

9. Explosives

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Demilitarized propellants as ingredients in commercial explosives

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ABSTRACT: The traditional way of disposing of demilitarized energetic materials was by open burning or open detonation. However, demilitarized energetic materials such as explosives and propellants are a useful source of energy for civilian applications. The excess military explosives and propellants can be reused as components in commercial explosives. ANFO (ammonium nitrate-fuel oil) is a very popular and inexpensive explosive. The influence of double base propellants (DBP) on detonation characteristics of ANFO was assessed. Properties of ammonium nitrate prills determine the physical stability and detonation characteristics of ANFO. Some physical characteristics of ammonium nitrate prills (densities, size distributions and structure examination by scanning electron microscopy) were determined. Investigated explosive mixtures contained 20, 40 and 60% of the propellants. We measured velocity of detonation and intensity of blast waves (peak blast overpressures) generated by the explosion of the mixtures. Positive phase impulses were also calculated. Some parameters of ANFO/DBP compositions increased along with the propellant content.

1 INTRODUCTION

The traditional way of disposing of demilitarized energetic materials was by open burning or open detonation. Known as OB/OD, this method consists of burning or exploding old ammunition in open sites designated for the purpose. In recent years, however, OB/OD – which involves release of toxic fumes into the atmosphere – has come into conflict with environmental, health and safety regulations. The idea to use the excess military explosives and propellants in commercial explosives seems to be attractive (van Rooyen 1994, Matseevich 1999, Burch et al. 2003). The propellant that consists basically of nitrocellulose can be removed relatively easily from the ammunition. A mixture of smokeless small-grained powder and ammonium nitrate, added for compensation of oxygen balance, is the simplest example of military explosive reuse (Vetlicky & Dosoudil 2000). Propellants can be used as sensitizer ingredients in watergel slurry explosives or water-in-oil emulsion explosives (Kaltsey et al. 1995, Okhrimenko et al. 1997, Eck et al. 2000). They

usually contain 25-35 % either single base or double base smokeless powder propellants.

There are numerous commercial explosives suitable for double base propellants incorporation (Maranda et al. 2002, Lipińska et al. 2003). Ammonium nitrate (AN), which is intended for use as an oxidizer in explosives, is manufactured in the form of porous prills. The prills can absorb liquid carbonaceous fuel to produce ANFO (ammonium nitrate and fuel oil). ANFO is one of the most popular industrial explosives because it is safe and easy to handle. It is also relatively inexpensive. Properties of AN prills determine the physical stability and detonation parameters of ANFO (Sugihara et al. 2003, Kwok et al. 2003).

2 MATERIALS

Three different types of commercial ammonium nitrate prills were chosen. They were products targeted for use as an oxidizer in explosives. They were commercial prills with additives, but the type and the amount of the additives were not known. The samples identified as AN 1 and AN 3, were

low-density porous AN type, AN 2 was a conventional porous prilled AN type.

Adequately, three types of commercial ANFO were used in this study. Designated as ANFO 1, ANFO 2 and ANFO 3, they were made of the above mentioned ammonium nitrate prills. An energetic additive double base propellant was chosen. Double base propellants contain nitrocellulose of various nitration levels, nitroglycerine and inert plasticizers to modify either the flame temperature or the physical properties of the propellant. Propellant contained 40 % of nitroglycerine. The propellant was in the form of squares of 2×2 mm, having a thickness of 0.25 mm.

3 METHODS

We determined some physical characteristics of prilled ammonium nitrate. They included bulk density, apparent density, size distribution and oil absorption. The bulk density refers to the density of prills including pores and inter-prills spaces. The apparent density means the mass of AN divided by its apparent volume (volume excluding open pores but including closed pores). The apparent density of AN was established by gas (helium) pycnometer. This provides a more accurate determination of void volumes than can be obtained via liquid displacement. The size distribution was determined by sorting the prills through sieves with various sizes. The prills were sifted in seven size ranges. For oil absorption test only prills over diameter of 1 mm were used. Method of oil absorption test involved measuring the percentage of fuel oil that could only be absorbed into the AN prills.

The external and internal structure of AN prills was examined by scanning electron microscopy. The sample preparation was a standard procedure.

The detonation velocity tests were conducted in steel pipes having an inside diameter of 36 mm, an outer diameter of 42 mm and a length of 210 mm. The explosives were loaded into pipes with mod-

erate tamping. Detonation velocity was determined by the measurement of the time of detonation wave transition through three sections; each of them was 40 mm long. Every explosive was initiated by RDX/Al booster with a detonator. Measurements of time were done by short circuit sensor method.

We also measured the intensity of blast waves generated by the explosion of ANFO/DBP mixtures. Investigated mixtures were loaded into paper tubes having an inside diameter of 45 mm and an outer diameter of 50 mm. The weight of every explosive was 350g. Two PCB quartz pressure transducers were located: the first one 2 m and the second one 3 m away from the centre of charges. The charges were hung 1.5 m above the ground. The gauges registered overpressure in the transient shock waves, sliding on the working surface of the device.

4 RESULTS & DISCUSSION

4.1 Physical characteristics of ammonium nitrate prills

The bulk density, apparent density and oil absorption test values of three different AN are summarized in Table 1. The size distribution test data are given in Table 2.

Table 1. Physical characteristics of AN prills.

Type	Bulk density [g/cm ³]	Apparent density [g/cm ³]	Oil absorption [%]
AN 1	0.82	1.61	3.3
AN 2	0.69	1.70	8.7
AN 3	0.72	1.69	9.1

Table 2. Size distribution of AN prills.

Type	Mass with prill diameter [%]						
	>2,50	2,00-2,50	1,60-2,00	1,25-1,60	1,00-1,25	0,80-1,00	<0,80
AN 1	2,7	15,1	81,5	0,2	0,5		
AN 2	1,1	7,3	75,8	8,6	4,9	1,4	0,9
AN 3	1,5	32,0	63,1	1,4	1,7	0,2	0,1

When a solid material is in granular or powdered form, the bulk contains three types of void: open pores, cavities with no access to an external surface and interparticle space.

The total volume of interparticle voids depends on the size and shape of the individual particles and how well the particles are packed. There is a significant difference in bulk density and apparent density of AN 1 and AN 2. Although AN 1 bulk density is higher, its apparent density is lower. That means that there are more closed pores in AN 1. There are no significant differences between AN 2 and AN 3. The volume of closed cavities in the cases of AN 2 and AN 3 is small, as the density of ammonium nitrate is $1,73 \text{ g/cm}^3$.

AN also differ in size distribution of prills that is wider in the cases of AN 2 and AN 3. Neither of the AN samples proved to contain a significant amount of fine material. The development of size distribution of AN 2 and AN 3 influences the bigger values in oil absorption test.

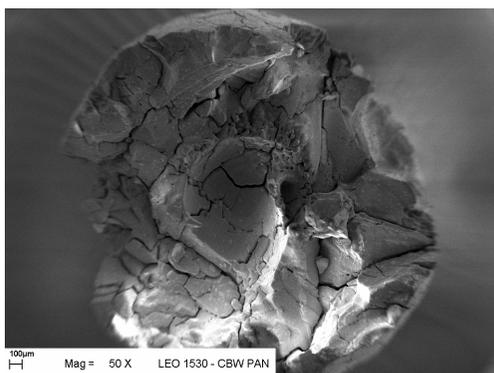


Figure 1. SEM micrograph on the cross-section of AN 1 prill.

4.2 Structure examination by Scanning Electron Microscopy

The external and internal structure of AN prills was examined by scanning electron microscopy. Although we can only examine the sample surface with a small viewing area it is sufficient for evaluating the differences in prill structure. We investigated the external and internal surface of AN prills. The external surface of AN prills is not smooth. The internal structure of the prills is more interesting. As depicted in Fig. 1, 3 and 5 AN prills have an internal central hollow, but AN 2 also have some smaller hollows around the central one. The internal structure of AN 1 is different (Fig. 2). There are lots of small pores and

the structure of AN resembles pumice-stone. These small pores have no connection with the external surface of the prills and that is why AN 1 prill has lower apparent density.

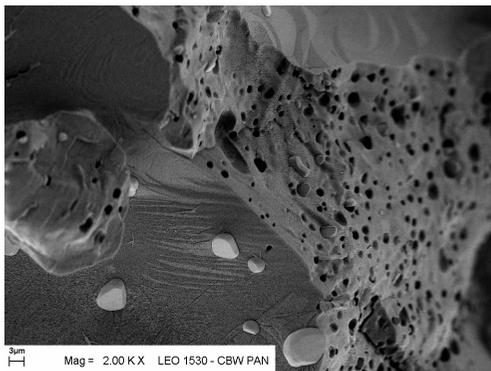


Figure 2. SEM micrograph on the internal surface of AN 1 prill.

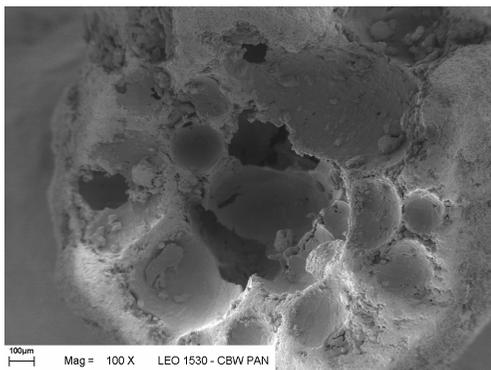


Figure 3. SEM micrograph on the cross-section of AN 2 prill.

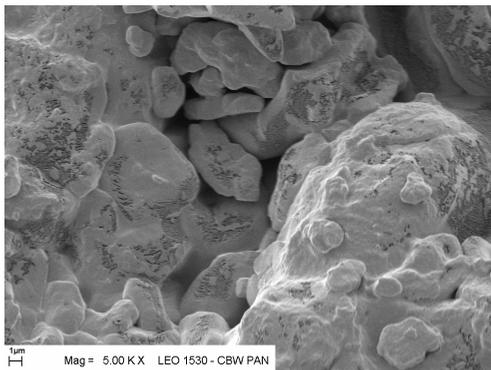


Figure 4. SEM micrograph on the internal surface of AN 2 prill.

The internal structure of AN 2 and AN 3, as shown in Figures 4 and 6, consists of interconnected grains.

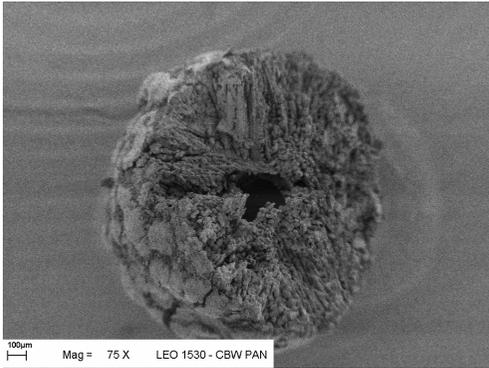


Figure 5. SEM micrograph on the cross-section of AN 3 prill.

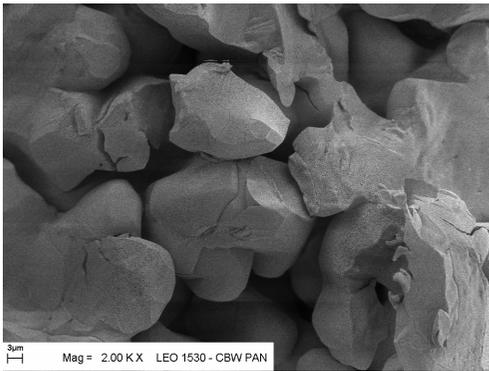


Figure 6. SEM micrograph on the internal surface of AN 3 prill.

4.3 Velocity of detonation

Compositions of investigated mixtures and results of detonation velocity measurements are presented in Table 3.

The low-density ANFO has the improved detonation characteristics, such as detonation velocity, in comparison with the conventional one. The results show that the addition of double base propellant increases detonation velocities of all the ANFO explosives. The bigger the propellant content is, the higher the detonation velocity of investigated explosives. That indicates detonation process in investigated mixtures propagates mainly between grains of propellant. The increase in detonation velocities is the most significant in the case of ANFO 1. That means that conventional ANFO can improve its detonation characteristics

by the addition of propellant of high detonation velocity. Explosives with 40% of double base propellant have the most favorable detonation parameters.

Table 3. Detonation velocities of investigated mixtures.

Explosive composition	Tap density [g/cm ³]	VOD [m/s]
Double base propellant	0.74	4290
ANFO 1	0.97	2000
ANFO 2	0.76	2560
ANFO 3	0.82	3110
ANFO 1/ DBP 80/20	0.94	3050
ANFO 1/ DBP 60/40	0.85	3540
ANFO 2 / DBP 80/20	0.78	3280
ANFO 2 / DBP 60/40	0.77	3610
ANFO 3/ DBP 80/20	0.80	3500
ANFO 3/ DBP 60/40	0.75	3740

4.4 Peak blast overpressure

The results of peak blast overpressure measurements obtained for investigated explosives are shown in Figures 7 and 8. Comparative tests were made for TNT. Mass of TNT charge was also 350g.

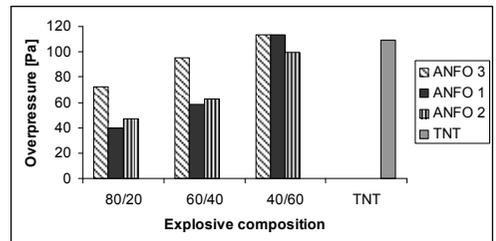


Figure 7. Peak blast overpressures for ANFO/DBP at 2 m.

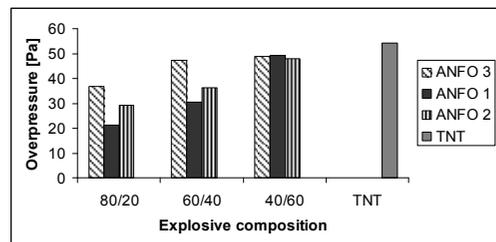


Figure 8. Peak blast overpressures for ANFO/DBP at 3 m.

As expected, peak blast overpressures of explosion products showed the same tendency as VOD values, growing with the increase of DBP content for ANFO. Both values obtained at the first and the second transducer (2 m i 3 m) for the mixtures containing 40% of ANFO and 60% of DBP were nearly the same. The increase in propellant content caused the significant grow in peak overpressure values for ANFO/DBP explosives, with the highest overpressure for 60% of DBP.

4.5 Positive phase impulses

The positive phase impulses were calculated by integrating the blast overpressure signals until a time when the pressure falls below atmospheric pressure. They are shown in Figures 9 and 10.

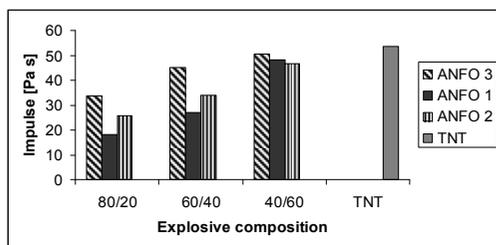


Figure 9. Positive phase impulses for ANFO/DBP at 2 m.

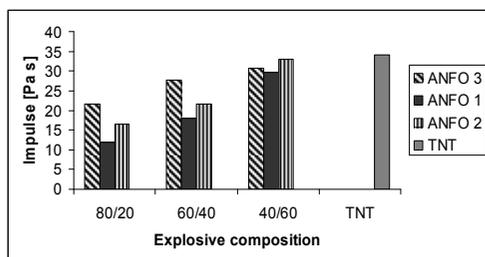


Figure 10. Positive phase impulses for ANFO/DBP at 3 m.

The impulses correspond with overpressure values. There are almost no differences in values of impulses for all the compositions containing 40% of ANFO and 60% of DBP, both at the distance of 2 and 3.

5 CONCLUSIONS

In the case of investigated mixtures the achievement and propagation of detonation is very complex. The large fraction of the total energy of the mixtures derives from reactions between

components. In the case of investigated compositions their parameters (detonation velocities, peak blast overpressures and positive phase impulses) increased along with the propellant content. That means a factor determining detonation parameters in ANFO/DBP explosives is the amount of energy that is generated in chemical reactions of the propellant in detonation wave. The improvement in detonation characteristics by the addition of propellant of high detonation velocity was especially visible for conventional ANFO.

Blast wave parameters were influenced by the conditions of measurements. All the charges were very lightly confined and their diameter was small. Practically there was no difference observed in blast wave parameter values among the mixtures of ANFO and 60% of DBP and it showed at high propellant content principal reaction is exothermic decomposition of the propellant. However, dominant reaction at lower propellant contents (20 and 40%) is explosive reaction of ANFO. It follows that investigated explosive mixtures are non-ideal. Probably there are no reactions between the propellant and ANFO.

The application of double base rocket propellants as raw materials for manufacturing of various explosive mixtures useful in civilian applications is a promising way of their disposal. Moreover, the use of these propellants as ingredients of commercial explosives would produce industrial explosives exhibiting a favourable cost for performance.

REFERENCES

- Burch D., Griggs J., Johnson M., Poehlein S., Sims 2003. Development of environmentally friendly demilitarization technologies. *Proc. of Euro Pyro, Saint Malo*. 23-27 June 2003: p. 583 – 596.
- Eck G., Machacek O., Tallent K. 2000. The use of surplus smokeless powder propellants as ingredients in commercial explosive products in the United States. Application of demilitarized gun and rocket propellants in commercial explosives, Dordrecht: Kluwer Academic Publishers: p. 119 – 131.
- Kaltsey V. I., Matseevich B. Glinskiy V. P., Plekhanov N. I., Shalygin N. K., Mardasov O. F., Fridman A. G. 1995. Vzryvchatye materialy iz utyliziruemykh boeprirasov: Problemy, reshenia assortiment Bezopasnost' truda v promyshlennosti, 12: p. 32 – 37.
- Kwok Q., Jones D., Kruus P. 2003. Investigation of the wettability of ammonium nitrate prills, *Proc. of the VI Seminar New Trends In Research Of Energetic Materials, Pardubice*: p. 183-195.
- Lipińska K., Lipiński M., Maranda A. 2003. Influence of double base propellants on detonation velocity of mining blasting agents, *Polish Journal of Applied Chemistry* 47, 3: p. 221-225.

- Maranda A., Lipińska K., Lipiński M. 2002. Analysis of possibility of waste energetic material application in mining blasting agents, *New Trends in Research of Energetic Materials, Proc. of the V Seminar, Pardubice*: p. 136 – 145.
- Matseevich B. 1999. Commercial explosives on the base of removed energetic condensed systems (conception, problems, decisions), *Proc. of Int. Conf. Krasnoarmejsk*: p. 1 – 11.
- Okhrimenko E. F., Ibragimov N. G., Afiatullof E. Kh., Lukin L. S., Yukov Yu. M., Ivanova I. P. 1997. Use of Powders in National Economy, Conversion concepts for commercial applications and disposal technologies of energetic systems. Dordrecht: Kluwer Academic Publishers: p. 213-219.
- Sugihara H., Y. Sato Y., A. Inoue A. 2003. Correlation between physical properties of PPAN and detonation characteristics of ANFO, *Explosives and Blasting Technique*, Lisse: Swets & Zeitlinger: p. 277-281.
- Van Rooyen F. 1994. International trends in demilitarization and disposal of energetic materials, *Proc. of NIXT'94 – Pretoria*: p. 392-402.
- Vetlicky B, Dosoudil T. 2000. Utilisation of double base powders and rocket propellants for production of “dry explosives of slurry type”, Application of demilitarized gun and rocket propellants in commercial explosives, Dordrecht: Kluwer Academic Publishers: p. 25 – 28.

Some applications of demilitarized energetic materials in blasting technique

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ABSTRACT: This paper proposes a specific way of disposal and/or utilization of demilitarized energetic materials (EMs), which is based on their application as fuel and sensitizing components of commercial mixtures of industrial explosives with approximately zero oxygen balance. This method of utilizing the demilitarized EMs is economically effective, safe and environmentally friendly. At present, the direct application of military explosives or propellants in blasting technique is undesirable, primarily because of their sensitivity to outer stimuli, the markedly negative oxygen balance and the impossibility of application of mechanized charging of boreholes. This paper also suggests that the approach to demilitarized EMs shows how advanced a particular country is from the standpoint of both expertise and legislature.

1 INTRODUCTION

The recent policy of détente and replacement of old armament systems by modern technologies have led, during the last fifteen years, to a large accumulation of useless ammunition. While the metal components of this ammunition represent attractive raw materials, its active components, which means high explosives, propellants and pyrotechnics components (i.e. militarily energetic materials) form, from the standpoint of their vast amounts, problematic waste materials classified as hazardous waste. This energy-rich waste is predominantly liquidated in the following ways:

- chemical conversion to higher value products for both civil purposes (raw materials for production of chemicals and plastics, Wanninger, 1995), but also fertilizers (Anon. 1922, Burch 1996) and military purposes (LOVA secondary explosives, Mitchell 2000);
- open burning (OB) of the explosives alone (particularly propellants, Wanninger 1995) or their mixtures with water and colloidal coal (Delyagin 2003, Karabasov 2001);
- open detonation (OD), particularly realized in areas with low population density (Finland, Hagforts 2002, Latvala 2002);
- closed detonation (CD) in a closed, strong metal sphere with a diameter of the order of 1–2 m, for bulk explosives and small whole-piece munitions, up to maximum weight of a few kilograms (Duijm 2002);
- fluidized bed combustion (FBC) for bulk explosives such as TNT that have been transferred to stable water-based slurries (Duijm 2002);
- rotary kiln (RK) for water-based slurries of bulk explosives or propellants such as nitrocellulose (Duijm 2002);
- mobile furnace (MF) for bulk explosives and small whole-piece munitions (Duijm 2002);
- storage and disposal by ocean or land burial (Ahnert 2000, Wulfman 1998);
- direct application in blasting, (Klusacek 1996, Machacek et al. 1999, Munroe et al. 1922, Wulfman 1995);

- reformulation to industrial explosives (Anon. 1922, Kalatsey 1975, Machacek et al. 1997, 1999, Maranda 2002, Morgan 1997, Rabotinski et al. 2000, Salygin et al. 2000, Wulfman 1997, 1998, Zabelin et al. 2003,) or to propellants (smokeless powders).

The interest in chemical conversion of demilitarized energetic materials (EMs) appeared as long ago as the early 1920s; at present, only economically advanced countries can afford to use this way of treatment. OB/OD are a potential source of air and water pollution. Deposition of old ammunition on the bottom of oceans, practised already since the First World War, is illegal at present (UN Law of the Sea, Wulfman 1998). Direct application of these EMs in blasting technique is problematic and it is dealt with in this paper along with the problem of their reformulation to industrial explosives.

2 MILITARY HIGH EXPLOSIVES AND PROPELLANTS IN BLASTING TECHNIQUE

Military high explosives and propellants are characterized by distinctly negative oxygen balance. In the case of rocket propellants, it is even desirable to obtain the explosion burning products of the lowest possible average molecular weight (meaning the highest possible content of carbon monoxide, hydrogen, etc.). With gun propellants, oxygen deficiency leads to excessive muzzle flash. Direct application of these materials in blasting technique is thus connected with potential pollution of the environment with carbon monoxide and other products of imperfect oxidation (Duijm 2002). Military TNT-based explosives could contaminate soil and ground waters by TNT and aminodinitrotoluenes (Hagforts 2002). Ecological risk assessment of detonation products seems to awake public interest (Duijm 2002, Weisberg 1999).

Dismantled military EMs are also generally much more sensitive to outer stimuli when compared with modern commercial secondary explosives. This is especially true of propellants, whose sensitivity to impact and particularly to friction and electric spark is generally considerably high (Salygin et al. 2000, Selesovsky 2002). Such risk can be well documented; for example, by the results of analysis of the accidental explosion of smokeless gunpowder in a temporary storage house in Taketoyo Plant (Kato 2002).

The EMs of propellant type (as indicated by their name) are exclusively constructed as propelling and/or spotting charge; hence they are capable of deflagration at a velocity of 1000–1800 m.s⁻¹ (Urbanski 1939, Kast 1920). However, depending on their composition, shape, specific surface, porosity, surface treatment, perforation of grain, and on the diameter and confinement of charge, some propellants can detonate at a velocity of 4880–7800 m.s⁻¹ (Kast 1920, Munroe 1995, Urbanski 1939, Schubert 2000).

Unsuitable grain size of both military high explosives (usually compact filling) and propellants makes it not possible to fill boreholes sufficiently. Mechanical disintegration of these EMs (grinding) in order to obtain suitable grain sizes represents a problematic and considerably risky operation. The unsuitable grain size of propellants often causes their incomplete decomposition in the process of explosion transformation with subsequent post-combustion in the debris, which is another risk factor of direct application of propellants in blasting technique.

However, the capability of rapid gas generation exhibited by gun propellants is exploited to fracture geologic formations containing fossil fuels (reactivation of oil and gas wells) – this procedure is called tailored pulse fracturing (Burch et al. 1996). Disruptive high explosives of TNT type, hexolites and pentolites can be used, after a slight modification of composition, to produce booster charges; however, they are unsuitable for direct application in modern blasting techniques.

Risk analysis of reasonable technologies for disposing of hazardous explosive waste shows that modern technologies such as high-pressure washout and FBC provide safe and environmentally acceptable solutions for demilitarization (Duijm 2002). Nevertheless, allowing for economics and the present state-of-the-art, the most appropriate solution to the problem of application of demilitarized EMs seems to be in their addition to modern slurry explosives in amounts of 25–35 % by wt. (Eck et al. 2000, Duijm 2002, Machacek et al. 1997, 2002, Maranda et al. 2002, Mitchell et al. 2000, Rabotinski et al. 2000, Salygin et al. 2000, Wulfman et al. 1995, 1997, 1998, Zabelin et al. 2003); the resulting mixture is characterized by approximately zero oxygen balance. A survey of a broad assortment of commercial explosives containing demilitarized EMs is presented in Kalatsey et al's paper, 1975. An addition of fine-grain powders, e.g. to emulsion explosives, can increase the working capacity of the resulting

mixtures by up to 20 % (Odintsov 1994). It was found that a critical amount of high explosives in the slurry or other explosive mixtures with inorganic nitrate oxidizing system varies approximately 30 % by wt. (Zeman et al. 2003). Explosive decomposition is not influenced by the structure of the oxidizing system (solution or crystalline) of such fortified mixtures; only when the content of the additives is above the critical value (Zeman et al. 2003). This is important for preparation of reliably detonating industrial explosives containing demilitarized EMs.

3 NEW TRENDS IN BLASTING TECHNIQUE AND INDUSTRIAL EXPLOSIVES

The Second World Conference on Explosives and Blasting Technique, held in Prague in 2003 clearly showed that the epoch of trial-and-error empirical blasting operations is over, and a new trend is generally gaining ground, that uses a technological-scientific approach based on computational planning of all types of blasting operation with perfect monitoring of all undesirable effects of the operation (seismiss, air-pressure effects, fly rock). This guarantees the viability of blasting operations in the future, even with proper consideration of strict environmental regulations. Complex computer programs are tailored for particular sites, and, used by competent experts, they guarantee safe and effective bursting operations. Effective blasting technique is thus becoming teamwork involving experienced specialists from various fields (mechanics of rocks, properties of explosives and their parameters inclusive of preparation and charging, computational models of the optimum parameters of blasting operation, reliable measurement of fragmentation and undesirable effects). It is only such a team that can provide reliable and functional service for customers and satisfy fully their requirements. In industrially developed countries, such teams operate successfully and the management of the respective mine/quarry can concentrate fully on their main task, i.e. how best to exploit the materials obtained.

In the field of commercial explosives, at present the dominating role is played by ANFO explosives and W/O emulsions prepared at the site of consumption and charged mechanically into the boreholes. A highly promising trend of R&D with already realized outputs is the nano-structured EMs (in the form of aerogels or xerogels, Vavra et al. 2003). The direct application of demilitarized

EMs, particularly smokeless powders, in blasting technique (Munroe 1922, Klusacek 1996, Machacek 1999) stands in sharp contradiction with the above-mentioned trend, and at present it rather represents a sign of misinterpretation of the problem by both experts and legislators. The re-use of energy of these materials added as fuel and sensitizing components to commercial explosives (Mitchell et al. 2000, Wulfman 1997, 1998, Machacek et al. 1997, Kalatsey et al. 1975, Rabotinski et al. 2000, Salygin et al. 2000, Zabelin et al. 2003, Maranda et al. 2002) is one of effective, safe, and environmentally friendly methods of liquidation, which is to a considerable extent compatible with the present trends in blasting technique. It should be emphasized that the liquidation of present military EMs is accompanied by ongoing R&D in the area of their replacement by new, so-called green EMs (GEMs) with easier disarmament and re-use (Anon. 2000).

4 CONCLUSIONS

Military energetic materials (EMs) are characterized by distinctly negative oxygen balance and relatively high sensitivity to outer stimuli, as compared with modern commercial explosives. Direct application of such explosives in blasting, especially TNT-based ones, could contaminate soil and ground waters by toxic products of incomplete detonation (post-combustion in the debris) and their following microbiological degradation. From the point of view of contemporary environment-protection regulations, aspects of work safety, intensification and mechanization of blasting operations, the direct application is undesirable. Their application as fuel and sensitizing additives to commercial explosive mixtures with approximately zero oxygen balance represents one of effective, safe, and environmentally friendly ways of their valuable liquidation. It can be stated that the approach to demilitarized EMs shows how advanced a particular country is from the standpoint of both expertise and legislature. Green EMs as charges in armament systems will facilitate the solution to problems of re-use or disposal of demilitarized EMs in the future, as compared with the present situation.

REFERENCES

- Ahnert, A. & Borowski, C. 2000. Environmental Risk Assessment of Anthropogenic Activity in the Deep-Sea. *J. Aqu. Ecosyst. Stress & Recovery* 7, 299–315.

- Anon. 1922. The Commercial Utilization of Smokeless Powder. Army Ordnance 2: 233.
- Anon. 2000. National Policy Dialogue on Military Munitions. Final Rep., The Keystone Center, USA, Sept. 2000.
- Burch, D. et al. 1996. Value Added Products from Reclamation of Military Munitions. *Proc. 22nd Int. Pyrotech. Seminar, IIT Res. Inst., Chicago*: 69–73.
- Duijm, N.J. & Markertt, F. 2002. Assessment of Technologies for Disposing Explosive Waste. In: J. Hayardous Mat. A90, 137–153.
- Delyagin, G.N. et al. 2003. Study of Properties of Ekovut Fuel Artillery Powder Additions and its Evaluation of Application Effectiveness in Blast-Furnance Smelting, Chernaya Metallurgiya, Bull. Nauch.–Techn. Ekonom. Inf., No. 6: 29–36; Chem. Abstr. 140 (2004) 131 419.
- Eck, G. et al. 2000. The use of Surplus Smokeless Powder Propellants in Commercial Explosives Products in the United States. In: O. Machacek (ed.), Application of Demilitarized Gun and Rocket Propellants in Commercial Explosives, Nato Sci. Series II., Mathematics, Physics and Chemistry- Vol. 3, Kluwer Acad. Publ., Dordrecht: 119–131.
- Hagforts, M. 2002. Environmental Impact of the Disposal of Old Ammunition in Open Surface Detonation. In: E. Kantolahti, A. Kariniemi and E. Pääkkönen (eds), *Proceedings of the FINNEX 2002 Seminar*: 163–175. Levi, Kittilä.
- Holmberg R. (ed.), 2003. Explosives and Blasting Technique, *Proc. of the 2nd World Conf. on Explos. & Blasting Techn.* A. A. Balakema Publ., Lisse.
- Kalatsey, V.I. et al. 1975. Explosives from Utilized Ammunition: Problems, Solutions, Assortment. Bezopasnost truda v promyshlennosti, No. 12, 32–37.
- Karabasov, Y.S. et al. 2001. D. V. Oleinikov, I. F. Kurunov and A. I. Isteev, Potential for the Use of Explosive Parts of Ammunition in Blast-Furnance Smelting. In: *Metallurgist* 45:350–353. New York.
- Kato, Y. 2002. Explosion of Smokeless Gunpowder in a Temporary Storage House. In *Proc. of the XIV Congress 2002*. NOVOTEL, Safex International., Amsterdam: 285–293.
- Kast, H. 1920. The Detonation of Explosives. Zeitschrift Gesamte Schiess- und Sprengstoffen 15: 195–197.
- Klusacek, J. 1996. An Exploitation of Demilitarized Military Explosives in the Civilian Blasting Technique (in Czech). In: *Proc. of the Int. Symp. „Ecological Liquidation of Explosives (Especially Propellants for Missiles)“*, Hotel Labe, Pardubice, Sept. 1996.: 11–13.
- Latvala, T. 2002. Mass Detonations in Finland. In: E. Kantolahti, A. Kariniemi and E. Pääkkönen (eds), *Proceedings of the FINNEX 2002 Seminar*: 176–180 Levi, Kittilä.
- Machacek, O. et al. 1997. Recycling of Excess and Demilitarized Energetic Materials in Commercial Explosive Application. In: K. K. Kuo (ed.), Challenges in Propellants and Combustion: 100 Years after Nobel (*The 4th Int. Symp. on Spec. Topics in Chem. Propulsion, Stockholm, May 1996*), New York, Begell House: 177–188.
- Machacek, O et al. 1999. Alternative Use of Military Propellants as Novel Blasting Agents, U. S. Pat. 5,608,184, Universal Tech. Corp., Dallas, Texas, March 1999.
- Machacek, O. 2002. Reuse of Demilitarized and/or Excess Energetic Material as Ingredients in Commercial Explosives. In: *Proc. of the XIV Congress 2002*. NOVOTEL, Safex International., Amsterdam: 221–223.
- Maranda, A. et al. 2002. Analysis of Possibility of Waste Energetic Material Application in Mining Blasting Agents. In: J. Vagenknecht (ed.), *Proc. of the 5th Seminar “New Trends in Reserach of Energetic Materials”*, Univ. of Pardubice, April 2002: 145–149.
- Mitchell, A.R. et al. 2000. Conversion of Demilitarized Explosives and Propellants to High Value Products. In: O. Machacek (ed.), Application of Demilitarized Gun and Rocket Propellants in Commercial Explosives, Nato Sci. Series II., Mathematics, Physics and Chemistry – Vol. 3, Kluwer Acad. Publ., Dordrecht: 49–57.
- Morgan, M.E. & Miller, P.L. 1997. Recycling Propellants and Explosives into the Commercial Explosive Industry. In: K. K. Kuo (ed.), Challenges in Propellants and Combustion: 100 Years after Nobel (*The 4th Int. Symp. on Spec. Topics in Chem. Propulsion, Stockholm, May 1996*), New York, Begell House: 199–204.
- Munroe C.E & Howell, S.P. 1922. Comminuted Smokeless Powder as a Blasting Agent. Bur. of Mines, Repts. of Investigations, No. 2386 (1922); Chem. Abstr. 16 (1922) 19995.
- Odintsov, V.V. & Pepekin, V.I. 1994. Evaluation of Detonation Parameters of the new Class of Emulsion Explosives. *Khim. Fizika* 13: 131–140 (see also *Khim. Fizika* 14: 132 (1995)).
- Rabotinski, N.I. et al. 2000. The Application of Reclaimed Explosives in Commercial Emulsion Explosives. In: O. Machacek (ed.), Application of Demilitarized Gun and Rocket Propellants in Commercial Explosives, Nato Sci. Series II., Mathematics, Physics and Chemistry – Vol. 3, 2000:193–198. Dordrecht, Kluwer Acad. Publ.
- Salygin, N.K. et al. 2000. Use of Converted High Energy Value Explosive Materials as Industrial Energetic Materials. In: O. Machacek (ed.), Application of Demilitarized Gun and Rocket Propellants in Commercial Explosives, Nato Sci. Series II., Mathematics, Physics and Chemistry – Vol. 3, 2000: 175–180. Dordrecht, Kluwer Acad. Publ.
- Schubert, H. 2000. Detonation Properties of Gun Propellants and Slurry Explosives and their Combination. In: O. Machacek (ed.), Application of Demilitarized Gun and Rocket Propellants in Commercial Explosives, Nato Sci. Series II., Mathematics, Physics and Chemistry – Vol. 3: 111–114. Dordrecht, Kluwer Acad. Publ.

- Selesovsky, J. 2002. Evaluation of Stability and Lifetime of the Military Explosives. Diploma project, University of Pardubice, June 2002.
- Urbanski, T. 1939. Detonation of Smokeless Powders. *Zeitschrift Gesamte Schiess- und Sprengstoffen* 34: 103–105.
- Vavra, P. et al. 2003. Energetic Materials, Trends and Requirements. Proc. of the Conf. “New trends in technology of ammunition loading and reloading”, Konstrukta Ltd.: 127–134. Trencin, Slovak Rep.
- Wanninger, P. 1995. Konversion von Explosivstoffen. *Chem. unserer Zeit* 29: 135–140.
- Weisberg, M. & Fischer, T. 1999. Ecological Risk Assessment for Detonation Emissions at an Army Depot. In: Annual Meeting & Exhibition Proc.– Air Waste Management Ass. 92 nd, St.Louis, Mo, US: 3059–3093.
- Wulfman, D.S. et al. 1995. Commercial Reformulation, an Economic Environmentally Benign Means of Using Explosives and Solid Propellants. *Proc. of the 21st Annual Conf. on Explos. & Blasting Techn., 1995*: 248–256.
- Wulfman, D.S. 1997. Environmentally Neutral Reformulation of Military Explosives and Propellants, Appl. Canadian Pat. CA 2,157,059, CIPO, Jan. 1997.
- Wulfman, D.S. et al. 1997. Reformulation of Solid Propellants and High Explosives: an Environmentally Benign Means of Demilitarizing Explosive Ordnance. *Canad. J. Chem. Eng.* 75: 899–912.
- Wulfman, D.S. 1998. Reclamation, Recovery and Reuse of Military Explosives and Propellants. *Canad. Chem. News* 76:15–17.
- Zabelin, L.V. et al. 2003. Water-containing Blasting Agent. *Rus. Pat. RU 2,217,401 (2003)*; *Chem. Abstr.* 140 (2004) 220 219.
- Zeman, S. Et al. 2003. A Study of Chemical Micromechanism Governing Detonation Initiation of Condensed Explosive Mixtures by Means of Differential Thermal Analysis. *Thermochim. Acta* 398: 185–194.

Research on permitted powdered emulsion explosive

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ABSTRACT: Beginning with the general layout of industrial explosive materials of China, the present safety situation of permitted explosives is analysed. A new industrial explosive – permitted powdered emulsion explosive (PPEE) is presented. It possesses unique microstructure and has remarkable advantages of both emulsion and powdered explosive. In this paper, the formulation, preparation technology and property characteristics of this kind of explosive are expounded. Its application in underground gas coal mines is also summarized. Results of tests and experiments show that this new type of industrial explosive performs perfectly. It could meet the needs of relevant gas mines and could bring great economic benefits to plants and units that manufacture or use it. It is a new type permitted explosive with a bright future.

1 INTRODUCTION

Influenced both by the traditional conservative ideas in the field of industrial explosives technology, powdered explosives were once one of the most popular explosives, especially in China where AN-TNT explosives were once one of the predominant brands of colliery-permitted explosive.

The permitted AN-TNT explosives have advantages such as an extensive raw material source, simple components, and easy-to-handle storage, transportation and application; on the other hand obvious defects include: (a) low ability of water resistance; (b) less safety. Therefore, there must be present more than 10 % of TNT explosive in order to guarantee its explosion effect.

As is well known, TNT is an elemental explosive with toxicity. It endangers people's health and pollutes the environment, therefore lowering its safety of production; hence, an added production cost in the manufacturing process. Moreover, ammonium nitrate has strong moisture absorption and agglomeration; as a result, the AN-TNT

explosives are ready to be damped and agglomerated accordingly; this, therefore, critically influences their use in terms of safety.

Emulsion explosive (EE) offers an excellent new opportunity for the use of explosive. With good production conditions and quality explosion effect, it is developing rapidly. Unfortunately, however, EE comes in the form of semisolid grease at normal temperature, resulting in some inconvenience in production. EE also contains some degree of water, thus influencing its energy releasing property and, hence, weakening the effect when it detonates. Re the current status of the development of industrial explosive in China, the national administration department is committed in its policy of industry and manufacture of civil explosion of China to quitting the use of type AN-TNT explosives with its backward production process within five to ten years. It was stated clearly in 'Ten-Five Development Proposal Program of National Industrial Explosives and Relate Raw Materials' that AN-TNT explosives will be gradually eliminated by developing and promoting permitted explosives with a high degree of safety. It is,

therefore, urgent to develop a high-safety non-TNT product, with good physical properties and high explosion effect.

2 CURRENT STATUS OF THE EMPLOYMENT OF PERMITTED EXPLOSIVE IN CHINA

Permitted explosives are classified, in terms of safety, into five classes in China. For reasons of sourcing primary material, manufacture process and production cost, currently used explosives in collieries rank from first to third class. The latter are developed slowly (C. Dong 1997).

From Table 1, it is clear that the explosives used in China fall into first and second grade; these are ordinary explosives in terms of safety. Compared with the use of explosives in some other countries the permitted explosives ranked third class and used in colliery mines in China is approximately equivalent to Eqs-1 made in Japan and P3 made in Britain, in terms of safety, but it cannot match WII made in Germany, III type made in Belgian and P4 made in Britain; moreover, its safety is much lower than that of WIII and IV, made in Germany and Belgian respectively.

Table 1. Safety of permitted explosives for collieries in different countries.

Countries	Permitted explosives		
	General safety	Medium safety	High safety
China	Class 1 and class 2	Class 3	—
Russia	III、IV	V	VI
Britain	P1	P2、P3	P4、P5
Germany	WI	WII	WIII
Belgium	—	III type	IV type
Poland	Coal dust safety	Gas safety	Special safety
Japan	400 g 600 g	Eqs - I	—
		Eqs - II	

3 PPEE AND CHARACTERISTICS OF ITS PRODUCTION PROCESS

– In powder state, these kinds of explosive meet the requirements of the charging operator in the factory and hobby shared by the blaster on

site, and hence are favourable for enhancing efficiency in production and use.

- With fewer components, high safety and quality explosion and favourable storage property, the explosives are of the same type as AN-TNT-free explosives, and possess unique microstructures of water in oil. Moreover, they contain no components harmful to people and the environment, releasing fewer toxicity gases when blasting and, as a result, endangering the environment less, meeting the requirements of the development program of civil blasting equipment.
- The production process is integrated; i.e. the production line treats the well-prepared water-in-oil phase through an integrated continuous process, including procedures of continuous emulsifying, atomizing to powder, and flowing drying. Furthermore, the integrated process has the functions of high efficiency recovery, production capacity adjustment, process coordination and automation monitoring – forming a complete system of production from feeding to discharging.
- The production of explosives can be carried out with non-stop operation and mechanization, conducive for productivity increase, reduction of labour and, therefore, the realization of large-scale production.

4 PRIMARY COMPONENTS OF PPEE

Based on the requirements of optimization design of components accompanying the practical experience of BGRMM (X. Wang 1994), the following materials were selected for the main components of the explosive: nitrate, water, waxes fats and macromolecule emulsifier.

Table 2. Formulation of PPEE.

Component	Wt.%
Oxidant	70–88
Oil	3–5.5
Water	3–7
Emulsifier	1.5–3.0
Inhibitor	5–18

In the work of determining the components, the following tests were conducted –mutual unity plus crystallizing point, kind and content of inhibi-

tor, explosion properties, blasting performance of explosive, safety properties and thermal difference. The components were worked out by comprehensive consultation of their stabilities, performance index, safety (Z. Liu 1986) as well as production cost. The final formulation is listed in Table 2.

5 PRODUCTION PROCESS OF PERMITTED EE

The explosive property does not depend on the components only. The production process also influences the property of the explosive. The production of colliery-permitted EE is approximately the same as the production of emulsified powdered granulated explosive (X.Wang 2000). The only difference is that some types of inhibitor should be introduced in the preparation of PPEE.

6 PROPERTIES OF PPEE

6.1 Physical properties

Yellow-brown in colour, loose and flowing, it does not stick to the hand and is not liable to vaporize [AQ2]. There has been no incidence of agglomeration and rigidity during the guarantee storage period. Its bulk specific gravity is 0.7~0.8 g/cm³, its cartridge density after mechanized loading ranges from 0.85 to 1.05 g/cm³, and its water content is below 3 % during the guarantee storage period.

6.2 Blasting performance

Data from Table 3 reveals that the PPEE is greatly superior to the domestic explosives in terms of its performance.

6.3 Storage properties

The tables above show that the PPEE holds good storage properties and therefore meets the requirement of coal mines.

6.4 Safety properties

Data from Table 6 presents the good safety properties of PPEE. These are of important practical significance to the underground coal-mine blasting.

Table 4. Storage performance of PPEE for second-class colliery.

Storage time (month)	0	1	2	3	4	5
Detonation velocity (m/s)	364 9	353 2	348 1	336 1	329 3	318 3
Brisance (mm)	15. 8	15. 1	14. 5	13. 6	12. 9	12. 5
Gap (cm)	14	13	11	10	9	8

Table 5. Storage performance PPEE for third-class colliery.

Storage time (month)	0	1	2	3	4	5
Detonation velocity (m/s)	346 7	338 2	332 3	327 6	319 5	302 2
Brisance (mm)	14. 9	14. 2	13. 5	13. 5	12. 1	11. 3
Gap (cm)	12	11	10	9	7	6

Table 6. Safety of PPEEs for colliery.

Class	Impact sensitivity (%)	Fri ction sensitivity (%)	Toxic gas (L/kg)	Soft y degee (g)	Defla gration resistence
2	2	0	29	387	0/10
3	0	0	19	564	0/10

Table 3. Comparison between perpowdered emulsion explosive and relative explosives in explosion performance.

Items Performance	PPEE class 2	Permitted AN-TNT No.3	PPEE class 3	Permitted EE Class 3
Detonation velocity (km/s)	3.2-3.7	≥2.5	3.0-3.4	≥2.8
Brisance (mm)	12.9-15.8	≥10	12.1-14.9	≥8
Lead block test (mL)	331	≥218	286	≥210
Gap (cm)	12	≥2	8	≥2

7 APPLICATION OF PPEE ON SITE

Before entering a coal mine for blasting experiments, a preliminary safety check was carried out by the Office of Coal Mine Industry Safety Mark (OCMISM). Experts called in by the OCMISM conducted a safety seminar regarding the underground test of the explosive. According to the proposal prepared in the seminar, Laohutai Coal Mine of Fushun Mine Group was determined for the testing. A -330 m operation face, general operation face and 6300 #[AQ3] transportation level excavation face were selected respectively to carry out the blasting experiments of 2 t of second-class and third- class respectively.

7.1 General conditions of the site, its geological status and the test of PPEE, class 2

General conditions of -330 m general mining face.

- This working face is located in the west of the field. The top bed is shale, and the bottom is tuff. The relative gas flux at working layers in the mining area is 6 m³/t; this may cause spontaneous combustion of the coal seam; and hence, local fan blowing ventilation was employed for the general working face.

Application of colliery-permitted powdered emulsion explosive class 2.

- Procedure: the test of second-class PPEE was conducted at a -330 m working face in the west mining area. Twenty-six boreholes with a depth of 0.9 m were arranged at the working face for the test, and 28 cartridges were used (Fig.1) – one cartridge for each hole except for the two holes with gangue at the north toe of the working face, where two cartridges were used in each hole. The blasting was fired according to the charging design in the operation program prepared in advance.

Results:

- (a) It was reported by the operators that this type of explosive was of powerful blasting, high blasting efficiency and fairly good blasting results. The fragmentation was moderate with no oversized blocks produced.
- (b) The fumes produced were fewer compared with the one used before and no pungency gas was released when blasting and therefore, did not irritate eyes and respiration. Furthermore,

there were no pungency gas smells during coal mining.

- (c) With less misfire, the borehole usage ratio was high. Measurement of the borehole usage ratio showed that it could be as high as 98 % using the explosive in general mining, and that in most mining cases the ratio could reach more than 98 %. During the application, there was no mute fire nor misfire, showing that the explosive was of good detonation properties.
- (d) The explosive consumption per unit was less. Statistics showed that the unit consumption was only 0.422 kg/t in the development of the -330 m working face, compared with 0.563 kg/t of the unit consumption of the earlier emulsion one, and that there was only 0.155 kg/t in the blasting of the -330 m general excavation face, compared with 0.202 kg/t of the previously used emulsion one. The contrast indicated that the use of PPEE class 2 could result in the same blasting effect as that of the use of emulsion one at an explosive unit consumption reduced by 23 %.
- (e) The explosive holds as good water resistance as the previously used emulsion one, and could be used in a wet site or hole with water accordingly.

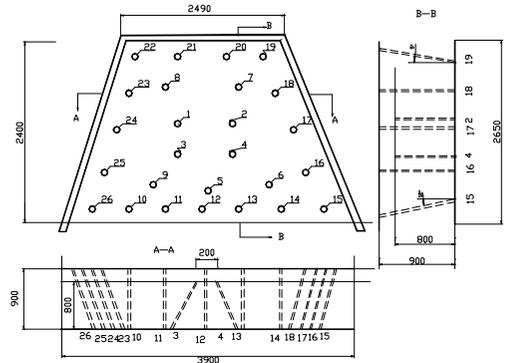


Figure1. Blasthole layout diagram for -330 m mining area excavation face.

7.2 General conditions of the site, its geological status and the test of PPEE class 3

General conditions of the 63002# working face:

- The gas flux in this area was 20.46 m³/t. The coal seams all had a danger of coal dust explosion, with the explosion index being 46.24 %, with a tendency to spontaneous

combustion. The combustion time tended to last for one to three months, the shortest time being 13 days. Local fan blowing ventilation was employed for the excavation working face.

Application of PPEE class 3:

- (a) Procedures: the excavation face had an area of 12 m². Fifty-three boreholes were arranged in this area, and one cartridge for one hole was designed for the blasting generally (Fig. 2). One extra cartridge was loaded in the hole located at the bottom, and also one extra may be loaded in the hole in some cut-forming holes located in the middle section; this was decided on practicalities, where necessary. The vertical depth of each hole, except some cut-forming holes, was generally 0.8 m.

Results:

- (a) The blasting showed that this type of explosive was of powerful blasting and fairly good blasting results with no oversized blocks produced.
- (b) The fumes produced by the blasting were fewer. Compared with the explosives employed before, the fumes produced by this kind of explosive were reduced dramatically, and moreover, no pungency gases were produced, making the coal-mining atmosphere free of irritation gases.
- (c) The borehole usage ratio was of a high level. Site measurements showed that the borehole usage ratio at this working face averaged out at over 95 % with no mute fire nor misfire.
- (d) The explosive consumption per unit was less. Statistics showed that the unit consumption was only 0.493 kg/t in the advancement of the 63002# transportation drift, compared with 0.657 kg/t of the unit consumption of the equivalent class emulsion explosives. The test showed that 25 % of the per unit consumption of explosive could be saved when using the type of PPEE.
- (e) The PPEE class 3 holds good water resistance, and could be used in a wet site or hole with water.

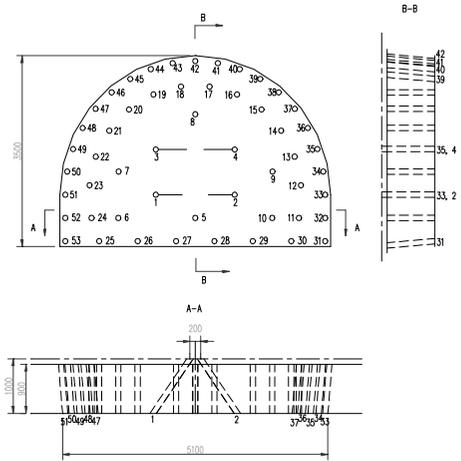


Figure 2. Blasthole layout diagram for 63002# transportation drift.

8 CONCLUSIONS

- The successful development of permitted powdered emulsion explosive contributes a new kind of explosive to the industry. With its good properties in terms of explosion, storage and safety, the explosive is of important practical significance both in upgrading colliery explosives and in enhancing safety of coal production in China.
- The test conducted in Laohutai Coal Mine showed that the unit consumption of second-class PPEE in the development of -330 m working face and general excavation face was 0.422 kg/t and 0.155 kg/t respectively, 23 % lower than that used previously; the unit consumption of third-class PPEE in the excavation of 63002# transportation drift was 0.493 kg/t; compared with the equivalent class colliery-permitted one previously used in this work, 25 % of unit consumption was saved.
- The continuous production of PPEE could dramatically reduce the working intensity of the operators, completely eliminate backward procedures such as pulverizing, mixing and manual charging in the production of AN-TNT, and hence enhance productivity. Moreover, since it does not contain TNT, its production does no harm to people's health and has no impact on environment; therefore, social benefits are clearly apparent.

- PPEE satisfies the requirement and developing trend of China's civil blasting legislations and, therefore, is promising for extensive application.

REFERENCES

- Dong, C. 1997. Status of colliery-permitted explosive and its relative standard in China (in Chinese). *Explosive Materials* 26 (1): 14-16.
- Liu, Z. 1986. Combustion-supporting of sodium chloride to blasting operation in coal mine (in Chinese), *Explosive Materials* 25 (2): 25-26.
- Wang, X.1994. *Emulsion Explosives* (English edn). Beijing: Metallurgical Industry Press.
- Wang, X., Wang, G., Zhang, X., Kang, T., & Li, Z. 2000. Emulsified powdered granulated explosive and its application. In R. Holmberg (ed), *Proceedings of the EFEE 1st world conference on explosives and blasting technique*, 251-253. Rotterdam: Balkema.

Underwater explosions, Part 1 - estimation of the test method for the determination of energy content of explosives

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ABSTRACT: Underwater explosions have been used for several decades for the determination of energy content of explosives. This test method is the only one by which shock, gas heave and total energy values can be measured separately. It enables the development of the energy content of explosives for different purposes; military high explosives should contain more shock energy whereas gas heave energy is a very important feature for the blasting explosives. The purpose of this study was to establish a test place for the underwater experiments in an old water filled open pit, to estimate the reproducibility of the energy measurements, to calculate the standard deviations and to compare the total energy content of commercial explosives to the theoretical values calculated by the thermo dynamical programme. The test method seems to work quite well especially for the homogeneous explosives. The difference between the energy content of theoretically calculated and measured values for the homogeneous emulsion explosives was about -1% and for the dynamite about -7%. The energy difference for the unhomogeneous ANFO was detected to be -19%. The diameter of the charge was 15 cm and it was obviously too small for ANFO to detonate ideally. On the basis of the test results this test method seems to fit best for the cap sensitive, completely homogeneous, spherical charges whose masses are big enough and which are initiated from the centre of the charge.

1 INTRODUCTION

Underwater explosions have been used for several decades for the determination of the energy content of explosives. The test method is the only one by which shock, gas heave and total energy values can be measured separately. It enables the energy content of explosives to be developed for different purposes; military high explosives should contain more shock energy whereas gas heave energy is a very important feature for blasting explosives.

The purpose of this study was to establish a test place for the underwater experiments in an old water filled open pit, to estimate the reproducibility of the energy measurements, to calculate the standard deviations and to compare the total energy content of different explosives to the theoretical values calculated by the thermo dynamical programme.

2. THEORY OF THE UNDERWATER EXPLOSION

When an underwater charge is detonated, it emits a shock wave to the surroundings. Very soon after the shock, the gases start to expand and to push the water ahead. The expansion of the gas bubble should stop when the pressure inside the bubble is at the same level as the surrounding hydrostatic pressure at the depth of charge.

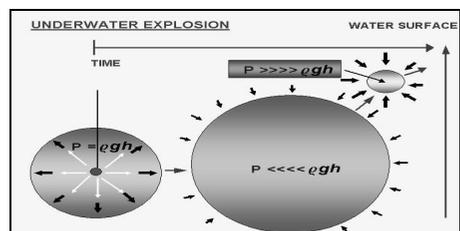


Figure 1. Underwater explosion.

However, because of the inertia of the water, the gas bubble continues to expand and finally the pressure inside the bubble is in much lower level than the hydrostatic pressure in water. Therefore the bubble starts to collapse and once more, because of the inertia of water, the pressure inside the bubble grows much higher than the hydrostatic pressure around. Finally the diminishing stops and the bubble emits a pressure peak, the first bubble peak, into the water. After this the bubble keeps on crowing and collapsing several times until the detonation gases break up into the free air (Fig. 1).

By recording the pressure-time history of the explosion on a pressure gauge, the shock and the gas heave energies can be determined and the total energy calculated. The shock energy can be integrated from the area of the shock peak of the curve and the gas heave energy calculated from the time which passes from the shock front to the first bubble peak.

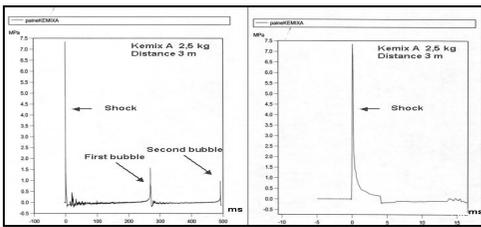


Figure 2. A typical pressure-time curve of an underwater explosion. The detonated charge consisted of 2.5 kg of aluminised emulsion explosive. The distance between the charge and the pressure gauge was 3 m.

2.1 Shock Energy

The shock energy can be determined by integrating the shock pressure peak from the pressure-time curve and calculating the result according to equation (1).

$$e_s = \frac{4\pi R^2}{W_w C_w} \int_0^{\theta} P^2 dt \quad (J/kg) \quad (1)$$

where R = distance between the centre of the pressure gauge and the charge (m); W = weight of charge (kg); ρ_w = density of water at the depth of charge and at the applied temperature (kg/m^3); C_w = speed of sound in water at the depth of charge and at the applied temperature (m/s). θ = time constant, the time which passes when maximum peak pressure P_m decays to value $P_m/e \approx 0,37P_m$; P = pressure-time curve.

2.1.1 Experimental data correction

The experimental measured shock energy has to be corrected because of three different reasons;

- Shock loss correction factor (μ). When the shock wave travels from the explosion site to the pressure gauge, it presses the water very hard. The water heats up fast and some of the energy will be lost. Therefore the experimental data have to be corrected. The loss of energy is proportional to the strength of the detonation pressure. Bjarnhold has published the shock loss correction factor as a function of the detonation pressure (Fig. 3). If one knows the density of the explosive and measures the velocity of the detonation, the detonation pressure can be calculated by equation (2);

$$P_d = \rho_o D^2/4 \quad (2)$$

where P_d = detonation pressure of the explosive (Pa); ρ_o = density of the explosive (kg/m^3); D = velocity of the detonation (m/s)

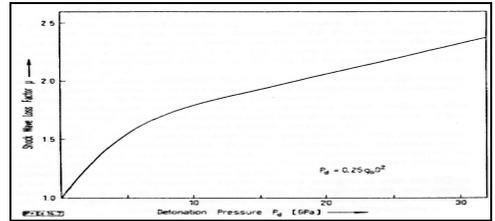


Figure 3. Shock loss factor as a function of detonation pressure.³

- Finite size of the pressure gauge (K_e). The finite geometrical size of the pressure gauge causes a systematic error, which has to be corrected.

$$\gamma = (d/C_w \theta) \quad (3)$$

where d = diameter of gauge; C_w = speed of sound in water; θ = time constant of shock
The correction factor (K_e) can be calculated by equation (4);

$$K_e = 1 + 0.29\gamma + 0.016\gamma^2 \quad (4)$$

- Shape correction factor (K_f). The shape of charge also effects on the measured data and

have to be corrected. For spherical charges $K_f=1$ where as for cylindrical charges $K_f=1.08-1.1$. The shape correction factor can be determined by equation (5);

$$K_f = \frac{E_{Total \text{ energy, SPHERICAL}}}{E_{Total \text{ energy, CYLINDRICAL}}} \quad (5)$$

CORRECTED SHOCK ENERGY:

$$Shock \text{ Energy } E_s = \mu K_e K_f e_b \quad (6)$$

2.2 Bubble or Gas Heave Energy

The Bubble or the Gas Heave Energy value of the explosive can be calculated by the equation (7):

$$e_b = \frac{1}{8C_w^3 K_f^3} \left[\sqrt{1 + 4Ct_b \left[\frac{P_h}{P_{hn}} \right]^{5/6}} - 1 \right]^3 \quad (7)$$

where e_b = bubble energy (J); C_w = speed of sound in water at the depth of charge and at the applied temperature of water (m/s); t_b = first bubble period, time which passes from the shock front to the first bubble peak.

$$K_f = 1,135 * \left(\frac{1}{W} \right)^{5/6} / P_h \quad (8)$$

ρ_w = density of water at the depth of charge and at the applied temperature (kg/m^3); P_h = total pressure (the air pressure and the hydrostatic pressure) (Pa). $C = b/a^2$; C = constant (bond calibration), a & b = constants. The constants can be solved by the bond calibration.

2.2.1 Experimental Data Correction

Shape correction factor (K_f). The shape of the charge also effects on the measured data of gas heave energy and therefore has to be corrected in similar way to the shock energy.

2.2.2 Bond Calibration

An underwater explosion creates reflections which may disturb the measurements at the pressure gauge. Therefore the measuring bond has to be calibrated. According to Bjarnholt and Holmberg there is a correlation between the first bubble period and the gas heave energy value.

$$t_b = K_1 E_b^{1/3} + K_2 E_b^{2/3} \quad (9)$$

where K_1 & K_2 = constants; t_b = bubble period; E_b = gas heave energy of the charge

$$K_1 = 1,135 * \left(\frac{1}{W} \right)^{5/6} / P_h$$

If there are no disturbances ($K_2 = 0$) the gas heave energy value can be solved by the equation (9) by only measuring the bubble period.

Because gas heave energy value is straight proportional to the weight of charge and if $K_2 \neq 0$ the equation can be written in form;

$$t_b = aW^{1/3} + bW^{2/3} \quad (10)$$

where a & b = constants; W = weight of charge; t_b = bubble period

and the bond calibration has to be carried out. It can be done by exploding different size of charges and by measuring the first bubble period of the explosions. The constants a and b may be solved by the least square fit to the measuring data ($t_b, W^{1/3}$). However, before the calculations, the bubble periods have to be normalised against the changes in atmospheric pressure during the measurements.

$$t_{bn} = t_b (P_h / P_{hn})^{5/6} \quad (11)$$

where t_{bn} = normalised bubble period (s); t_b = measured bubble period (s); P_h = total pressure (air pressure + hydrostatic pressure) (Pa)



Size cm	Bubble period s	Weight kg	Air pressure Pa	Hydrostatic pressure Pa	Total pressure Pa
23 x 25	0.3900	11.469	101900	80584	182484
23 x 25	0.3900	11.484	101900	80584	182484
23 x 25	0.3919	11.463	101870	80584	182454
23 x 25	0.3899	11.514	101870	80584	182454
23 x 25	0.3899	11.453	101870	80584	182454
20 x 25	0.3479	7.960	101830	80584	182410
20 x 25	0.3479	7.983	101830	80584	182410
20 x 25	0.3499	8.009	101820	80584	182404
20 x 20	0.3249	6.406	101820	80584	182404
20 x 20	0.3239	6.454	101800	80584	182384
16 x 16	0.2599	4.411	101800	80584	182384
16 x 16	0.2619	5.254	101800	80584	182384
16 x 16	0.2598	5.250	101770	80584	182354
11 x 11	0.1814	1.046	102110	80584	181794
11 x 11	0.1794	1.056	102110	80584	181794
11 x 11	0.1814	1.039	101180	80584	181764
7.5 x 7.5	0.1236	0.326	101180	80584	181764
7.5 x 7.5	0.1226	0.326	101120	80584	181704
7.5 x 7.5	0.1236	0.322	101120	80584	181704
5 x 5	0.0827	0.097	101120	80584	181704
5 x 5	0.0827	0.097	101120	80584	181654

Figure 4. Bond calibration, charges, bubble periods, air-hydrostatic- and total pressures.

CORRECTED BUBBLE OR GAS HEAVE ENERGY VALUE

$$Gas \text{ Heave Energy } E_b = K_f (e_b / W) \text{ (J/kg)} \quad (12)$$

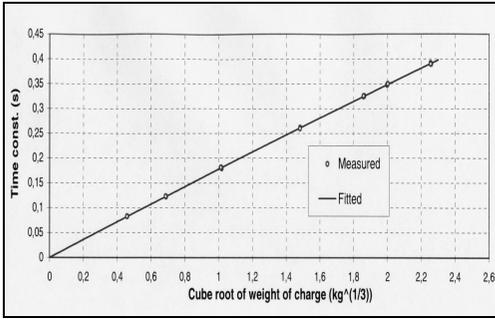


Figure 5. Pond calibration. Normalised bubble period as a function of cube root of the weight of charge.

Constant $a = 0,18202329294774$

Constant $b = -0,00390474611358$

2.3 Total Energy

The total energy by weight can be calculated by equation (13);

$$Total\ energy\ E_{TOTAL} = \mu K_e K_f e_s + K_f e_b / W = K_f (\mu K_e e_s + e_b / W) = E_s + E_b\ (J/kg) \quad (13)$$

3 TEST ARRANGEMENTS

The test place was established in an old water filled open pit owned by Avesta Polarit Chromium mining company. The mine locates about 600 km north of Helsinki at Kemi.



Figure 6. Water filled open pit.

The work was started by measuring the depth profile of the water filled pit. The charges were installed in such away that the reflections of the shock wave couldn't disturb the measurements at the pressure gauge and the length of the measuring cables were minimised.

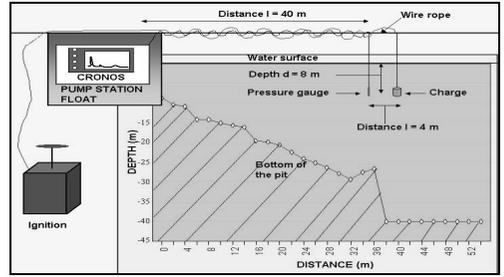


Figure 7. Depth profile of the open pit and the test arrangements.

To prevent the shock waves reflecting to the pressure gauge, the free distance from the charge to the walls of the pond must be at least five times the radius of the explosion bubble (L_{min}) and the free distance to the surface and to the bottom of the pond at least twice the radius of bubble (H_{min}).

The radius of the explosion bubble can be calculated by the equation:

$$a_m = \left[\frac{1,3 Q W}{1+h/10} \right]^{\frac{1}{3}} = 3,29\ m \quad (14)$$

a_m = radius of explosion bubble (m) = 3,29 m

Q = heat of explosion (MJ/kg) = 4.3 MJ/kg Emulsion.

W = weight of charge (kg) = 11.5 kg Emulsion.

h = depth of charge (m) = 8 m.

In case of emulsion explosive with 11.5 kg charges the minimum distances for the open space are $L_{min} = 16,5$ m and $H_{min} = 6,6$ m.

3.1 Instrumentation

The time-pressure curves were measured by Series 138A Tourmaline Crystal based Underwater Blast Pressure Sensor and recorded by the CRONOS (Combined Recording or Notebook System) measuring unit. The overall length of the sensor cable was 50 m and it was directly connected to the ICP channel of CRONOS and supplied by 4 mA DC current. The measuring system was checked and ensured in case of signal damping by measuring several identical shots with and without the signal amplifier. Because no difference were detected, all the measurements were carried out without the signal amplifier to keep the measuring system as simple as possible.

The shooting depth was 8 m and the temperature of the water at the measuring depth was measured by the TESTO measuring unit. The air pressure information was supplied by the Finnish Institute of Meteorology at one hour-intervals from the Kemi-Tornio airport which locates about

2 km north of the pit. The density of the water and the speed of sound in water at the depth of 8 m and at the applied temperature were calculated by the Sea Water Equation Calculator at the address:

<http://ioc.unesco.org/oceanteacher/resourcekit/M3/Coveers/SeaWaterEquationOfState/Sea%20Water20%EQuation20%of20%State%20Calculator.htm>. The calculator was supplied by The John Hopkins University Applied Physics Laboratory in USA.

4 RESULTS

4.1 Emulsion explosive

Table 1. Emulsion explosive.

Size	Weight	E	E	E
cm		Bubble	Shock	Total
23x23	kg	MJ/kg	MJ/kg	MJ/kg
1	11.469	1.86	1.34	3.20
2	11.453	1.85	1.30	3.15
3	11.514	1.85	1.24	3.09
4	11.463	1.86	1.25	3.12
5	11.484	1.85	1.44	3.29
Ave	11.477	1.9	1.3	3.2
s	0.024	0.01	0.08	0.08

Depth $h = 8$ m $\rho_{\text{Emulsion}} = 1\,150$ kg/m³
VOD = 5 200 m/s Constant $a = 0.1820232929$
Shock Loss Factor $\mu = 1.73$ Constant $b = -0.003904746$
Shape factor $K_f = 1.0$ Diameter (gauge) = 0.094 m
Theoretically calculated value $E_{\text{Total}} = 3.2$ MJ/kg
 $\Delta x = (3.169-3.2)/3.2 * 100\% = -0.96\%$

4.2 Dynamite

Table 2. Dynamite.

Size	Weight	E	E	E
cm		Bubble	Shock	Total
15x40	kg	MJ/kg	MJ/kg	MJ/kg
1	10.320	2.25	1.88	4.13
2	10.320	2.17	1.69	3.86
3	10.360	2.23	1.67	3.90
4	10.300	2.23	1.83	4.06
Ave	10.325	2.2	1.8	4.0
s	0.025	0.04	0.10	0.13

Depth $h = 8$ m $\rho_{\text{Dynamite}} = 1\,500$ kg/m³
VOD = 6 500 m/s Constant $a = 0.182023$
Shock Loss Factor $\mu = 1.95$ Constant $b = -0.003904$
Shape factor $K_f = 1.0373$ Diameter (gauge) = 0.094 m
Theoretically calculated value $E_{\text{Total}} = 4.3$ MJ/kg
 $\Delta x = (3.987-4.3)/4.3 * 100\% = -7.3\%$

4.3 On Site Sensitized Emulsion Explosive

Table 3. On Site Sensitized Emulsion Explosive.

Emulsion-booster	Weight	E	E	E
cm		Bubble	Shock	Total
15x50	kg	MJ/kg	MJ/kg	MJ/kg
1	8.508	1.66	1.43	3.08
2	8.630	1.69	1.47	3.16
3	8.522	1.68	0.731	<-reject
Ave	8.563	1.7	1.4	3.1
s	0.062	0.02	0.10	0.05

Depth $h = 8$ m $\rho_{\text{Emulsion}} = 963$ kg/m³
VOD = 3 900 m/s Constant $a = 0.1820232929$
Shock Loss Factor $\mu = 1.43$ Constant $b = -0.003904746$
Shape factor $K_f = 1.0373$ Diameter (gauge) = 0.094 m
Diameter of the cylinder charge $d = 0.15$ m
Length of the cylinder charge $l = 0.5$ m
Theoretically calculated value $E_{\text{Total}} = 3.2$ MJ/kg
 $\Delta x = (3.121-3.2)/3.2 * 100\% = -2.47\%$

4.3 ANFO

Table 4. ANFO.

Emulsion-booster	Weight	E	E	E
cm		Bubble	Shock	Total
15x50	kg	MJ/kg	MJ/kg	MJ/kg
1	8.120	2.21	1.00	3.21
2	8.120	2.21	0.99	3.20
3	8.130	2.22	1.01	3.24
4	8.080	2.25	1.00	3.25
Ave	8.113	2.2	1.0	3.2
s	0.022	0.02	0.10	0.05

Theoretically calculated value $E_{\text{Total}} = 4.0$ MJ/kg
 $\Delta x = (3.223-4.0)/4.0 * 100\% = -19.43\%$

5 CONCLUSIONS

The underwater explosions as a test method for the determination of energy content of explosives seem to work quite well, especially for the homogeneous explosives. The difference between the theoretically calculated and measured energy values for the homogeneous emulsion explosives are about 1-3 %, tables 1 and 3, although one of the determinations for shock energy of the on site sensitized emulsion explosive failed, and for dynamite about -7%, (Fig. 2). The energy difference for the unhomogeneous ANFO was -19%. The diameter of the charge was 15 cm and it was obviously too small for ANFO to detonate ideally.

On the basis of the information above, the test method seems to fit best for the cap sensitive,

completely homogeneous, spherical charges whose masses are big enough and which are initiated from the centre of the charge.

The underwater explosions are the only test method by which one can separate the shock and gas heave energy values from each other and therefore makes it possible to develop the properties of explosives for different purposes; military high explosives need more shock energy whereas gas heave energy is a very important feature for blasting explosives.

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REFERENCES:

- Bjarnholt, G. 1980. Suggestions on Standards for Measurement and Data Evaluation in the Underwater Explosion Test. *Propellants and Explosives*, Vol. 5., p. 67-74.
- Bjarnholt, G., Holmberg, R., Explosive Expansion Work in Under Water Detonations. 1976. *6th Int. Symp. on Detonation*, p. 540-550.
- Bjarnholt, G. 1978. Comparison of underwater detonation performance of two different explosive charges. *Swedish Detonic Research Foundation, Report DS: 12*.
- Cameron, A.R. 1995. The underwater evaluation of the performance of bulk commercial explosives. *Technical Information Digest; Underwater blasting. International Society of explosives Engineering*. 81-94.
- Du Plessis, M. P. 1987. The Underwater Explosion Test for Commercial Explosives. *Explosives Engineering*, Winter 1987.
- Hattori, Katsuhide; Kato, Yukio; Fukatsu, Yoshiaki; Mori, Nobuo; Tokita, Kazushi. 1986. Effects of detonation velocity and ballistic mortar value on underwater explosion performance of emulsion explosive. *Proc. Sym. Explos. Pyrotech.* 13th II 17 - II 23.
- Harries, G., Beattie, T. 1998. The underwater testing of explosives and blasting. Australia. *Sym. Ser. Australa. Inst. Min. Metal*, 23-5. ISSN: 0314-6154.
- Held, M.; The physical phenomena of underwater detonations. 1997. *Huoyao Jishu*, 13(2), 1-12. ISSN: 1013-767X.
- Kato, Yukio, Torii Akio, Ishida Toshio, Hattori Katsuhide. 1991. Correlation between detonation properties and underwater explosion performances of emulsion explosives., *Int. Annual. Conf. ICT, 22nd (Combust, React. Kinet.)*, 80/1-80/11.
- Kato Yukio; Takahashi, Katsuhiko; Torii Akio; Kurokawa Koichi; Hattori Katsuhide. 1999. Underwater explosion of aluminized emulsion explosives. *Explosives & Propulsion Division. Int. Annu. Conf. ICT*, 30 7/1-7/10.
- Mohanty, M. 1995. Energy, strength and performance and their implications in rating commercial explosives. *Technical Information Digest; Underwater blasting. International Society of explosives Engineering*. 47-60.
- Miao, Qinshu; Xu Gengguang; Wang Tingzeng. 2001. Study on the underwater explosion performance of aluminized explosives. *National Key Laboratory of Prevention and Control of Explosion Disasters. Theory and practice of Energetic Materials. Proceedings of the International Autumn Seminar on Propellants, Explosives and Pyrotechnics, 4th*, Shaoxing, China, Oct. 25-28, 2001 342-346.
- Paterson, S., & Begg A.H. 1978. Underwater Explosion. *Propellants and Explosives*, Vol 3., p. 63-69.
- Sanchidrian, Jose. A. 1998. Numerical modeling evaluation of underwater energies. *Union Espanola de Explosivos, Propellants, Explos., Pyrotech.*, Madrid, Spain, 23(6) 301-308 ISSN: 0721-3115.
- Sharma, A. K., Shukla, S. K., & Murty, D. S. 1993. Experimental determination of energy of explosion with help of underwater shock wave and bubble pressure pulses. *Indian J. Pure Appl. Phys.*, 31(9), 646-50. ISSN: 0019-5596.
- Satyavratana, P.V., & Vedam, R., 1980. Some Aspects of Underwater Testing Method. *Propellants and Explosives*, Vol 5., p. 62-66.
- Susanszky, Zoltan. 1995. New aspects of shock waves in underwater blasting. *Technical Information Digest; Underwater blasting. International Society of Explosives Engineering*. 1-24.
- Strahle, Warren C; & Liou, S. G. 1994. Physical and Chemical Observations in Underwater Explosion Bubbles. *Symp. (Int.) Combust.*, (Proc.), 25th, 89-94, ISSN: 0082-0784.
- Stroemsoe, E., & Eriksen, S.W. 1990. Performance of high explosives in underwater applications. Part 1. *CHNO explosives. Propellants, Explos., Pyrotech.*, 15(2), 48-51. ISSN: 0721-3115.
- Stroemsoe, E., & Eriksen, S. W. 1990. Performance of high explosives in underwater applications. Part 2. *Aluminized Explosives. Propellants, Explos., Pyrotech.*, 15(2), 52-3. ISSN: 0721-3115.
- Yanak, J.J. 1970. Predicting Blasting Strengths of Explosives from Underwater Tests, *Proc 12th Symposium Mech.*, Rolla. p. 331-340.

Experimental research and numerical simulation on DDT of powdered emulsion explosives

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ABSTRACT: In this paper, deflagration to detonation transition (DDT) experiment of powdered emulsion explosives (PEE) is carried out. It can be found that without sufficient and continuous heat power supply, PEE is unable to combust constantly by itself, and the DDT phenomena hardly occur in porous beds filled with PEE. The DDT phenomena can occur in porous beds within a certain range of charge densities and under strong confinements. The curve showing the relationship between predetonation distance and charge density is U-shaped. As to the porous beds of the same density, the smaller the average PEE particle size, the shorter the predetonation distance. The flame front propagates along axial and radial directions and the axial velocity is much higher than the radial one. PEE melts before combustion. The initial and final parameters of subsonic compaction wave alter continuously. The initial parameters of ultrasonic compaction wave are discontinuous, but its final ones become smoother. For the beds with the same volume fraction, the detonation velocity, pressure and particle velocity of non-ideal gas are larger than that of ideal gas distinctly. However, the gas-phase density of ideal gas is larger than that of non-ideal gas. The larger the initial volume fraction of porous beds, the greater the difference between the detonation parameters. A one-dimensional, two-phase flow DDT model was established and the numerical simulation of the DDT process of PEE made. The calculated values of predetonation distance, detonation velocity and pressure accord with the experiments results.

1 INTRODUCTION

Powdered emulsion explosives (PEE) are a kind of industrial explosive without TNT (X. Wang 1994). Along with the increasingly wide application of PEE, higher safety quality and reliability are demanded (T. Guo, 1998). Deflagration to detonation transition (DDT) is a common phenomenon of energy materials deflagration (propellants and explosives and so on) (X. Jiang 1992). It is of great practical significance for the production, transportation and storage of explosives to research the process of DDT.

The research of DDT began in the 1940s. After years of exploration and successful experimentation (A. Macek 1959), conclusions on research of DDT by R.R. Bernecker and the seven-phase view of the DDT process (R.R. Bernecker 1985). and on the study of the mechanism of DDT (M. Alexel 1999) have been suggested.

2 EXPERIMENTS

2.1 Experimental facilities

According to research of the DDT phenomenon, constraint condition (R.R. Bernecker 1982), initiation intensity (Z. Jin 1994, A.G. Butcher 1981), physical attribute and chemical build-up of material and loading intensity can affect the DDT process. Three parts constitute the DDT experimental facilities: DDT tube, initiation system and bed. The PEE is unable to combust constantly by itself. In order to obtain steady detonation, the length and diameter of DDT tube should be larger than usually specified in document data (P.B. Butler 1982). The main parameters of the DDT tube are: outer diameter 55 mm, inner diameter 37 mm, length 550 mm and compression value 0.18 Gpa, all of which ensure the safety of the DDT tube in the process of convection combustion. According to results, in this paper, resistance wire

is adopted for bed combustion. The resistance value is $250\ \Omega$, while the power supply voltage is 220 V. The initiation system consists of an electricity source, leading wire, resistance wire and DDT tube plug.

The experiment shows that PEE that excludes aluminum powder or whose content is below 4 %, cannot combust constantly by itself and the DDT phenomena hardly occur. In order to obtain DDT phenomena, three PEE samples, with average particle size of 92, 130 and $150\ \mu\text{m}$ respectively, are added with 8 % aluminum powder ($68\ \mu\text{m}$ particle size) separately as research objects.

2.2 Strain test

Five strain chips are located along the DDT tube axis with the same interval of 50 mm. Pressure and resistance sensor is pasted on the chock plug of the bottom of the bed for the direct contact of sensor and bed. A trigger probe is disposed at 350 mm from the initiation point, which connects strain chips, pressure and resistance sensor and trigger probe with a recording device. In the process of experiment, the trigger probe broke during detonation and sent pulse signals, the recording device thus started up for recording data.

2.3 Pressure test

The strain chip and pressure sensor are combined for the analysis of pressure change in the DDT process. Strain chips are attached to the outer surface of the DDT tube at equal intervals. A manganin pressure and resistance sensor is located on the choke plug at the bottom of the bed.

The pressure test system consists of a strain chip, a pressure and resistance sensor, a YLY4A strain stress meter, a pulse constant-current source, a transient recorder (model: TDS654C, TDS540, TDS2440) and trigger probe and so on. Using ionizing probe-to-trigger signals, when the shock wave affects the sensor and the sensitive part of the strain chip, the electric resistance is changed and the output voltage is changed accordingly. The detonation wave breaks over the ionizing probe, which produces impulse signals and triggers the recorder. The output voltage of the pressure and resistance sensor and strain chip, recorded by oscilloscope, becomes waves.

2.4 Velocity test

In the process of DDT, light will be produced in the chemical reaction front. By collecting optical

signals, the optical fibre velocity system can determine the velocity of combustion wave and detonation wave. The operating principle of the optical fibre velocity system is to utilize the optical signals collected by fibre probe on the reaction front; the optical signal can be transformed into an electrical signal through tripolar transistor, then the optical fibre velocity device will change the electrical signal into a sequential signal and send it to the recorder. The ionizing probe can trigger the signal for the recording system. The diameter of the pure quartz optical fibre is $400\ \mu\text{m}$ and the maximum diameter of the outer coating is 1.4 mm.

3 RESULTS

Three kinds of PEE sample, with average particle size of 92, 130 and $150\ \mu\text{m}$ respectively, have added 8 % aluminum powder ($68\ \mu\text{m}$ particle size) before loading and are tested in the DDT experiment under different loading densities. Figure 1 is the fragment of DDT tube after detonation.



Figure 1. DDT tube pieces after detonation.

3.1 Results of strain test

It may be seen from the records of the strain chip that in the earlier stage, only after a certain period, the waveshape of output pressure of each strain chip shows obvious variation: the first pressure wave detected by strain chip does not exist at the beginning, but is produced as the result of bed combustion; as combustion reaction becomes stronger, pressure increases in the bed, making the pressure wave stronger. Therefore, the pressure wave propagates continuously and with acceleration. At a certain point, it changes into

Table 1. Strain chip data of bed with density of 0.78 g/cm³ and particle size of 130 μm .

Strain chip	1	2	3	4	5	Triggle probe
Location <i>x</i> (mm)	85	145	205	265	325	505
Time point <i>t</i> (μs)	-	-181	-102	-64.9	-46.5	0
	405					
Average velocity (m/s)		268	760	1617	3261	-

shock waves. The propagation velocities of the pressure wave are listed in Table 1.

As illustrated in Table 1, the velocity of pressure wave accelerates quickly from 268 m/s to 3261 m/s, showing that the pressure wave will accelerate and change into a shock wave.

3.2 Results of pressure test

In the experiment, the pressure and resistance sensor is attached to the surface of the top of the DDT tube chock plug. When the detonation wave

3.3 Results of velocity test

Twelve probe holes are set along the DDT tube with the same interval of 40 mm. Selecting a pole at one side of the bed bottom to install an ionizing probe to trigger net signals, the other 11 holes are inserted with optical fibre probe. During the experiment, the DDT tube should be placed horizontally and the optical fiber should be inserted until the axis is in the middle of the bed.

As the combustion wave passes through the probe, the output voltage suggested by the wave shape changes markedly. Therefore, according to the different variations of the output voltage signals of different probes, the combustion veloci-

Table 2. DDT velocity test result of porous bed with density 0.78g/cm³, particle size 130 μm

Probe	1	2	3	4	5	6	7	8	9	10	11	12
location (mm)	65	105	145	185	225	265	305	345	385	425	465	505
time point (μs)	-1320	-605	-332	-160	-97.9	-67.3	-52.3	-41.7	-31.3	-21.1	-10.4	0
Time (μs)	715	273	172	62.1	30.6	15	10.6	10.4	10.2	10.7	10.4	
Average velocity (m/s)	56	146	233	643	1308	2670	3769	3825	3922	3738	3857	

affects the sensor, the resistance value increases and pressure signals are produced by impulse net. Several shape comparisons of the pressure wave on the bottom of the bed are made. This shows that, although the loading densities and particle sizes are different, the variation shape of pressure wave is basically the same. From the wave shape of different samples, it is clear that after net break-over, all the pressure signals increase for a small period of time. It also shows that all beds are compressed and then compacted. Because the materials are different, the detonation wave must have left a reflection and a superposition phenomenon on the pressure and resistance device. A peak value of the wave shape of every kind of sample, exceeding steady state of detonation pressure, appears before the second platform. The pressure test results are shown in Tables 3, 4 and 5.

ties in the different bed locations are calculated. Table 2 shows the DDT velocity test result. The probe location in this table is the distance from the probe's hole to the initiation end surface of the bed.

Figure 2 shows the relationship between the front and the time point of the combustion wave. The propagation rule of the combustion wave moving in the tube is presented as well as the process from the convection current at low velocity to steady state detonation. Combined with the average propagation velocity of the combustion front in Table 2, the process can be divided into two stages; convection combustion, in which the velocity increases continuously, and steady state detonation. The intersection point of the two stages is the critical detonation point. In the first stage, the wave propagates at low velocity, the curve of the front location and its time point is

close to exponential form; whereas in the stage of steady state detonation, led by the shock wave, the chemical reaction zone propagates at steady velocity to the non-combustion zone; the curve of location and time is linear. The average steady state detonation velocity of the graph is 3822.2 m/s. In Table 2, it can be seen that the intersection point is between the sixth and the seventh probes. Fitting the exponential curve of the former six points and the linear of the latter six points, the crossing point is the critical detonation point. After analysis, the critical detonation point of this experiment is determined at 278 mm from the initiation surface of the bed. This distance is the predetonation distance of the bed.

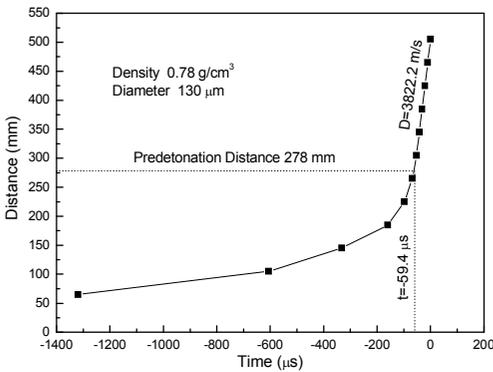


Figure 2. Propagation trace of combustion front.

The corresponding time point in this experiment is $-59.4 \mu s$. This indicates that it takes $59.4 \mu s$ for the detonation wave to travel from the critical detonation point to trigger probe (probe 12).

3.4 DDT experiment results of different loading densities

Tables 3, 4 and 5 show the DDT experimental results of different loading densities. The particle sizes of PEE sample are 92, 130 and $150 \mu m$ accordingly.

3.5 Analysis and discussion

Drawing the induced detonation distance and different loading densities of the three particle sizes in graph 8 and making a comparison, all of the fitting curves of particle sizes are 'U' shaped and with a density scope. It is most likely that DDT phenomena happen in the scope and that the scopes of all three are very similar. With same density, although there are small differences in the

induced detonation distances, some shared characteristics are discernible. With same density, the longest induced detonation distance is $150 \mu m$, the next, $130 \mu m$ and the third, $92 \mu m$, indicating that under same density, the smaller the particle size, the shorter the induced detonation distance and the easier the DDT phenomenon. This accords with the characteristics of convection combustion of a porous bed. As for beds with same density, because of the same pore spaces, the smaller the particle size and the more the particles in a unit volume, the bigger the total specific surface area, the easier for combustion and the easier for detonation.

If the strain chip test result and optical fibre probe test result are drawn in one graph, the propagation trace of the pressure wave and combustion wave with 0.78 g/cm^3 , $130 \mu m$ average particle size can be obtained; see Figure 4.

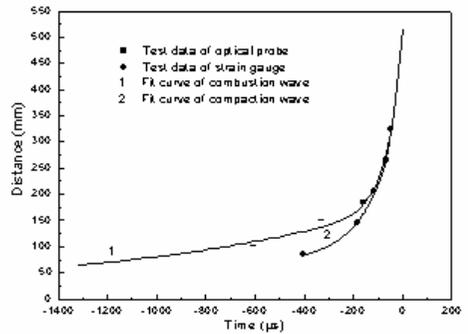


Figure 4. Propagation trace of combustion wave and pressure wave.

Based on the test result of the strain chip and optical fibre probe, the average propagation velocity of the pressure wave and combustion wave in different locations is presented in Figure 5.

Combining Figures 4 and 5, the DDT process of PEE can be divided into four stages: (a) Convection combustion at low velocity. After the start of combustion of the porous bed, the convection wave combusts rapidly. At this stage, the combustion wave propagates almost linearly with low velocity increasing slowly; (b) compression convection combustion.

Table 3. Natural parameters of bed detonation with average particle size of 92 μm .

No.	Loading density (g/cm^3)	Go or fail	Detonation velocity (m/s)	Induced detonation distance (mm)	Time (μs)	Detonation pressure (GPa)
1	0.55	Fail	-	-	-	-
2	0.57	Fail	-	-	-	-
3	0.67	Go	3682.1	306	54.0	3.09
4	0.71	Go	3794.6	298	54.6	3.70
5	0.74	Go	3851.7	275	59.6	3.46
6	0.78	Go	3957.7	268	59.9	3.19
7	0.82	Go	3977.9	265	60.3	3.63
8	0.84	Go	3989.0	269	59.2	2.92
9	0.86	Go	4029.5	275	57.0	4.19
10	0.86	Go	4038.7	282	55.3	4.00
11	0.88	Go	4107.9	287	53.2	3.90
12	0.88	Go	4112.5	285	53.6	4.28
13	0.93	Fail	-	-	-	-

Table 4. Natural parameters of bed detonation with average particle size of 130 μm .

No.	Loading density (g/cm^3)	Go or fail	Detonation velocity (m/s)	Induced detonation distance (mm)	Time(μs)	Detonation pressure (GPa)
1	0.56	Fail	-	-	-	-
2	0.67	Go	3486.8	317	53.9	3.44
3	0.71	Go	3595.5	310	54.2	3.62
4	0.73	Go	3653.6	286	59.9	3.60
5	0.75	Go	3746.6	281	59.8	2.95
6	0.78	Go	3822.2	278	59.4	3.36
7	0.82	Go	3875.6	274	59.6	3.49
8	0.84	Go	3942.0	281	56.8	3.68
9	0.89	Go	3997.3	297	52.0	3.81
10	0.89	Go	4063.6	304	49.5	4.49
11	0.92	Fail	-	-	-	-
12	0.93	Fail	-	-	-	-

Table 5. Natural parameters of bed detonation with average particle size of 150 μm .

No.	Loading density (g/cm^3)	Go or fail	Detonation velocity (m/s)	Induced detona- tion distance (mm)	Time (μs)	Detonation pressure (GPa)
1	0.56	Fail	-	-	-	-
2	0.71	Go	3416.8	304	58.9	3.37
3	0.76	Go	3587.2	285	61.4	3.76
4	0.78	Go	3654.5	282	61.1	3.15
5	0.80	Go	3766.9	277	60.7	3.49
6	0.82	Go	3779.8	278	60.2	4.20
7	0.84	Go	3831.4	287	56.9	4.56
8	0.86	Go	3862.7	290	55.6	4.15
9	0.88	Go	3882.1	293	54.5	3.88
10	0.89	Go	3910.7	304	51.5	4.36
11	0.92	Fail	-	-	-	-

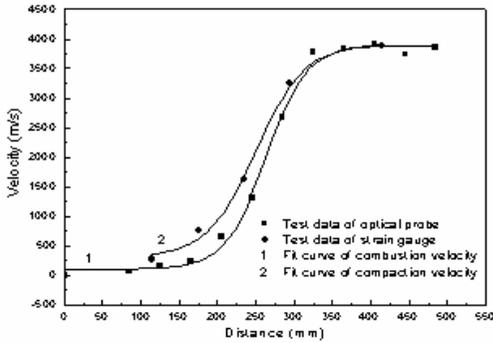


Figure 5. Velocity verification of combustion wave and pressure wave.

After the period of convection combustion, the gaseous product accelerates the pressure to a certain point; a pressure wave emerges behind the combustion wave with a certain intensity, propagating to the unburnt area. Under the driven force of pressure, it enters the stage of pressure combustion. The combustion wave propagates in exponential shape at an accelerating velocity. The velocities of pressure and combustion also increase in exponential shape; (c) shock wave to detonation wave: at a certain point when the pressure wave propagates to the unburnt area in accelerating velocity, the velocity exceeds the matrix sound velocity of materials and forms a shock wave (strong pressure wave). Through calculation, the matrix sound velocity of the PEE bed (0.78 g/cm³ loading intensity, 130 μm average particle size) is 1366.7 m/s. It may be seen that when the pressure wave velocity achieves the matrix sound velocity, the shock wave is still behind the combustion wave, indicating that the shock wave forms after the combustion wave. After formation, the shock wave runs after the combustion wave with a higher velocity and catches up the combustion wave in a very short time. At this time, both the shock wave and the combustion wave reach detonation velocity, thus detonation is formed in the bed; (d) steady state detonation. The shock wave induces the chemical reaction area and propagates at a steady velocity to the unburnt explosives

4 NUMERICAL SIMULATION ON DDT PROCESS OF PEE

Utilizing finite difference calculus and self-adapting Cartesian net division technology, DDT numerical simulation is carried out with 0.78g/cm³

loading intensity of PEE and 130 μm of average particle size. Figures 6 and 7 are pressure distribution charts calculated by numerical simulation.

It may be seen from Figures 6 and 7 that before the time point of 3.089 ms, the distributions of pressure lay smoothly along the distance axis without pressure peak. The pressure only begins from the initiation surface and descends along with distances to a minimum value. After 3.089 ms, the peak appears on the pressure distribution curve, which is along the axial direction. At the beginning, the peak is not obvious, but with time, it moves forward and accelerates rapidly. According to this trait, the propagation trace of the pressure peak is obtained.

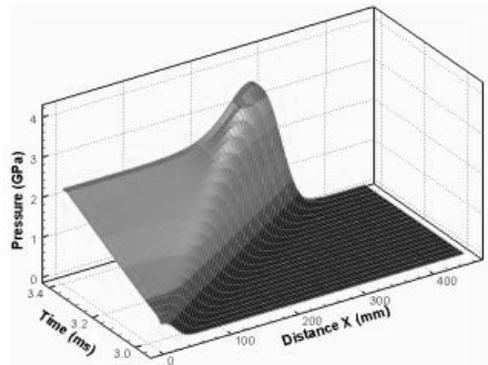


Figure 6. Tridimensional distribution of meteorological pressure, time and distance.

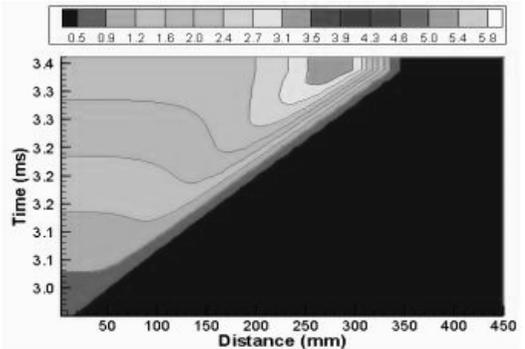


Figure 7. Constant value line of meteorological, time and distance.

Pressure peak and the propagation traces of the combustion wave front are different at the beginning. With time, the two traces approach each other and eventually overlap. According to the calculated result of the pressure distribution, pressure peak propagation can also be divided into

three stages: (a) Before the time point of 3.089 ms, the heaviest pressure point in the bed is on the initiation surface. The pressure distribution on the axial direction shows that the pressure distribution is smooth at this stage without pressure peak; it declines to a minimum from the initiation surface. (b) From 3.089 ms, the steady state detonation begins from 3.421 ms. When combusting at 3.089 ms, the pressure peak appears on the axial direction, corresponding to 84 mm behind the combustion wave front. In time, the pressure peak goes forward and accelerates increasingly. The accelerating speed exceeds the propagation velocity of the combustion wave front, thus the pressure peak approaches ever closer the combustion wave front. Pressure accelerates at high speed, the pressure distribution on the axial direction becomes ever steeper. The shock wave nature is observed. (c) After 3.421 ms, the pressure peak surpasses the combustion wave front. At this time, the velocity of the combustion wave front reaches the steady state detonation velocity. From then on, the pressure peak stops accelerating, but, in the form of a detonation wave, induces the chemical reaction area propagating steadily at a certain detonation velocity. Because both the combustion wave front and the pressure peak are the results of explosive particle combustion and chemical energy release, a relationship must exist between the two. The results of numerical calculation prove this viewpoint and the three stages correspond to each other. As to the DDT process under different loading densities, the propagation traces of the pressure peak and combustion wave front can also be divided into the same three stages, only with different time points of each stage.

The numerical results accord well with the experimental results.

5 CONCLUSIONS

- According to the DDT experimental result of different loading densities, the relationship curve of induced detonation distance and loading density is “U”-shaped. It is considered that there is an optimal density interzone where it is most easy for DDT process in bed.
- From the DDT experiments of PEE of different particle sizes, it is found that of same loading density, the smaller the particle size, the shorter the induced detonation distance and the easier generation of DDT process.
- Basing on the experimental results, the DDT mechanism of PEE is analysed and the DDT process can be divided into 5 stages: initiation, convection combustion at low velocity, compression combustion at high velocity, transformation from shock wave to detonation and steady state detonation.
- Utilizing finite difference calculus and self-adapting Cartesian net division technology, numerical calculation of DDT process is carried out and the result is accordant with experimental data. By numerical simulation, the details of combustion wave front propagation, compression wave development, formation of shock wave and steady state detonation of porous bed DDT process are presented and generation and development reasons of some common physical phenomenons of DDT process are analysed.

REFERENCES

- Alexel M. Khokhlov & Elaine S. Oran. 1999. Numerical simulation of detonation initiation in a flame brush, the role of hot spots. *Combustion and Flame* 119, 400–416.
- Bernecker, R. R. & Price. 1982. Burning to detonation transition in porous beds of a high-energy propellant. *Combustion and Flame* 48, 219–231.
- Butcher, A. G. et al. 1981. Effects of igniter and compaction on DDT run up in plastic pipes. *Proceedings of 7th Symposium(Inter) on Detonation* 142.
- Butler, P. B., Lembeck, M. F. & Krier, H. 1982. Modelling of shock development and transition to detonation initiated by burning in porous propellant beds. *Combustion and Flame* 46, 75–93.
- Guo T. 1998. Present situation and development of the industrial explosives in China (in Chinese). *Explosive Material* 27(3): 12–16.
- Jiang, Xi. & Wang S. 1992. Numerical simulation of deflagration to detonation transition in high loading energetic material bed (in Chinese). *Expulsion and Shock Wave* 12(2): 97–105.
- Jin, Z. Yang, T. Yuan, Y. Zhang, X. & Guan, H. 1994. Studies of deflagration to detonation transition in granular propellants bed (in Chinese). *Expulsion and Shock Waves* 14(1): 66–72.
- Macek, A. 1959. Transition from deflagration to detonation in cast explosives. *J. Chem. Phys.* 31(1): 162–167.
- Wang, X. 1994. *Emulsion Explosives* (English edn), Beijing: Metallurgy Industry Press.

