Title	Studies on Explosion. I.
Author(s)	WAKAZONO, Yoshikazu; KITAO, Shigetaka
Citation	Bulletin of the Disaster Prevention Research Institute (1965), 14(3): 27-40
Issue Date	1965-03-25
URL	http://hdl.handle.net/2433/123766
Right	
Type	Departmental Bulletin Paper
Textversion	publisher

Kyoto University

Studies on Explosion. I.

By Yoshikazu WAKAZONO and Shigetaka KITAO

1. Introduction

The exploding or detonating properties of ammonium nitrate (AN) have been recognized for many years as accidents by explosion take place in many factories and storages dealing with AN. Also, it has been generally known that the exploding force of AN increases when the AN includes some carbon sources.

On account of its exploding properties, AN has been utilized as material for the coal mining ammonium nitrate explosives and as a blasting agent with carbon black or aluminium powder. Of late, ammonium nitratefuel oil mixtures (AN-FO) have been used for blasting in many countries, especially in U.S.A. and Canada.

Studies on the exploding properties of AN-FO have been in progress for some years. At present, it is important to understand them for more effective blasting or new utilization of AN-FO. It is also significant to study them in view of the reactions which propagate on the boundary between solid (AN) phase and liquid (FO) phase. In the present report we want to consider the properties of AN-FO which we have made clear to some extent by observing several kinds of AN with the electron and optical microscopes, by measuring detonating velocity and by carrying out some sensitivity tests.

2. Prilled ammonium nitrate

The ammonium nitrate used for blasting agents called AN-FO is the granular porous AN with low density, and, is generally called "prilled AN". At first, we took optical microscopic photographs of a slice of granular
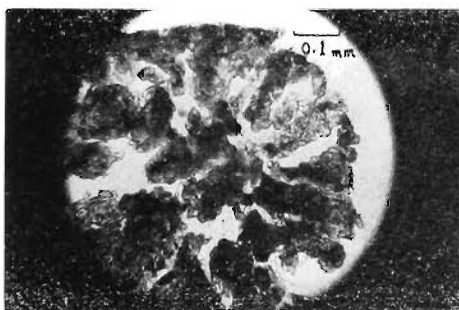

Photo. 1. Optical microscopic photograph of prilled AN (1).
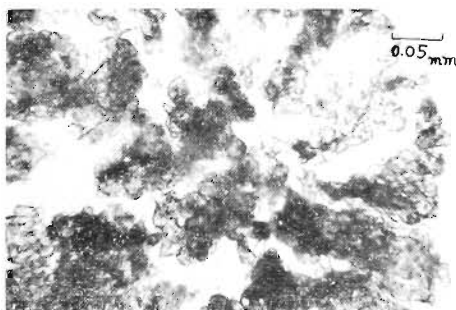
Photo. 2. Optical microscopic photograph of prilled AN (2).

porous prilled AN as shown in photos 1 and 2.   By these photos we could
recognize that a pill of granular porous prilled AN consisted of smaller
particles which are called the "primary particles" and that the granular
porous prilled AN pill formed the "secondary particle" by itself.   These
aspects of prilled AN are more obvious in Photo 2.

We made further observation with the electron microscope of the surface
of the "primary particle" and that of the ordinary crystalline AN with
high density, and photographs such as photos 3 and 4 were taken.   These
photos showed the difference in the surfaces of the prilled AN and the
ordinary crystalline AN.   Upon investigation of Photo 3, we recognized that
the surface was rugged and that in its blackish portions there existed the
surfactant or the anti-caking agents.   However, such features could not be
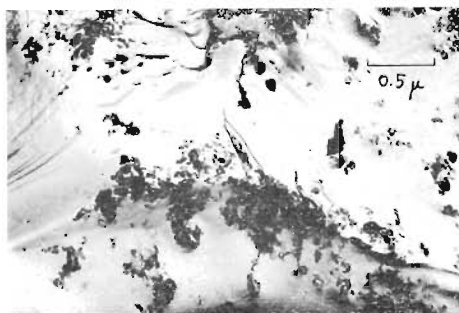observed on the surface of the ordinary crystalline AN as shown by Photo 4.

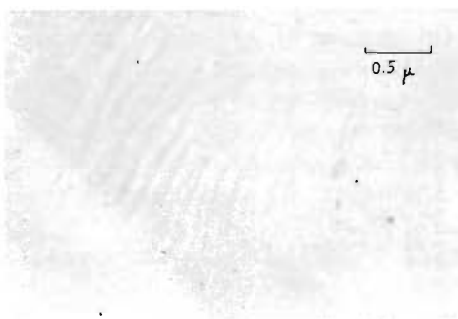Photo. 3. Electron microscopic photograph
of prilled AN.

Photo. 4. Electron microscopic photograph
of ordinary crystalline AN.

Through these observations, we could recognize that the prilled AN was
a kind of granular porous AN with many cavities.   Therefore, we can
understand that the bulk density of prilled AN is below $1.0 \, \text{g/cm}^3$, while
that of ordinary AN is about $1.7 \, \text{g/cm}^3$.

Because the reaction of AN-FO is caused on the boundary between the
solid (AN) phase and the liquid (FO) phase and because its velocity is
influenced by the size of the area where AN and FO are in contact with one
another, the detonation velocity and sensitivity of AN-FO, when the prilled
AN is used, are higher than those when the ordinary crystalline AN with
high density is used.   It is, therefore, important to study the mutual rela-
tions between porosity, bulk density, particle size, detonation velocity, sensi-
tivity, and other related factors.

3. Measuring of detonation velocity of AN-FO

In order to conduct experiments on the exploding properties of AN-FO, we
measured the porosity of prilled AN in terms of the ratio of oil absorp-
tion, its bulk density and the detonation velocity of AN-FO.   Then, we tried
to detect the relation between them.

3-1 Measuring methods of properties of AN and AN-FO

3-1-1 Measuring methods of oil absorption and bulk density

When the prilled AN is used for AN-FO, its porosity has some significance from the view point of the exploding reaction of AN and FO. We, therefore, measured the porosity of prilled AN of the oil absorption by the following method: After filling the glass pipe as shown in Fig. 1 with 100 g of prilled AN and adding to this 100cc of FO, the pipe was kept in that condition for 5 minutes. Then, drawing out the oil from the bottom of the glass pipe by a vacuum pump, we measured the weight of the oil remaining within the prilled AN, and the oil absorption ratio was obtained as "the proportion of the remaining oil to 100 g of AN". Also, the bulk density of prilled AN was obtained by measuring its weight and volume.
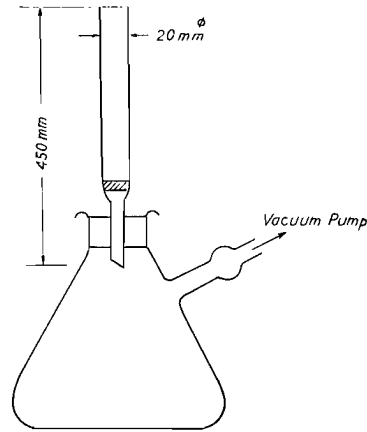
Fig. 1. Measuring of oil absorption.

3-1-2 Measuring method of detonation velocity and mixing ratio of AN and FO

We measured the detonation velocity of AN-FO by the Dautriche method[1].

It is said that the explosion of AN-FO is theoretically most effective when the ratio of AN/FO is 94.3/5.7. We tested the influence of oil content upon the detonation velocity of AN-FO and the result is shown in Fig. 2, which reveals that the oil content most effective in increasing detonation velocity is about 5.5%. In this experiment, the mixing ratio of AN/FO was 94.5/5.5. For the initiation of AN-FO, we used, a No. 8 electric cap and a 10 g tetryl pellet.
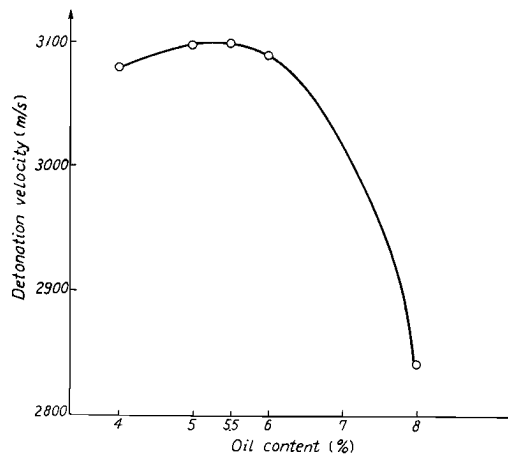
Fig. 2. Influence of oil content upon detonation velocity.

3-2 Samples of AN

For the samples, we used several kinds of AN as shown by Table 1: non-coating prilled AN, prilled AN coated with surfactant, prilled AN coated with anti-caking agents, powdery AN with low density and prilled AN of Spencer Chemical Company Limited. Their bulk density and oil absorption are shown by Table 1. Their particle size ranges from 6 to 20 mesh except

the powdery AN, and their water content is 0.3% or below.

As the sampls for the experiment on the relation between particle size and detonation velocity, we used four kinds of prilled AN coated with surfactant as shown by Table 2. Their bulk density is about 0.8 g/cm³ and their water content is 0.25% or below. For the tests on water content, we used prilled AN coated with surfactant as shown by Table 3; its bulk density being about 0.8 g/cm³.

3-3 Experimental results

We measured the detonation velocity of the different kinds of AN-FO listed in 3-2 above and obtained the experimental results shown by tables 1, 2 and 3.

TABLE 1. Bulk density, oil absorption and detonation velocity.

Samples	Bulk density (g/cm³)	Oil absorption (g/100 gAN)	Detonation velocity (m/s)
Noncoating prilled AN	0.717	17.2	3,200
	0.840	9.6	2,750
	0.918	8.0	2,610
	1.010	4.6	2,340
Prilled AN with surfactant	0.747	22.4	3,480
	0.848	16.3	3,220
	0.926	11.8	2,980
	1.038	6.3	2,560
Prilled AN coated with anti-caking agents	0.736	20.9	3,370
	0.838	15.3	2,650
	0.874	13.0	2,380
	0.944	10.0	non-detonation
Powdery AN with low density	0.500	42.9	3,790
Spencer's prilled AN (N–IV)	0.758	14.0	2,820
	(0.833)	(11.6)	(2,500)

TABLE 2. Particle size and detonation velocity.

Samples		Particle size (mesh)	Detonation velocity (m/s)
Prilled AN with surfactant. Bulk density : 0.8 g/cm³ Water content : below 0.25%	1	+10	2,600
	2	−10~+14	2,780
	3	−14~+20	3,000
	4	−20~+32	3,480

TABLE 3. Water content and detonation velocity.

Samples	Water content (%)	Detonation velocity (m/s)
Prilled AN coated with surfactant. Bulk density: 0.8 g/cm³	0.259	2,780
	0.51	2,790
	1.55	2,785
	4.23	2,800
	6.16	2,785
	8.30	2,770
	10.10	2,705
	12.45	2,440

3-3-1 Relation between bulk density and detonation velocity

From Table 1, we could calculate the relation between bulk density and detonation velocity of AN-FO as shown by Fig. 3.

From this result, we recognized that the smaller the bulk density was, the higher the detonation velocity became, and that the detonation velocity of AN-FO was variable even if its bulk density was constant on account of the differences in the characteristics of its coating agents.

3-3-2 Relation between oil absorption and detonation velocity

By Table 1, we could show the relationship between the oil absorption and detonation velocity of AN-FO as shown by Fig. 4.

From this result, we concluded that the detonation velocity became high with increase in the ratio of oil absorption. This fact means that the propagation

Fig. 3. Relation between bulk density and detonation velocity.

Fig. 4. Relation between oil absorption and detonation velocity.

of detonation takes place more smoothly and rapidly in AN-FO especially when the porosity of the AN is larger than that of non-porous AN and FO. That is to say, the more porous the prilled AN is, the higher the detonation velocity becomes. Further, it is to be noted that the coating agents have many influences upon the detonation velocity.
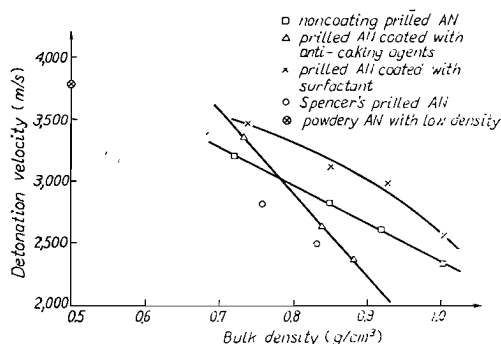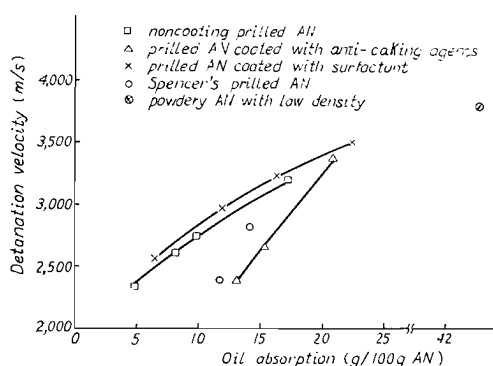
3-3-3 Relation between oil absorption and bulk density

From Table 1, we could also show the relation between oil absorption and bulk density in Fig. 5.
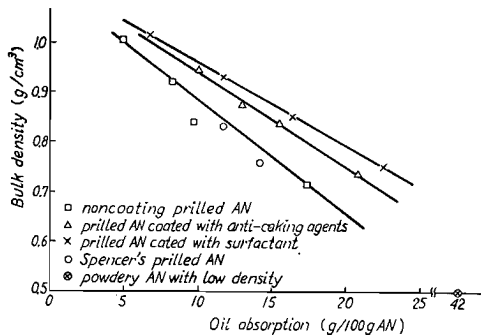
Fig. 5. Relation between oil absorption and bulk density.

From these results, we recognized that the relation between oil absorption and detonation velocity was linear and that the smaller the bulk density was, the higher the oil absorption was. This means that prilled AN with low bulk density is more porous than prilled AN with higher density. Also, from the fact that the prilled AN with coating agents has larger oil absorption than the prilled AN without coating,

it was recognized that coating agents had some influence on the detonating force and velocity of AN-FO.

3-3-4 Relation between particle size and detonation velocity

From Table 2, the relation between particle size and detonation velocity is shown in Fig. 6 below.

From these results, we recognized that the particle size of prilled AN has many influences on the detonation velocity of AN-FO and is one of the important factors in deciding it.

3-3-5 Effect of water content on detonation velocity
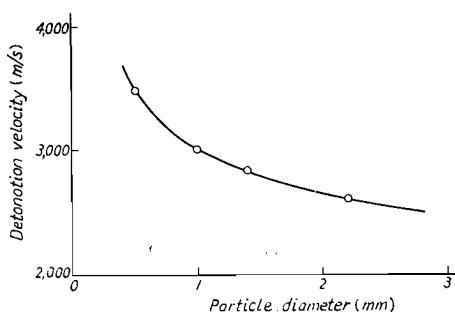
From Table 3, the relation of

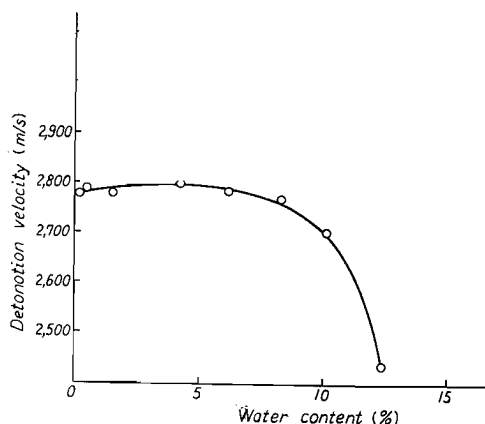Fig. 6. Relation between particle size and detonation velocity.

Fig. 7. Effect of water content on detonation velocity.

water content and detonation velocity is shown in Fig. 7 above.

From these results, we recognized that when the water content was 8% or above, the detonation velocity of AN-FO decreased abruptly. This fact can never be neglected when AN-FO is used in moist conditions.

3-4 Consideration

Through these experimental results, we came to the conclusion that the decisive factors in the detonation velocity of AN-FO could be bulk density, oil absorption, particle size and water content, if other conditions, such as initiation, were constant.

4. Sensitivity tests of AN-FO

Detonation velocity is not always relative to the sensitivity of AN-FO. We made several sensitivity tests to find out the differences between AN-FO and granular TNT with 7% water content. They were fall hammer tests and cap sensitivity tests in iron pipes and vinyl chloride pipes.

4-1 Testing methods

Using the same kind of samples, we employed the three testing methods as follows :

4-1-1 Fall hammer test

This testing method has been generally used for almost all explosives. The sensitivity of an exploding agent is described by "the number of detonation per the number of tests" together with the weight of hammer and the height from which the hammer is dropped, which decide th eeffectiveness of explosion.

4-1-2 Cap sensitivity tests with iron pipes

The effectiveness of explosion was determined by initiating the explosive agents loaded in an iron pipe with several kinds of electric caps such as No. 3, No. 6 and No. 8, and comparing the respective iron fragments remaining after the detonation.

4-1-3 Cap sensitivity tests by vinyl chloride pipes

This testing method was almost the same as that of 4-1-2. In this method, however, the effectiveness of the explosion of the agents was confirmed by the condition after explosion of the detonating fuse which was inserted at the end of the vinyl chloride pipe as shown in Fig. 8.

Fig. 8. Cap sensitivity test with vinyl chloride pipes.

Initiation of the agents loaded in the vinyl chloride pipe was conducted with a No. 6 electric cap.

4-2 Samples of exploding agents

For the samples, we used prilled AN as shown in Table 1 and granular TNT containing 7% of water.
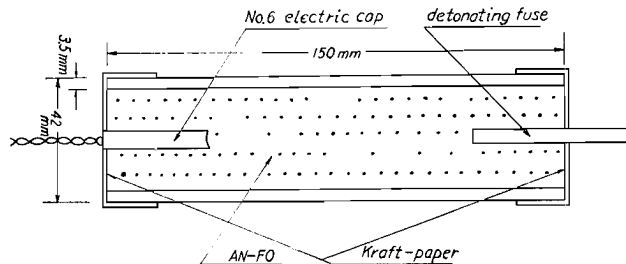
4-3 Experimental results

The experimental results are shown by tables 4 and 5 and photos 5, 6, 7, 8 and 9.

4-3-1 Results of the fall hammer tests

The results of the fall hammer tests of AN-FO and granular TNT are shown in Table 4.

TABLE 4. Results of fall hammer tests.

Samples	Sensitivity (semi-detonations/tests)
Powdery AN with low density	4/10
Prilled AN coated with surfactant (bulk density : 0.747 g/cm³)	2/10
Granular TNT (water content : 7%)	0/10

By "semi-detonation" in Table 4 we mean such a state where the effectiveness of explosion is rather low, but where some trace of detonation is recognizable. From the above results, we knew that the sensitivity of granular TNT (water content: 7%) is lower than that of AN-FO mixtures composed of low density prilled AN and FO.

4-3-2 Results of cap sensitivity tests with iron pipes

Results of cap sensitivity tests with iron pipes are shown by Table 5 and photos 5, 6, 7, 8 and 9.

From the above enumerated results, it was observed that the smaller the size of electric cap was, the smaller the sensitivity became, and that the

TABLE 5. Cap sensitivity tests with iron pipes and vinyl chloride pipes.

Samples	Bulk density (g/cm³)	Iron pipes			Vinyl chloride pipes
		with a No. 8 e.c.	with a No. 6 e.c.	with a No. 3 e.c.	
Prilled AN coated with surfactant	0.747	○	△	△	×
	0.848		△	△	×
	0.926	△	×		×
	1.038		×		×
Prilled AN coated with anti-caking agents	0.736	△	△		×
	0.838	×			×
Powdery AN with low density	0.500	○		△	○
Spencer's prilled AN	0.758	△	△		×
Granular TNT (water content : 7%)		×			×

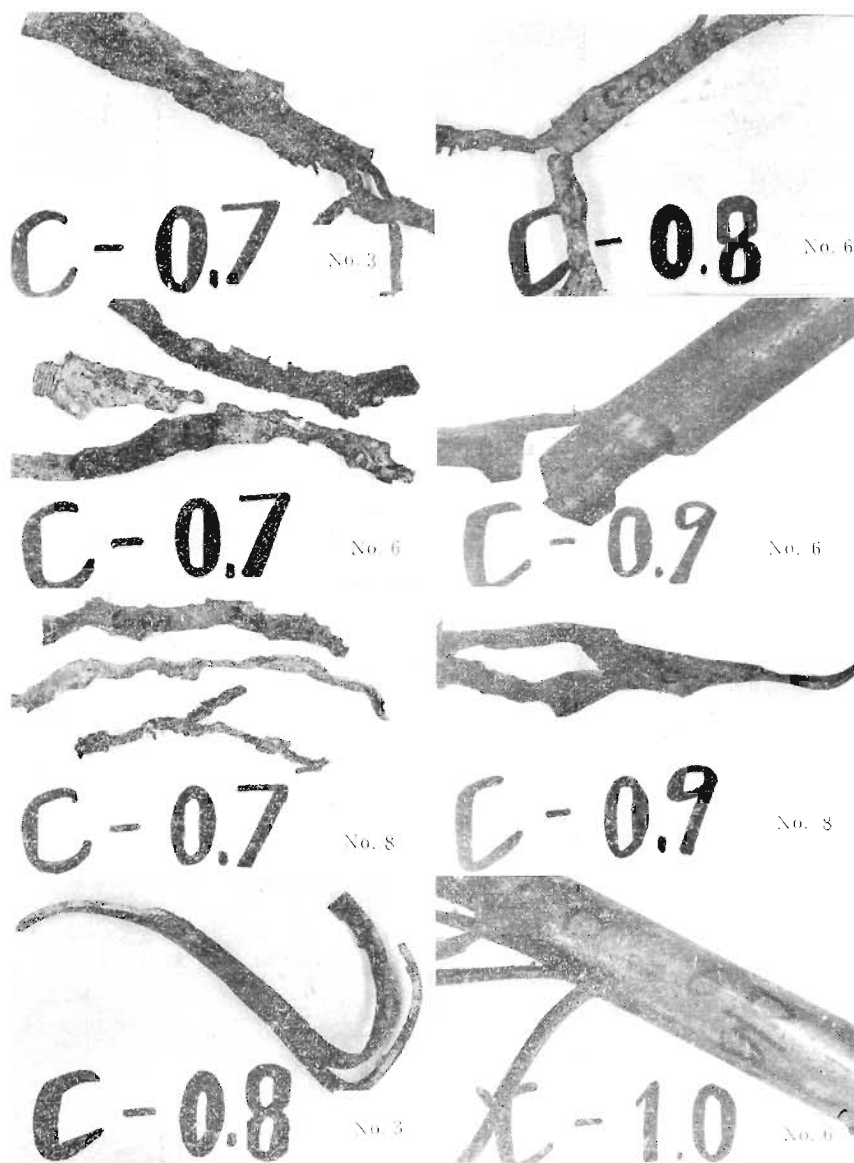○ : detonation   △ : semi-detonation   × : Non-explosion

Photo. 5.   Prilled AN coated with surfactant and FO.
Numbers in right bottom corners show size of electric caps used.

sensitivity of AN-FO increased with the decrease in the bulk density of AN.

4-3-3 Results of cap sensitivity tests with vinyl chloride pipes

We show the results in Table 5 above, disclosing non-explosions except with low density powdery AN.

4-4 Consideration

Through the results of these sensitivity tests, the following properties of
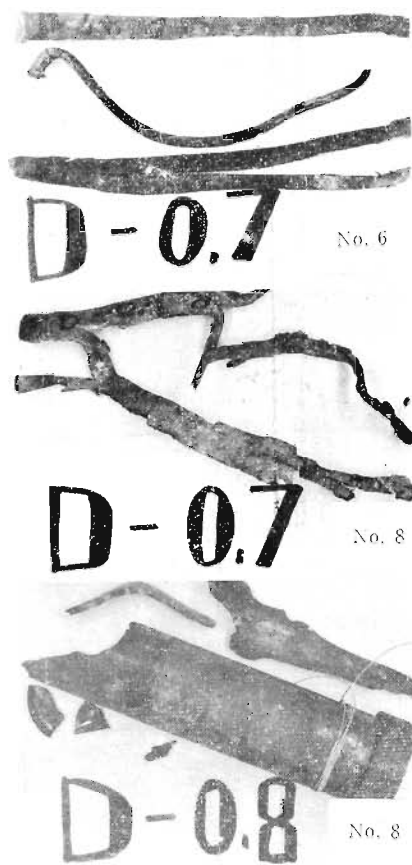
Photo. 6.   Prilled AN coated with anti-caking agents and FO.

Photo. 9.   Granular TNT (water content : 7%)

Photo. 7.   Powdery AN with low density and FO.

Photo. 8.   Spencer's prilled AN.

AN-FO were recognized : Both the bulk density of AN and the coating agents have remarkable influence upon the sensitivity of AN-FO, and AN-FO with higher sensitivity than granular TNT can be composed, if proper selection is made concerning the bulk density of the prilled AN and its coating agents.

5. Tests on the explosion of AN-FO in iron pipes

In paragraph 3 above we discuss the properties of prilled AN and recognize that the detonation velocity of AN-FO is influenced by the bulk density, oil absorption, particle size, and water content of the prilled AN when the loading and initiating conditions of AN-FO are constant.

Further, we made tests on the explosion of AN-FO on a comparatively large scale in order to find out to what extent the booster and loading conditions influence upon the detonation velocity of AN-FO when the properties of prilled AN are constant.

5-1 Testing method

During these experiments on the explosion of AN-FO, we again measured the detonation velocity of AN-FO by the Dautriche method using iron pipes. The mixing ratio of AN/FO was 94.5/5.5.

5-2 Sample of prilled AN

The prilled AN as shown in Table 6 was used.

5-3 Experimental results

TABLE 6. Sample of prilled AN.

Bulk density (g/cm³)	0.806
Particle size (mesh)	8~20
Water content (%)	0.02
Surfactant content (%)	0.5

TABLE 7. Relation between diameter of iron pipes, kind of booster and detonation velocity.

Diameter of pipe		Loading volume (cm³)	Weight of ANFO (g)	Detonation velocity (m/s)		
inch	cm			Tetryl 10 g	Hexogen 10 g	Dynamite 10 g
1	2.54	127	121	2870	2670	2550
1 1/4	3.50	240	228	3110	3090	2980
2	5.08	508	483	3290	3265	3170
3	7.62	1140	1083	3430	3360	3240
4	10.16	2030	1929	3420	3380	3250

Length of pipe : 250 mm, loading density : 0.95 g/cm³, dynamite : ammonia gelatine.

TABLE 8. Relation between weight of booster and detonation velocity.

Diameter		Loading volume (cm³)	Weight of ANFO (g)	Weight of booster		Detonation velocity (m/s)
inch	cm			g	%	
1	2.54	127	121	10	8	2870
1 1/4	3.50	240	228	10	4	3110
2	5.08	508	483	10	2	3290
3	7.62	1140	1083	10	1	3430
4	10.16	2030	1029	10	0.5	3420
5	12.70	3140	2983	10 / 30	0.3 / 1	3340 / 3720
6	15.24	4550	4323	10 / 40	0.2 / 1	2875 / 3890

Length of pipe : 250 mm, loading density : 0.95 g/cm³, kind of booster : Tetryl.

TABLE 9. Relation between diameter of iron pipes, loading density and detonation velocity.

Diameter		Loading volume	Loading density 0.8 (g/cm³)		Loading density 0.9 (g/cm³)		Loading density 0.95 (g/cm³)		Loading density 1.0 (g/cm³)	
inch	cm		Weight of ANFO (g)	Detonation velocity (m/s)	Weight of ANFO (g)	Detonation velocity (m/s)	Weight of ANFO (g)	Detonation velocity (m/s)	Weight of ANFO (g)	Detonation velocity (m/s)
1	2.54	127	101	2545	114	2820	121	2870	127	2885
1 1/4	3.50	240	192	2955	216	3085	228	3110	240	3120
2	5.08	508	406	3015	457	3245	483	3290	508	3310
4	10.16	2030	1624	3100	1827	3350	1929	3420	2030	3435

Length of pipe: 250 mm, booster: Tetryl 10 g.

We obtained the results shown in Tables 7, 8 and 9.

5-3-1 Influence of booster on detonation velocity

From Table 7, we obtained the relation between the diameter of the iron pipes and the detonation velocity as shown in Fig. 9.

From the above figures, it was recognized that the detonation velocity of AN-FO increased with increase in the diameter of the iron pipes from 1 to 3 inches, when the weight of the booster was fixed at 10 grams, and that the detonation velocity was also influenced by the kind of components making up the booster. If a booster with higher detonation velocity is employed, the detonation of AN-FO also gains a high velocity in iron pipes within the same range of diameter.

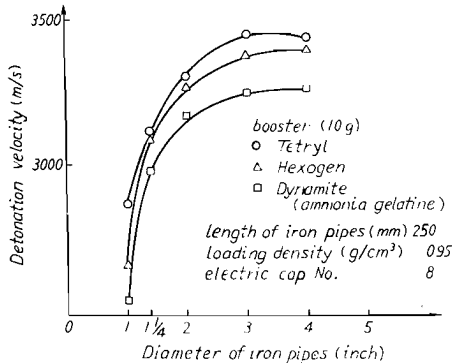Then, we obtained from Table 8 the result as shown in Fig. 10.

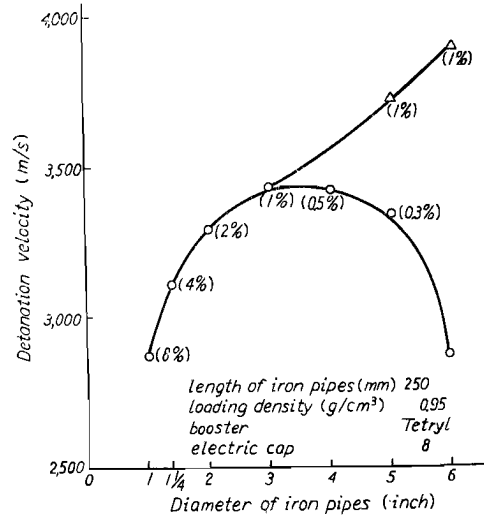Fig. 9. Influence of kind of booster on detonation velocity.

Fig. 10. Influence of weight of booster on detonation velocity.
Ratio of booster per loaded ANFO is shown in parentheses.

From this figure, we knew that the detonation velocity of AN-FO was subject to the influence of the weight of the booster and the proportion of

the booster to the loaded AN-FO. In other words, the detonation velocity of AN-FO could not be increased, when the proportion of the booster to the loaded AN-FO decreased, even if the diameter of the iron pipes was increased from 1 to 6 inches.

5-3-2 *Influence of diameter of iron pipes on detonation velocity*

From Table 9, we obtained the figures on the influence of the diameter on the detonation velocity of AN-FO as shown in Fig. 11.

From the above figure, it was observed that the detonation velocity of AN-FO increased with the increase in the diameter of iron pipes from 1 to 4 inches, if the loading density was constant. It seems that the limiting diameter of detonation is approximately 1 inch with these initiating conditions, and it is considered that the diameter is influenced by both the weight and the kind of booster and is changeable with the variation of loading density of AN-FO.
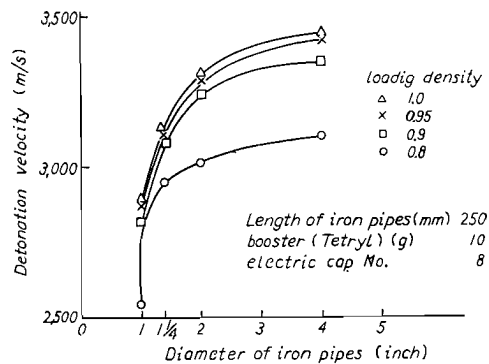

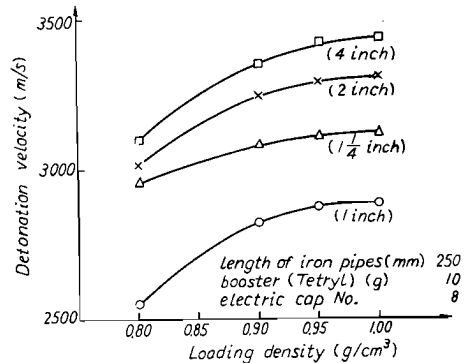Fig. 11. Influence of diameter on detonation velocity.

Fig. 12. Influence of diameter and loading density on detonation velocity.

5-3-3 *Influence of loading density on detonation velocity*

Table 9 can be illustrated by Fig. 12.

From the above figure, we recognized that if the diameter and the initiating conditions were constant, the detonation velocity increased with the increase in loading density from 0.8 to 1.0 g/cm³. In most cases, with constant loading density, the detonation velocity of AN-FO increases with the increase in both the loading diameter and the weight of booster.

5-4 *Consideraiton*

Through these observations, we came to the conclusion that if the properties of prilled AN are constant, the detonation velocity of AN-FO is regulated by controlling the quality, quantity of booster, loading density and the length and diameter of iron pipes. However, generally speaking, the detonation velocity of AN-FO increases as the diameter of iron pipes, the loading density of AN-FO and the quantity of booster increase. It is noteworthy that these characteristics observed in AN-FO are not so clearly recognizable in other types of explosives.

6. Conclusion

The first series of our experiments on the exploding properties of ammonium nitrate fuel oil mixtures (AN-FO) as described above have thus revealed that as far as the propagation of detonation is concerned, AN-FO has distinct differences from other ordinary explosives. The detonation velocity, and exploding force together with the sensitivity of AN-FO are subject to the marked influence of the bulk density, oil absorption, particle size, coating agents, and water content of ammonium nitrate (AN) as well as the initiating conditions, loading length, diameter and density of AN-FO.

The exploding or detonating properties of AN-FO are influenced by the reaction of AN upon FO which is caused on the boundary between the solid (AN) phase and liquid (FO) phase, while other explosives are not affected by such factors as surface effects. The peculiarity that distinguishes AN-FO from other explosives such as dynamite can be seen from the fact that such factors as those mentioned above are decisive for the detonation velocity and/or the propagation of the reaction of AN upon FO.

Therefore, it is considered important to have a proper understanding of the peculiar aspects of the properties of AN-FO for its more effective application, and at the same time, for the solution of the mechanism of explosion, it is of great importance to conduct researches, with due consideration of the surface effects, into the reactions caused on the surface or boundary between liquid and solid phases such as those which occur with AN-FO.

Acknowledgement

Reference

1) Wakazono, Y., Sato, C. : Studies on the granular explosives (1st Report), Journal of the Industrial Explosives Society, Japan, Vol. 25, No. 4 (1964) 63-69.