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An investigation of some characteristics of explosive ammonium nitrate-reducing fuel mixtures

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AN INVESTIGATION OF SOME CHARACTERISTICS OF EXPLOSIVE AMMONIUM NITRATE-REDUCING FUEL MIXTURES

BY

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A

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Figure 1. Explosion at Test Site

PREFACE

Nitrate of Ammonia . . . is in many ways an ideal body for an explosive, for not only is it resolved completely into gases on detonation, but these gases . . . contain free oxygen. . . . It is, however, very hygroscopic and this has stood in the way of its more general employment. Means have been found to overcome this difficulty, and I am prepared to prophesy that we shall hear a great deal more of it in the future.

William Cullen, LL.D.

in his Presidential Address
"Modern Mining Explosives"
at the 39th Session of the
Institution of Mining and
Metallurgy (England), London,
Oct. 17, 1929.

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INTRODUCTION

Ammonium nitrate as a source of explosive energy, only a laboratory curiosity for a long time, has for the last fifty years undergone considerable development. It has advanced to a position where it now accounts for the greater part of the energy used in commercial blasting.

The discovery of nitroglycerine by Ascanio Sobrero in 1846 at that time did not seem too significant, as this substance was too dangerous to handle to promote ample use as an explosive. Only when in 1866 Alfred Nobel mixed nitroglycerine with diatomaceous earth (kieselguhr) and thus made the first dynamite, a comparatively safe explosive was introduced which soon should originate or revolutionize whole industries. While an excellent absorbent, kieselguhr is also a heat absorbing ingredient. So Nobel's next important invention introduced an "active" dynamite absorbent in place of kieselguhr. This invention led to the development of the straight dynamites which are still important commercial explosives. Present straight dynamites contain woodpulp or wood flour as absorptive ingredients.

As early as 1867, the same year in which Nobel obtained his English patent for dynamite, a Swedish patent was issued to Ohlsson and Norrbein for an explosive mixture called ammoniakkrut[1] consisting of ammonium nitrate either alone or in mixtures with charcoal, sawdust, naphtalene, picric acid, nitroglycerine or nitrobenzene. Nobel acquired this patent and soon presented his series of ammonium nitrate explosives which he called extra dynamites. When safety regulations in coal mines,

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[1]All references are in the bibliography.

where easily explosible methane and coal dust represent considerable safety hazards in the use of explosives, required an explosive with a low detonation temperature, another series of ammonium nitrate explosives was introduced. Due to the low detonation temperature of ammonium nitrate the "permissible" explosives contain up to 95% ammonium nitrate and little or no nitroglycerine. This continued the trend toward the replacement of nitroglycerine by ammonium nitrate in commercial explosives. An obstacle was the high hygroscopicity of ammonium nitrate. In 1885 R. S. Penniman presented "Protected Nitrate of Ammonia for Use in Explosive Compounds," (US Patent 312010), in which he introduced a coating with petrolatum, which waterproofed the ammonium nitrate sufficiently.[2] Other important coatings include the calcium stearate coating, patented by Baker and Johnson in 1936, and the Cairns PRP—petroleum, rosin, petrolatum—coating for ammonium nitrate, patented in 1941 and 1944.[3]

In 1912 a patent was granted to Norbert Caipek for "Safety Explosives": "I have invented certain new and useful improvements in the manufacture of safety explosives of which the following is a specification. An explosive mixture of 88% of nitrate of ammonium, 6.25% of turmeric charcoal, and 5.75% of sandal wood charcoal."[4] So here an ammonium nitrate explosive was proposed which did not contain any nitroglycerine. However, further development had to wait another twenty years. In 1935 a patent was given to William Kirst and Clifford Woodburg, "Ammonium Nitrate Explosives": "The object of our invention is to provide explosives of increased safety because of their greatly

reduced degree of sensitiveness. A further object is such an explosive, containing ammonium nitrate as the principal ingredient. A still further object is to provide explosives of the kind described that cannot be exploded by the ordinary blasting caps, but that can be used satisfactorily in many blasting operations when primed with an adequate booster charge of explosive. We prefer, however, to employ organic fuels as sensitizing agents. In such capacity, we may use fuels containing oxygen, for example, glycol, glycerine and the like, aldehydrates, of which sugar, starch and cellulose are examples. We may use also fuels containing no oxygen, and consisting of carbon or compounds of carbon and hydrogen. As examples of satisfactory fuels of this class, we may cite various forms of carbon, hydrocarbon, and the like. We prefer, however, to use coal as fuel with ammonium nitrate. We find a satisfactory composition to result when the relative proportions are selected of 92%—95% ammonium nitrate and 5--8 parts of coal."[4] This development led to the production of DuPont's blasting agent "Nitramon" in 1935. This product is packed in tightly sealed metal cans to provide for unlimited water resistance and contains no nitroglycerine whatever. It cannot be detonated by the strongest of commercial blasting caps, detonating cord, flame, shock, friction, or impact, and thus provides ultimate safety. Its blasting strength is developed by the use of special primers containing TNT.

Late in 1952 Messrs. Hugh B. Lee and Robert Akre of Maumee Collieries Company began testing a new method of blasting with an ammonium nitrate explosive. This explosive consisted of common

ammonium nitrate fertilizer to which a small percentage of hydrocarbon had been added. The explosibility of such a mixture had become known more publicly when oil from broken ship fuel lines mixed with an ammonium nitrate cargo and initiated by a fire led to the Texas City Disaster in April 1947.[5] After more than two years of development work this new blasting method was ready to be patented and became known as the "Akremite" method. The patent was granted in 1955 to Hugh B. Lee and Robert N. Akre and assigned to the Maumee Collieries Company, Terre Haute, Indiana, for "Blasting Process": "Ammonium nitrate is less effective as a blasting explosive when not charged into the drill holes in such manner that air spaces are eliminated as far as possible. Any type of waterproof flexible material of sufficient strength to avoid breaking or rupturing can be used to construct the bags, such as polyethylene or Pliofilm. When the bags are dropped into a drill hole they expand and deform when they hit bottom and fill the entire hole, leaving substantially no air spaces between the bags and the wall of the bore. Thus the cushioning of the shock by air spaces is practically eliminated in our method."[4] There were a number of features which helped to advertise this new development:

Economy: Explosive costs, which comprise the largest single supply cost item in strip mining, were reduced by one third and more.

Effect: The new explosive nevertheless provided good overburden fragmentation. A number of tests proved that the breaking effect

of Akremite has equalled that of more than twenty varieties of explosives on a pound for pound basis.[6]

Safety: The materials are safe to handle. The Akremite ingredients, ammonium nitrate and carbon black, and the mixture itself are not cap-sensitive. This also provides for a reduction in transportation costs, the highest rates being for commercial explosives.

As can be seen the Akremite patent covers mainly the new theory of blasting, making use of an ammonium nitrate--carbon black mixture and the unique method of packaging the explosive in expansible polyethylene bags which would snugly fill out the drill hole. As other mine operators (as consumers of ammonium nitrate) and manufacturers (as producers of ammonium nitrate) became interested in the use of an ammonium nitrate--non nitroglycerine--mixture as an explosive, organized research went under way to investigate different types of mixtures to obtain a mixture of optimum qualities. Scientifically only little was known about such mixtures. There were questions about their behavior under modified conditions: how would, for instance, a change in particle size of the ammonium nitrate influence the explosive effect of the mixture; what would a change in the percentage of added fuel oil accomplish?

It was the purpose of the investigation described herein to find the answers to some of the questions which arise with the use of an ammonium nitrate--non nitroglycerine--mixture as an explosive, such as

a) the effect of the percentage of fuel oil in the mixture

b) the effect of the loading density of the mixture

c) the effect of the diameter of the charge

d) the effect of the particle size of the ammonium nitrate

e) the effect of different reducing fuels

f) the effect of different primers.

REVIEW OF LITERATURE

The blasting method employing fertilizer grade ammonium nitrate (FGAN) mixtures as explosives was developed in the field. So it is only natural that the earliest reports about this blasting method were drawn up by men connected with the field operations. In these reports more emphasis was placed upon the practical aspects of the method than on a scientific analysis of the basic relations in the use of such an explosive. A large number of basic problems is still being investigated. Only a limited number of publications is available so far, which give information about the latest research results. While reviewing these reports it appeared useful to also consider some reports of earlier research on similar problems with ammonium nitrate. Finally a short review is given on the methods of measuring the detonation velocity of explosives.

Reports from Field Operations

For better comparison the significant data of the reports from field operations employing fertilizer grade ammonium nitrate (FGAN) explosive mixtures have been collected and assembled in Table I. In respect of the mined materials a wide variety is covered. Originating in the blasting of overburden in coal strip mines the method soon was adopted in a number of iron ore mines of the Mesabi Range. Other mining operations followed prompted by the reports of considerable savings in blasting costs in the use of this new method. For better

TABLE I OPEN PIT OPERATIONS EMPLOYING AMMONIUM NITRATE EXPLOSIVES

Author	Operation	Material Blasted	Diameter of Drillhole	Explosive Mixture Used	Primer	Remarks
4	Cananea Sonora, Mexico	Disseminated Copper ore	9"	100 lbs FGAN + 1½ gal fuel oil Oil poured into bag (300 lbs of mixture per hole)	100 lbs 60% Quarry Gel + Primacord	Fragmentation better than with 60% gelatine dynamite alone
4	Jackpile Mine, Laguna Indian Res., New Mexico	Sandstone overburden	6 3/4" 7 7/8"	80 lbs FGAN + 3/4 gal fuel oil, Oil poured into bag 24 hours before using mixture	Free running 40% dynamite in decks, each deck with separate primacord	
4	Berkeley Pit, Butte, Montana	Disseminated copper ore	9" 6 1/4"	80 lbs FGAN + 1 gal fuel oil, Oil poured into bag	5½ lb can "Nitramite" + Primacord	
4	Yerington Mine (1958), Weed Heights, Nevada	Porphyry copper ore	7 3/8"	80 lbs FGAN + 1 gal fuel oil Oil poured into bag	Hercules XC-49 + Primacord	
35	Yerington Mine (1956), Weed Heights, Nevada	Porphyry copper ore	7 3/8" - 8"	130 lbs FGAN + 50 lbs 40% AN-Dynamite (FGAN poured around column of dynamite)	Special 60% gelatin (25 lbs) + Primacord	

TABLE I CONTINUED

Author	Operation	Material Blasted	Diameter of Drillhole	Explosive Mixture Used	Primer	Remarks
36	Yerington Mine (1956), Weed Heights, Nevada	Porphyry copper ore	7 3/8" - 8"	175 lbs FGAN + 1 gal fuel oil, ½-1 gal fuel oil poured in each 80 lb bag	Special 60% gelatin (25 lbs) + Primacord	
37	McIntyre Development, Tahawus, New York	Ilmenite and magnetite	9" 6 1/2"	Canned high explosives, "Nitro-Carbo-Nitrates" + 80 lbs FGAN	Canned high explosives	FGAN comprises only 26% (weight) of total charge per hole
11	Hawkins Mine (Mesabi Range), Minnesota	Taconite		80 lbs FGAN + 3½ qts fuel oil poured into hole simultaneously	7" x 24" special primer	
38	Hawkins Mine Mesabi Range Minnesota	Taconite	6" 9"	80 lbs FGAN + 1 gal fuel oil		
6	Maumee No. 20 + No. 27 Indiana	Overburden		Akremite 9" x 27" cartridges	Extra dynamite AL-4 (20 lbs in polyethylene bag) + fuse + No. 6 regular detonators (delay type)	

TABLE I CONTINUED

Author	Operation	Material Blasted	Diameter of Drillhole	Explosive Mixture Used	Primer	Remarks
39	Maumee No. 20 + No. 27 Indiana	Overburden: sandstone hard shales limestone	10 5/8"	Akremite 9" x 27" cartridges in poly-ethylene bags	Extra dynamite + Primacord	Deck charges are common practice, separate primers used for each deck
7	Colonial Mine Kentucky	Overburden: hard abrasive sandstone sandy shale limestone	6" 7 1/2" 10 5/8"	Akremite cartridges: 5" x 32" (20 lbs) 6½"x 34" (33 1/3 lbs) 9" x 26" (50 lbs)	60% gelatin dynamite (12½ lbs) + detonating fuse + cap	Successful in horizontal holes also
40	Empire No. 6 Mine Walker County Alabama	Overburden: blue shales hard sandy shales	7 3/8" vertical, 6 1/2" horizontal	Akremite	5"x13" primer of 75% gelatin (12½ lbs)	
40	Robbins Mine Oneonta labama	Overburden: hard sandstone hard and soft shales	9"	Akremite		No trouble with as much as two feet of water in the holes
9	Calcite plant. Rogers City Michigan	Limestone	7 7/8" 9 7/8" 10 5/8" 12 1/4"	100 lbs FGAN + 8 lbs fuel oil thoroughly mixed		Mixing is done by special machine

TABLE I CONTINUED

Author	Operation	Material Blasted	Diameter of Drillhole	Explosive Mixture Used	Primer	Remarks
9	Cedarville Quarry U. P. Michigan	Dolomite	6 1/4" 7 7/8"	Commercially compounded AN-mixture		
41	Benson line New York	Magnetite Martite	9"	100 lbs FGAN + 1 gal fuel oil Oil poured into bag	Canned agent "Nitramite"	Diffi ulties with wet holes
42	M. A. Hanna Company Open pits, Mesabi Range Minnesota		9"	95% FGAN + 5% carbonaceous material in 50 lb polyethylene bags	Semi-gelatin powder	

effect a number of operators employed deck charges. This means that the load column of ammonium nitrate in the hole is interrupted by charges ("decks") of higher strength explosives to provide a booster effect. Sometimes each deck has a separate primer. The fragmentation obtained was in general satisfactory if not better than with the use of explosives used prior to the adoption of ammonium nitrate mixtures.

The Akremite mixture (see statement of patent on page 4) requires a thorough mixing of the components of the explosive, ammonium nitrate and carbon black, as the latter is too viscous to effect an even distribution by itself. The mixing apparatus is described in detail by Miner.[7] When fuel oil is used as sensitizer, it in general seems to be assumed that the pouring of the fuel oil into the bag of the ammonium nitrate provides for a sufficient intimacy of mixing. This assumption is supported by Cook.[8] An experiment is described in which eighty pounds of prilled ammonium nitrate were poured into a nine inch diameter tube and then five pounds of No. 2 fuel oil were poured on top of the ammonium nitrate column. Samples of the ammonium nitrate--fuel oil mixture, taken at the top, in the middle, and at the bottom of the column ten minutes later, showed that the oil had penetrated the entire column and had become uniformly enough distributed that none of the samples showed more than five percent variation from the mean in the oil analysis. Still, the occasional appearance of brown or yellow nitrous oxide smokes after firing[9] showed that parts of the ammonium nitrate burned rather than detonated, although the amount of added fuel oil should rather provide for an oxygen negative explosion. However, due to the

excellent fragmentation results it apparently did not seem worth the expenditure to facilitate a more balanced explosion through the preparation of a more intimate mixture. Only in one report a more thorough mixing is considered of importance.[9] A special machine was designed which provides a finely divided fuel oil spray to be injected into the running ammonium nitrate while it is poured into the hole. The proper percentage mix of ammonium nitrate and fuel oil is assured by the use of a flow control meter for the nitrate and an adjustable nozzle mechanism for the fuel oil spray.

Wet or moist holes remain a major problem. Sall[10] describes how the Akremite polyethylene bags, although within limits waterproof as long as they do not tear, cause difficulty by tending to float atop the water in the hole. Following dropped bags then plug up the hole above the water level. A similar difficulty was encountered by Grant[11] in the use of ammonium nitrate mixtures in waterproof metal containers. This led to experiments to increase the density of the explosive mixture to make it sink in water. The adding of ferrosilicon to the ammonium nitrate for this purpose was soon dropped when it was found that this caused too great a reduction in the blasting force of the mixture. The mixing of 15% grain size ammonium nitrate with 85% prilled ammonium nitrate increased the density sufficiently and also showed satisfactory results, although there was again a slight reduction in blasting force. It is the expressed opinion in a number of reports that ammonium nitrate explosive mixtures would find a considerably wider field of application should the manufacturing industry be able to provide a waterproof

ammonium nitrate. A step in this direction has been taken by Farnum and Cook[3] with the development of some slurry explosives for use in large diameter underwater blasting. Mixtures of ammonium nitrate, trinitrotoluene (TNT) and as much as 27% water have been employed successfully. Due to the heat loss in the vaporization of these large percentages of water, the explosion temperature of the slurries is lower than that of corresponding (equal AN/TNT ratio) dry mixtures. However, due to the higher density of the slurries their explosion pressure and therefore their work potential is considerably higher.

Reports from Research

It was the object of early investigations to determine the explosibility of ammonium nitrate as related to a number of factors. Based on the experienced insensitivity of ammonium nitrate toward mechanical action such as impact, shock, and friction and toward the influence of heat,[2, 12] it was concluded that a correspondingly strong initiating agent is required to cause its explosive decomposition. The factors that influence the sensitiveness of ammonium nitrate toward an initial impulse and thereby toward the ease with which an explosion may be brought about are density, fineness (form and size of grains), and the effect of added materials. The influence of temperature on the sensitiveness to explosion was found rather negligible, as shown in Table II.

TABLE II

Relation of Temperature to Sensitiveness to Explosion in Ammonium Nitrate[2]

Temperature of Nitrate Degree F	Number of Detonators Fired in Charge	Result	Compression of Lead Block Inches
69.8	8	No Detonation	None
122	5	No Detonation	None
122	6	Partial Detonation	None
158	5	Partial Detonation	None
198.5	1	No Detonation	None
198.5	2	No Detonation	None
198.5	3	Detonation	5/16

Description of test: Two-pound charges of fine grained ammonium nitrate in tin cans were heated in a paraffin bath to the desired temperature. Can and contents were then placed on a lead block, 4 inches high and 2½ inches in diameter, and detonated by one or more No. 8 electric detonators imbedded in the ammonium nitrate. After explosion the effect on the lead block was measured.

Initiating Agents (Primers). Early tests on the sensitiveness of ammonium nitrate to detonation by blasting gelatine are described in Table III. Sherrick[13] graded various high explosives in respect of their efficacy as boosters for ammonium nitrate in this order: high content ammonium nitrate explosive (9% nitroglycerine), picric acid, tetryl, trinitrotoluene, 60% gelatine dynamite, 40% ammonia dynamite, amatol 80/20; the high content ammonium nitrate explosive being the most efficient and the amatol 80/20 being the least efficient.

Field practices and tests with ammonium nitrate--fuel oil mixtures indicated that 60% strength dynamite or equivalent is satisfactory for an initiating charge.[14] A primer of 40% strength dynamite was considered a minimum. In experiments with very small primers it was found that in some instances there were complete failures, while in others detonations were of very low order, with velocities about one fifth of normal. This was considered as an indication of incomplete or partial detonation resulting from borderline priming.[15] It is stated that a decrease in blast hole diameter requires an increase in the load percentage of the detonating explosive. Field tests have shown that the percentage of the initiating explosive of about five percent of the total charge for holes of a diameter of seven inches and larger has to be increased to 25% for holes with a diameter of two to four inches. In these tests it has also been found that priming was more effective with a series of smaller charges than with one bigger charge.[14] The degree of confinement of the charge and the composition of the ammonium nitrate—fuel oil mixture are also considered factors of influence in the determination of a minimum booster.[8, 14]

TABLE III

Sensitiveness of Ammonium Nitrate to Detonation by Blasting Gelatine[2]

Weight of AN Grams	Weight of Blasting Gelatine Grams	Result	Compression of Lead Block Inches
400	100	Detonation	5/8
400	75	Detonation	1/2
400	50	Detonation	1/2
400	25	No Detonation	None

Description of test: Ammonium nitrate in beaker was placed on lead block, 4 inches high and 2¼ inches in diameter, and then detonated by imbedded charge of blasting gelatine with primacord and cap. After explosion the effect on lead block was measured.

Density and Particle Size. It was concluded from earlier density tests that the probability of initiating a detonation in ammonium nitrate decreased with an increase in its density.[16] In the same way as with blasting gelatine a content of air bubbles furthers the ease of detonation, so the air content of low density coarse grained ammonium nitrate seemed to facilitate the initiation, while ammonium nitrate of the highest possible density, such as is obtained by fusing and solidifying the salt, could not be detonated at all.[12] However, it was found that the blasting effect of ammonium nitrate decreased materially if the coarser grains lowered the density too much.

Later research found that, if the initial detonation was produced, the particle size distribution rather than the average particle size was the important factor. In tests carried out with ammonium picrate,[17] the finest materials studied (all particles smaller than 44 microns) had a detonation rate approximately equal to the theoretical one. The admixture of a small percentage of coarse material, which caused only a slight change in the average particle size, produced a marked lowering of the velocity of detonation. If the fine particles were completely replaced by coarse particles, the decrease of the detonation velocity was greater and it was more pronounced the greater the size of the particles.

These results could be explained by means of Eyring's grain-burning theory.[18] "In the short time during which the explosive grain is exposed to the high detonation temperature (a microsecond or less) the heat is unable to penetrate deeper than the surface layers of the

grains. Consequently each grain of explosive begins reacting at its hot surface, and the reaction progresses layer by layer until it reaches the center of the grain. The reaction of each grain within the reaction zone of a detonation is thus a sort of cigarette burning, in which one layer of molecules is not ignited until the previous layer is consumed. This grain-burning theory is supported by the impossibility of heat conduction through a grain and the experimentally observed effect of the grain radius on the reaction time."

Based on this theory it was shown for several explosives how the length of the reaction zone is dependent upon the grain radius of the explosive substance. As the reaction zone length exerts a controlling influence on the stability of propagation and the velocity of the detonation wave the importance of the control of the grain size of an explosive became manifest. It was stated that a fine-grained explosive should always detonate stably while in a sufficiently coarse-grained explosive it might well be impossible to maintain a stable detonation wave.

In describing the effect of low density, mention was made of the importance to stability of detonation of the number of contact points one grain has to the surrounding grains. If by more loose packing the density of the explosive is lowered, so is then the number of contact points between grains. This will lengthen the reaction zone and will decrease the rate of detonation. In mixing different particle sizes, small particles might fill the voids between larger particles without increasing the number of contact points between grains. Thus, the

over-all density might be increased without having an effect on the detonation rate, or certain proportions of different grain sizes mixed will decrease the number of contact points and thus the detonation rate when the over-all density is kept constant.[18]

Research on ammonium nitrate--hydrocarbon mixtures showed similar results. In mixtures with petroleum--resin--petrolatum the coarser ammonium nitrate was relatively less sensitive, sensitivity being defined as the relative ease of producing a detonation in the explosive mixture. The stability of detonation proved to correspond to the sensitivity in these tests: only the mixtures detonating with a relatively small primer, which were those containing fine-grained ammonium nitrate, showed satisfactory propagation of the detonation. All tests were carried out with 1 7/8 inch diameter charges.[19]

With the introduction of explosive mixtures composed of fertilizer grade ammonium nitrate and fuel oil also a new grain form of ammonium nitrate was presented, the "prilled" ammonium nitrate. The success of these explosive mixtures was partly credited to this grain form. It was the inherent structure of the prilled grain which proved to be of great advantage. The porosity of the prill allowed the fuel oil to permeate most of the particle and thus let the mixture provide the effect of fine-grained nitrate intimately incorporated with the added fuel oil. T is combined with the apparent low density as a result of the porosity made the prilled ammonium nitrate mixtures meet the requirements of two influencing factors:[14] a low density, generally of the order of 0.8 grams per cubic centimeter, which is important

because these mixtures become less sensitive as the density is increased,[15] and more surface area which facilitates uniform penetration with the sensitizing fuel oil.[8] It was observed that the velocity of detonation was fifteen to twenty per cent higher in mixtures with prilled ammonium nitrate than it was in mixtures with any other type of ammonium nitrate. Unit volume comparative tests showed that prilled ammonium nitrate, although weighing eighteen per cent less than the other types of nitrate solid, give equal blast performance, and in unit weight tests the prilled ammonium nitrate produced about twenty per cent more blast energy.[14]

Added Substances. Early investigations, originated after a number of disastrous explosions in plants for the production of ammonium nitrate on a large scale, proved the effect of impurities or added substances on the explosibility of ammonium nitrate.[2] This research led to the expressed opinion that ammonium nitrate by itself should not be considered as an explosive.[20] Only the carbonaceous materials, used during the production to remove impurities and color or added to provide a coating for better moisture resistance, would tend to sensitize the ammonium nitrate.[21] Tests showed how relatively small percentages of carbonaceous material considerably increased the sensitiveness of ammonium nitrate to detonation. Russel Cook[22] observed the maximum effect with an admixture of only one per cent petrolatum, in comparison to two per cent of petrolatum, one per cent of trinitrotoluene, and one half per cent of trinitrotoluene. Results of other tests,[19] this time with an admixture of petroleum—resin—petrolatum (PRP),

showed that a very sharp maximum sensitivity occurred at 0.75 per cent to 1.5 per cent PRP content, while compositions with both 0 per cent and 10 per cent PRP content failed to detonate with the primer used, a 60 per cent straight dynamite cartridge, 1¼ inches in diameter and eight inches long. The sensitizing effect of the hydrocarbons was explained as follows: ammonium nitrate contains twenty per cent more oxygen than is required for its complete combustion, that is, to oxidize the hydrogen to water, evolving nitrogen in the form of the gaseous element. The introduction of materials containing carbon permits the formation of other gases, carbon monoxide or carbon dioxide, which are more easily formed than free oxygen. The heat evolved in this reaction[23] causes the sensitization of the ammonium nitrate. Consequently almost any number of carbonaceous or combustible materials could be used as an admixture with ammonium nitrate to produce a satisfactory explosive.[15] However, combustibles differ considerably in their effect upon the rate of detonation and the net blast energy of the ammonium nitrate mixture. The reason for this difference is the fuel value of the combustibles, that is, the amount of heat their combustion would produce, and their quality to provide for an intimate mixture with the grained ammonium nitrate. Materials most commonly used are finely divided carbon black, pulverized coal, fuel oil, and various combinations of these three.

While in earlier tests an oxygen balanced composition of 94.6 per cent ammonium nitrate and 5.4 per cent PRP proved to be less sensitive than compositions with 0.75 per cent to 1.5 per cent PRP,[19] recent tests with oxygen balanced mixtures of prilled ammonium nitrate and

fuel oil gave the most satisfactory results,[14] in respect to sensitivity and in terms of higher detonation velocities and greater energy yield. Again the grain-burning theory[18] could aid in the explanation of this phenomenon. In the earlier mixtures only the surface of the single ammonium nitrate grain was covered with the carbonaceous material, so that the combined reaction of nitrate and combustible could only take place on the outer layer but not in the following inner layers of the grain. On the other hand the porosity of the prilled ammonium nitrate grain presumably allowed a combined reaction also in the inner layers.

Other factors of influence in sensitizing ammonium nitrate and its mixtures were also investigated:

The importance of confinement was early recognized. In a number of tests it was found impossible to cause unconfined ammonium nitrate at ordinary temperatures to detonate, but when confined it was detonated by several of the initiators employed. The certainty with which detonation could be effected increased with the degree of confinement.[16] The effect of confinement on the propagation of detonation was explained by the following thought: since the explosive decomposition of ammonium nitrate evolves a positive quantity of heat, this reaction should be self-sustaining if the entire mass of the ammonium nitrate would be at such temperature that the heat loss from the system, by conduction and escape of heated gases, would be balanced by the heat evolution. This is more likely to be realized in stronger confinement.[13]

Confinement was also found important in the use of ammonium nitrate--fuel oil mixtures. These mixtures did not shoot reliably

unconfined, even with large primers. However, when confined in a borehole with essentially no free space in the hole, the mixtures detonated regularly when properly stemmed and primed.[15] This fact showed especially in the better performance of mixtures poured loosely into the borehole compared to the performance of mixtures loaded in metal containers. The loose mixture would fill much better irregular spaces in the hole.

Tests were also made concerning the critical diameter. This is the minimum diameter for cylindrical charges, below which steady detonation will not propagate. The critical diameter of dry ammonium nitrate is approximately nine inches.[3] Trial shots with a 94/6 mixture of ammonium nitrate and fuel oil were made in boreholes drilled with a 1.5 inch bit, providing a hole of approximately 1.7 inches in diameter. The charges were found to propagate satisfactorily the entire length of six feet of the boreholes. The occasional discovery of unexploded mixture led to the conclusion that a diameter of 1.7 inches was slightly below the true critical diameter for the mixture used, but that the strength of the primer insured propagation over the length of six feet.[8]

Velocity of Detonation. The thermo--hydrodynamic theory of detonation permits the calculation of the equation of state of the products of detonation. However, only one of the factors of the equations of the theory, namely the detonation velocity D, can be measured experimentally, except for some limited pressure tests with very small amounts of explosive. By establishing the relations between the

detonation velocity and the equation of state, the thermo--hydrodynamic theory provides for the determination of other pre-calculated detonation properties such as pressure and temperature by means of the measured detonation velocity. Due to these relations the detonation velocity of an explosive has been an important characteristic to determine the value of a substance as an explosive. This emphasizes the importance of velocity tests.

Early velocity tests on ammonium nitrate carried out according to D'Autriche's method showed that the velocity of detonation increased with increasing diameter of the test tube and decreased with increasing distance from the point of initiation and with increasing moisture content. The influence of the initiating agent was found to vary only within moderate limits and to correspond in general to the detonation velocity of this initiating explosive. The velocity of detonation of ammonium nitrate increased with increasing density of loading and also with increasing strength of confinement. The observed detonation velocity of ammonium nitrate was about 8,200 feet per second; the diameter of the charge and the loading density were not recorded.[12]

Detonation velocity tests on ammonium nitrate—fuel oil mixtures, detonated in five inch diameter charges in thin paper tubes, were described by Cook.[8] Results of these tests are shown in Table IV. The compositions, densities, and average velocities are given together with the computed theoretical ideal velocities obtained through the application of the calculation methods of the thermo--hydrodynamic theory.[3] Similar results for fine-grained trinitrotoluene were listed for

TABLE IV

Observed and Computed (Hydrodynamic) Velocities of Prilled Ammonium Nitrate-No. 2 Fuel Oil Mixtures

Composition	98/2	94/6	90/10	TNT Fine Grained
Density (g/cm^3)	0.8	0.8	0.8	0.8
D	7218	8333	7841	14320
D^+	12139	13780	13541	14320

D = observed detonation velocity in feet per second, in 5" diameter charges

D^+ = computed ideal detonation velocity in feet per second

comparison. Attention was called to the fact that the actual detonation velocities of the ammonium nitrate mixtures were much lower than their ideal detonation velocities.

Reference was made to an earlier publication,[24] in which the theory was developed that the actual detonation velocity of an explosive is dependent upon the fraction of completed reaction N that took place in the "detonation head", that is, the zone between the shock front and some critical layer in the detonation wave which is known as the Chapman-Jouguet plane. It was assumed that at this plane the rarefaction of the detonation wave would be sufficient to interrupt the supply of chemical energy to the detonation wave and thus to discontinue the increase in detonation velocity. This critical plane would move closer to the shock front if there were poorer confinement, owing to the influence of release waves from the sides. If this plane was sufficiently close to the end of the reaction zone, the explosive would be ideal ($D = D^*$), but if it would appear considerably in front of the end of the reaction zone, the detonation would be non-ideal (D smaller than D^*). It was shown as result of experimental evidence how the length of the detonation head was dependent upon the diameter of the charge, but not upon the length of the reaction zone. In smaller diameter charges an explosive with a long reaction zone would therefore have a comparatively short detonation head, also a small fraction of completed reaction N within this head, and thus a low detonation velocity. An increase in charge diameter would result in an increase in the length of the detonation head until finally the Chapman-Jouguet plane would be sufficiently

close to the end of the reaction zone that the fraction N of reaction completed would approach the value of 1.0 and the actual detonation velocity would approximate or equal the ideal detonation velocity of the explosive.

Detonation velocity tests in 10 5/8 inch diameter boreholes resulted in velocities of about 12,000 feet per second for ammonium nitrate—carbon black mixtures, and 13,000 feet per second for ammonium nitrate—fuel oil mixtures. In six inch diameter holes the velocities were 800 to 1000 feet per second lower. Mixtures in these large holes propagated at constant velocities over columns of at least thirty feet in length.[15]

Overdrive. The overdrive principle in the use of heavy primacord fuse to detonate ammonium nitrate—fuel oil mixtures was postulated by Tikker.[25] It was claimed that a primer of heavy primacord running through the whole length of a charge of an ammonium nitrate—fuel oil mixture would cause the mixture to detonate at a higher effective velocity than its own characteristic velocity due to a boosting or overdrive effect of the primacord. The blasting method on which the principle was based employed one-foot long strips of heavy (400 grains per foot) primacord connected to a primacord (50 grains per foot) trunk line which ran through the whole length of the charge. Investigation showed that a one-foot length of heavy (400 grains per foot) primacord only inconsistently initiated a 94/6 ammonium nitrate—fuel oil mixture, The conclusion was reached that the consecutive explosions of the heavy primacord strips, which might or might not initiate the surrounding

mixture, accounted for the high detonation velocity measured, while the detonation wave of the ammonium nitrate mixture travelled at it's own characteristic speed for short length propagation.[8] In addition to these findings one of the field reports described the blast initiated by means of the primer described above as completely unsatisfactory.[11]

Measurement of Detonation Velocity

There are several methods in common use to measure detonation velocities. They may be divided into two basic groups: optical or photographic methods and chronographic methods.[26]

The photographic methods have the advantage of providing a continous record of the detonation, so that changes in velocity and points of fluctuation are automatically registered. A number of disadvantages have been overcome. The photographic technique was introduced by Mallard and LeChatelier in 1883, which employed a rotating drum camera. The principle is in general, that a film fixed to a rotating drum is moved at right angles to the direction in which the detonation propagates in the explosive cartridge. The light emitted from the detonation draws a line on the film at a slope to the direction of motion of the film. The slope of this line is a measure of the velocity of the detonation. The steeper the line is on the film, the greater is the detonation velocity. In the earlier use of this method it was a serious difficulty that high-velocity explosives detonating with spacious flames caused a lack of definition by drawing traces on the film, which were too wide. Clear lines could only be obtained by using narrow cartridges of great

length and placed well away from the camera. This led to the introduction of the "fine slit" technique by Jones in 1928. Thus, the field of view of the camera was restricted to a thin line ("slit") along the cartridge. The original rotating drum cameras had writing speeds up to about 500 feet per second. An increase in writing speed was achieved by successful application of the rotating-mirror principle.[27,28] The instrumentation designed by Frazer[29] in 1935 supposedly had writing speeds of up to 3300 feet per second. In this device a two-sided rotating mirror transferred the light from the detonation onto the film. Improvements in the mounting of this mirror made even higher writing speeds possible. The latest high-speed camera design employs an image converter tube, as described by Courtney-Pratt[30] in 1949.

The chronographic methods are based on the possibility of recording the arrival of the detonation wave at two or more points of known distance apart in the explosive medium. It is the principle of the chronographic methods to employ probes that are placed at fixed points on,or in the explosive. The pressure discontinuity or ionization present in the detonation wave then causes the external circuitry associated with the probes to produce a signal as the detonation wave reaches each probe in turn. The signals are sent to a mechanical or electronic recording instrument which also provides the necessary time base.

The spark chronograph designed by Mettegang in 1903 and improved by Kast in 1913 was the first standard chronographic device to measure detonation velocity.[31] In the use of this instrument fine wires were threaded through a train of cartridges at various points of known

distances apart. Each wire was connected in series with the primary circuit of an induction coil. The advancing detonation wave by breaking the wires caused a change of current in the primary circuit and induced some current in the secondary circuit. The secondary circuit was interrupted by a spark gap, one of the electrodes being a soot covered drum rotated by a motor at constant speed. Each wire fracture therefore produced a spark which left a small mark on the drum. The time elapsed between the breaking of two wires could then be determined by the distance between the two corresponding spark marks on the drum and the rate of rotation of the drum. To provide for a reasonable accuracy of the measurements, however, the wires in the cartridges had to be separated by distances of two to seven feet, depending on the range of velocity to be measured. This required a long file of explosive cartridges, and the result obtained represented an average value for a long column of cartridges rather than the value for a single cartridge.

The method devised by D'Autriche in 1906 is the simplest way to measure the detonation velocity on shorter lengths of explosives, although the accuracy of this method does not satisfy all needs. It depends on the comparison of the unknown velocity of an explosive with the known velocity of another explosive, the latter in general being commercial primacord. This test is described by Taylor.[26]

To receive a greater precision of measurement than can be obtained with the two methods mentioned, the application of the "condenser-discharge" method was introduced. In this method the charge or discharge of a condenser through a resistance is started by one event and stopped by

another. The change in potential across the condenser is then a measure of the time between the two events. In a detonating explosive the triggers may be provided by the fracture of a wire (break system) or by the ionization of the detonation wave which may render a small gap conducting (make system). The principles of this method are applied in the chronoscope, described by Nisewanger[32] and Brown, and in most later designs of chronographic instruments for the measurement of detonation velocities.[33]

EXPERIMENTAL

Purpose of Investigation

The purpose of the investigation described herein was to find the answers to some of the questions that arise in the use of ammonium nitrate-reducing fuel mixtures as explosives, such as

a. the effect of the percentage of fuel oil in the mixture
b. the effect of the loading density of the mixture
c. the effect of the diameter of the charge
d. the effect of the particle size of the ammonium nitrate
e. the effect of different reducing fuels, and
f. the effect of different primers.

Plan of Experimentation

The performance parameters of an explosive, such as detonation pressure and temperature, detonation velocity, and the potential available work, may be calculated by means of the equations of the thermohydrodynamic theory. However, the detonation velocity is the only parameter which can be measured experimentally and thus serve as a means to confirm the calculated results. For this reason the detonation velocity has been used empirically as the measure of the intensive property of an explosive. All influences on the performance of an explosive are judged by their effect on the detonation velocity, which has somewhat restricted application. To gain information experimentally on the effect of variables such as percentage of fuel oil, particle

size, loading density, or diameter of charge, on the performance of the explosive mixture, their effect on the detonation velocity of this mixture was studied. Therefore it was the object of the experimentation to measure the detonation velocity of the explosive mixtures while modifying the different variables.

In preparation for tests to measure the detonation velocity of ammonium nitrate mixtures, series of tests were made to study the explosibility of the mixtures. These tests were carried out without the instrumentation to measure the detonation velocity, and although only of a qualitative nature, they provided valuable information for the later experiments.

Apparatus and Materials

The equipment for the explosibility tests could be divided into two groups: mixing equipment and blasting equipment.

The mixing equipment included all utensils necessary to provide for a thorough mixing of the components of the mixture and to facilitate the loading of the mixture into the test pipes. These included a scale for the weighing of the ammonium nitrate, a graduated cylinder and a hygrometer to determine volume and density of liquids to be added, and several tubs, bowls and wooden spoons for the actual mixing.

The blasting equipment included all parts and instruments necessary to carry out the tests.

The test pipes, which served as containers for the explosive mixture, consisted of black iron pipes. The pipe is completely destroyed

during a successful test. Except for the tests with varying diameter all tests were made with three-inch diameter pipes. One end of the pipe was closed by a welded-on iron plate, the other end was sealed with a pipe cap. Each cap had a small hole in the center for the wires of the electric blasting cap.

Blasting cable, about three hundred feet in length, connected the wires of the electric cap and the electric blasting machine of the No. 10 hand-operated twist type.

The detonation velocity tests required the addition of a third group of equipment: the instrumentation for the measurement of detonation velocity.

The instrumentation employed for the measurement of the detonation velocity was an oscillograph connected with a pin set-up. It was in general the instrumentation described by Pound,[34] although some modifications of the pin set-up were made due to special conditions.

The special pin-oscillograph system employed a modified Tektronix 535 oscilloscope in connection with three additional circuits. A triangular wave generator had the purpose of creating a "zig-zag" raster type trace on the oscilloscope screen, which was considerably longer than a straight trace, and thus allowed for more accurate measurements. A marker generator supplied a time standard for the measurements, by superimposing on the zig-zag trace small horizontal time calibration markers, at pre-determined time intervals of two microseconds or 0.2 microseconds. A pulse forming circuit, housed in a plug-in box near the blasting site, changed the conduction between ground and the metal

pins in the detonating explosive to the proper amplitude and duration voltage pulse, so that it could appear on the oscilloscope trace as signals. These signals were displayed as horizontal pips and were of higher amplitude and of longer duration than the time calibration markers. Therefore, they could be easily distinguished. The oscilloscope had a five-inch diameter cathode ray tube screen which was suitable for the mounting of oscillograph cameras. Thus, the oscilloscope trace could be recorded photographically (Figure 2).

The total number of pins inserted in the explosive at known distances apart was eleven, the first pin being the trigger pin. The iron pipe wall was used as a common ground. Each of the pins in the explosive and a screw in the pipe wall were linked by a twenty-foot length of No. 24 enameled wire to a Cinch-Jones twelve prong connector which was connected to the plug-in box. When a pin was shorted to ground by the ionization in the detonation wave, the pipe wall serving as ground lead, a signal voltage was produced across a load resistor in the plug-in box. This signal was differentiated and sent through a co-axial cable, about 250 feet in length, to the signal mixer box of the oscillograph system. The first pin in the explosive was used as a trigger pin only, hence its cable went through the mixer box and directly to the trigger input of the oscilloscope. All the other co-axial cables were connected in parallel in the signal mixing box and then went to the horizontal input of the oscilloscope (Figures 3 and 4).

Following the initiation of the explosive mixture the advancing ionized detonation wave contacted the trigger pin in the explosive,

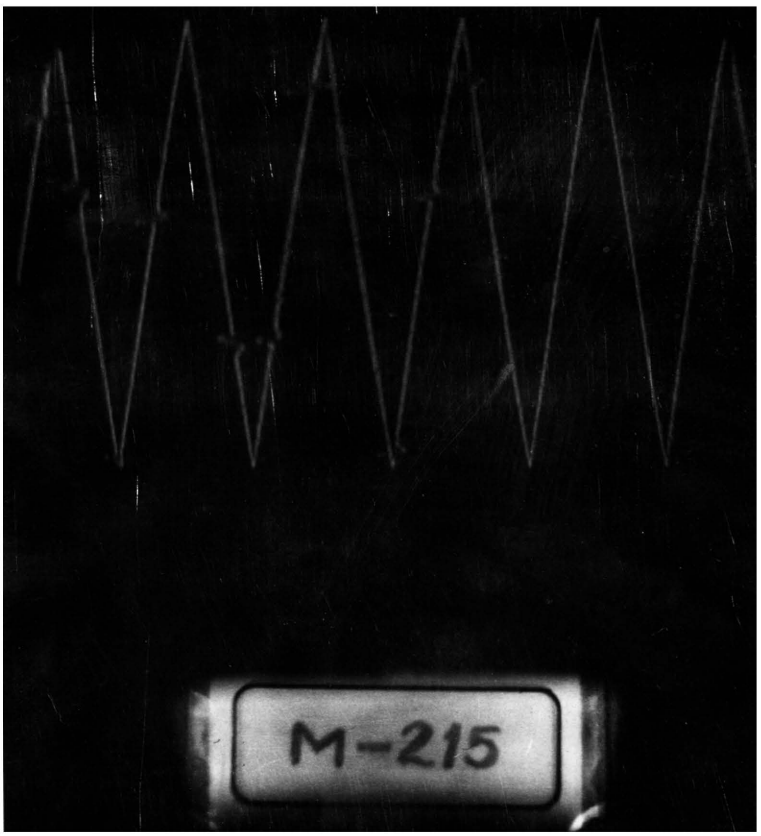
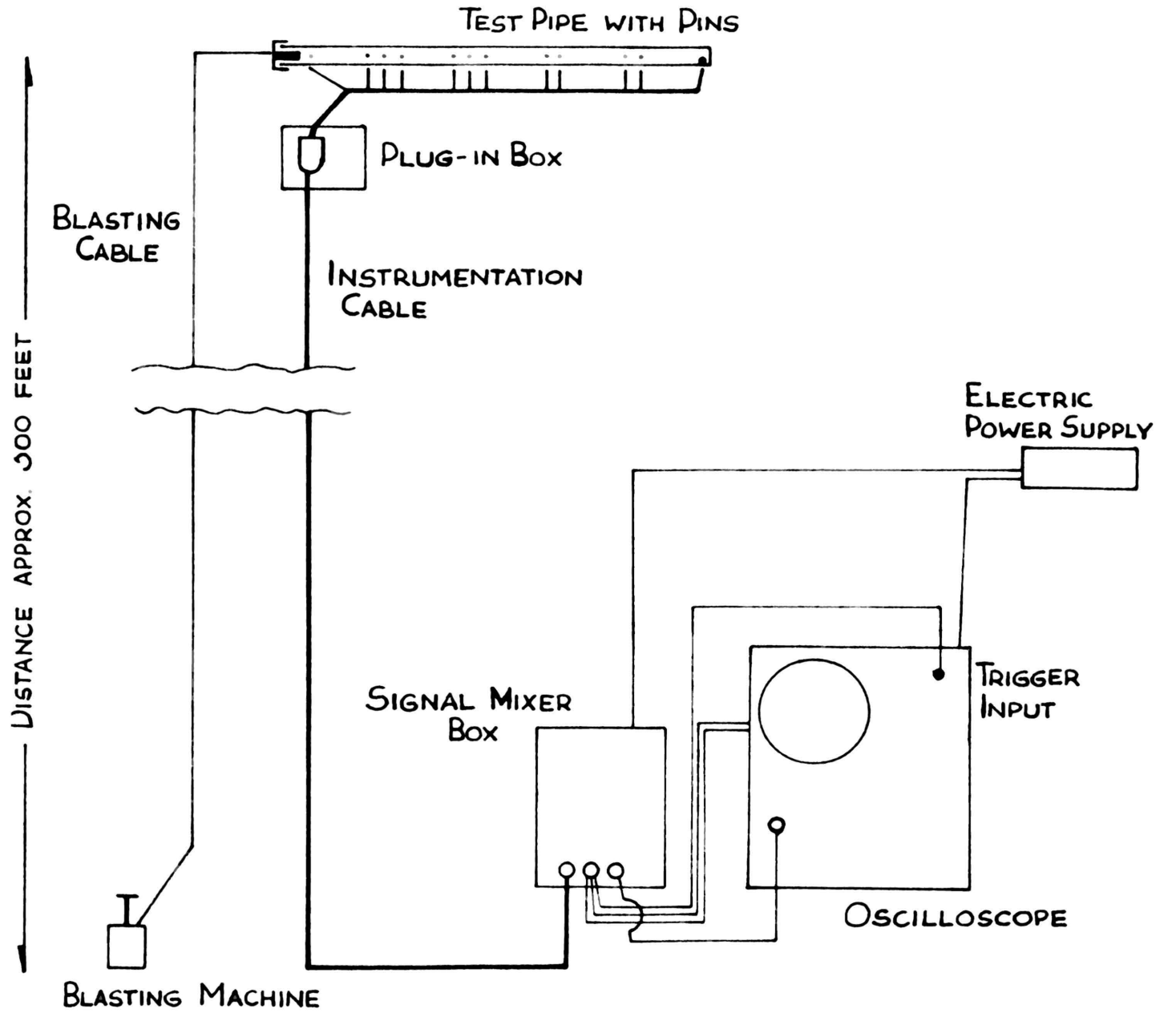


Figure 2. Photographic Record of Oscilloscope Trace

FIGURE 3. SKETCH OF THE INSTRUMENTATION FOR THE MEASUREMENT OF THE DETONATION VELOCITY.



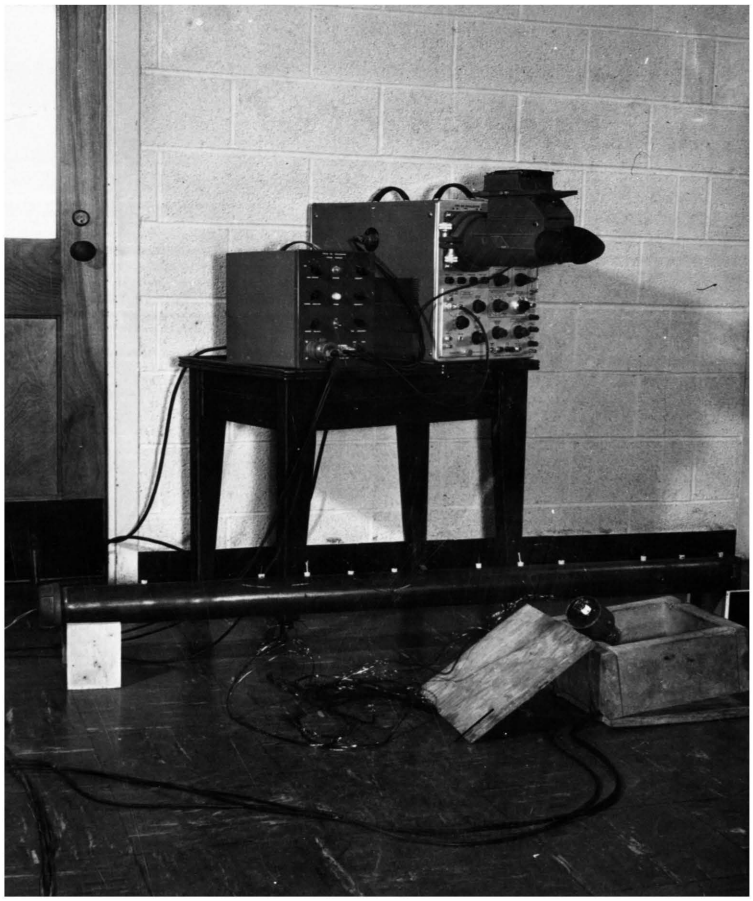


Figure 4. Instrumentation for the Measurement of the Detonation Velocity

which caused a voltage pulse to unblank the oscilloscope tube and to start one sweep. The progressing detonation wave then shorted to ground the other pins in successive order and thereby created signals which appeared as pips on the oscilloscope trace. The distance between pins in the explosive was known. The time the detonation wave needed to travel from one pin to the next was shown by the distance between pins on the trace and could be checked by the number of superimposed time calibration markers between the pips, each of the markers representing two microseconds in normal setting of the instrumentation. Thus the detonation velocity could be calculated easily. Occasionally one signal out of the ten would be lost due to a broken wire or a poor connection. By grouping the pins in groups of two, three or four, the distance between groups being different from the distance between pins in a group, it was possible to identify the missing signal and thus still be able to utilize the record of the experiment.

In the original pin-set-up it was planned to insert metal pins sheathed in an insulation of plastic tubing through properly spaced holes in the test pipe into the explosive. However, it was not possible to completely seal the plastic tubing, and the conductivity of the hygroscopic ammonium nitrate permitted a direct electrical short circuit between pins and pipe wall. To eliminate this possibility and to facilitate a better sealing of the pins, the pins were inserted into corks first, the corks then being plugged into appropriate holes in the pipe. But a trial run with a loaded pipe showed that the conductivity of the un-initiated ammonium nitrate mixture still caused too much

leakage between the pins and the pipe wall. To meet this problem each pin was substituted by a loop of enameled wire sheathed in No. 18 plastic tubing and led through the cork. While this wire now was insulated from the undetonated mixture, the ionization and heat of the detonation wave would break the insulation in a fraction of a microsecond and then permit the necessary conduction. The ground wire was connected to the pipe wall with a brass screw near the end plate, so that the pipe wall would remain grounded even when parts of it already has been blown off by the progressing detonation wave.

The ammonium nitrate employed in most tests was a prilled fertilizer grade ammonium nitrate, which in general contained about three percent by weight of diatomateous earth as a coating substance to prevent caking. A screen analysis of typical fertilizer grade was shown in Table V. During the preliminary test series without instrumentation a prilled high density ammonium nitrate was tested which had a density of 62 pounds per cubic foot and did not contain a coating agent. Other experiments were made with regular fertilizer grade ammonium nitrate which had been coated with ten to twelve percent of myristic acid for the purpose of waterproofing. A series of tests was carried out with a by-product in the production of fertilizer grade, the so-called recirculation product (RCP), which was of finer average particle size than the regular fertilizer grade as was shown in the screen analysis in Table VI.

The fuel oil used as mixture component was a No. 2 fuel oil. The findings of the analysis of two samples were shown in Table VII.

TABLE V

Screen Analysis of Typical Fertilizer Grade Ammonium Nitrate

Particle Size (mesh)	Per Cent	Per Cent Cumulative
+ 8	1.7	1.7
- 8 / +10	10.6	12.3
-10 / +12	27.2	39.5
-12 / +14	36.3	75.8
-14 / +16	15.7	91.5
-16 / +20	7.2	98.7
-20	1.3	100.0

Density of Prill	100 - 110 lbs/ft^3
Density of Ammonium Nitrate	50 lbs/ft^3
Content of SiO_2-Coating	2.5% - 3%
Density of Ammonium Nitrate with Coating	47 lbs/ft^3

TABLE VI

Screen Analysis of Typical

Ammonium Nitrate-Recirculation Product

Particle Size (mesh)	Test A Per Cent	Test B Per Cent	Average of Tests A and B Per Cent	C ulative Per Cent
+10	-	-	-	-
-10 / +20	15.37	14.89	15.13	15.13
-20 / +35	50.88	51.37	51.12	66.25
-35 / +48	12.34	12.16	12.25	78.50
-48 / +65	7.68	7.94	7.81	86.31
-65 / +150	9.19	9.18	9.19	95.50
-150/ +200	3.15	3.10	3.12	98.62
-200	1.39	1.36	1.38	100.00

TABLE VII

Analysis of No. 2 Fuel Oil

Element	Test A Per Cent	Test B Per Cent
Carbon	84.23	86.59
Hydrogen	12.93	13.56
Sulphur	0.37	0.43
Specific Gravity at 60° F		0.8337 g/cm^3 or 38.23 API
Heat of Combustion		19689 Btu/lb or 10.93 Kcal/g
Approximate Assumed Chemical Formula		$C\ H_{1.87}\ S_{0.002}$
Percentages in Stoichiometric Mixture to Provide Oxygen Balance		94.4% Ammonium Nitrate 5.6% Fuel Oil

Procedure

In preparing the mixtures of ammonium nitrate with fuel oil or other carbonaceous materials a number of calculations is necessary. As these calculations have to be repeated with each test, a set of tables was drawn up in which most of the values needed were pre-calculated and could be obtained readily. These tables provided information about the amount of mixture to be filled into the test pipe to provide for the desired loading density.

The normal procedure for a single test was as follows: Composition of the mixture, diameter of test pipe, and loading density of the charge was determined. The length of the pipe to be used was measured. Taking into account the four inches of length needed for the primer, the amount of mixture needed to provide for the desired loading density of the charge was found in the corresponding table. All these data were written on the recording sheet of the test.

An appropriate amount of dry ammonium nitrate was weighed out and filled into the mixing tub. For the standard test pipe, three inches in diameter and five feet long, this amount of ammonium nitrate was normally 6000,6500 or 7000 grams, according to the amount of mixture needed for a low, medium or high loading density. The fuel oil was poured into a graduated cylinder (1000 milliliter) and its density was measured by means of a hygrometer. The volume of oil needed to provide desired weight percentage in the mixture was then calculated. The amount of oil required was measured in the graduated cylinder and poured into

the ammonium nitrate in the mixing tub. The substances were mixed thoroughly by hand or with wooden spoons (Figure 5). When the components were intimately mixed, the correct amount of mixture needed, which had been obtained from a table of pre-calculated values, was weighed and poured into the test pipe.

The iron test pipe to be used was prepared for loading by closing the pre-drilled holes which were to take the corks of the pin set-up with dummy corks. The mixture was poured into the pipe through a funnel (Figure 6). In most cases the pipe was vibrated with a hammer to make the mixture settle to the required mark four inches below the rim of the pipe. Then the primer was inserted. The standard primer used consisted of a bundle of four halves of 60% strength dynamite cartridges and a No. 2 electric blasting cap. This primer filled the space provided for it almost completely. (In the preliminary tests for the sensitivity of some mixtures the standard primer consisted of one cartridge of 60% strength dynamite and a No. 9 electric blasting cap. The space around the primer in the test pipe was filled with mixture. The loading densities in these tests were not pre-determined.) The wires of the electric cap were led through a hole in a wooden plug, three inches in diameter and about one inch thick, which filled the space inside the pipe cap, and then through a hole in the pipe cap. The pipe cap was screwed on tight. The loaded pipe was then carried from the mixing site to the blasting site, the latter being approximately three hundred feet away behind an earth embankment, fifteen feet in height.

Figure 5. Mixing of the Explosive

Figure 6. Filling of the Test Pipe

At the blasting site the dummy corks in the pipe were replaced by the corks containing the wires of the pin set-up (Figure 7). These wires, about twenty feet in length, were connected to the plug-in box by means of a twelve lead Jones plug. The plug-in box rested in a specially made protective wooden box which was imbedded in the top of the embankment (Figure 8). The wires of the primer were connected to the blasting cable and the preparations for the test were completed.

The described preparation work took twenty to thirty minutes per test, employing three men: one in charge of mixing, one in charge of the instrumentation, and one helper.

The instrumentation, oscilloscope and oscillograph signal generator, was set up on a table in a heavy wooden shelter at the mixing site. A camera was attached in front of the cathode ray tube of the oscilloscope. The film used was Kodak Tri-X film in single sheets which were inserted into a plate adapter. At blasting time the instrument operator opened the shutter of the camera while counting loud to three. At count two the shutter was opened, at count three the helper operated the electric blasting machine. This simple synchronization proved to be satisfactory.

The instrument man kept a record of all tests on special prepared sheets, to which the negatives of the oscillograph records were attached later. The mixing man kept notes, which were later transferred to the the permanent test records. From these two sources the data were obtained for the tables of results and for the corresponding diagrams.

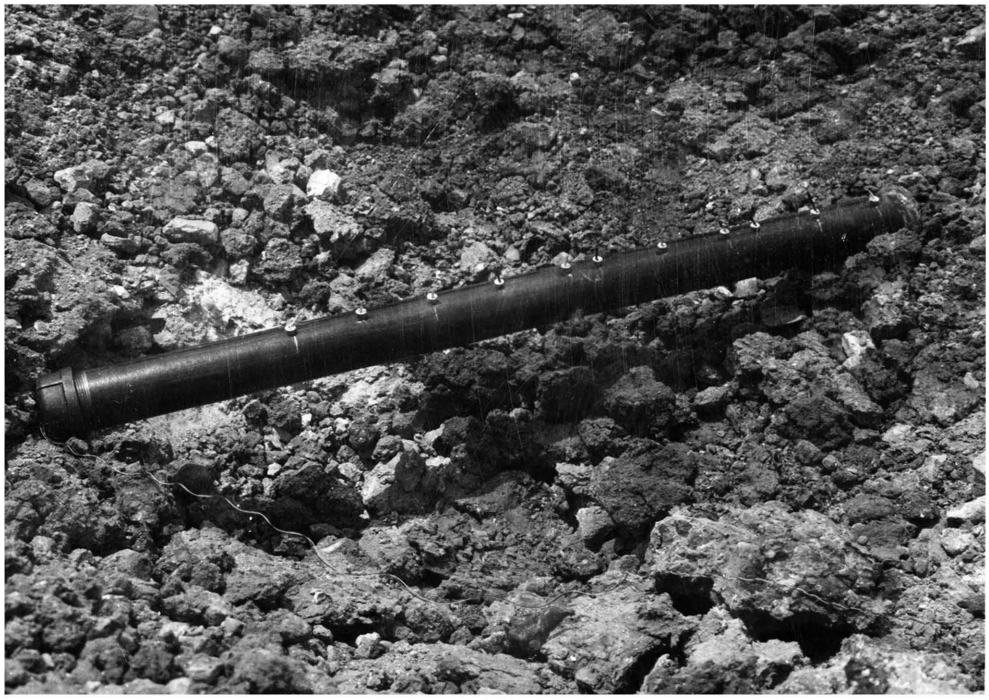


Figure 7. Test Pipe with Wires of Pin Set-up

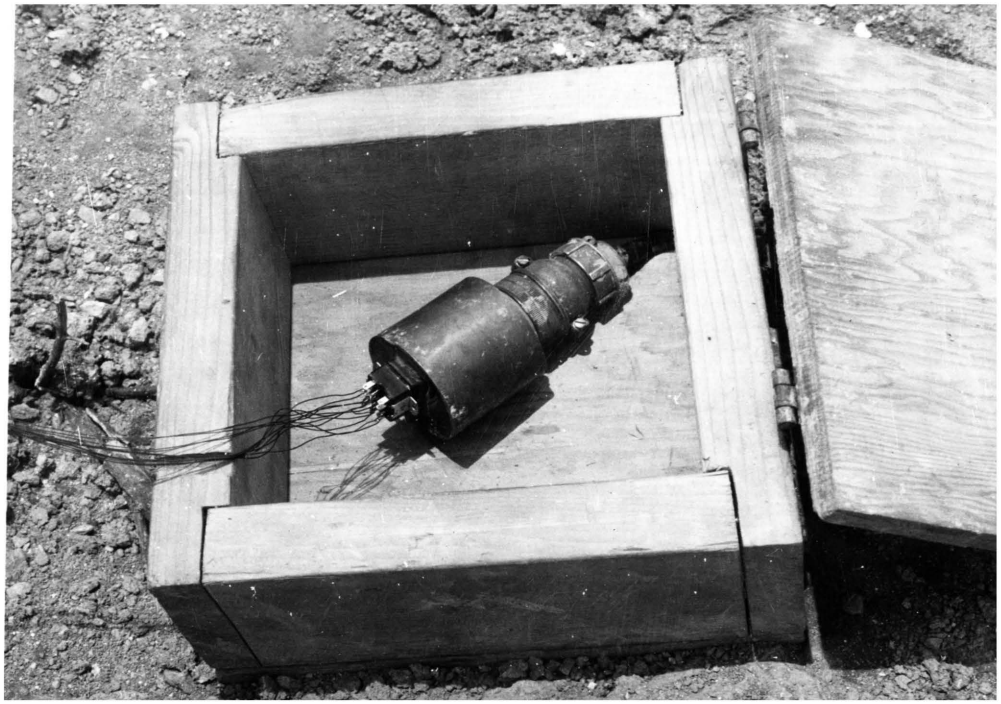


Figure 8. Plug-in Box

DATA, RESULTS AND DISCUSSION

Preliminary Tests

More than one hundred preliminary tests were performed without the instrumentation for the measurement of the detonation velocity. The purpose of these tests was to gain information about the explosibility of fertilizer grade ammonium nitrate-fuel oil mixtures under various modifications. Experiments were made to study the effect of the percentage of fuel oil in the mixture, the effect of the loading density of the charge, the effect of the particle size of the ammonium nitrate, the effects of the diameter and of the length of the charge, and the effect of different primers in respect to the possibility of initiation of the mixtures. Other tests included those with special types of ammonium nitrate and those using lampblack oil as reducing fuel in the mixture.

The data and results of these tests is listed in Tables VIII to XV. These include the test number, the composition of the mixture tested, the loading density of the charge and the diameter of the charge. The particle size of the ammonium nitrate is listed only, either in the "Remarks" column or a special "Particle Size" column, when specially screened ammonium nitrate was used as mixture component. A screen analysis of regular fertilizer grade ammonium nitrate is given in Table V.

The primer used in most of these tests consisted of one cartridge of 60% strength dynamite and a No. 9 electric blasting cap. If a stronger

primer was used, namely one cartridge of 90% strength gelatine dynamite, 1 3/4 inches in diameter and eight inches long, with a No. 9 electric blasting cap, this fact was recorded in the "Remarks" column. Comparative tests for the effect of these and other primers were listed in Table XV.

With respect to the results of the preliminary sensitivity tests the essential information to be gained was if the test would yield a complete detonation of the charge or not. In case the experiment was successful, that is, the mixture tested under some special modification detonated completely, the test shows a blank space in the "Results" column of the table in which it was listed. Unsuccessful tests in which the primer failed to initiate the charge of mixture were marked by the work "Failure" in the "Results" column. In most of the latter the primer had split the test pipe for a length of one to two feet and the ammonium nitrate mixture was partly scattered on the ground. In some of these tests a new primer of higher strength was inserted into the split end of the pipe on top of the remainder of the mixture in the pipe and was initiated. These secondary tests were marked by the addition of the letter A to the original test number. Partial detonations of the mixture in which a larger part of the test pipe was destroyed and after which no scattered mixture could be found on the ground rarely occurred.

The tests for the effect of the percentage of fuel oil in the mixture on the sensitivity were listed in Table VIII (three-inch diameter charges) and Table IX (two-inch diameter charges). The test pipes were the black iron pipes, the same as others used throughout the

TABLE VIII

Sensitivity Tests for the Effect of the Percentage of Fuel Oil in the Mixture

d = loading density of the charge (g/cm^3)

D = diameter of the charge (inches)

AN = fertilizer grade ammonium nitrate

Test No.	AN Fuel Oil Mixture	d g/cm^3	D inches	Remarks	Results
4	95/5	0.779	3		
24	95/5	0.784	3		
25	95/5	0.862	3		
3	95/5	0.870	3		
26	95/5	0.879	3		
44	95/5	0.854	3	fiber pipe	failure
41	95/5	0.858	3	fiber pipe	failure
23	90/10	0.838	3		
22	90/10	0.904	3		
5	90/10	0.926	3		
6	90/10	0.928	3		
9	85/15	0.899	3		
7	85/15	0.963	3		
8	85/15	0.969	3		failure
10	85/15	0.976	3		failure

TABLE IX

Sensitivity Tests for the Effect of the Percentage of Fuel Oil in the Mixture

d = loading density of the charge

D = diameter of the charge

AN = fertilizer grade ammonium nitrate

90% Dyn. = 90% strength gelatine dynamite primer, one cartridge

Test No.	AN Fuel Oil Mixture	d g/cm^3	D inches	Remarks	Results
84	98/2	0.920	2		
86	98/2	0.946	2		
85	98/2	0.954	2		failure
85A	98/2		2	90% Dyn.	
68	97/3	0.965	2		
14	95/5	0.878	2		
27	95/5	0.892	2		
29	95/5	0.921	2		
28	95/5	0.946	2		
56	95/5	0.956	2		
54	95/5	0.970	2		
57	95/5	0.971	2		
55	95/5	0.974	2		
53	95/5	0.981	2		
66	92.5/7.5	0.944	2		
67	92.5/7.5	0.955	2		
21	90/10	0.867	2		
20	90/10	0.872	2		
63	90/10	0.901	2		failure
65	90/10	0.910	2		failure
64	90/10	0.912	2		failure
15	90/10	0.933	2		
58	90/10	1.020	2		failure
60	90/10	1.027	2		failure
59	90/10	1.040	2		failure
61	90/10	1.051	2		failure
62	90/10	1.061	2		failure
17	85/15	0.974	2		failure
16	85/15	0.975	2		failure

course of this investigation. In an experiment with three-inch diameter fiber pipes (tests No. 41 and 44) detonation failed. As the mixture used in these two experiments proved to detonate consistently in iron pipes, it was concluded that the fiber pipe material was not suitable for this investigation. It was assumed that the fiber material could not offer sufficient confinement to the explosive to secure a stable detonation.

In three-inch diameter charges ammonium nitrate mixtures containing five, ten, and fifteen percent fuel oil could be initiated rather consistently by the standard primer of these tests. The only failures occurred with 85/15 ammonium nitrate-fuel oil mixtures with loading densities over 0.965 grams per cubic centimeter. The decrease of the test pipe diameter from three inches to two inches brought about a decrease of the sensitivity of the mixtures. With loading densities above 0.900 grams per cubic centimeter mixtures containing two percent and ten percent fuel oil failed to detonate with the standard primer, while 85/15 ammonium nitrate-fuel oil mixtures could not be detonated at all. This confirmed the results of earlier research, that an excess of fuel oil in the mixture and an increased loading density would decrease the sensitivity of the mixtures.[15] The failure of mixtures with highly positive or negative oxygen balances also gave support to the assumption that the maximum sensitivity of the mixtures should occur near the oxygen balanced composition. The 98/2 ammonium nitrate-fuel oil mixture which had failed to detonate with a 60% strength dynamite primer subsequently was initiated by a 90% strength gelatine dynamite primer.

The results of the tests for the effect of the loading density on the sensitivity of 95/5 and 90/10 ammonium nitrate-fuel oil mixtures are tabulated in Table X. The 95/5 ammonium nitrate-fuel oil mixture detonated consistently even at higher loading densities. The 90/10 ammonium nitrate-fuel oil mixture failed to be initiated by the primer used when the loading density was increased over 0.900 grams per cubic centimeter (in two-inch diameter tests pipes). This again emphasized previous reports that an increase in loading density would result in a decrease in sensitivity.

In Table IX the data are listed for tests on the effect of the diameter of the charge on the sensitivity of a 95/5 ammonium nitrate-fuel oil mixture. In the tests with 1.5 inches and one inch as charge diameter the ammonium nitrate used in the mixture was of the particle size -30/+35 mesh. With ammonium nitrate of this fine particle size the mixture seemed to detonate even in one-inch diameter charges if the low loading density, between 0.8 and 0.95 grams per cubic centimeter, could be maintained, which permits initiation readily. The failures of tests 76 and 77, both employing a 95/5 mixture of this fine particle size ammonium nitrate and fuel oil, were further explained by the foot notes in Table XII, in which again the importance of the loading density was emphasized. As was apparent, 95/5 fertilizer grade ammonium nitrate-fuel oil mixtures could be initiated consistently by the standard primer employed in a diameter of charge as small as two inches. Sensitivity tests with regular ammonium nitrate-fuel oil mixtures in charges with even small diameter were not performed in this stage of the investigation

TABLE X

Sensitivity Tests for the Effect of Loading Density

d = loading density of the charge

D = diameter of the charge

AN = fertilizer grade ammonium nitrate

Test No.	AN Fuel Oil	d g/cm^3	D inches	Remarks	Results
14	95/5	0.878	2		
27	95/5	0.892	2		
29	95/5	0.921	2		
28	95/5	0.946	2		
56	95/5	0.956	2		
54	95/5	0.970	2		
53	95/5	0.981	2		
4	95/5	0.779	3		
24	95/5	0.784	3		
25	95/5	0.862	3		
26	95/5	0.879	3		
21	90/10	0.867	2		
20	90/10	0.872	2		
63	90/10	0.901	2		failure
65	90/10	0.910	2		failure
58	90/10	1.020	2		failure
59	90/10	1.040	2		failure
61	90/10	1.051	2		failure
62	90/10	1.061	2		failure
23	90/10	0.838	3		
22	90/10	0.904	3		
6	90/10	0.928	3		

TABLE XI

Sensitivity Tests for the Effect of the Diameter of Charge and Tests for the Effect of the Length of Charge

d = loading density of the charge

D = diameter of the charge

ps = particle size of the ammonium nitrate (mesh)

90% Dyn. = 90% strength gelatine dynamite primer

L = length of the charge

Test No.	AN Fuel Oil Mixture	d g/cm^3	D inches	L feet	Remarks	Results
4	95/5	0.779	3			
25	95/5	0.862	3			
26	95/5	0.879	3			
14	95/5	0.878	2			
27	95/5	0.892	2			
53	95/5	0.981	2			
71	95/5	1.010	1.5		-30/+35 ps	
78	95/5	0.946	1		-30/+35 ps	
76	95/5		1		-30/+35 ps	failure
77	95/5		1		-30/+35 ps	failure
11	95/5	0.883	3	20		
18	95/5	0.889	2	21		
30	95/5	0.901	2	21		
12	90/10	0.935	3	20		failure
12A	90/10		3	17	90% Dyn.	
19	90/10	0.892	2	21		
31	90/10	1.001	2	21		failure
31A	90/10		2	17	90% Dyn.	failure
13	85/15	0.993	3	21		failure

TABLE XII

Sensitivity Tests for the Effect of Particle Size of the Ammonium Nitrate

d = loading density of the charge

D = diameter of the charge

ps = particle size of the ammonium nitrate

an = screened ammonium nitrate

Test No.	AN Fuel Oil Mixture	d g/cm	D inches	ps mesh	Results
48	95/5	0.922	2	-10/+12	
36	95/5	0.917	3	-14/+16	
49	95/5	0.910	2	-18/+20	
70	95/5	1.108	1.5	-18/+20	failure
51	95/5	1.109	1.5	-18/+20	failure
37	95/5	0.809	3	-30/+35	
71	95/5	1.010	1.5	-30/+35	
50	95/5	1.059	1.5	-30/+35	
78	95/5	0.946	1	-30/+35	
76	95/5	a)	1	-30/+35	failure
77	95/5	b)	1	-30/+35	failure

a) The amount of mixture filled in the pipe in this test was too small to have insured complete filling of the pipe. The mixture probably clogged in the pipe during filling before reaching the bottom of the pipe. The end of the pipe blown off in one piece, 1'2" long, seemed to confirm this assumption.

b) The density was not determined because of an apparent error in the record of this test. However, the amount of mixture used indicated a rather high loading density.

however, charges with smaller diameter were initiated successfully in the test series studying the effect of the diameter of the charge on the detonation velocity and will be discussed there.

A number of tests were performed to investigate the effect of the length of the charge on the stability of the detonation. These tests were also tabulated in Table XI. Mixtures which in previous tests had proven to detonate in charges of normal length, that is, a length of seven feet in these preliminary tests, were loaded into pipes of twenty or twenty-one feet length. The failures in these tests were due to the higher loading densities in comparison to the tests with normal length charges. A comparison with tests in normal length charges with corresponding loading densities, as they are listed in Table X, would show that at these loading densities also normal length charges failed to detonate. (The loading densities in all these preliminary tests were not predetermined or controlled.) From the successful tests of this series it was concluded that, if initiation of the explosive mixture was secured, it would detonate stably also over greater lengths of charge. This conclusion would, however, only pertain to the diameters of charge tested, namely two and three inches, and larger diameters.

The data and results of tests investigating the effect of the particle size of the ammonium nitrate used in 95/5 ammonium nitrate-fuel oil mixtures are listed in Table XII. Following Eyring's grain-burning theory emphasizing the effect of more uniform and finer particle size, it was expected that screened ammonium nitrate with an only small particle size distribution and in the case of the -30/+35 mesh ammonium

nitrate with an also smaller average particle size would increase the sensitivity of the ammonium nitrate-fuel oil mixtures. Therefore the tests were carried out in charges of smaller diameter in order to investigate at the same time the influence of the diameter of the charge. Consequently the failure of some of the tests in this series could be assumed to be due to the small diameter of charge, as the mixtures used in these tests detonated in charges of larger diameter. The assumption that a decrease in particle size and particle size distribution of the ammonium nitrate would increase the sensitivity of the mixtures was confirmed.

The tests for the effect of different primers were listed in Table XIII. It was found that a primer consisting of one cartridge of 60% strength dynamite, 1¼ inches in diameter and eight inches long, consistently initiated a 95/5 ammonium nitrate-fuel oil mixture. A primer consisting of one cartridge of 40% strength dynamite, 1¼ inches in diameter and eight inches long, failed to initiate the detonation of this mixture.

To test the postulate of the overdrive theory by Tikker[25] a number of tests were performed employing heavy primacord as primer. Using one-foot length of heavy primacord with a No. 9 electric blasting cap as primer the 400 grains per foot primacord and the 300 grains per foot primacord initiated the 95/5 ammonium nitrate-fuel oil mixture successfully while the 200 grains per foot primacord and the 150 grains per foot primacord failed to do so.

TABLE XIII

Tests for the Effect of Different Primers

Test pipe diameter: 3 inches

Composition-%: 95/5 AN/fuel oil

d = loading density of the charge

PC = primacord

gr = grains per foot

Test No.	d g/cm^3	Primer	Results
1	0.883	40% dynamite, 1 cartridge	failure
4	0.779	60% dynamite, 1 cartridge	
24	0.784	60% dynamite, 1 cartridge	
97	0.800	400-gr. PC, 1 1'-length	
99	0.778	300-gr. PC, 1 1'-length	
100	0.794	200-gr. PC, 1 1'-length	failure
98	0.787	150-gr. PC, 1 1'-length	failure
94	0.790	50-gr. PC,(through whole length of charge +400-gr. PC,)	
96	empty pipe	50-gr. PC,(through whole length of pipe +400-gr. PC,)	?
95	0.782	50-gr. PC,)through whole length of charge +150-gr. PC;)	?

Two tests were performed in which a primer of heavy primacord was running through the whole length of the charge of a 95/5 ammonium nitrate-fuel oil mixture. This primer was prepared by taping one-foot long strips of heavy primacord end to end to a primacord (50 grains per foot) trunk-line to the end of which a No. 9 electric blasting cap was connected. These tests appeared to be successful. A third test employed the same type of primer in any empty pipe. The latter test was carried out to make a comparative study of the edges of breakage on the small pieces of the iron test pipe which could be found after the detonation. In the first two tests the pipes were broken into small pieces as normal and no scattered mixture could be found on the ground. However, the edges of breakage of the small pieces had a different appearance than they had after previous tests with this mixture and the standard primer. It seemed as if there was less work performed on these edges, which were coarse and angular and not fused and edged as they were after previous successful ammonium nitrate-fuel oil mixture detonations. So it was assumed that the explosion of the primacord would break the test pipe before the detonating ammonium nitrate-fuel oil mixture, if it was initiated, could break it. How the primacord alone would break the test pipe was then demonstrated in test No. 96 with an empty pipe. Because the primacord alone could break the test pipe there was no assurance for the other two tests that the ammonium nitrate mixture detonated also, although no evidence of unexploded mixture could be found on the ground. However, the force of the primacord explosion could have widely scattered the ammonium nitrate mixture rather easily.

These were only the preliminary tests without the instrumentation for the measurement of the detonation velocity. A more detailed study of the effect of different primers and methods of initiation was carried out with the instrumentation. These tests were listed in Tables XXV and XXVI and were described in the accompanying discussion.

An extensive number of sensitivity tests was performed with mixtures in which special types of ammonium nitrate were used. These tests were listed in Table XIV.

The first of these special type mixtures was a product with the comparatively high density of sixty-two pounds per cubic foot. (Regular fertilizer grade ammonium nitrate has a density of forty-seven pounds per cubic foot.) This product did not contain the three percent of diatomaceous earth as a coating substance for moisture resistance. The high density ammonium nitrate was tested in 95/5 mixtures with fuel oil and also with lampblack oil. After tests in three-inch diameter charges had failed, additional tests were performed in four-inch diameter and six-inch diameter charges. These tests also yielded detonation failures. In conclusion it could be said that this type of ammonium nitrate was unsatisfactory as a component of explosive ammonium nitrate-reducing fuel mixtures.

The problem of finding a waterproof explosive ammonium nitrate-reducing fuel mixture was recognized also by other research and was mentioned in the review of literature. In this investigation a number of tests were carried out with a special ammonium nitrate (WP) which had been coated with ten to twelve percent of myristic acid as waterproofing agent. In dry condition, this product proved to be a good explosive,

TABLE XIV

Sensitivity Tests for the Effect of Different

Types of Ammonium Nitrate

HD = high density ammonium nitrate (d = 62 lbs/ft^3)
WP = special ammonium nitrate, coated with waterproofing agent
DE = diatomaceous earth (coating substance)
MA = myristic acid (coating substance)
WD = woodpulp FO = fuel oil
AL = powdered aluminum LB = lampblack oil
AN = fertilizer grade ammonium nitrate
D = diameter of charge d = loading density
pc = 50-grain primacord trunkline running through whole length of charge
90% Dyn. = 90% strength gelatine dynamite primer, 1 cartridge

Test No.	d g/cm^3	D in.	Corposition - % of Mixture	Remarks	Results
32	0.937	3	95HD/5FO		failure
33	1.030	3	95HD/5FO		failure
42	0.987	3	95HD/5FO	HD with 3% DE	failure
45	1.014	4	95HD/5FO		failure
45A	1.014	4	95HD/5FO	90% Dyn.	failure
81	1.004	6	95HD/5FO		failure
81A	1.004	6	95HD/5FO	90% Dyn.	failure
83	1.062	3	95HD/5LB		failure
83A	1.062	3	95HD/5LB	90% Dyn.	failure
87	0.943	3	100HD-WP/O (10% MA) dry		detonation incomplete
88	0.943	3	100HD-WP/O (sat. in AN-)	90% Dyn.+pc	failure
89	0.943	3	100HD-WP/O (solution)	90% Dyn.+pc	failure
93	1.001	3	80HD/20AL		detonation doubtful
38	0.792	3	100WP/O dry		
39	0.792	3	100WP/O sat. in water	90% Dyn.	failure
40	0.792	3	100WP/O sat. in Water-2'	90% Dyn.	failure
69	0.892	2	100WP/O dry		
72	0.886	1.5	100WP/O dry		
74	0.886	3	100WP/O sat. in water	90% Dyn. +3pc	failure
75	0.886	3	100WP/O sat. in water	90% Dyn.+6pc	failure
82	0.886	3	100WP/O sat. in water	90% Dyn.+3pc	failure
90	0.637	3	97X/3FO X = 83.3WP/16.7WD		failure

because the myristic acid is also a highly carbonaceous substance ($C_{14}H_{28}O_2$). Even in charges with diameters as small as two and 1.5 inches the ammonium nitrate (WP) charges detonated successfully over the whole length of the charge. Also in the high density product the coating of myristic acid provided enough sensitization to yield at least a partial detonation in a three-inch diameter charge (test No. 87), which had not been achieved by mixtures of this product with fuel oil or lamp-black oil. However, the WP-product did not fulfill its purpose as a waterproof explosive. Ammonium nitrate (WP) charges saturated with water failed to detonate even with such primers as three or six lines of primacord (50 grains per foot) running through the whole length of the charge and connected to a cartridge of 90% strength gelatine dynamite on top of the charge. It seemed that the amount of heat necessary to vaporize the water content in the mixture was too high to allow for an initiation of the mixture. In one test (No. 40) the mixture was saturated with water only to a length of two feet from the bottom of the charge, the remaining five feet length of the charge being left in dry condition. This test was successful. Apparently the amount of heat required to vaporize the content of water in this test could be supplied by the detonating dry ammonium nitrate.

To increase the capacity of the ammonium nitrate to absorb the water, it was mixed with fine ground woodpulp to form an 83.3/16.7 mixture. This mixture was combined with fuel oil in the proportions of 97 percent ammonium nitrate-woodpulp mixture and three percent fuel oil. But even in dry condition this mixture did not detonate. For the

time being the attempts to find an ammonium nitrate which would yield a waterproof explosive remained unsuccessful.

A series of tests was carried out with ammonium nitrate-lampblack oil mixtures and was tabulated in Table XV. The lampblack oil is a soot oil, containing about 8.5 percent carbon. The sensitivity of the ammonium nitrate-lampblack oil mixtures corresponded approximately to that of ammonium nitrate-fuel oil mixtures of equal composition percentages.

Also in Table XV the data and results were listed of a number of tests for the effect of powdered aluminum as sensitizing agent in mixtures with ammonium nitrate. The stoichiometric percentages to provide for an oxygen balanced mixture are approximately 85/15 ammonium nitrate-aluminum. In these tests (except for test No. 92) 80/20 ammonium nitrate-aluminum mixtures were employed. These mixtures proved to be very sensitive. The aluminum additive yielded a successful detonation in a mixture with regular ammonium nitrate in a diameter of charge of only one inch and produced a partial detonation in a mixture with the normally inert high density ammonium nitrate. The high capacity of powdered aluminum as a sensitizer in mixtures with ammonium nitrate was clearly demonstrated.

TABLE XV

Sensitivity Tests for the Effect

of Different Reducing Fuels

FO = No. 2 fuel oil

LB = lampblack oil, containing about 8.5% carbon

AL = powdered aluminum

HD = high density ammonium nitrate (d = 62 lbs/ft^3)

d = loading density of the charge

D = diameter of the charge

Test No.	Fuel	Composition - %	d g/cm^3	D in.	Remarks	Results
43	LB	95/5	0.907	3		
47	LB	90/10	0.993	3		
46	LB	85/15	1.069	3		failure
46A	LB	85/15	1.069	3	90% Dyn.	failure
52	LB	95/5	0.965	2		
73	LB	95/5	0.962	1.5		
79	LB	95/5	0.879	1		failure
80	LB	95/5	0.890	1		failure
83	LB	HD95/5	1.062	3		failure
83A	LB	HD95/5	1.062	3	90% Dyn.	failure
91	AL	80/20	0.913	3		
101	AL	80/20	1.141	1		
92	AL +FO	83.4/15/1.6	0.972	1		
93	AL	HD80/20	1.001	3		partial detonation

DETONATION VELOCITY TESTS

The selected data and results compiled and discussed in the following were obtained from the records of nearly three hundred tests in which the instrumentation for the measurement of the detonation velocity had been applied. It was the object of these tests to investigate the effects of a number of parameters on the detonation velocity of ammonium nitrate-reducing fuel mixtures.

The Effect of the Percentage of Fuel Oil. The records of the tests in which the effect of the percentage of fuel oil in the mixture had been investigated were shown in Table XVI. The standard diameter of the test pipes was three inches. In the tests with regular fertilizer grade ammonium nitrate (AN) the loading density was kept at 0.900 grams per cubic centimeter. The tests with the ammonium nitrate recirculation product (RCP) showed that this low loading density was difficult to obtain. Especially mixtures with a high percentage of fuel oil could not be filled so loosely as to keep the loading density at this low value. This was due to the high density of the recirculation product itself because of less air space between grains as a result of the smaller average particle size of this product and to the fact that high fuel oil percentages would cause an additional increase in the over-all density of the mixture. Therefore the loading density for the tests with RCP-mixtures was determined to be 1.100 grams per cubic centimeter, which seemed to be satisfactory in mixtures with high percentages of fuel oil. However, with lower fuel oil percentages this loading density could not

TABLE XVI

Tests for the Effect of the Percentage of Fuel Oil in the Mixtures

d = loading density of the charge (g/cm^3)

D = detonation velocity (feet/second)

Test pipe diameter: 3 inches

Test No.	Composition - % AN/Fuel Oil	d g/cm^3	D Feet/Second
279	99/1	0.900	8440
278	98/2	0.900	10437
277	97/3	0.900	11200
276	96/4	0.900	11850
229	95/5	0.900	11706
275	95/5	0.900	12156
270	94/6	0.900	12012
269	93/7	0.900	12007
268	92/8	0.900	11979
267	91/9	0.900	11767
266	90/10	0.900	11581
265	89/11	0.900	11581
263	88/12	0.900	11535
262	87/13	0.900	11293
264	86/14	0.900	failure
	RCP/Fuel Oil		
347	96/4	1.050	13610
355	94/6	1.050	13760
356	93/7	1.050	13590
249	95/5	1.100	14639
342	94/6	1.100	15207
346	92/8	1.100	13350
287	90/10	1.100	13267
286	89/11	1.100	13138
285	88/12	1.100	12714
283	87/13	1.100	12125
282	86/14	1.100	12161
284	85/15	1.100	failure
	-10/+12/Fuel Oil		
237	96/4	0.850	11100
235	95/5	0.850	11279
236	94/6	0.850	11319

be obtained with the loading method employed and for these tests had to be lowered to 1.05 grams per cubic centimeter. Several tests with a mixture using -10/+12 mesh particle size ammonium nitrate were carried out with a loading density of 0.850 grams per cubic centimeter.

In mixtures with regular ammonium nitrate the lowest percentage of fuel oil with which a detonation of the mixture could be obtained was one percent, the highest was thirteen percent. A recirculation product ammonium nitrate-fuel oil mixture yielded a detonation also with a fuel oil percentage of fourteen percent. The detonation velocities measured were plotted against the percentages of fuel oil in the mixture in Figure 9 in order to show how the percentage of fuel oil would influence the detonation velocity of the mixture. It was apparent from this figure that the maximum detonation velocity of an ammonium nitrate-fuel oil mixture would be obtained if the mixture was oxygen balanced, that is, it would contain 94.4 percent ammonium nitrate and 5.6 percent fuel oil. With increasing percentage of fuel oil the detonation velocity of the mixture would decrease slowly while with decreasing percentage it would drop sharply.

The fraction N of completed reaction in the detonation head, the latter being considered the detonation velocity determining region of the reaction zone, was also plotted against the percentage of fuel oil in the mixture. This value N was obtained from the application of an empirical equation given by Cook.[24] The values of the theoretical or ideal detonation velocities of the mixtures were obtained from the application of the calculation methods of the thermo-hydrodynamic theory.

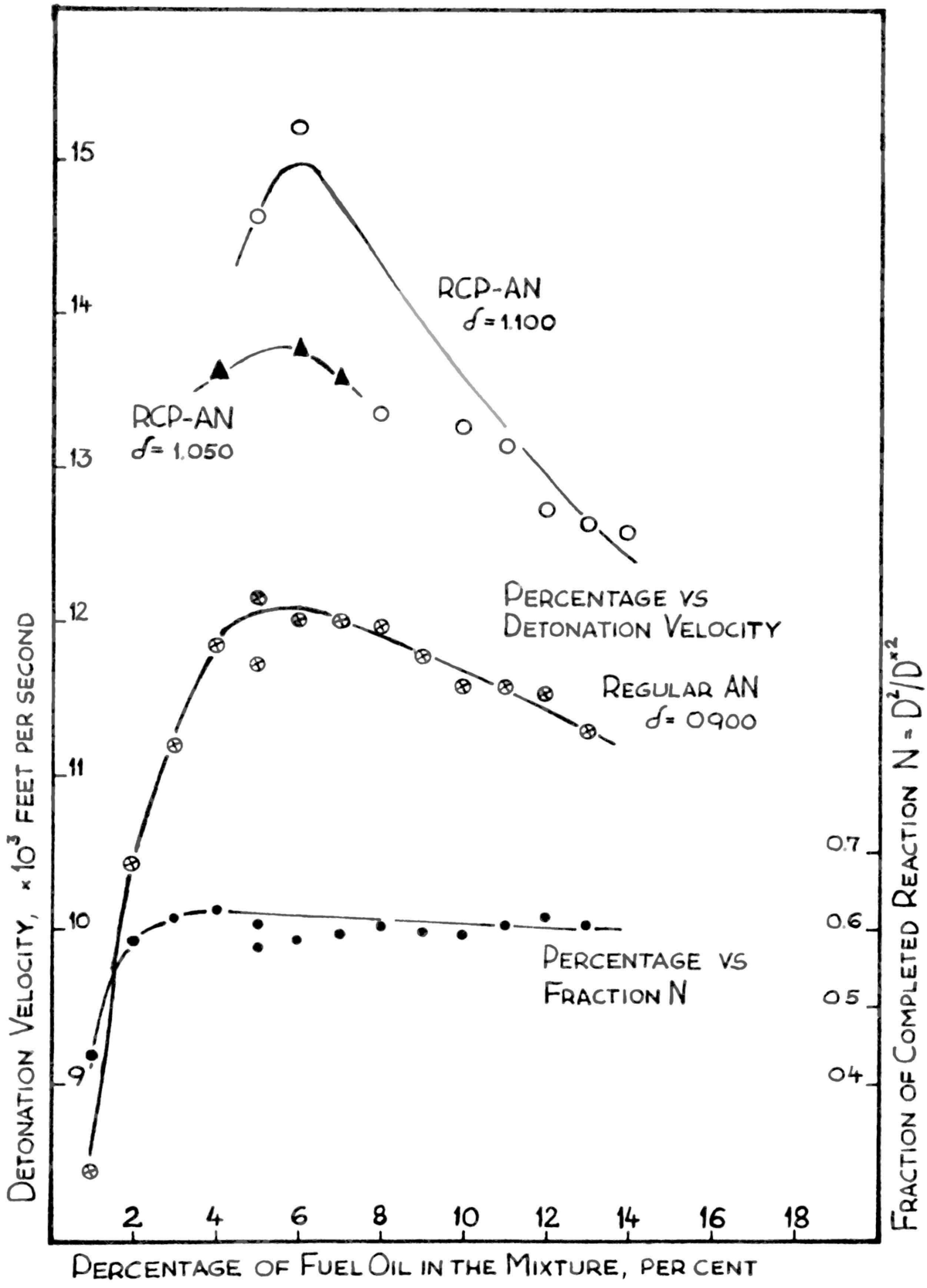


FIGURE 9. EFFECT OF THE PERCENTAGE OF FUEL OIL IN THE MIXTURES WITH AMMONIUM NITRATES ON THE DETONATION VELOCITY AND THE FRACTION OF COMPLETED REACTION N OF THE MIXTURES.

The data and results of the calculations of the values of N were listed in Table XVII. Except for the low percentages of fuel oil this fraction N seemed not to vary too much with a change in the percentage of fuel oil in the mixture, indicating that the increase or decrease in detonation velocity owing to the change in the percentage of fuel oil was not as much due to a change in the amount of the fraction of completed reaction N as to the difference in the amount of energy or heat supplied by this fraction.

The Effect of the Loading Density of the Mixture. Several series of tests were made to study the effect of the loading density of the mixture on the detonation velocity. In each series all other parameters such as diameter of charge, particle size of the ammonium nitrate, composition of the mixture, and type of primer were kept constant while the loading density was increased gradually with eac' test.

All the test series could be classified into two groups. The first group consisted of the five test series in which the diameter of the charge was changed with each new series. In these tests the mixture had a composition of ninety-five percent ammonium nitrate and five percent fuel oil. A standard primer was employed consisting of a bundle of four halves of 60% strength dynamite cartridges held together by the wires of a No. 9 electric blasting cap. In the tests with two-inch diameter pipes due to the smaller diameter a bundle of only two halves of a 60% strength dynamite cartridge could be used as primer. The six-inch and eight-inch diameter pipes had iron plates welded to both ends, to one of

TABLE XVII

Fraction of Completed Reaction N in the Tests for the Effect of the Percentage of Fuel Oil in the Mixture

D = measured detonation velocity (feet/second)

D+ = ideal detonation velocity (feet/second)

N = fraction of completed reaction (= D^2/D^{+2})

Loading density of the charge = 0.900 g/cm^3

Test pipe diameter: 3 inches

Composition - % AN/Fuel Oil	D Feet/Second	D^+ Feet/Second	N
99/1	8440	12775	0.43649
98/2	10437	13625	0.58678
97/3	11200	14300	0.61343
96/4	11850	14950	0.62828
95/5	11706	15400	0.57780
95/5	11931	15400	0.60022
94/6	12012	15650	0.58912
93/7	12007	15575	0.59431
92/8	11979	15400	0.60506
91/9	11767	15225	0.59733
90/10	11581	15050	0.59213
89/11	11581	14850	0.60819
88/12	11535	14680	0.61742
87/13	11293	14500	0.60657

these end plates with a two and one half-inch hole in it was attached a piece of three-inch diameter pipe about four inches long as a mouthpiece. This mouthpiece was to hold the standard primer. While in the tests with six-inch diameter pipes this primer proved to be sufficient to secure initiation of the mixture it failed to detonate the charges in the eight-inch diameter pipes. It was assumed that this failure was caused by the proportion of diameter of primer to diameter of charge. Therefore, in the following tests a layer of 60% strength dynamite obtained from twenty broken up cartridges filled the last four inches of the eight-inch diameter pipe. A standard primer was inserted into the mouthpiece as usual. These charges detonated satisfactorily. In addition to the loading density tests with regular fertilizer grade ammonium nitrate (AN) with the diameter of charge as the second changing parameter, for comparison a test series was performed with a 95/5 mixture of ammonium nitrate recirculation product (RCP) and fuel oil in three-inch diameter pipes. The results of all these tests were listed in Table XVIII. In the second group of loading density tests the diameter of the charges was three inches throughout, while the particle size of the ammonium nitrate used was changed with each new series. The mixtures in these tests had a composition of ninety-four percent ammonium nitrate and six percent fuel oil. The results of these tests were shown in Table XIX.

The data and results in Tables XVIII and XIX were employed in drawing Figures 10 and 11, which show the relationship between loading density and detonation velocity as found in these loading density tests. The lower limit of the loading density to be tested was set by the

TABLE XVIII

Tests for the Effect of the Loading Density

Composition - %: 95/5 AN Fuel Oil
d = loading density of the charge (g/cm^3)
D = detonation velocity (feet/second)

Test No.	Diameter of Test Pipe Inches	d g/cm^3	D Feet/Second
357	2	0.750	9630
358	2	0.800	10270
359	2	0.850	10530
360	2	0.900	10810
310	2	0.900	10136
361	2	0.925	failure
206	3	0.750	11100
239	3	0.750	10714
226	3	0.770	11000
240	3	0.770	11288
231	3	0.800	10875
241	3	0.800	10879
230	3	0.850	11450
229	3	0.900	11706
275	3	0.900	12156
232	3	0.950	12300
202	4	0.750	11488
203	4	0.800	11819
204	4	0.850	12422
208	4	0.880	13105
207	4	0.900	13506
222	6	0.770	12400
210	6	0.800	12850
212	6	0.800	12763
223	6	0.850	13361
225	6	0.880	13850
224	6	0.900	14367
242	8	0.850	13725
326	8	0.900	13990
343	8	0.900	14140
Composition - %:	95/5 RCP/Fuel Oil		
234	3	0.850	12629
238	3	0.850	12581
243	3	0.850	12908
244	3	0.880	12743
245	3	0.900	12493
246	3	0.950	13044
247	3	1.000	13600
248	3	1.050	14175
249	3	1.100	14639

TABLE XIX

Tests for the Effect of the Loading Density

Composition - %: 94/6 AN/Fuel Oil

Test Pipe Diameter: 3 inches

d = loading density of the charge (g/cm^3)

D = detonation velocity (feet/second)

Test No.	Particle Size Mesh	d g/cm^3	D Feet/Second
236	-10/+12	0.850	11319
216	-10/+12	0.915	12300
250	-14/+16	0.800	11706
251	-14/+16	0.850	11872
252	-14/+16	0.900	12300
253	-14/+16	0.950	12722
258	-14/+16	1.000	13111
254	-18/+20	0.800	11944
255	-18/+20	0.850	12300
256	-18/+20	0.900	12750
257	-18/+20	0.950	13422
259	-18/+20	1.000	13739
183	-20 (RCP)	0.888	12793
271	-20 (RCP)	0.900	12975
272	-20 (RCP)	0.900	13328
355	-20 (RCP)	1.050	13760
342	-20 (RCP)	1.100	15207
348	-30/+60	0.850	13430
349	-30/+60	0.900	14030
350	-30/+60	0.950	15080

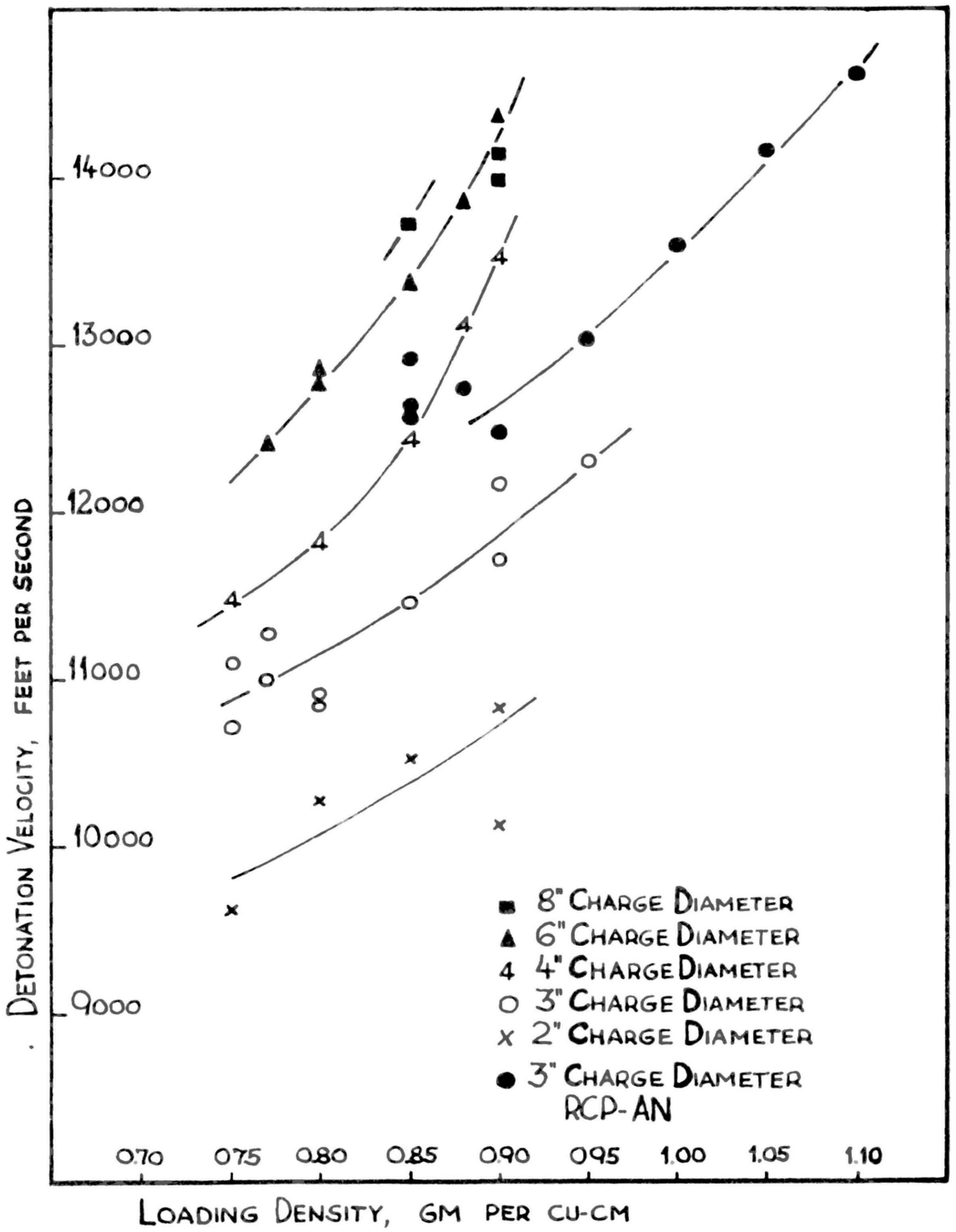


FIGURE 10. EFFECT OF THE LOADING DENSITY ON THE DETONATION VELOCITY OF 95/5 AMMONIUM NITRATE - FUEL OIL MIXTURES.

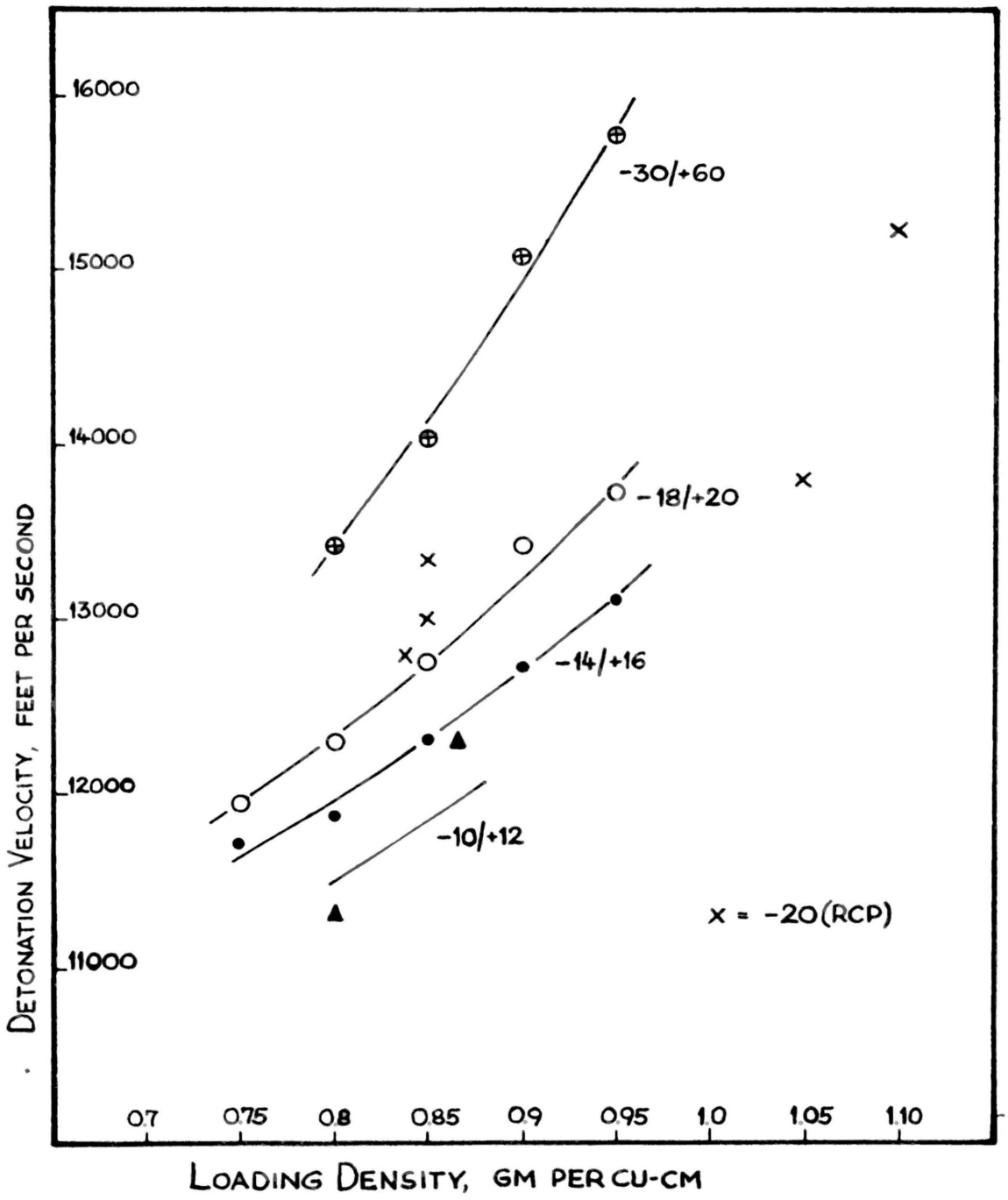


FIGURE 11. EFFECT OF THE LOADING DENSITY ON THE DETONATION VELOCITY OF 94/6 AMMONIUM NITRATE - FUEL OIL MIXTURES, WITH AMMONIUM NITRATE OF DIFFERENT PARTICLE SIZE (IN MESH).

approximate density of the loose mixture, the upper limit was set by the limitations of the equipment employed and the procedure followed in filling the mixture into the pipes. With more force applied to the filled mixture than just the hammering of the test pipe probably even higher loading densities could be obtained than the ones recorded, although the gain of experience from such tests should be only slight.

The diagrams (Figures 10 and 11) show that the detonation velocity of ammonium nitrate-fuel oil mixtures increased with an increase in loading density. This appears only logical as more energy should be supplied to the detonation wave when more mass reacts per unit volume. The only limitation imposed by an increasing loading density seemed to be its decreasing sensitivity as mentioned earlier.

The Effect of the Diameter of the Charge. Two groups of tests were performed to investigate the effect of the diameter of the charge. The first group employed a 95/5 mixture of regular fertilizer grade ammonium nitrate and fuel oil at a loading density of 0.900 grams per cubic centimeter, the second used a 94/6 composition of recirculation product ammonium nitrate and fuel oil, also at a loading density of 0.900 grams per cubic centimeter. The diameters of charge tested were in line with the diameters of the test pipes available. The primer for the one-inch and 1.5-inch diameter tests was one half of a 60% strength dynamite cartridge. All the other charges were initiated with primers as described in the loading density tests. The data and results of the diameter tests were listed in Table XX.

TABLE XX

Tests for the Effect of the Diameter of the Charge

d = loading density of the charge (g/cm^3)

D = detonation velocity (feet/second)

Composition - %: 95/5 AN/Fuel Oil

Test No.	d g/cm^3	Diameter of Test Pipe Inches	D Feet/Second
312	0.900	1	failure
311	0.900	1.5[a]	9150
310	0.900	2	10136
360	0.900	2	10810
229	0.900	3	11706
275	0.900	3	12156
207	0.900	4	13506
224	0.900	6	14367
326	0.900	8	13990
343	0.900	8	14140
Composition - %: 94/6 RCP/Fuel Oil			
316	0.900	1	inadequate record
274	0.900	1.5[a]	10439
273	0.900	2	11321
271	0.900	3	12975
272	0.900	3	13328
315	0.900	4	14667
335	0.900	6	15400
314	0.900	8	15483

[a]Actual diameter of test pipe was 1.5625 inches

Employing these data and results Figure 12 was drawn showing the relationship between diameter of charge and detonation velocity. It was apparent that the diameter of charge had a marked effect on the detonation velocity. In small diameters, that is from 1.5 to four inches, the detonation velocity increased rapidly with increasing diameter of charge. In medium diameters, from four to six inches, the increase in detonation velocity with increasing diameter became smaller, and it remained only slight when the diameter of the charge was increased above six inches. It was assumed that with further increasing diameter of charge the detonation velocity would eventually approximate the ideal detonation velocity of the mixture, which according to Cook[8] could take place at diameters as large as 55 to 65 inches. Consequently the measured detonation velocities of the eight-inch diameter tests with the regular ammonium nitrate-fuel oil mixture, which appeared to be rather low, had to be considered slightly erratic owing to reasons which at this time have not been determined. It was remarkable that charges with the small diameter of 1.5 inches could be detonated securely.

It seemed of interest to find out how the results of these diameter tests would agree with the postulate that the detonation velocity would be determined by the fraction N of reaction completed within the detonation head.[24] By means of Cook's empirical formula this value N was calculated for all diameter tests as listed in Table XXI. The N values then were plotted against the diameters in Figure 12. As could be seen the increase in the value of N with increasing diameter of charge corresponded to the increase in measured detonation velocity. This confirmed Cook's theory, which also was based on experimental evidence.

TABLE XXI

Fraction of Completed Reaction N in the Tests for the Effect of the Diameter of the Charge

D = measured detonation velocity (feet/second)

D^+ = ideal detonation velocity (feet/second)

N = fraction of completed reaction (= D^2/D^{+2})

Loading density of the charge: 9.900 g/cm^3

Composition - %: 95/5 AN/Fuel Oil

Test Pipe Diameter Inches	D Feet/Second	D^+ Feet/Second	N
1.5[a]	9150	15387	0.35361
2	10136	15387	0.43393
2	10810	15387	0.49356
3	11706	15387	0.57877
3	12156	15387	0.62412
4	13506	15387	0.77045
6	14367	15387	0.87181
8	13990	15387	0.82666
8	14140	15387	0.84448
Composition - %: 94/6 RCP/Fuel Oil			
1.5[a]	10439	15650	0.44492
2	11321	15650	0.52328
3	12975	15650	0.68736
3	13328	15650	0.72527
4	14667	15650	0.87832
6	15400	15650	0.96830
8	15483	15650	0.97877

[a]Actual diameter of the test pipe was 1.5625 inches.

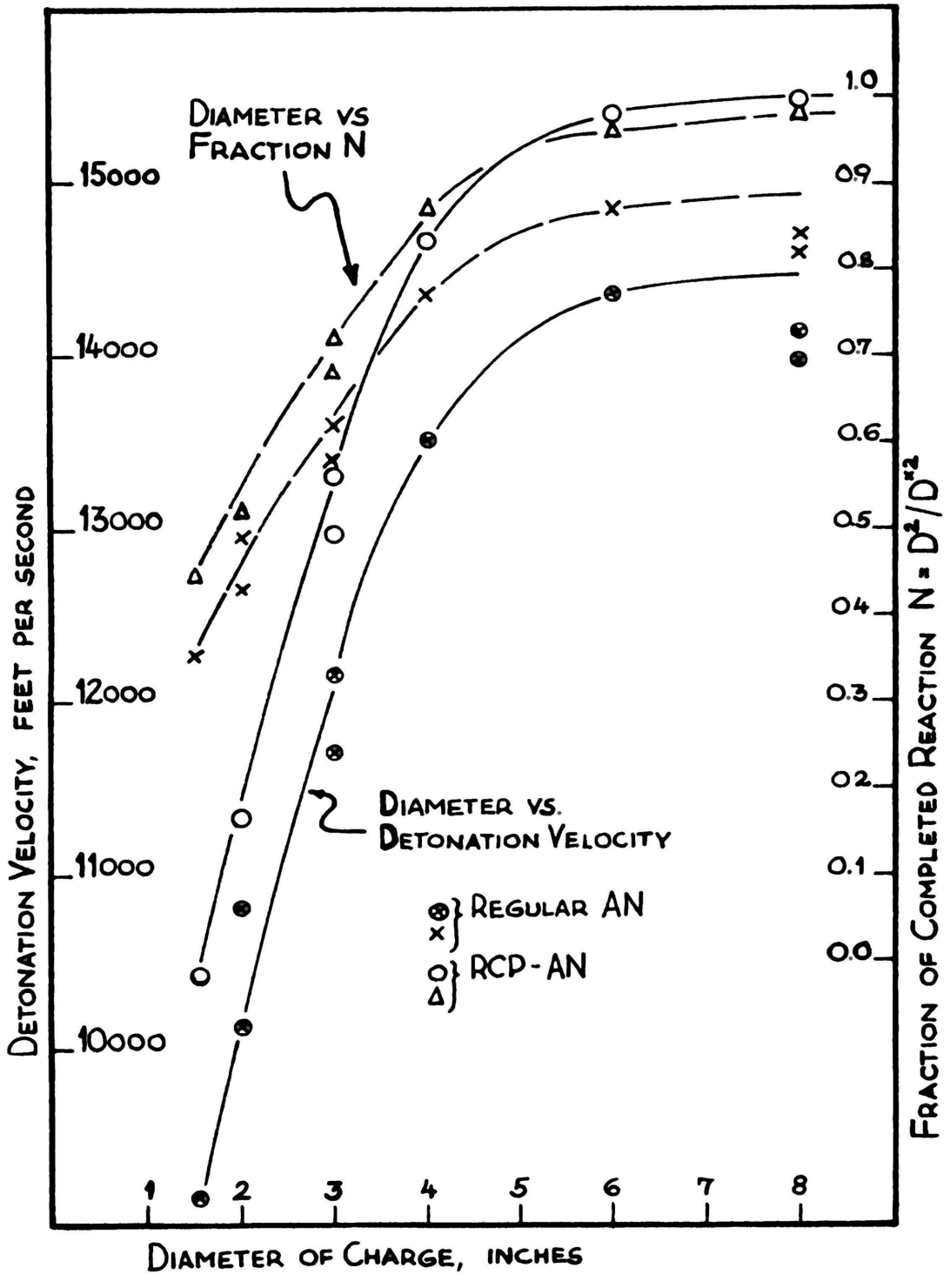


FIGURE 12. EFFECT OF THE DIAMETER OF CHARGE ON THE DETONATION VELOCITY AND THE FRACTION OF COMPLETED REACTION N OF 95/5 AMMONIUM NITRATE- AND RCP- FUEL OIL MIXTURES.

The Effect of the Particle Size of the Ammonium Nitrate. The tests investigating the effect of the particle size of the ammonium nitrate in the mixture were tabulated in Table XXII. In some of the tests the loading density had not been kept at the required value for comparative tabulation of 0.850 grams per cubic centimeter. The values of the average detonation velocity obtained in these tests were corrected approximately to the density of 0.850 by applying the curve constructed from the results of tests for the effect of the loading density. Once again the value N of the fraction of reaction completed within the detonation head was then calculated for all tests and the results were listed in Table XXIII.

In Figure 13 the detonation velocity and the value N were then plotted against the particle size. The plotting of the regular fertilizer grade ammonium nitrate as -12/+14 mesh particle size and of the recirculation product ammonium nitrate -20 mesh was arbitrary, but seemed justified as these particle sizes pertained to the largest screen fractions of those products. It is admitted that the curves drawn in Figure 13 are rather freely conceived: a larger number of data would be necessary to verify the course of the curves. However, they were based on the definite indication of the apparent trend that the fraction N and the detonation velocity increase with increasing particle size. Furthermore, this would agree with the theory developed concerning the relation between particle size and detonation velocity, a corollary of Eyring's grain-burning theory. This theory pointed out that a decrease in particle size would bring about a decrease in the length of the

TABLE XXII

Tests for the Effect of the Particle Size of the Ammonium Nitrate

d = loading density of the charge (g/cm^3)

D = detonation velocity (feet/second)

Test pipe diameter: 3 inches

Composition - %: Ammonium Nitrate/Fuel Oil

Test No.	d g/cm^3	Particle Size Mesh	D Feet/Second
230	0.850	-12/+14[b]	11450
108	0.854	-12/+14[b]	11520[a]
111	0.831	-10/+12	12200[a]
235	0.850	-10/+12	11279
113	0.892	-20[c]	12455[a]
238	0.850	-20[c]	12581
234	0.850	-20[c]	12629
243	0.850	-20[c]	12908
114	0.900	-20[c]	13220[a]
Composition - %: 94/6 Ammonium Nitrate/Fuel Oil			
142	0.792	-12/+14[b]	11280[a]
270	0.900	-12/+14[b]	11560[a]
236	0.850	-10/+12	11319
216	0.915	-10/+12	11455[a]
251	0.850	-14/+16	11872
255	0.850	-18/+20	12300
183	0.888	-20[c]	12690[a]
348	0.850	-30/+60	13430

[a]Detonation velocity value approximately corrected to d = 0.850

[b]Regular fertilizer grade ammonium nitrate (=AN)

[c]Recirculation product ammonium nitrate (=RCP)

TABLE XXIII

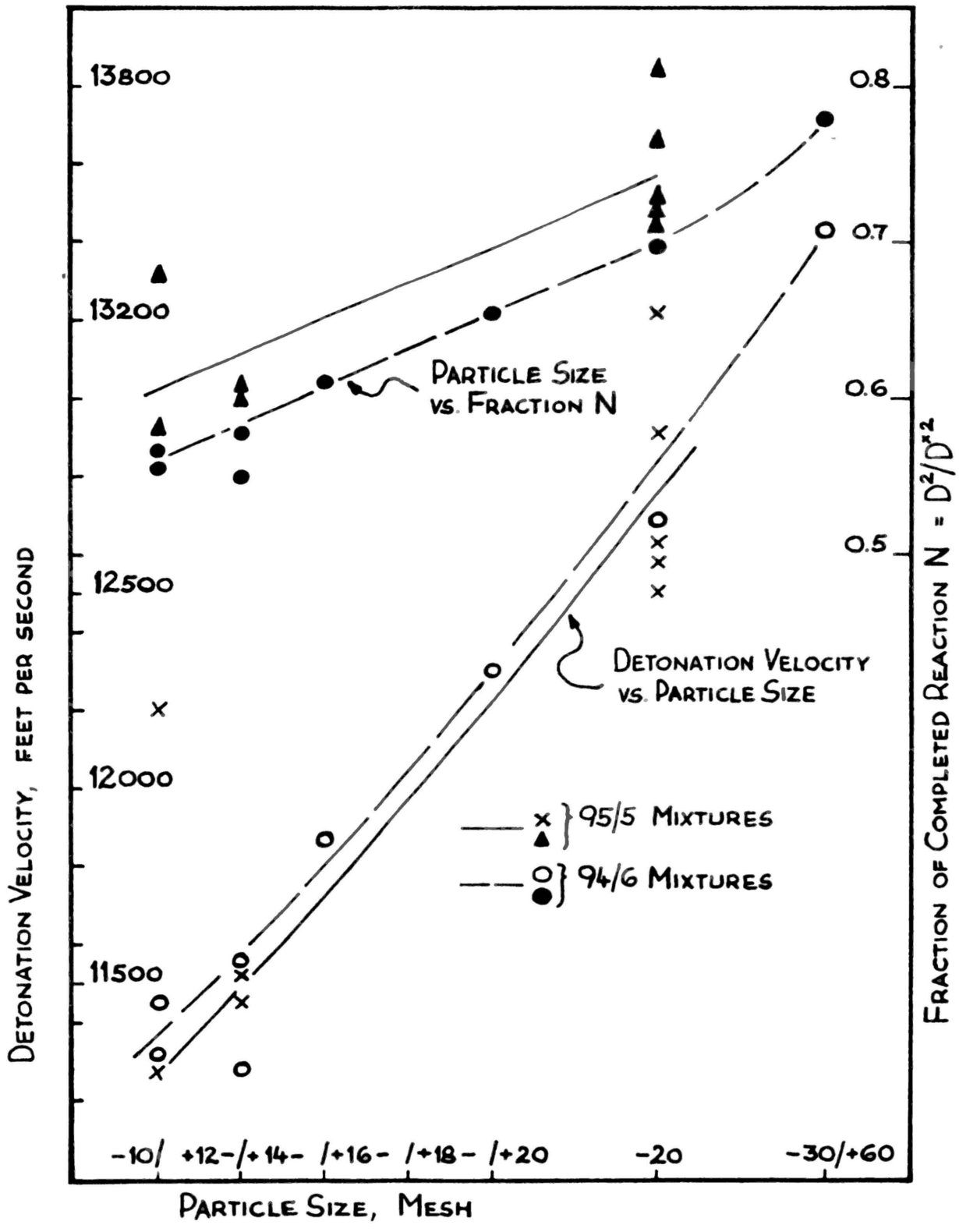
Fraction of Completed Reaction N in the Tests for the Effect of the Particle Size of the Ammonium Nitrate

D = measured detonation velocity (feet/second)
D^+ = ideal detonation velocity (feet/second)
N = fraction of completed reaction ($=D^2/D+2$)
Loading density of the charge: 0.850 (g/cm^3)
Test pipe diameter: 3 inches
Composition - %: 95/5 Ammonium Nitrate/Fuel Oil

Particle Size Mesh	D Feet/Second	D^+ Feet/Second	N
-10/+12	12200[a]	14764	0.68282
-10/+12	11279	14764	0.58362
-12/+14[b]	11450	14764	0.60145
-12/+14[b]	11520[a]	14764	0.60883
-20[c]	12455[a]	14764	0.71167
-20[c]	12581	14764	0.72614
-20[c]	12629	14764	0.73169
-20[c]	12908	14764	0.76438
-20[c]	13220[a]	14764	0.81395
Composition - %: 94/6 Ammonium Nitrate/Fuel Oil			
-10/+12	11319	15190	0.55526
-10/+12	11455[a]	15190	0.56868
-12/+14[b]	11280[a]	15190	0.55144
-12/+14[b]	11560[a]	15190	0.57916
-14/+16	11872	15190	0.61084
-18/+20	12300	15190	0.65568
-20[c]	12690[a]	15190	0.69792
-30/+60	13430	15190	0.78169

[a]Detonation velocity value approximately corrected to d = 0.850
[b]Regular fertilizer grade ammonium nitrate (=AN)
[c]Recirculation product ammonium nitrate (=RCP)

FIGURE 13. EFFECT OF THE PARTICLE SIZE ON THE DETONATION VELOCITY AND THE FRACTION OF COMPLETED REACTION N OF 95/5 AND 94/6 AMMONIUM NITRATE - FUEL OIL MIXTURES.



reaction zone. As the length of the detonation head, which is the detonation velocity determining region zone, was stated not to be dependent upon the length of the reaction zone but mainly upon the diameter of charge which was kept constant in these tests, it is logical to conclude that with decreasing particle size the end of the reaction zone will approach the Chapman-Jouguet plane, which represents the end of the detonation head. That would mean that the fraction N of reaction completed within the detonation head will become larger. And this again would result in a higher detonation velocity according to Cook's formula. Taking into account the standard deviation of the test results, which can be considerable, the results of the experiments seem to agree with the theory.

The Effect of Different Reducing Fuels. In Table XXIV the data and results were listed of the tests investigating the effect of different reducing fuels. The fuels used included No. 2 fuel oil, lampblack oil (slurry), tetra draings (tetra), naphtha, turpentine, and powdered aluminum, also combinations of some two of these fuels. For comparison the results of tests with corresponding percentages of the No. 2 fuel oil normally used in the ammonium nitrate mixtures were listed with the results of tests with other fuels.

Test No. 161 which employed a 90/10 ammonium nitrate-slurry mixture failed to yield a detonation of the mixture. However, this test employed the original standard primer consisting of one whole cartridge of 60% strength dynamite. Some previous tests with a 90/10 ammonium nitrate

TABLE XXIV

Tests for the Effect of Different Reducing Fuels

Test pipe diameter: 3 inches

Test No.	Composition - %	Components of Mixture	d g/cm^3	D Foot/Second
107	96/4	AN/fuel oil	0.887	11443
154	96/2/2	AN/fuel oil/tetra	0.874	10100
108	95/5	AN/fuel oil	0.854	11763
230	95/5	AN/fuel oil	0.850	11450
157	95/5	AN/naphtha	0.800	no detonation
160	95/5	AN/slurry	0.835	10625
233	95/5	AN/turpentine	0.850	11457
142	94/6	AN/fuel oil	0.792	10689
270	94/6	AN/fuel oil	0.900	12012
281	94/6	ANuc/fuel oil	0.900	11886
155	94/6	AN/tetra	0.875	8538
227	94/6	AN/turpentine	0.850	11550
146	94/3/3	AN/fuel oil/tetra	0.882	11100
163	94/3/3	AN/fuel oil/slurry	0.839	10878
143	92/8	AN/fuel oil	0.798	10938
268	92/8	AN/fuel oil	0.900	11979
152	92/4/4	AN/fuel oil/tetra	0.854	11106
266	90/10	AN/fuel oil	0.900	11581
159	90/10	AN/naphtha	0.891	no detonation
161	90/10	AN/slurry	0.812	no detonation
147	90/5/5	AN/fuel oil/tetra	0.880	11100
162	90/5/5	AN/fuel oil/alum	0.886	11272
260	88/12	AN/fuel oil	0.850	11118
153	88/6/6	AN/fuel oil/tetra	0.903	10894
164	69/15.5/15.5	AN/alum/water	1.192	9863
166	66.4/14.9/18.7	AN/alum/water	1.422	no detonation
165	59.7/13.4/26.9	AN/alum/water	-	no detonation

Legend: AN = fertilizer grade ammonium nitrate, with 3% coating
ANuc = uncoated ammonium nitrate
slurry = soot oil, containing 8.5% carbon
tetra = tetra drainings
alum = aluminum powder

fuel oil mixture using this primer had also been unsuccessful. The successful test listed (No. 266) employed the new standard primer consisting of a bundle of four halves of 60% strength dynamite cartridges. It could be possible, therefore, that a 90/10 ammonium nitrate-slurry mixture would also detonate with the use of the new standard primer.

The recorded results in Table XXIV show that the admixture of other organic fuels than No. 2 fuel oil to ammonium nitrate does not result in a marked change of the detonation velocity of such mixtures. In addition the detonation velocities yielded by these other mixtures were in general below those of ammonium nitrate-fuel oil mixtures. For this reason No. 2 fuel oil remained to be considered as the most suitable reducing agent for explosive ammonium nitrate-fuel oil mixtures.

A number of tests was carried out to study the performance of ammonium nitrate-aluminum slurries. As can be seen only the slurry with a water content of 15.5 percent detonated successfully, while slurries with higher water content failed to detonate. This agreed approximately with Cook's[3] report about the results of experiments with various ammonium nitrate-aluminum-water mixtures.

The Effect of Different Primers. The data and results investigating the effect of the primer employed to initiate the ammonium nitrate-fuel oil mixture were listed in Table XXV. These tests were carried out with a 95/5 mixture of regular ammonium nitrate and fuel oil in standard three-inch diameter pipes. The loading density in these tests varied but did not in general deviate too much from the mean loading density of

TABLE XXV

Tests for the Effect of Different Primers

Test pipe diameter: 3 inches, Composition - %: 95/5 AN/Fuel Oil

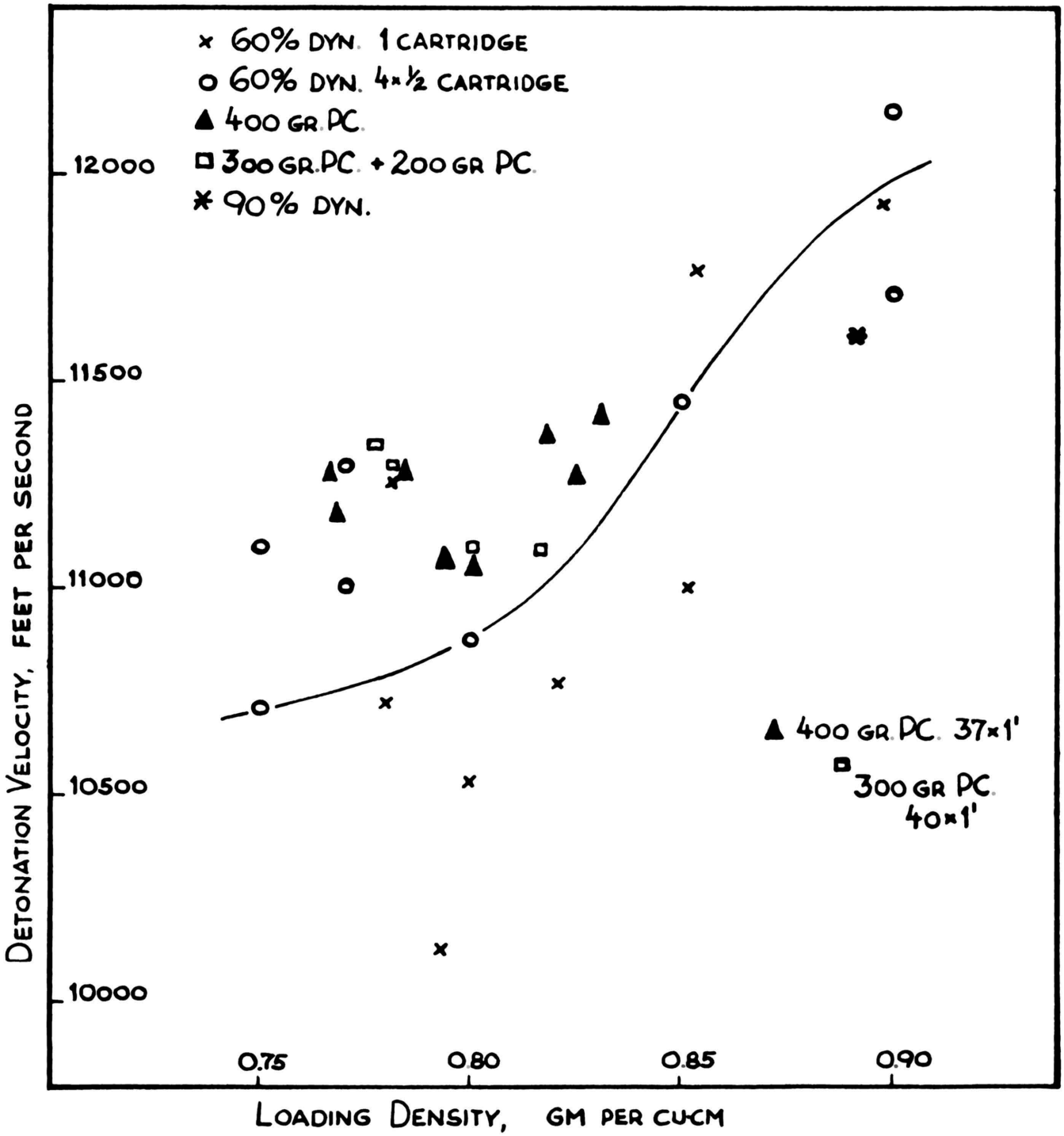
Test No.	Primer	d g/cm	D Foot/Second
1	40% dynamite, 1 cartridge	0.883	no detonation
194-C	40% dynamite, 1 cartridge	0.776	no detonation
106	60% dynamite, 1 cartridge	0.898	11925
108	60% dynamite, 1 cartridge	0.854	11763
133	60% dynamite, 1 cartridge	0.793	10125
134	60% dynamite, 1 cartridge	0.821	10768
136	60% dynamite, 1 cartridge	0.800	10534
140	60% dynamite, 1 cartridge	0.780	10725
176	60% dynamite, 1 cartridge	0.852	11000
189-C	60% dynamite, 1 cartridge	0.782	11256
230	60% dynamite, 4 ½-cartridges	0.850	11450
145	90% dynamite, 1 cartridge	0.892	11606
117	400-gr. PC, 1 1'-length	0.825	11263
148	400-gr. PC, 1 1'-length	0.831	11419
190-C	400-gr. PC, 1 1'-length	0.767	11279
191-C	400-gr. PC, 1 1'-length	0.768	11171
188	400-gr. PC, 2 6"-lengths	0.794	11064
186	400-gr. PC, 4 3"-lengths	0.818	11371
178	400-gr. PC, 37 1'-lengths	0.872	10656
149	300-gr. PC, 1 1'-length	0.841	no detonation
192-C	300-gr. PC, 1 1'-length	0.784	11278
193	300-gr. PC, 2 6"-lengths	0.817	11089
177	300-gr. PC, 40 1'-lengths	0.888	10569
100	200-gr. PC, 1 1'-length	0.794	no detonation
195-C	200-gr. PC, 1 1'-length	0.775	no detonation
196	200-gr. PC, 2 6"-lengths	0.816	no detonation
197-C	200-gr. PC, 2 6"-lengths	0.777	11343
98	150-gr. PC, 1 1'-length	0.787	no detonation
127	400-gr. PC, 1 1'-length +150-gr. PC, 1 1'-length	0.801	11042

Legend: PC = Primacord
gr. = grains per foot

of all tests. The tests tabulated in Table XXV refer to the experiments with primers only at one end of the explosive ammonium nitrate mixture column. These primers included cartridges of dynamite of different strength and short pieces of heavy primacord of different grain strength. In cases where more than one length of primacord was used the pieces were taped together in bundles with friction tape. Tests with numbers containing the letter C refer to confinement tests which were described more in detail under the next heading.

Employing the data and results listed in Table XXV, Figure 14 was drawn plotting the loading density of the primer tests against the detonation velocity of these tests. In addition to the values of the primer tests, the values of the loading density tests with a 95/5 ammonium nitrate-fuel oil mixture was plotted to obtain the loading density curve. This was done in order to emphasize the assumption that the type of primer used does not seriously change the typical detonation velocity of the mixture. As can be seen most of the values plotted are within the limits of normal deviation from the curve, which was considered to show the actual relationship between loading density and detonation velocity. The normal deviation in these detonation velocity tests was considered to amount to about five hundred feet per second. No explanation could be found at this time for the apparently anomolous fact that in two tests such comparatively strong primers as bundles of thirty-seven one-foot lengths of 400-grain primacord or of forty one-foot lengths of 300-grain primacord yielded detonation velocities in the mixtures considerably below the normal velocity.

FIGURE 14. EFFECT OF THE PRIMER ON THE DETONATION VELOCITY OF A 95/5 AMMONIUM NITRATE-FUEL OIL MIXTURE.



The tests listed in Table XXVI concerned the use of primer charges which extended throughout the whole length of the column of explosive mixture. Such a primer charge was prepared by leading a line of 50-grain primacord through the whole length of the pipe. To this line one-foot long pieces of higher strength primacord were attached with tape, either end to end or spaced known distances apart, and the ammonium nitrate-fuel oil mixture was filled around this line. Electric blasting caps were used as detonators. These tests were performed in order to investigate further the overdrive theory.

As is apparent the measured detonation velocities of these tests were rather inconsistent. It seemed safe to follow the conclusion of Cook,[8] that the consecutive explosions of the heavy primacord strips accounted for the high detonation velocities measured, while the ammonium nitrate mixture would detonate at its own speed for short length propagation. The latter would account for the low values of detonation velocity occasionally measured (tests 137 and 131).

The Effect of Confinement. The use of the iron test pipes was of advantage in this investigation because it facilitated convenient handling and application of the pin-oscillograph instrumentation, however, the iron test pipes resembled only to a limited degree actual bore hole conditions. In order to approximate more closely those actual conditions and also to find the answer to some questions which arose from an apparent discrepancy between the findings of iron test pipe tests and reports from field operations, this in the use of heavy primacord as initiating agent,

TABLE XXVI

Tests for the Effect of Different Primers, Continous Charges

Test Pipe diameter: 3 inches
Composition - %: 95/5 AN/fuel oil

Test No.	Primer	d g/cm^3	D Foot/Second
137	50-gr. PC +400-gr. PC, end to end	0.782	H 23800 L 11450 A 17813
129	50-gr. PC +400-gr. PC, 3′ spacing	0.803	Interpr. Diff.
131	50-gr. PC +400-gr. PC, 3′ spacing	0.777	H 19900 L 12050 A 15170
122	50-gr. PC +300-gr. PC, 1′ spacing	0.829	Interpr. Diff.
130	50-gr. PC +300-gr. PC, 3′ spacing	0.794	Interpr. Diff.
120	50-gr. PC +200-gr. PC, 2.5′ spacing	0.824	H 33330 L 18520 A 24090
121	50-gr. PC +150-gr. PC, 1′ spacing	0.810	H 29880 L 13300 A 20232

Legend: PC = Primacord
gr - grain
H = highest velocity recorded
L = lowest velocity recorded
A = average detonation velocity, calculated from all velocities recorded
Interpr. Diff. = Interpretation Difficulties with the record

several experiments with confined test pipes were performed. In these tests the standard three-inch diameter test pipes were surrounded by a mantle of concrete, about three inches thick, This was achieved by placing the iron test pipe in the middle of a ten-inch diameter sheet metal pipe which was closed at one end by a bottom plate. Small iron pipes, one-half inch in diameter, led from the wall of the test pipe to suitable holes in the sheet metal pipe, to hold the corks and insulated wires of the pin set-up. The space between the outer wall of the test pipe and the inner wall of the sheet metal pipe was then filled with concrete. The iron test pipe stuck out of the concrete sufficiently to permit the iron cap to be screwed on. The results of these tests were tabulated in Table XXVII together with results of comparative tests performed with pipes without concrete mantle.

These results did not provide sufficient information as to the effect of the confinement on the detonation velocity of the mixture, however, the tabulated results emphasized another significant fact, which was in agreement with previous findings.[12,15] This was the effect of the confinement on the sensitivity, that is the ease with which the explosive mixture can be initiated. In three instances confined charges detonated where comparative unconfined charges, that is, charges in iron test pipes, failed to yield a detonation (tests 149 and 192-C, 196 and 197-C, 109 and 199-C). It was known from the hydrodynamic theory that an expansion of the explosion products before the explosive reaction is complete and the resulting pressure drop behind the detonation front, the so-called rarefaction, strongly influence the rate of detonation of an explosive.

TABLE XXVII

Tests for the Effect of Confinement

Test pipe diameter: 3 inches

Composition - %: 95/5 AN/fuel oil

Test No.	Primer	d g/cm^3	D Foot/Second
140	60% dynamite, 1 cartridge	0.780	10725
189-C	60% dynamite, 1 cartridge	0.782	11256
117	400-gr. PC, 1 1'-length	0.825	11263
190-C	400-gr. PC, 1 1'-length	0.767	11279
191-C	400-gr. PC, 1 1'-length	0.768	11171
149	300-gr. PC, 1 1'-length	0.841	no detonation
192-C	300-gr. PC, 1 1'-length	0.784	11278
196	200-gr. PC, 2 6"-lengths	0.816	no detonation
197-C	200-gr. PC, 2 6"- lengths	0.777	11343
1	40% dynamite, 1 cartridge	0.894	no detonation
194-C	40% dynamite, 1 cartridge	0.776	no detonation
100	200-gr. PC, 1 1'-length	0.794	no detonation
195-C	200-gr. PC, 1 1'-length	0.775	no detonation
Composition - %: 90/10 AN/fuel oil			
109	60% dynamite, 1 cartridge	0.871	no detonation
199-C	60% dynamite, 1 cartridge	0.806	10725
266	60% dynamite, 4 ½-cartridges	0.900	11581

Applied to the primer, the rarefaction might decrease the efficacy of the primer just enough to cause it to fail to initiate the ammonium nitrate-fuel oil mixture. This could apply to the 95/5 ammonium nitrate-fuel oil mixtures employing 300-grain and 200-grain primacord as primer, and also to the 90/10 ammonium nitrate-fuel oil mixtures which were comparatively less sensitive due to their high negative oxygen balance, employing 60% strength dynamite primers. It seemed possible, therefore, as concluded from the results of these tests, that the stronger confinement delayed the early expansion of the explosive products long enough to conserve enough pressure and heat to facilitate the complete initiation of the ammonium nitrate-fuel oil mixtures. Following this line of thought it also might be assumed that stronger confinement would increase the detonation velocity of the mixtures, which should be subject to further investigation.

CONCLUSIONS

An approximately oxygen balanced mixture of ammonium nitrate and fuel oil, that is, a mixture containing ninety-four to ninety-five percent ammonium nitrate and six to five percent fuel oil, seemed to provide the highest detonation velocity and consequently the optimum blasting effect.

An increase in the loading density of an ammonium nitrate-fuel oil mixture was found to decrease its sensitivity but to increase its detonation velocity and energy yield.

Approximately oxygen balanced ammonium nitrate-fuel oil mixtures could be detonated successfully in charges with diameters as small as two inches, providing the minimum confinement of iron test pipes. The detonation velocity of the mixtures was strongly influenced by the diameter range, that is, diameters between 1.5 and 4 inches. In this range a small increase in diameter would result in a marked increase in detonation velocity and vice versa.

A decrease in average particle size of the ammonium nitrate in the ammonium nitrate-fuel oil mixtures resulted in a marked increase of the detonation velocity of these mixtures.

Of the different organic reducing fuels tested as components of ammonium nitrate-reducing fuel mixtures, the No. 2 fuel oil was found to provide the best results in terms of better sensitivity and higher detonation velocity of the mixture.

After initiation was secured the strength of the primer seemed to have no pronounced effect on the detonation velocity of the ammonium nitrate-fuel oil mixtures. The postulate of the overdrive theory could not be substantiated.

Stronger confinement of the charge was found to increase the sensitivity of ammonium nitrate-fuel oil mixtures within the range of confinement and densities tested.

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VITA

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He received his elementary education at schools in Winsen / Luhe, Blankenburg / Harz and Celle and his secondary education at the Gymnasium Ernestinum in Celle, from which he graduated in March 1949. He entered the Mining Academy Clausthal in Fall 1951 as a student in mining engineering and in the Fall 1952 transferred to the then reopened department of mining and metallurgy at the Technical University Berlin-Charlottenburg. He was the recipient of an exchange scholarship of the Federal Republic of Germany and of four consecutive scholarships of the state of Berlin. In 1955 he obtained a Fulbright Grant and a scholarship from the Department of State's International Educational Exchange Program to study mining engineering at the University of Missouri School of Mines and Metallurgy in Rolla. He received the degree of Bachelor of Science in Mining Engineering from this school in 1956. In fall 1956 he entered the graduate school of the Missouri School of Mines and became a graduate assistant in the Mining Department. In 1957 he received a research assistantship from the Monsanto Chemical Company research fund.

His practical experience includes work for a total of five years as a student trainee and miner in coal and metal mines in Germany, England and Arizona.

In 1957 he was elected as a member of Sigma Gamma Epsilon, honorary earth science society.