increasing charge diameter. The ratio of explosive to copper mass is kept nearly constant according to Table 4.

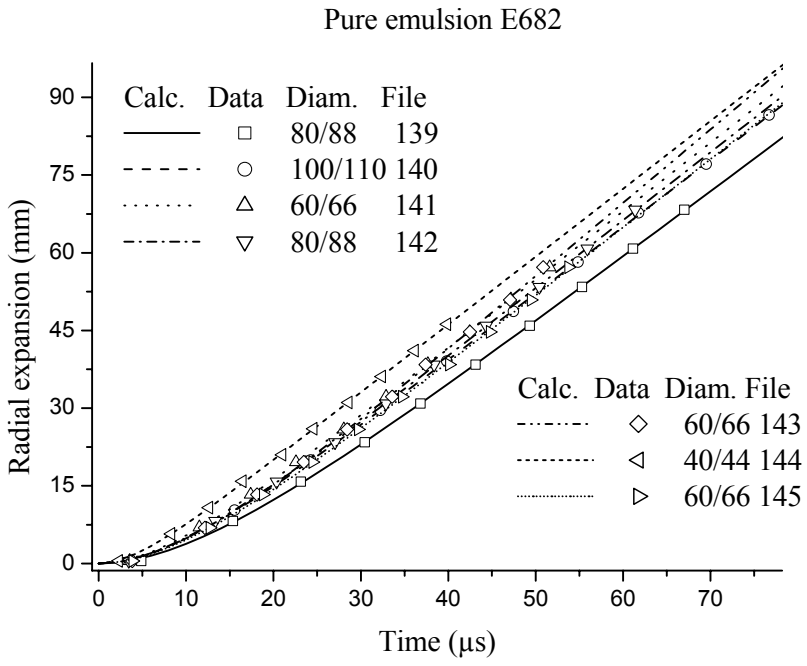


Figure 5. The radial expansion Δr_m as function of time for pure E682.

The radial expansion for E682 with 20% ANFO is shown in Figure 6. The general trend is similar to that for pure E682, with an increasing initial expansion rate with decreasing charge diameter.

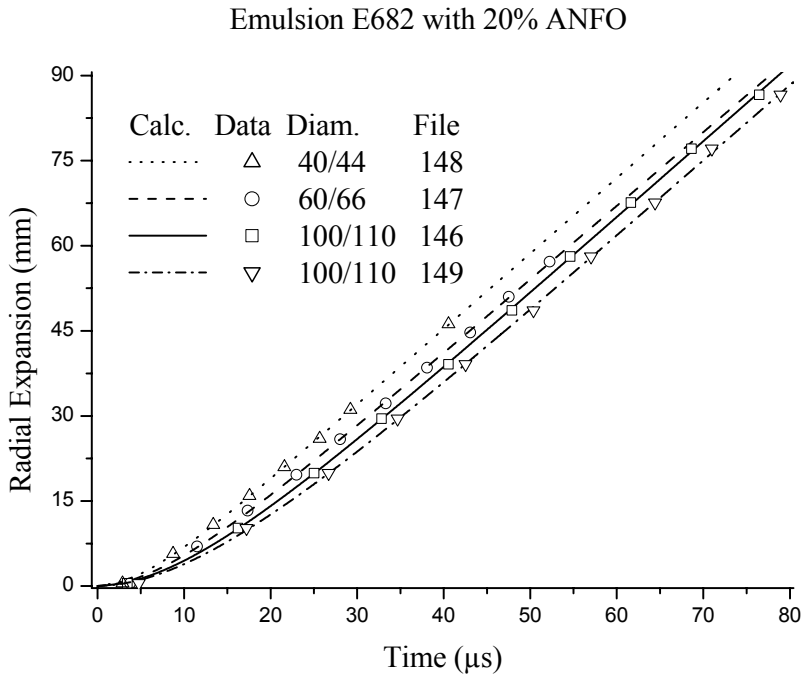


Figure 6. The radial expansion Δr_m as function of time for E682 with 20% ANFO.

The calculated curves where obtained by fitting a combined linear and exponential function to the data (Hornberg & Volk, 1989). This function is given by the Equation below:

$$\Delta r_m = a \cdot \left[t_{\exp} - t_0 - \frac{1}{b} \cdot \left(1 - e^{-b \cdot (t_{\exp} - t_0)} \right) \right] \tag{3}$$

Here a, b and t_0 are curve fit parameters. $t = t_{exp} - t_0$ is a time shift which lets the expansion curves start at $t = 0$, $\Delta r_m = 0$. The radial velocity and acceleration are given by Equations 4-5.

$$\Delta \dot{r} = a \cdot \left(1 - e^{-b \cdot (t_{\exp} - t_0)} \right) \tag{4}$$

$$\Delta \ddot{r} = a \cdot b \cdot e^{-b \cdot (t_{\exp} - t_0)} \tag{5}$$

The cylinder expansion tests result in kinetic data that can be used to evaluate the work capacity of an explosive. The well-known Gurney equation (Gurney 1943 & Kennedy 1997) gives the relation between the work capacity (Gurney energy), E_G and the final tube wall velocity (Gurney velocity), U_L:

$$E_G = \frac{U_L^2}{2} \left[\frac{M}{C} + \frac{1}{2} \right] \tag{6}$$

Here U_L (m/s) is the Gurney velocity, E_G (J/kg) is the Gurney energy, M (kg) is the metal mass and C (kg) is the explosive mass of cylinder:

$$\frac{M}{C} = \frac{\rho_{Cu} \cdot (R_y^2 - R_i^2)}{\rho_{expl} \cdot R_i^2} \tag{7}$$

4 Discussion of data.

The Gurney equation relates the mass, momentum and energy conservation equations to both the explosive gases and the metal confinement (Kennedy 1997). The radial velocity distribution inside the gases is assumed to be linear. The energies due to heat, deformation and friction are considered negligible compared with the kinetic energy of explosive and metal. The Gurney velocity is the final velocity during the later stage of tube wall expansion.

The radial wall expansion over time and VOD are measured. Here the final metal velocity perpendicular to the tube axis, U_m, was evaluated by setting $U_m = a$ in Equation 8. Thus U_L comes out by Equation 8 and 9 (Kennedy 1997).

$$\theta = \arctan\left(\frac{U_m}{VOD}\right) \tag{8}$$

$$U_L = 2 \cdot VOD \cdot \sin\left(\frac{\theta}{2}\right) \tag{9}$$

Evaluating the acceleration of the copper wall makes it is easier to see that the initial expansion rate is increasing with decreasing charge diameter, see the acceleration evaluation for pure E682 in Figure 7.

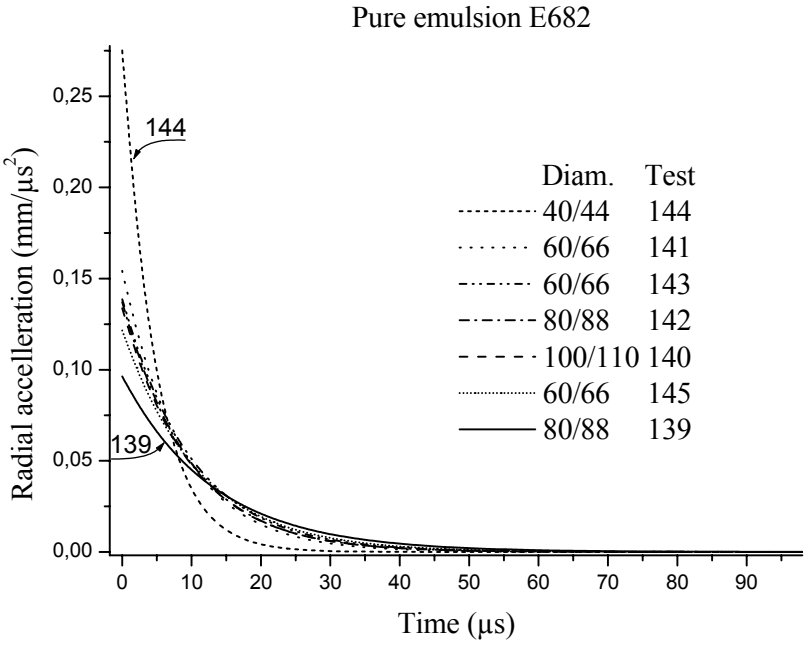
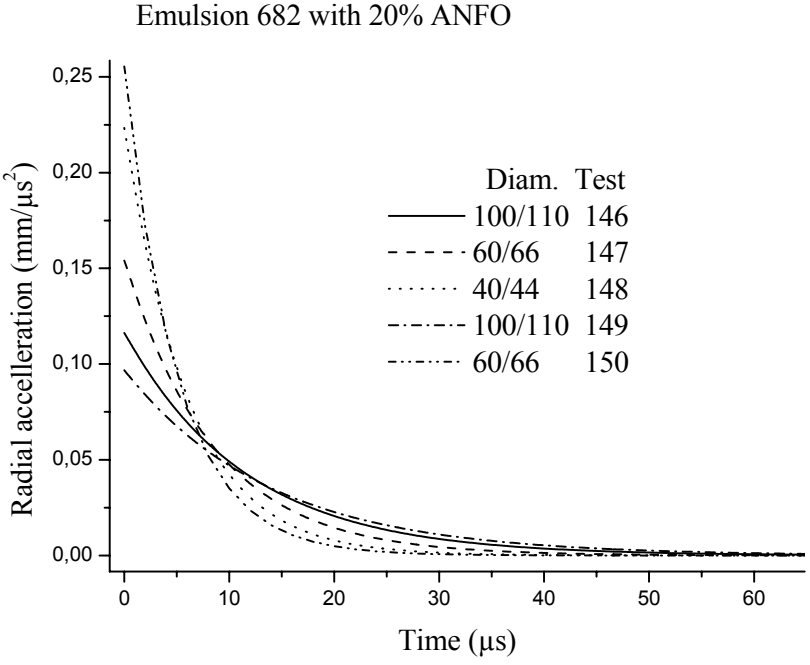


Figure 7. The radial acceleration of the copper wall for pure E682.

The radial acceleration for E682 with 20% ANFO is shown in Figure 8. With the exception of test 150, there is a clear trend that a smaller charge diameter leads to faster initial acceleration. This is natural since the mass of coppar decreases much more than the accelerating detonation pressure when the charge diameter decreases (keeping a constant ratio of metall mass to explosive mass).



Figur 8. The radial acceleration as function of time for E682 with 20% ANFO.

This increase in acceleration is easy to explain. Consider the initial acceleration of the copper wall the first microseconds. The wall pressure, P_w, is proportional to the CJ pressure, P_{CJ}, and acts over the inner wall surface. Newton's second law leads to the radial acceleration, a_r, of the tube wall where ρ_{Cu} is the density of the tube material and t_w is the tube wall thickness:

$$a_r \propto \frac{P_{CJ}}{\rho_{Cu} \cdot t_w} \tag{10}$$

The CJ pressure is related to the VOD (Davis 1997):

$$p_{CJ} \propto VOD^2 \tag{11}$$

Based on our experiments, the VOD drops from about 5700 m/s for 100 mm tubes to about 5300 m/s for 40 mm tubes in the case of the emulsion with 20% ANFO see table 4. At the same time the wall thickness is reduced from 5 mm to 2 mm. This results in the following ratio of the initial tube wall acceleration:

$$\frac{a_{r(100)}}{a_{r(40)}} = \frac{5700^2/5}{5300^2/2} = 0.46 \qquad (12)$$

The ratio should be smaller in the case of the pure emulsion due to the smaller VOD reduction caused by the diameter effect but this was not seen in this evaluation. This ratio is in agreement with the experimental results, 0.49 in the case of pure E682 and 0.48 in the case of E682 with 20% ANFO.

Also, it is seen that larger diameters show a more slower decreasing acceleration than the thinner ones. This is natural since the pressure drop is faster in time for the smaller charge diameters. The initial movement of the copper wall starts smoothly with no "jump off" or pressure spike for nonideal explosives compared with ideal explosives (Davis & Hill 2001). This is probably due to the extended reaction zone in the non-ideal explosives (Östmark et al. 2002).

Table 8 gives the computed "a" and "b"-values used in Equation 3. "a" represents the asymptotic expansion velocity perpendicular to the tube axis, U_m, in Equation 8. U_L has been calculated by using Equations 8 and 9. "1/b" measures the length of acceleration phase.

Table 8. Curve fit constants and computed true maximum expansion velocities (Gurney velocity).

Test	ANFO (%)	Charge diameter (mm)	a (m/s)	$b \cdot 10^4$ (s^{-1})	1/b (μs)	a·b ($mm/\mu s^2$)	U_L (m/s)
139	0	80	1262	7.632	13.10	0.0963	1239
140	0	100	1291	10.36	9.653	0.1337	1267
141	0	60	1323	11.66	8.576	0.1543	1296
142	0	80	1314	10.43	9.588	0.1371	1288
143	0	60	1379	10.05	9.950	0.1386	(1349)
144	0	40	1310	21.00	4.762	0.2751	1285
145	0	60	1320	9.210	10.86	0.1216	1294
146	20	100	1341	8.672	11.53	0.1163	1313
147	20	60	1300	11.85	8.439	0.1540	1272
148	20	40	1331	16.78	5.959	0.2233	1300
149	20	100	1333	7.258	13.78	0.0967	1305
150	20	60	1287	19.84	5.040	0.2553	1261

The statistics for the Gurney velocity become 1284 ± 21 m/s (mean ± standard deviation) if specimen 143 is excluded, see below.

Figures 9 and 10 show the value of "a" and initial acceleration "a·b" as function of charge diameter:

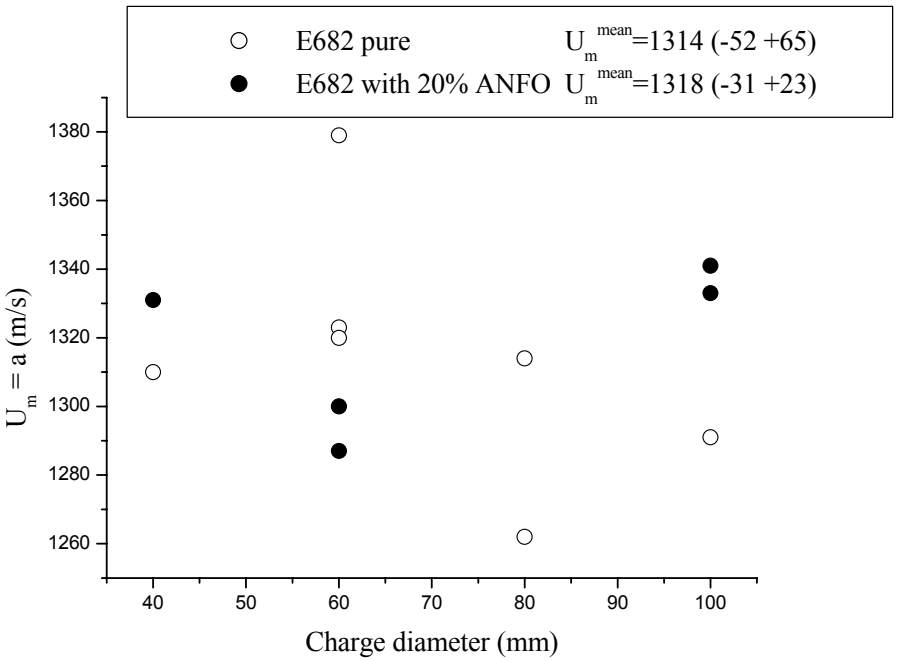


Figure 9. The constant "a"=U_m vs charge diameter for E682.

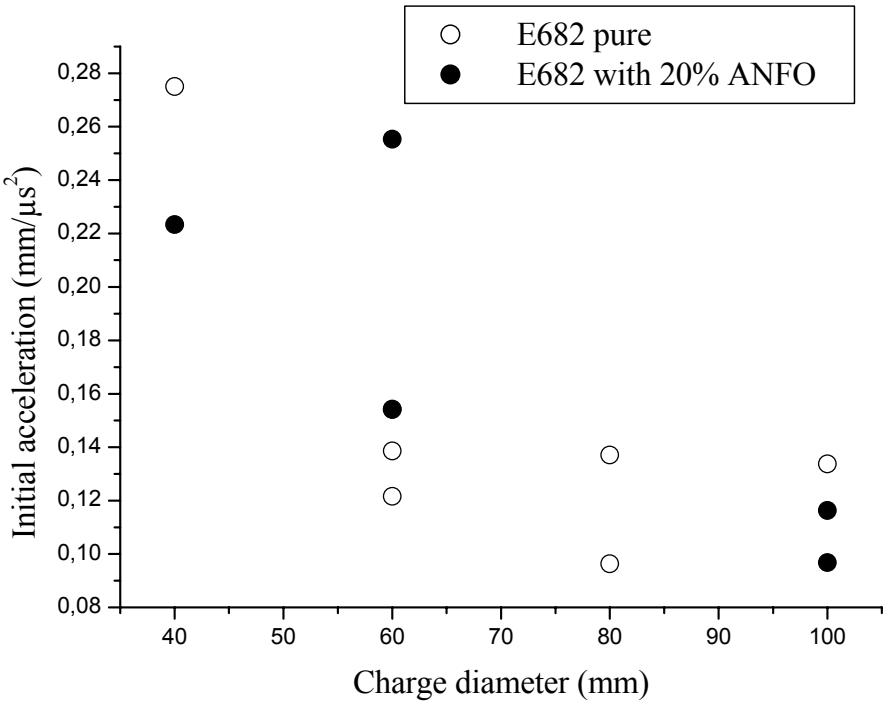


Figure 10. The initial acceleration "a·b" vs charge diameter of E682.

The metal acceleration depends on the charge diameter as seen in Figure 10 where it is clear that smaller tubes have a faster initial acceleration than the larger ones.

Another way of looking at the expansion data is to plot the metal velocity against the relative volume expansion instead of time. The relative volume is simplified by neglecting the axial expansion and only taking into account the radial expansion, like:

$$\frac{v}{v_0} = \frac{r^2}{r_0^2} \tag{13}$$

Figure 11 shows the metal velocity as function of the volume expansion ratio for the present tests with pure E682:

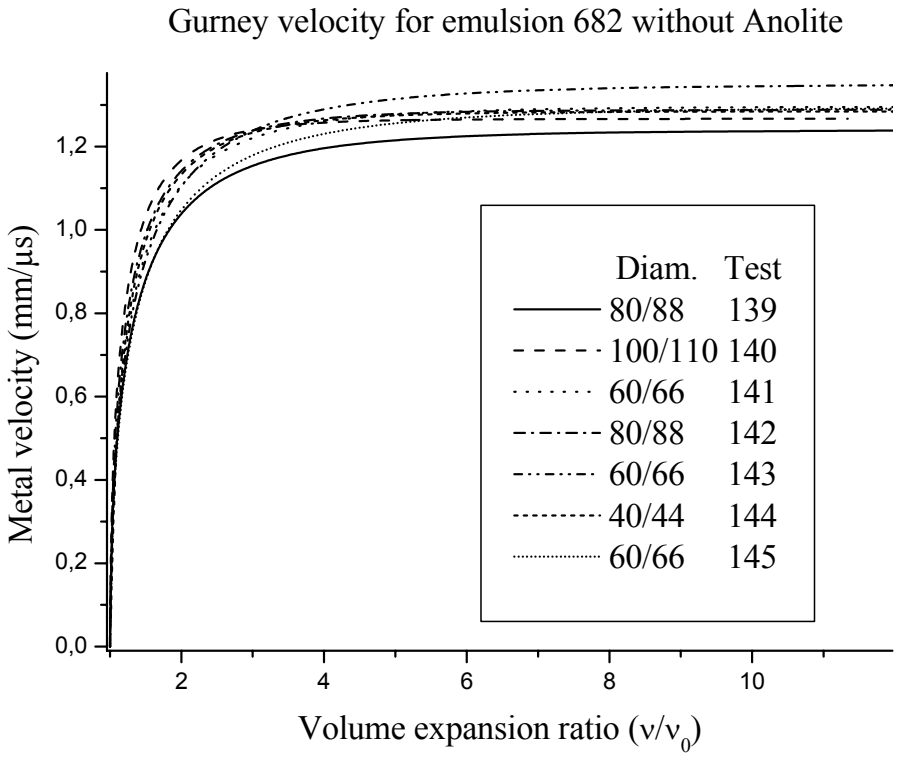


Figure 11. The metal velocity as function of volume expansion ratio for pure E682.

It is seen that test 143 (∅ = 60 mm) reaches a higher final metal velocity than the others. This could be explained by uneven rupture of the copper cylinder, which might have caused the loss of two data points from the contact pins in this test. A possible thinner wall caused by irregularity in the copper tube quality would also lead to faster wall velocities and earlier rupture.

Test 139 (∅ = 80 mm) is slower than the others, which might be explained by a thicker tube wall than specified. The tube wall thickness was 4 ± 0.4 mm in the case for the ∅ 80/88 tubes while the other tubes held less than ± 0.1 mm variation in tube wall thickness. Unfortunately,

this variation was detected during the experiments. Such a large variation results in an experimental error larger than the effect of the addition of ANFO or changing charge diameter. The final Gurney velocity for pure E682 reaches 1278 ± 22 m/s (mean ± standard deviation), test 143 excluded.

The same situation persists when E682 is mixed with ANFO. The metal velocity reaches about 1290 ± 22 m/s, see Figure 12. This does not differ significantly from the pure E682 result.

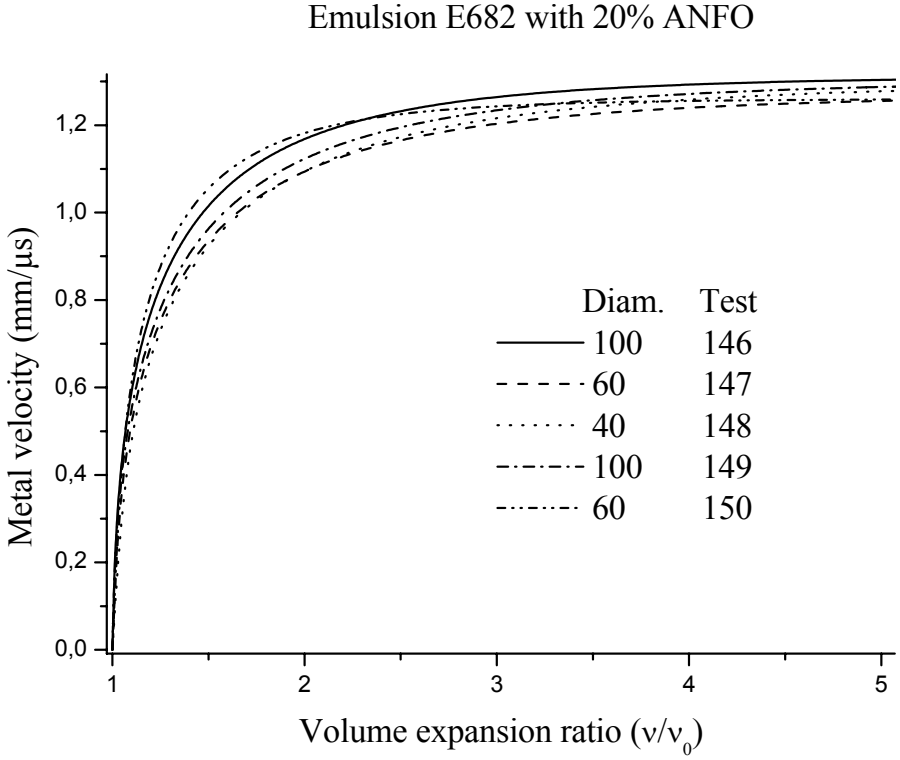


Figure 12. The metal velocity of E682 with 20% ANFO.

The final metal velocity seem to be almost independent of the tube diameter and reaches about 1290 m/s. There is no clear trend that the final velocity depends on the charge diameter. In the case of ideal explosives, the final velocity should be constant regardless the charge diameter when using scaled cylinders.

Table 9 shows the development of the Gurney energy term $E(\nu/\nu_0)$ of Equation 6 at two different volume expansion ratios. The Gurney energy term is expressed as actual kinetic energy in percent of final Gurney energy at specific volume expansion ratios of $\nu/\nu_0 = 5$ and 10. By sorting the 4:th column after increasing % of final Gurney energy it is seen that the addition of ANFO does not decrease the reaction rate in the afterburn zone. The E682 with 20 % ANFO for the present study seem to be slightly faster which could be due to the higher density compared with pure E682. Also, the diameter does not clearly change the final expansion rate as is also seen in Figure 9.

Table 9. Gurney energy term at expansion ratios of 5 and 10 for the tests.

Test	ANFO (%)	Charge diameter (mm)	% of E_G at $v/v_0 = 5$	% of E_G at $v/v_0 = 10$	E_G (MJ/kg)
139	0	80	95.2	98.8	1.65
145	0	60	95.5	98.9	1.81
143	0	60	95.9	99.0	(1.96)
148	20	40	96.6	100.0	1.74
141	0	60	96.7	99.4	1.83
149	20	100	97.1	99.4	1.75
147	20	60	97.6	100.0	1.67
142	0	80	98.3	100.0	1.78
144	0	40	98.9	100.0	1.79
146	20	100	98.9	100.0	1.77
140	0	100	99.4	100.0	1.73
150	20	60	100.0	100.0	1.64

The statistics for the Gurney energy become $E_G = 1.74 \pm 0.10$ MJ/kg when test 143 is excluded.

If the first and the second column are plotted, it is possible to see an effect of diameter and 20 % ANFO addition but this effect is of the same order as the experimental scatter and can not be considered significant, see Figure 13:

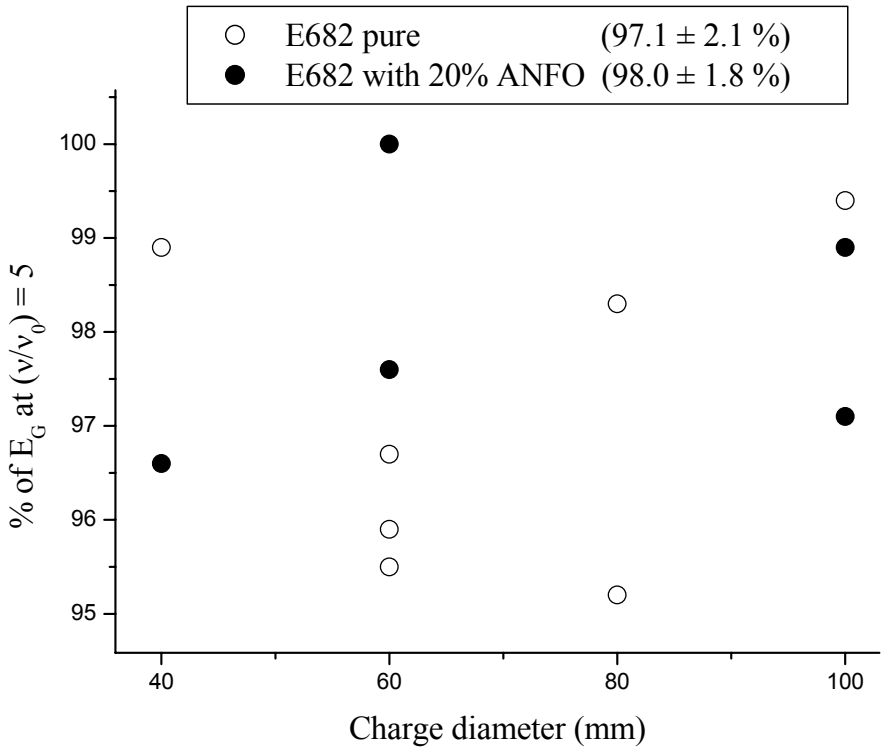


Figure 13. The % of final Gurney energy at $v/v_0=5$ for E682.

Results from the earlier study done by Nie (2001) show that pure E682 reacts somewhat faster than E682 with 20% ANFO, see Table 10, which is sorted after column 4. It is also seen that the 80 mm charge diameter shots have abnormally high Gurney energies.

Table10. Gurney energy at expansion ratios of 5 and 10 for E682 done by Nie (2001).

Test	ANFO (%)	Charge diameter (mm)	% of E_G at $v/v_0 = 5$	% of E_G at $v/v_0 = 10$	E_G (MJ/kg)
010319	20	40	95.4	99.4	1.73
010405b	20	100	95.4	99.5	1.95
010410	0	80	95.6	99.6	(2.25)
010220	0	80	96.9	99.6	(2.30)
010315	20	80	97.1	99.5	(2.10)
010405a	20	80	97.5	100.0	(2.01)
010418	0	100	98.3	100.0	1.80
010110	0	100	100.0	100.0	1.72
001214	0	40	100.0	100.0	1.89

Figure 14 shows the % of final Gurney energy at $v/v_0=5$ for the old tests with E682.

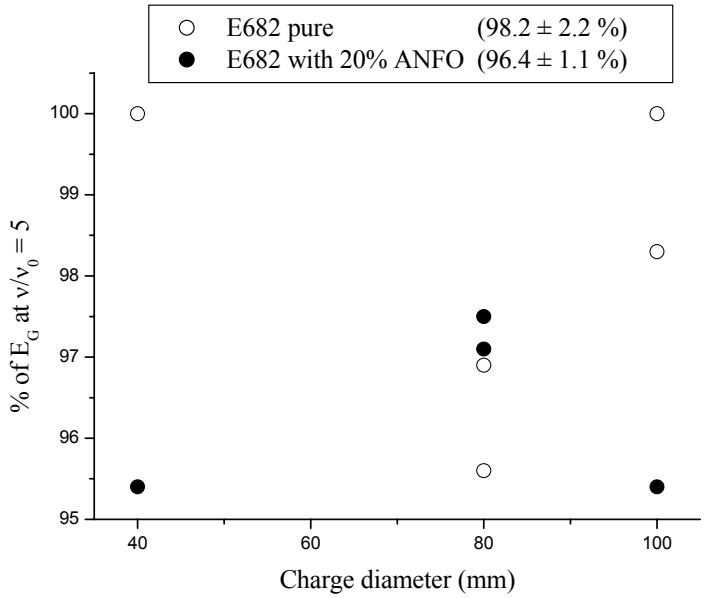


Figure 14. The % of final Gurney energy at $v/v_0=5$ for E682, tests done by Nie (2001).

Even though there is a large scatter in Figures 13 and 14 it is seen that both show maximum for the E682 with 20% ANFO and a minimum for pure E682. The expected trend would have been a decreasing % of final Gurney energy as function of diameter since a smaller diameter leads to a more curved detonation front and hence a longer afterburn zone. Note that the scatter of the results are of the same order as the above mentioned trends and hence no conclusion can be drawn.

Figure 15 shows the VOD as function of inverse charge diameter for the present study and for the old study done earlier by Nie (2001). The new VOD values for pure E682 are significantly lower than the older values. Regarding E682 with 20% ANFO, the agreement is fairly good between the present and the old study.

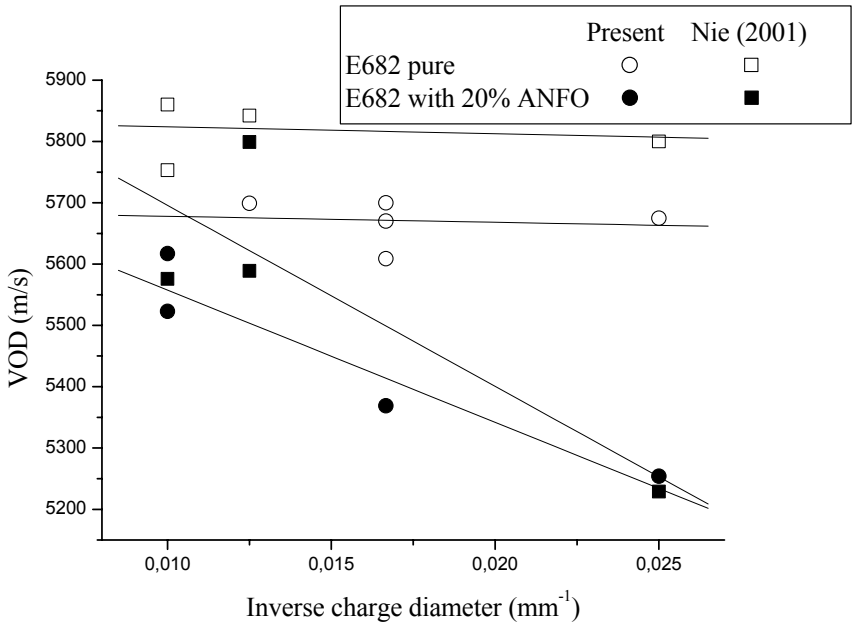


Figure 15. VOD(1/∅) for the present study in comparison with the batch used by Nie (2001).

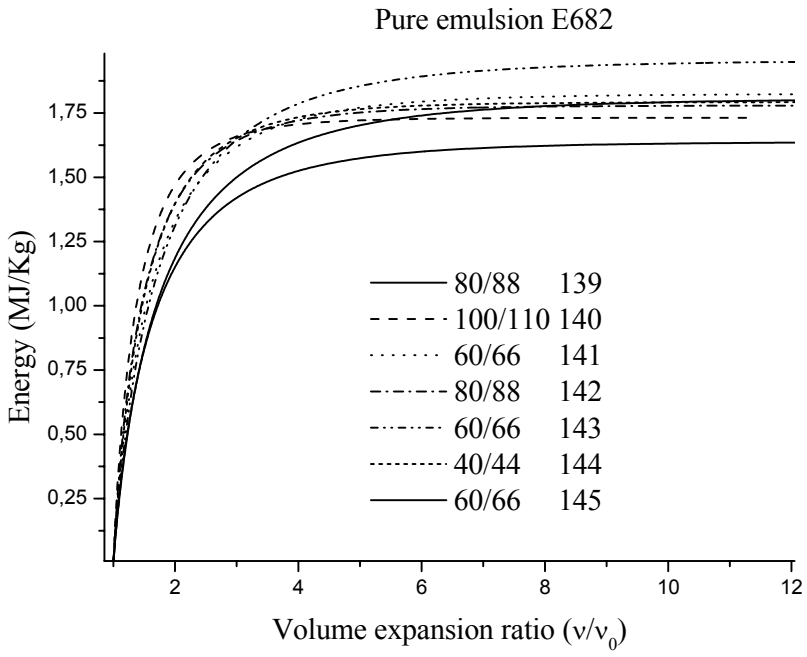


Figure 16. The Gurney energy term as function of volume expansion ratio for pure E682.

Figure 16 above shows the Gurney energy for pure E682. Tests 139 and 143 follow the same trend as shown for the metal velocity in Figure 10. Within the experimental scatter and range, it is not possible to say that the Gurney energy depends on the charge diameter. The Gurney energies for pure E682 reach a stable value around 1.77 ± 0.06 MJ/kg, test 143 excluded.

According to Garza et al. (1992) the Gurney energy did not change between two cylinder tests with ANFO in ∅50.8/55.88 mm and ∅101.6/111.76 mm tubes. This indicates that it remains constant when changing charge diameter even though the detonation velocity and the curvature of the detonation front both change, see p 167 in Nie (2000). As shown above however, the acceleration phase is different for different charge diameters in the scaled experiments.

The Gurney energy for E682 with 20% ANFO does not show any clear trend with charge diameter and it reaches about 1.71 ± 0.07 MJ/kg, see Figure 17 and 18 below:

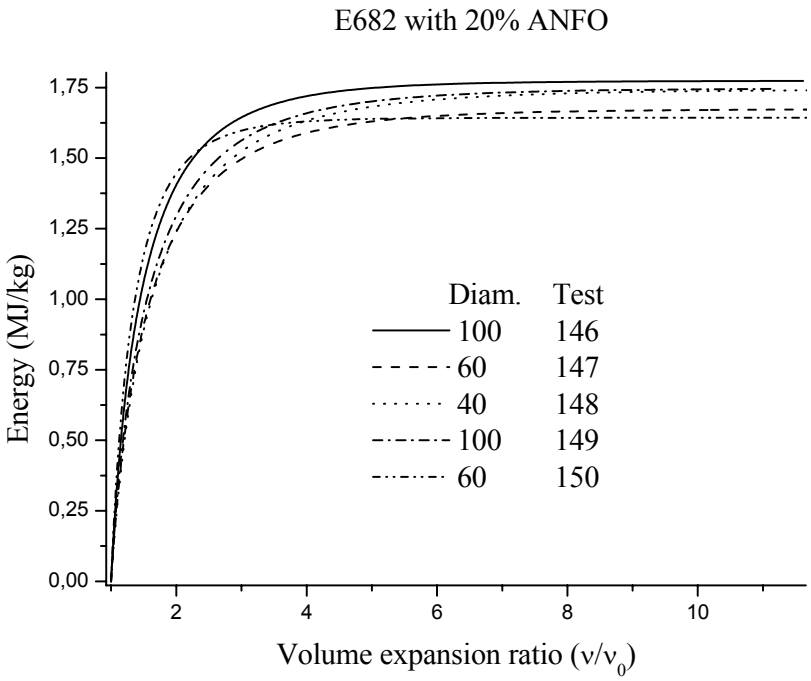


Figure 17. The Gurney energy term for E682 with 20 % ANFO.

E682 with 20% ANFO has a slightly higher explosion energy (E_0) than the pure E682. The density increases from 1130 kg/m^3 to 1200 kg/m^3 when adding ANFO. Also, a Tiger calculation shows that the explosion energy, which increases from 3.07 to 3.21 MJ/kg, results in a 11% charge increase from 3.47 to 3.85 MJ/dm^3 on a volume basis.

100%	E682	E_0 = 3.07 MJ/kg or 3.07·1130 = 3.47 MJ/dm^3
80%	E682 + 20% ANFO	E_0 = 3.21 MJ/kg or 3.21·1200 = 3.85 MJ/dm^3

This should give a higher Gurney energy when adding ANFO but the utilisation ratio E_G/E_0 is slightly lower for emulsions with ANFO than for pure emulsions (Nyberg et al. 2003). The average utilisation ratios in Table 11 are 0.58 ± 0.03 (test 143 excluded) for pure E682 and

0.53 ± 0.03 for E682 with 20% ANFO. An estimate of available volume based Gurney energy is done below:

E682 0% ANFO: $E_G = 3.07 \cdot 0.58 = 1.78$ MJ/kg or $1.78 \cdot 1130 = 2.01$ MJ/dm^3
E682 20% ANFO: $E_G = 3.21 \cdot 0.53 = 1.70$ MJ/kg or $1.70 \cdot 1200 = 2.04$ MJ/dm^3

There is a small difference between pure E682 and E682 with 20% ANFO. This may be seen in the small difference in Gurney velocities between pure E682 and E682 with 20% ANFO. Similar energy utilisation ratios were found for the tests made by Nie (2001), see table 12.

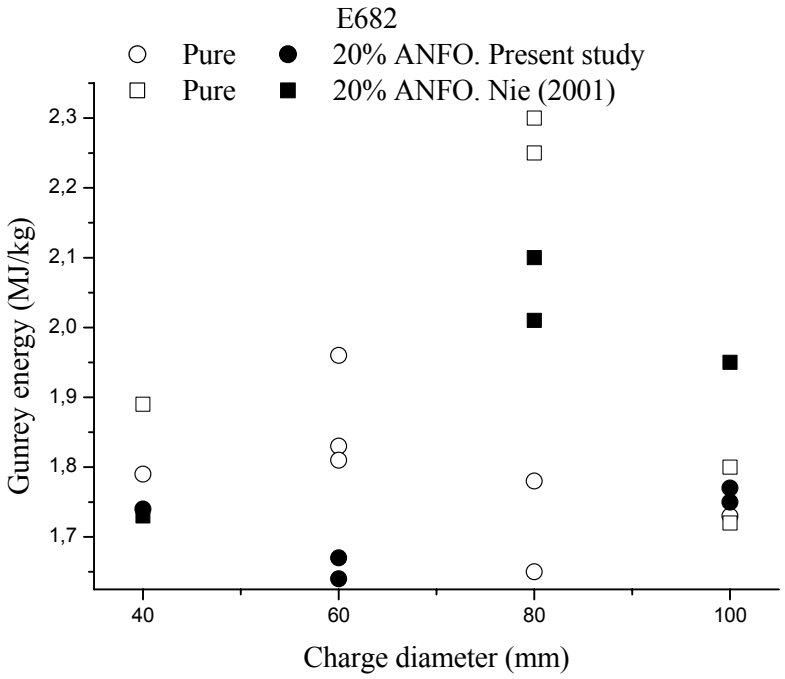


Figure 18. The Gurney energy as function of charge diameter for E682.

Table 11. Gurney energy and the energy ratio with the explosion energy E_0, present study.

Test	ANFO (%) (Anolit)	Charge diameter (mm)	E_G (MJ/kg)	E_G/E_0	E_G (MJ/dm^3)
139	0	80	1.65	0.54	1.89
140	0	100	1.73	0.56	1.95
141	0	60	1.83	0.60	2.05
142	0	80	1.78	0.58	2.03
143	0	60	(1.96)	(0.64)	(2.23)
144	0	40	1.79	0.58	2.00
145	0	60	1.81	0.59	2.05
146	20	100	1.77	0.55	2.13
147	20	60	1.67	0.52	2.00
148	20	40	1.74	0.54	2.09
149	20	100	1.75	0.55	2.11
150	20	60	1.64	0.51	1.96

Table 12. The Gurney energy and the energy ratio with the explosion energy E_0, (Nie 2001).

Test	ANFO (%) (Prillit A)	Charge diameter (mm)	E_G (MJ/kg)	E_G/E_0	E_G (MJ/dm^3)
010319	20	40	1.73	0.54	2.01
010405b	20	100	1.95	0.61	2.27
010410	0	80	2.25	0.73	2.63
010220	0	80	2.30	0.75	2.69
010315	20	80	2.10	0.65	2.44
010405a	20	80	2.01	0.63	2.34
010418	0	100	1.80	0.59	2.10
001214	0	40	1.89	0.62	2.21
010110	0	100	1.72	0.56	2.01

Note: ρ (E682) = 1169 kg/m^3 and ρ (E682 20% Prillit A) = 1163 kg/m^3. Anolit is the same product as Prillit A according to Dyno Nobel.

5 Conclusion

The detonation velocity for E682 with 20% ANFO, present study, decreases from 5620 to 5250 m/s, i.e. by 7 % when the charge diameter decreases from 100 to 40 mm. The detonation velocity for pure E682 decreases less than 2% for the same change in charge size.

The Gurney velocity or the true final velocity of the copper wall does not show any trend with charge diameter. The Gurney velocity of the copper wall is about 1285 m/s for both pure E682 (0% ANFO) and for E682 with 20% ANFO. The standard deviation for 11 tests is less than 25 m/s and the range 1240-1315 m/s

The acceleration is faster for the thinner tubes due to the moderate drop in detonation pressure caused by the drop in detonation velocity. The range of values is about 0.1-0.3 mm/μs^2.

The Gurney energy and the utilization of the explosion energy seem to be unaffected by the charge diameter in the range studied, 40-100 mm. The value is 1,74 MJ/kg with a standard deviation of about 0,06 MJ/kg for 11 tests. The range of measured values is 1,65-1,83 MJ/kg.

The Gurney energy for pure E682 is slightly higher than for E682 with 20 % ANFO, 1,77 MJ/kg versus 1,71 MJ/kg. This difference is hardly significant considering the experimental scatter. Compensating for the difference in density, 1130 versus 1200 kg/m^3, gives volume based values that are still closer. Within the limits of our experiments we have found that the Gurney energy does not significantly change when adding ANFO to E682.

The energy utilisation ratio is 0,58 ± 0,03 for pure E682 and 0.53 ± 0,03 for E682 with 20% ANFO, which is very close to Titan 6000 series bulk emulsion at similar densities.

The Gurney energy from the present study of E682 is lower than that in the previous study by Nie (2001) indicating differences E682 batches. This could be seen by the differences in density. The ANFO quality could also be of some importance, even if the Anolit used in the present study shouldn't differ much from the Prillit A used in the previous study.

6 References

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