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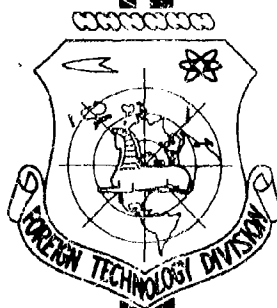
# TRANSLATION

POWDERS AND EXPLOSIVES

By

A. G. Gorst

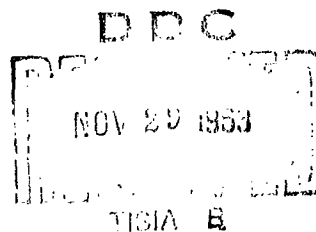
## FOREIGN TECHNOLOGY DIVISION



AIR FORCE SYSTEMS COMMAND

WRIGHT-PATTERSON AIR FORCE BASE

OHIO



## UNEDITED ROUGH DRAFT TRANSLATION

POWDERS AND EXPLOSIVES

BY: A. G. Gorst

English Pages: 271

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## TABLE OF CONTENTS

	<u>Page</u>
Historical Sketch . . . . .	1
Section I. Theory of Explosives	
Chapter I. General Characteristics of Explosives and their Classification.	
1. General considerations concerning explosion. 1. Definitions. 2. Conditions determining chemical explosion . . . . .	25
2. Explosives as a source of energy and their classification. 1. Comparison of explosive energy with fuel energy. 2. Relation of the power generated in an explosion to the energy release rate. 3. Classification and general characteristics of the explosive transformation phenomenon. 4. Classification of explosives. . . . .	28
Chapter II. Sensitivity of explosives and the initial impulse.	
1. Definitions . . . . .	30
2. The nature of the sensitivity of explosives . . . . .	30
3. Kinds of initial impulse. 1. Thermal impulse. Basic considerations concerning thermal decomposition. 2. Experimental determination of ignition temperature. 3. Mechanical impulse. 4. Sensitivity to detonation of another explosive. 5. Detonation by influence. 6. Transmission of detonation from cartridge to cartridge. 7. The effect of various kinds of initial impulse on an explosive. Simple initial impulse . . .	44
4. Factors influencing the sensitivity of explosives. 1. Physical structure and density of the charge. 2. Shape and size of the crystals. 3. Temperature. 4. Admixtures. 5. Chemical factors . . . . .	63

### Chapter III. Stability of Explosives and Method of its Determination.

	<u>Page</u>
1. Changes in explosives during storage . . . . .	70
2. Physical and chemical stability of explosives . . . . .	71
3. Factors determining the chemical stability of explosives. 1. Chemical structure. 2. Admixture of catalysts and stabilizers. 3. Storage conditions of explosives. . . . .	72
4. Experimental determination of chemical stability. 1. Abel heat test. 2. Vieille test. 3. Repeated Vieille test. 4. Weight test. 5. Manometric and electrometric tests . . . . .	74
5. The significance of chemical stability of explosives . .	79

### Chapter IV. Heat and Temperature of Explosion, Composition, Specific Volume, and Pressure of the Products of Explosive Transformation.

1. Heat of explosive transformation. 1. Definitions. 2. Hess's law. 3. Determination of the heat of formation of an explosive composed of simple substances by its heat of combustion. 4. Computation of the heat of explosive transformation of an explosive. 5. Experimental determination of the heat of explosive transformation . . . . .	81
2. Explosion temperature . . . . .	84
3. Equation for the decomposition reaction of explosives. 1. Oxygen balance. 2. Equation for the decomposition reaction of an explosive with a positive or null oxygen balance. 3. Explosive with negative oxygen balance - oxygen content insufficient for oxidizing all of the carbon into CO (free carbon remains in the explosive transformation products). 5. Equation for powder deflagration reaction . . . . .	89

### Chapter III. Stability of Explosives and Method of its Determination.

	<u>Page</u>
1. Changes in explosives during storage . . . . .	70
2. Physical and chemical stability of explosives . . . . .	71
3. Factors determining the chemical stability of explosives. 1. Chemical structure. 2. Admixture of catalysts and stabilizers. 3. Storage conditions of explosives. . . . .	72
4. Experimental determination of chemical stability. 1. Abel heat test. 2. Vieille test. 3. Repeated Vieille test. 4. Weight test. 5. Manometric and electrometric tests . . . . .	74
5. The significance of chemical stability of explosives . .	79

### Chapter IV. Heat and Temperature of Explosion, Composition, Specific Volume, and Pressure of the Products of Explosive Transformation.

1. Heat of explosive transformation. 1. Definitions. 2. Hess's law. 3. Determination of the heat of formation of an explosive composed of simple substances by its heat of combustion. 4. Computation of the heat of explosive transformation of an explosive. 5. Experimental determination of the heat of explosive transformation . . . . .	81
2. Explosion temperature . . . . .	84
3. Equation for the decomposition reaction of explosives. 1. Oxygen balance. 2. Equation for the decomposition reaction of an explosive with a positive or null oxygen balance. 3. Explosive with negative oxygen balance - oxygen content insufficient for oxidizing all of the carbon into CO (free carbon remains in the explosive transformation products). 5. Equation for powder deflagration reaction . . . . .	89

4. Volume of the gaseous products of the decomposition of the explosives. 1. Calculation of the volume of the products of explosive transformation. 2. Experimental determination of the volume of explosive transformation products .....	112
5. Pressure of the products of explosive transformation. 1. Determinations. 2. Computation of the pressure of the combustion products of an explosive. 3. Experimental determination of the pressure of the deflagration products of a powder .....	104

#### Chapter V. The Combustion of Gaseous and Condensed Explosives.

1. The origination and propagation of combustion in gaseous substances. 1. The mechanism of spontaneous combustion of a gaseous mixture. 2. Delay of spontaneous combustion. 3. Mechanism of combustion propagation of gaseous mixture .....	114
2. Mechanism of combustion of condensed explosives. 1. Mechanism of combustion of explosives and powders according to Byelyayev. 2. Conditions of steadiness of combustion of an explosive .....	118
3. Burning of powders .....	125

#### Section II. High Explosives

1. General requirements for explosives used as ammunition fillers. 1. Calculation of the stresses originating in the bursting charge during firing. 2. Calculation of the stresses originating in the bursting charge when the projectile pierces armor. 3. General requirements for an explosive used as ammunition filler, in relation to the sensitivity to mechanical effect .....	131
2. Nitric acid esters (nitrates). 1. Pyroxylin. 2. Nitroglycerine. 3. Nitroglycol. 4. Dinitro-diglycol. 5. PETN .....	139

3. Nitrocompounds. 1. General information. 2. TNT. 3. Picric Acid. 4. Ammonium picrate. 5. Tetryl. 6. Cyclonite. 7. Xylol. 8. Dinitronaphtalene. 9. Dinitrobenzene. 10. New and powerful explosives ...	143
4. Explosive mixtures. 1. Ammonium nitrate explosives. 2. Chlorate and perchlorate explosives. 3. Explosives on a base of liquid oxidizers .....	154

#### Section V. Colloid Powders

1. General information .....	163
2. Classification of colloid powders .....	166
3. Materials used in the production of colloid powders. 1. Pyroxylin. 2. Nitrocellulose solvents. 3. Stabilizers. 4. Plasticizers. 5. Flegmatizers. 6. Graphite .....	167
4. Production of pyroxylin powders .....	175
5. Powders on a difficult-to-volatilize solvent. 1. Nitroglycerine powders of the ballistite type. 2. Diglycol powders of the ballistite type. 3. Nitro- glycerine powders of the cordite type .....	181
6. Properties of colloid powders. 1. Physical properties. 2. The content of moisture and residual solvent. 3. Ballistic properties of powders. 4. Electrification of colloid powders. 5. Comparison of the properties of powders on a volatile and difficult-to-volatilize solvent .....	184
7. Characteristics of powder elements and powder brands. 1. Shape of powder elements. 2. Powder marking .....	188
8. Use of colloid powders .....	194
9. Special forms of pyroxylin powder. 1. Quick-burning powders. 2. Flegmatized powders. 3. Flashless powders. 4. Flareback .....	195

10.	Charges and igniters. 1. Definitions and classifications. 2. Propelling charges. 3. Special, practice, and blank charges. 4. Igniters.....	199
11.	Barrel erosion.....	206

### Section VI. Black Powder

1.	Composition and components of black powder .....	213
2.	Properties of black powder.....	215
3.	The production of black powder.....	216
4.	Grades of black powder .....	217
5.	Uses of black powder .....	219

### Section VII. Pyrotechnics

1.	Components of pyrotechnic compositions .....	220
2.	General requirements for pyrotechnic compositions and media .....	224
3.	Properties and testing of pyrotechnic compositions. 1. Properties of pyrotechnical compositions. 2. Testing pyrotechnic compositions. Sensitivity to mechanical effect. 3. Computation of the density of a compressed composition .....	225
4.	Illuminating compositions. 1. Luminous characteristics of illuminating compositions and media. 2. Choice of illuminating composition components with high luminous indexes. 3. Sensitivity of illuminating compositions to mechanical effect and choice of oxidizer. 4. Effect of binders on the properties of illuminating compositions. 5. Formulas for illuminating compositions. 6. Conditions of blocking illuminating substances. 7. Example of illuminating projectile .....	227

	<u>Page</u>
5. Photo-illuminating compositions (Photo blends .....	237
6. Tracer compositions .....	238
7. Night signalling compositions. 1. General information concerning signalling media. 2. Light-producing characteristics of signal compositions. 3. Selection of the components for signalling purposes. 4. Compositions for red fire. 5. Green fire compositions. 6. Yellow fire compositions. 7. Uses of night signalling compositions .....	244
8. Daylight signalling compositions .....	249
9. Masking smokes .....	252
10. Incendiary substances and compositions. 1. Classification. 2. Thermites and Thermite compositions. 3. Incendiary compositions with oxygen-containing salts. 4. Incendiary substances not containing oxidizers. 5. Spontaneous-combustion incendiary substances. 6. Uses of incendiary compositions and substances .....	254
11. Ignition compositions .....	260
Literature .....	268



## HISTORICAL SKETCH

The long period of the development of the culture concerning the discovery of a method for utilizing fire up to the invention of gun-powder takes in an entire epoch. During this period of time, human society in the majority of countries went through a gradual process of formation of a primitive type of communism and servitude, and then entered into the era of feudalism. While these societies were developing and then subsequently declining, man began to slowly recognize nature, and slowly tried to utilize its resources for his own interests. Technology was being correspondingly developed at a slow pace. Thus, many thousands of years elapsed from the discovery of the bow and arrow up to the time of the invention of gun powder and firearms.

The Discovery of Saltpeter and Invention of Gunpowder. Saltpeter was discovered hundreds of years ago in China. The Chinese were the first to discover the capability of saltpeter to support combustion, and they used it in incendiary compositions. Later on, they used saltpeter in the production of rockets which served for propelling arrows.

During the course of many centuries, a gradual perfecting of saltpeter-containing compounds took place. Various components in various proportions were selected for these compounds, and their processing methods were improved. The result of this was the evolution of a substance with heretofore unknown explosive properties - powder, which we today call gun, or black, powder.

The Chinese scholar, Sun-Tai Mao, described the composition of gunpowder and the formula for its preparation in his work "Dantsin" around 600 A. D.

Information concerning saltpeter and its use passed on from the Chinese into India, and, from there, to the Arabs and Greeks.

The Emergence of Firearms. The appearance of gunpowder was a necessary prerequisite for the beginnings of firearms. On the other hand, such a possibility was prepared for through the development of catapult weapons in the pre-firearms era. The ballista cross-bow and arquebus, which were created during the development of the bow and catapults, resemble firearms to a large extent.<sup>1</sup> The elasticity of the drawn bow string served as the propellant for arrows (cross-bow and arquebus) and bullets (arquebus). The creative ability of more than one generation was needed in order to substitute the work of the drawn bow-string by the work of powder gases and, through that, to create firearms which would be of practical use.

Firearms were invented in China in 1132. The barrel was made out of a length of bamboo tube. The "Tukochin" firearm was invented in China in 1259. Projectiles could be fired from this weapon. This weapon also had a long bamboo barrel. Gunpowder was already being widely used in China in military operations during these years (XIIth and XIIIth centuries), whereas it began to be used in Europe only in the XIVth century. Firearms appeared in Europe during the first half of the fourteenth century. In Muscovite Russia, gunpowder and firearms appeared around 1382, for

it is a well-known fact that gunpowder was used by artillery in defense of Moscow in that year.

Gun Powder. From the time of the appearance of firearms and approximately up to the middle of the nineteenth century, i.e. a period of almost 500 years, not even one new explosive was discovered, besides gunpowder, which was practical for propelling purposes, shell propellants or blasting purposes. Owing to the routineness and stagnation of the feudalistic system, and to the predominance of the church in spiritual life, science and technology developed extremely slowly. Only with the origination and development of capitalism did the development of natural sciences, including chemistry and physics, accelerate. This created the conditions for the discovery of new explosive substances.

The works of M. V. Lomonosov played a very important role in the development of gunpowder. A rational proportion among the components of this powder was established on the basis of these works towards the end of the 18th century. This proportion is still in use today. Only then was the technology of gun-powder production perfected.

Methods of Igniting Gunpowder. Beginning with the first prototypes of firearms, and up to the beginning of the 19th century, i.e. a period of 500 years, gunpowders were ignited through a "primer". The weapon had a vent which expanded outwards and was finished off with a pan for the primer. In the early days, the

primer was ignited by pieces of smoldering coal. Later on, this was done by means of glowing sticks. Wicks were used after this. Matchlocks appeared in the 16th century. The flint lock was the most perfect of these. Peter the First introduced the flint lock into the Russian Army in 1701, and they were part of the standard military ordnance for about 150 years, until the end of the Crimean War.

The first flint lock had a number of serious defects. Therefore, attempts to find better ways to ignite the powder charge in a weapon were started already at the close of the 18th century.

The possibility of solving this problem was facilitated by the earlier development of chemistry, and, in particular, by the discovery of Berthollet's salt. A few years after the discovery of this salt, the Scot, Forsythe, proposed the use of a chlorate mixture, which was easy to explode upon striking and produced a spark which was sufficient to ignite the powder. Pea-sized balls, grains, and lozenges, which were later coated with wax, were made of such mixtures. These mixtures were called percussion compounds. A special lock was invented, the percussion hammer of which had a striker pin which hit into the flash pan. This flash pan held the percussion lozenge or ball.

In 1815, the English inventor Igg proposed to press the percussion mixture into a metal jacket - a cap. Thus, the friction primer came into being.

The production of friction caps, with fulminate of mercury in the percussion compound, was started in Russia in 1843 at the Okhtensk powder works.

The Quest for a Powerful Gunpowder. During the second half of the 18th century, in connection with the development of industrial capitalism, a need for powder, which was more powerful than gunpowder, arose. This powder was to be used for the mining industry and military purposes. Research was initiated in order to find such a powder.

The first venture in this field was carried out by the French chemist, Berthollet. He proposed to prepare a powder consisting of a mixture of Berthollet's salt (discovered by him in 1786), carbon, and sulfur. After several unforeseen explosions with resulting serious loss of human life, the experiments were discontinued.

Berthollet's failure can be explained by the fact that only the fundamentals of inorganic chemistry were in existence at that time. These fundamentals were insufficient for the creation of a new, powerful powder and for new explosives. The emergence of a new branch - organic chemistry - was necessary to achieve this purpose. This fact was borne out through a further development of science. Meanwhile, organic chemistry started to be developed only during the last 20 years of the 19th century.

The Discovery of Nitrocellulose and Nitroglycerine. Two noteworthy discoveries were based on the attainments of organic chemistry - the discovery of nitrocellulose (Braconnot 1832) and nitroglycerine (Sobrero 1846). These two discoveries were the basis for a further development of gunpowder and high explosives.

The discovery of nitrocellulose subsequently brought about a

turning point in the history of gunpowder - colloidal powder was invented. The discovery of nitroglycerine led to the discovery of the phenomenon of detonation and high explosives, which was the result of the problems facing the rapidly-developing mining industry in the 19th century.

The rapid development of industry and the huge amounts of progress which were attained in the fields of physics, chemistry, mathematics and mechanics in the 19th century were also accompanied by great progress in military science.

Rifled artillery pieces were put into service practically simultaneously (around 1860) in Russia and other European countries. This led to a large increase in range and improved accuracy of fire in comparison with the hitherto-used smooth-bore artillery. At the same time, the urge for a further improvement in the ballistic qualities of artillery and small arms required a still faster solution to the previously mentioned problem - the finding of a powder which was more powerful than the old, black powder.

Attempts to Use Nitrocellulose for Firing Purposes. No interest was shown in nitrocellulose for several years after its discovery. Academician G. I. Gess and Colonel Fadeyev investigated the properties of nitrocellulose during 1846-1848, and they showed that it was several times more powerful than black powder.

Experiments were taking place in various countries during the following years, which had as their purpose a study of the possibility of using nitrocellulose instead of black powder for

firing purposes. These experiments ended in failure for a long time. The chief difficulty lay in the fact that, in firing with loose nitrocellulose, an extremely rapid and, through that, non-uniform combustion of it occurred. The result was the generation of a very high pressure which caused a large shell dispersion or even ruptured the weapon.

The Beginnings of the Need for Smokeless Powder. Magazine-fed rifles were developed in various countries during the 1870's in order to increase the rate of fire of small arms. However, in comparison firing tests, the magazine-fed rifles, for all intents and purposes, were not superior to the single-shot rifles with respect to impact count. The reason for this was that, in rapid fire with the magazine-fed rifles, the smoke did not have time to dissipate and the riflemen had difficulty in seeing the target. In connection with this, the problem of finding a low-smoke or smokeless powder was presented in all its sharpness.

Invention of Smokeless Powder. After prolonged experiments, the French chemist, Vieille, was the first to obtain smokeless nitrocellulose powder in 1884. His invention consisted in the gelatinization of nitrocellulose by treating it with a hydroxy-ether mixture. A fine-grained powder was produced from this mass which was used for rifles and as a strip-type powder for cannon.

Owing to its compact structure, the powder which was obtained in this manner burns in parallel layers. This makes it possible to control the combustion time of the powder charge by means of altering the sizes of the powder elements.

In 1888, A. Nobel invented nitroglycerine (ballistite) powder. In 1889, Noble<sup>2</sup> and Abel invented in England a nitroglycerine powder of another type (cordite).

The problem of sustained fire with magazine-fed rifles was solved with the use of smokeless powder. It was possible to reduce the caliber of the rifle at the same time (on account of making it easier to clean the bore, which heretofore was made difficult due to the large amount of foulings from the black powder). The muzzle velocity, range, and accuracy of fire were increased. The flatness of the trajectory and penetrating ability of the bullet were also correspondingly increased.

To the same extent, the use of smokeless (colloidal) powders marked a turning point in artillery technology, where the muzzle velocity of the shell, range, and accuracy of fire also increased sharply.

Smokeless powder is also a necessary prerequisite for the production of automatic weapons, machine guns in particular.

The Role of Russian Scientists in the Development of Powder Technology. The work of Russian scientists and specialists had a great impact on the development of gunpowder technology.

I. N. Shishkov made an analysis of the combustion products of black powders and computed the combustion temperature for the first time in the 1850's. N. P. Fyedorov published a noteworthy study concerning the composition of gunpowder residue and products of the decomposition of black powder under various pressures. N. V. Mayevskiy (1829-1892) and A. V. Gadolin proposed a ballis-



tically-suitable shape for black powder grains in the form of a cubic prism with one or seven channels. These two shapes are once again being used in contemporary one- and seven-channeled grains of colloidal powders. In the early 1890's, Professor of the Artillery Academy N. N. Fyedorov and Instructor S. V. Panpushko, in conjunction with two employees of the Okhtensk powder works, A. V. Sukhinskiy and E. V. Kalachyev, developed in a very short period of time an industrial process for the production of nitro-cellulose powder. They produced two forms of powder - lamellar for rifles and strip-type for cannon.

In 1891, D. I. Mendeleev developed a unique form of nitro-cellulose powder - pyrocolloidal.

D. I. Mendeleev also proposed a method for dehydrating nitro-cellulose with alcohol, thus simplifying the operation and making it safer. He also proposed a method for trapping the alcohol and ether vapors, which work was completed by V. N. Nikol'skiy under Mendeleev's guidance. In 1895, Nikol'skiy developed a method for the removal of the residual solvent from the powder through soaking.

The chemical stability of nitrocellulose powder was greatly increased at the beginning of the 20th century by introducing diphenylamine into the composition as a stabilizer. This was done on the basis of investigations which were carried out by N. A. Golybitskiy, V. N. Nikolskiy, and others. The theory of the nitrating mixture, which was developed by A. V. Sapozhnikov, and the relationship which he established between the nitrating mix-

ture and degree of nitration of cellulose are of significant importance to the nitrocellulose industry.

The achievements of the Russian scientists and specialists were also made use of in the powder-producing factories of other nations. In particular, the D. I. Mendeleev nitrocellulose powder was accepted in industry of the U. S. A.

The Discovery of High Explosives. In 1854, the famous Russian chemist, Nikolay Nikolayevich Zinin, for the first time posed the question of using nitroglycerine as an explosive, and, under his direction, the Russian artillery officer, V. F. Pyetrushevskiy, developed a method for large-scale production of nitroglycerine and a method for its explosion. Pyetrushevskiy developed the first powder-type dynamite, called "magnesia".

For a number of reasons, the artillery command refused to utilize nitroglycerine for shell fillers, which caused the experiments to be discontinued. They were renewed at a later time through the initiative of the military engineer O. B. Gern, who was interested in using nitroglycerine for demolition work.

Nitroglycerine was used for the first time by Pyetrushevskiy's collaborators for blasting operations in the gold fields of Eastern Siberia.

In 1865, Captain Andriyevskiy, a collaborator of N. N. Zinin, suggested a fulminate detonator, the use of which greatly increased the shattering effect of explosives and led to the discovery of the detonation phenomenon.

The introduction of nitroglycerine as an explosive, quickly

leading to the invention of the detonator and to the discovery of the detonation phenomenon, laid the foundation for the rapid development of high explosives. It turned out that a large number of chemical compounds and their mixtures, whose explosive properties were not too well known, could be detonated by a detonator. The force of the detonation is many times more powerful than the detonation force of black powder. Such compounds as picric acid, for instance, are among these compounds. Picric acid was used as a coloring agent for a hundred years with no suspicion on anyone's part that it could also be used as an explosive.

The honor of the further development and practical utilization of the noteworthy works of the Russian scientists belongs to the Swedish engineer, A. Nobel. Nobel perfected the design of the detonator and invented a number of dynamites and nitroglycerine powders (ballistites).

The Application of High Explosives in Artillery. The Russians decided to accept nitrocellulose as a filler for artillery shells in 1876. However, the development of a method for filling was difficult owing to its newness and difficulty of the task. The filling of shells with damp nitrocellulose was developed only during the beginning period of the year 1890, and, furthermore, this method was used for only a few mortar and cannon shells whose caliber was from 8 to 11 inches.

The filling of ammunition with nitrocellulose instead of black powder was an important stage in the history of artillery. But, on account of the high sensitivity of dry nitrocellulose to mechani-

cal effects, it could only be used in shells with a dampness content of 18-20%. Maintaining such dampness required a constant supervision over the nitrocellulose. It was also necessary to exercise control over its chemical stability.

In connection with the defects which are intrinsic to nitrocellulose, after Turpin (France discovered a method to detonate from a booster with cast picric acid (melinite) towards the close of the 1890's, a number of nations decided to substitute it for nitrocellulose as a shell filler. The Russians decided to use the properties of this substance and started to fill shells with this at the beginning of the 1890's. This work was conducted by S. V. Panpushko. A method for filling several large-caliber shells with melitine was developed in 1894. During this period, a method for filling the shells used by the Model 1877 field piece with melitine was developed. During testing of these shells, two guns ruptured, causing fatalities. This failure, the causes of which were not sufficiently investigated at that time, slowed down the introduction of high explosives as a shell filler for field pieces for a long time.

The works which were conducted along these lines in other countries were also not too successful. Even though the English armed forces were equipped with lyddite shells (English term for melinite) toward the close of the 1890's, the amount of incomplete shell bursts during the Boer War (1899-1902) amounted to 100%. This was due to the imperfect design of the fuses. The shelling effect was completely unsatisfactory, and worse than in the case where black powder shells were used.

With the appearance of rapid-fire field artillery at the beginning of the twentieth century, the opinion was that all of the tasks required in combat operations could be fulfilled with one gun: a light field-piece firing one type of shell - shrapnel. In connection with this idea, the light field artillery h. e. shell was removed from the ordnance in several European countries. Japan was the only country to use the high-explosive shell for the 75 mm field and mountain gun. This shell was filled with 800 grams of picric acid ("Shimoze").

#### The Development of Ammunition after the Russo-Japanese War.

The Russo-Japanese War had an important effect on the development of military technology in general and on the development of ammunition in particular. This war completely resolved the moot question concerning the value of the high explosive shell in ground combat.

During the Russo-Japanese War, troops and materiel occupied well-organized trenches and wood- and earth- dugouts for a prolonged period for the very first time. These engineer-constructed field fortifications were set up not only on the main line of resistance, but also in the rear areas. Powerful high explosive shells and long-range heavy artillery was needed to demolish them. The importance of large-caliber high-explosive shells containing a picric acid charge of up to 40 kg (in 12-inch shells) for naval engagements was also manifested in this war. Naturally, these shells could not pierce even light armor, but their bursts caused a large amount of destruction on the ship. Finally, the Russo-Japanese War showed that the new methods employed in the conduct

of war require a large expenditure of ammunition, which fact was not observed in previous wars.

All of this caused many countries to introduce miscellaneous and numerous field pieces into their ordnance and to stock-pile large supplies of ammunition in the interim between the Russo-Japanese War and World War I.

Trotyl (TNT) was introduced in Russia as a shell filler during this period (1909).

#### Growth of Ammunition Consumption from the World War I Period.

Shortly after the outbreak of World War I new circumstances came into existence, which greatly increased the consumption of ammunition, and, correspondingly, explosives.

First of all, in spite of the prevailing opinion, it was determined at the very beginning of the war that artillery fire would inflict the heaviest losses and was, therefore, the most deadly. This led to a further increase in artillery. At the same time, trench mortars appeared in large quantities during World War I. These were invented and first used by the Russian armies during the siege of Port Arthur by the Japanese. This mortar was primarily a smooth-bore weapon loaded from the muzzle, and with a range of 0.5 to 1 kilometer. They were called bomb-throwers and trench mortars. Hand and rifle grenades were used in large quantities for the first time in World War I. Heavy machine guns, and, at a later date, automatic rifles also made an appearance in large numbers.

Secondly, defense in World War I was not only perfected en-

gineering-wise, but also greatly strengthened on account of the increasing fire-power of artillery and small arms. Infantry was not in a position to break through the enemy defenses without a previous preparation for this break-through with special engineering means. Artillery was the decisive means, because prior to the appearance of chemical offensive means as well as of tanks and aviation at a later period, only the heavy fire of the artillery could demolish the defensive installations of the enemy, to destroy or demoralize their defenders, to silence their fire, and to enable the attackers to break through the defenses with fewer casualties.

The dynamics of the growth of ammunition expenditure for the relatively short historical period from 1870-1945 are of some interest.

During the Franco-Prussian War of 1870-1871, the Prussians used up 650,000 shells. The Russians used up 900,000 shells in the Russo-Japanese War.

The ammunition expenditure for the entire period of World War I consisted of (in millions of artillery rounds of all calibers):

Russia	.	.	.	.	up to 50
Austria-Hungary	.	.	.	.	about 70
Germany	.	.	.	.	about 275
England	.	.	.	.	about 170
France	.	.	.	.	about 191

(75 and 155 mm)

The overall artillery ammunition expenditure for the period of World War I was more than a billion rounds at a cost of more

than 50 billion rubles.

Not only the overall ~~ammunition~~ expenditure, but also their tremendous expenditure in narrow sectors of the front in separate operations, is enlightening. Thus, for instance, the preparatory artillery fire prior to the infantry assault and protection for the Allied attacking forces at Verdun on a 15 kilometer front during the period 13-26 August 1917 required the expenditure of about three million 75 mm and one million heavy-caliber shells. This artillery ~~ammunition~~ expenditure was of about 120,000 tons, which means that about 8 tons of shells were fired per 1 meter of front. This figure does not include land mines.

Ammunition expenditure was even greater in World War II. Massed artillery fire was used in the direction of the main effort. Where the number of pieces per kilometer of front did not exceed 160 during an assault on the enemy in World War I, during World War II the number of pieces and mortars used in separate operations amounted from ~~250~~ 250 to 610 per kilometer of front.

During the years of World War II, the U. S. A. produced 331,000,000 shells, 377,000 tons of mines, 5,900,000 tons of aircraft bombs, and scores of millions of rounds of small arms ammunition.

The ammunition expenditures which were great even in World War I, speeded up the development and introduction into ordnance of new explosives shortly after the outbreak of this war. This was done in order to meet the requirements of unforeseen massive demands for explosives.



Of this group, the ammonium-nitrate explosives took on a basic importance. These explosives consisted of an ammonium nitrate mixture with TNT, trinitroxylenes, as well as with other nitro compounds. The raw material source of their basic components was ammonium nitrate.

This class of explosives was used for the first time during the 1880's by I. M. Chel'tsov, who, in 1886, proposed to use a mixture composed of 72.5% picrate, called "thunderbolt", as a filler for mines and shells. Later on, when the production of TNT, dinitronaphthalene, etc., became organized, ammonium nitrate explosives which contained these nitro compounds began to be produced.

High Explosives in the USSR. The production of high explosives was at a retarded pace in pre-revolutionary Russia. Some of the explosive-producing factories were owned by foreign interests previous to World War I. It is quite natural that they did not care too much about developing the technology of this industry, but were only interested in profits.

Therefore, it was necessary to import large quantities of explosives during World War I. The proposal of A. A. Solonin to use amatol - a mixture of ammonium nitrate and TNT - as a filler for shells, and ammonal - a mixture of ammonium nitrate with aluminum and hylyl - as a filler for hand grenades was of great importance.

When high explosives were first used as ammunition fillers, this ammunition was filled by pouring melted substances into them (except nitro-cellulose). The introduction of pour-type ammonium

nitrate explosives brought about the development of new loading methods, which, however, remained very imperfect throughout the course of the entire war. The methods for loading with pour-type explosives were improved after World War I. Nonetheless, the old method of loading still found extensive use in conjunction with the new methods.

Of the scientists and specialists who had a decisive influence on the development of the ammunition-loading pursuit in Russia, the attainment of the pioneer in this field, S. V. Panpushko, should be pre-eminent. E. G. Gronov developed amatol-loading during World War I.

During the Soviet period, N. T. Zveryev made further improvements in the use of TNT as a filler. N. T. Zveryev made more important contributions in the technique of loading ammunition by the endless-screw method, which was developed by him during 1929-1931. This method solved the problem of using ammonium nitrate explosives as ammunition filler in the Great Patriotic War.

Anti-Tank Ammunition. Tanks appeared on the battlefield for the first time in World War I. Specially-designed shells which could pierce the armor plating were needed in order to successfully engage them. The killing effect of such a shell must be beyond the armor plate, i.e. on the inside of the tank. Due to the requirements of a rapid rate of fire, these shells were of small caliber at first. A requirement for greater power in the explosive was a natural sequel.

Research and study into the properties of high explosives was intensified after World War I. A use for PETN and cyclonite as high explosives was found.

The appearance of such rapidly moving targets such as tanks and airplanes made it necessary to be able to observe the trajectory of the bullet or small-caliber shell, so that aimed fire could be employed. This problem was solved by the use of tracers.

A further development in ammunition for anti-tank guns led to the employment of shaped-charge shells during World War II. The phenomenon of shaping was first discovered in 1864 by M. M. Boryeskov. The Soviet scientists and artillerists made use of this theory in the Great Patriotic War and produced various types of shaped-charge ammunition.

Explosives in World War II. PETN and cyclonite were produced in large quantities for the first time in World War II. No other new explosives, with the exception of some minor substances, appeared in any of the warring nations.

The work of plants and research laboratories were apparently directed to increasing the quantity of the explosives produced at that time with preservation of the highest possible qualities for the purpose of satisfying the greatly increasing need of loading all types of ammunition, including the previously unforeseen demand in aircraft high explosive bombs.

Ignition and Initiating Means. For a long time, solid shot was fired from cannon, and only beginning with the close of the 17th and beginning of the 18th centuries was there an appearance

of bursting, spherical shells loaded with powder and provided with a wooden time fuse filled with powder.

The reequipping of artillery with rifled pieces led to the development of new types of shells (cylindrical) with impact and time fuses with friction primers.

Fulminate detonators were employed for stimulating the high-explosive shells. In 1900, combination detonators were proposed, in which up to  $3/4$  of the fulminate of mercury was substituted by TNT or tetryl, which secured the production and use of the detonators and which greatly increased their initiating ability. A further increase in the power was obtained by substituting the TNT in combination fuses with tetryl at first, and then with PETN and cyclonite.

The works of A. A. Solonin had a great impact on the perfection of azide detonators. He studied the derivation and properties of azide and trinitroresorcinate of lead in great detail and then developed methods for their employment in detonators.

Back in the days of World War I, S. P. Vukolov and R. V. Mussyelius developed several test samples of azide detonators for fuses which were used for naval-type shells. The works of our talented designers, E. G. Gronov, A. A. Dzyerzhkovich, V. I. Rdultovskiy, A. K. Yurvyelin and others played an important role in the development of primers.

The works of the Soviet primer specialists were of great inspiration in the Great Patriotic War.

Development of Pyrotechnics. It has been noted above that fire was used as a means of combat even back in antiquity and that the Chinese employed combustible substances for several centuries prior to our era.

For a long time, the development of pyrotechnics in Russia proceeded mainly along the lines of fireworks compositions. Starting with the 19th century, Russian scientists started to study the compounds for military purposes. K. I. Konstantinov (1819-1871) did a lot for the development of Russian domestic pyrotechnics. He carried out many studies, designed several rockets and set up their production during the Crimean War of 1853-1854. The works of V. N. Chikolyev and F. F. Matyugo played a prominent role in the further development of pyrotechnics. In conjunction with other scientists, they laid down the scientific principles of pyrotechnics in the middle of the last century. The works of these scientists were continued by P. S. Tsytovich (1883-1894) and F. V. Styepanov (1821-1909).

The importance of the works of the eminent Russian physicist-chemist, N. N. Byeketov, must also be mentioned in particular. He discovered aluminothermic reactions in the 1860's. The noteworthy studies of N. N. Byeketov led to the origination of a new branch of metallurgy and of a new type of extremely effective combustible compounds - thermites and slightly-gaseous or non-gaseous thermite mixtures.

A prominent role in the development of pyrotechnics up to 1914 and during the period of World War I was played by Ershov,

Sannikov, Gorbov, Pogrebnyankov, and others.

Bombardment Aviation and Rocket Shells. The problem of shelling the enemy's far rear areas already came up in World War I. The famous German long-range gun (Big Bertha), which shelled Paris in 1916 from a range of about 100 km, had a certain, short-lived, morale success, but it turned out to be ineffective and too expensive.

The problem of shelling the enemy's far rear areas was solved in World War II by the employment of bombardment aviation for this purpose. Long-range guided missiles appeared toward the end of the war. Once again the problems of extreme-range shelling were solved. In addition to this, rockets assumed a great importance as a means for the destruction of the enemy's manpower, tanks, aircraft and other targets.

Atomic Weapons. After World War I, the chemists were faced with the problem of creating a super-powerful explosive which would exceed many times the force of the explosives known at that time. A study of the problem showed that contemporary chemistry was in a position to come up with an explosive whose force would exceed such known explosives as nitroglycerin even four- or fivefold.

The problem of getting a super-powerful explosive could be solved only a quarter of a century later by contemporary nuclear physics. With respect to energy capabilities of the latter, this can be quickly ascertained by the data relating to the decomposition of uranium, where an energy of 18 billion kilocal/kg

is released. When the uranium decay explosion takes place, the temperature builds up to about 10 million degrees. (The maximum temperature during the explosion of ordinary explosives amounts to about 4000<sup>0</sup>.) The discovery of the chain reaction of radioactive uranium decay made it possible towards the end of World War II, to create a weapon of tremendous power - the atomic bomb. Still more powerful sources of energy were discovered later on - thermonuclear reactions, which were the basis for the creation of the hydrogen bomb.

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A striking feature in the organization of scientific-research operations in the Soviet period is the fact that, when any arbitrary and more or less complex problem has to be solved, teams of scientists and engineers of varying specialties are put on the project, instead of just individuals. If, in the beginning, a scientist verifies and works out some problem on the basis of new ideas, then, at a later period, beginning with a predetermined phase, collective effort proved to be the most fruitful. Just this kind of effort on the part of our scientists and engineers, who were filled with Soviet patriotism, brought about to a significant extent the remarkable attainments of Soviet science and technology.

Soviet scientists successfully continued the works of their talented predecessors, they made great contributions in the

development of a wide circle of issues concerning the theory, production and employment of military high-explosives and gun powders, which helped to assure the supply of the Soviet armed forces in the Great Patriotic War with all types of high-quality ammunition in the required quantities.



## SECTION I

### THEORY OF EXPLOSIVES

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#### CHAPTER I

##### GENERAL CHARACTERISTICS OF EXPLOSIVES AND THEIR CLASSIFICATION

###### 1. General Considerations Concerning Explosion

1. Definitions. The term explosion means a very rapid development of mechanical work which is caused by the sudden expansion of gases or vapors. The causes of this sudden expansion of gases or vapor can be variegated. We shall mention some of these.

a. An abrupt change in the physical state of a system, as, for instance, the rupture of a vessel of compressed gas. When gas expands, a rupture of the vessel's wall takes place; the splinters fly at a rapid pace; and circumambient objects are demolished or damaged. The explosions caused by similar physical processes are called physical explosions.

b. A rapid chemical reaction with the formation of gaseous or vaporous products, which are accompanied by the generation of heat. An example of this can be the explosion of gunpowder, where a rapid chemical reaction among the saltpeter, carbon, and sulfur

takes place. This reaction is accompanied by the emission of a large amount of heat. The forming gaseous products, which have been heated to a high temperature by the reaction temperature, have a high pressure, and, in expanding, produce mechanical work.

Explosions caused by a rapid chemical reaction are called chemical explosions. Chemical reactions which are accompanied by, or are capable of being accompanied by an explosion, are called explosive transformations.

Substances which are capable of explosive transformation are called explosives.

c. Fast-acting nuclear or thermonuclear reactions (reactions of fission or fusion of atomic nuclei) at which a tremendous amount of heat is liberated. The reaction products - the jacket of the atomic or hydrogen bomb and a certain portion of medium surrounding the bomb - are instantaneously converted into extremely high-temperature gases which possess a correspondingly high pressure. This phenomenon is accompanied by tremendous mechanical work.

Explosions which occur as the result of such reactions are called atomic explosions.

We shall examine only chemical explosions and the pertinent explosives in this book.

2. Conditions Determining Chemical Explosion. A chemical explosion is determined by four conditions: exothermic nature of the chemical reaction, the quantity of gases or vapors in the re-

action products, fast chemical reaction rate, and power of self-propagation.

a. Exothermic nature of the reaction. In order to carry out mechanical work during an explosion, it is necessary to expend an equivalent amount of energy. The source of energy in an explosive is the heat of the chemical reaction. If a supply of energy from without (endothermic reaction) is required for the chemical transformation of a substance, then such a transformation cannot be accompanied by an explosion. Only those substances where there is an evolution of heat during chemical transformation can be explosive.

b. The presence of gaseous substances in the presence of chemical transformation. Just as in the case of any heat machine, a working body - gases or vapors - are needed to convert the heat generated by chemical reactions into mechanical work. When gases or vapors are not present, such a conversion is impossible, and, as a result, the phenomenon of explosion is also impossible.

c. Fast chemical reaction rate. This condition is obviously associated with the first two conditions: the exothermic nature of the reaction should guarantee a rapid rise in temperature, and the presence of gases or vapors in the reaction products requires the completion of the reaction previous to the time when the gases or vapors begin to expand and spread through the unreacted parts of the substance.

d. Power of self-propagation. An explosive transformation generally originates within a limited sector of the substance under

the effect of an external impulse. This is possible in the case when the begun chemical reaction propagates spontaneously along the substance. This condition is associated with the first three conditions to a certain extent.

## 2. EXPLOSIVES AS A SOURCE OF ENERGY AND THEIR CLASSIFICATION

### 1. Comparison of explosive energy with fuel energy.

The overall amount of energy emitted by an explosion of explosives which are equal by weight to the quantity of a mixture of ordinary combustible substances with oxygen is lower than the heat of combustion. This can be readily seen from Tables I and II.

Another picture can be obtained by comparing the same quantities taken not as a unit of weight, but as a unit of volume (Tables III and IV).

It is evident from a comparison of Tables I and II that, in the combustion of ordinary combustible substances with gaseous hydrogen heats which are two to three times greater than in the explosion of 1 kg of explosive are emitted per 1 kg of the mixture. A comparison of the temperatures of these same reactions, related to a unit of volume (Tables III and IV) indicate that the concentration of energy in liquid and solid explosives in a unit of volume is 200 to 500 greater than in the case of ordinary fuels, and 1000 greater than in the case of a mixture of hydrogen and oxygen.

TABLE I

Explosive	Heat of Explosion Kilocal/kg
Gunpowder	665
TNT	950
Pyroxylin	1025
Nitroglycerine	1500

TABLE II

Heat of Combustion of Combustible Mixtures with Gaseous  
Oxygen

Fuel	Heat of Combustion in kilocal/kg
Carbon	2140
Benzene	2330
Hydrogen	3230

TABLE III

Explosive	Heat of Explosion Kilocal/kg
Gunpowder	800
TNT	1460
Pyroxylin	1330
Nitroglycerine	2400

TABLE IV

Heat of Combustion of combustible mixtures with gaseous oxygen

Fuel	Heat of Combustion Kilocal/kg
carbon	4.2
Benzene	4.4
Hydrogen	1.7

2. Relation of the power generated in an explosion to the energy release rate. Aside from the high volumetric concentration of energy, its very rapid rate of release is characteristic in the case of explosives.

The life of an explosive transformation for various explosive charges can be from several hundred to hundred-thousandth and millionth parts of a second. This factor determines the high power which is developed in an explosion. We shall demonstrate this by using TNT as an example.

Nine hundred and fifty kilocal are emitted in the explosion of 1 kg of TNT. Assuming that the propagational explosion products are adiabatic on account of the brevity of the process, and taking the efficiency as equal to 10%, we find that the mechanical work which can be created by the explosion products of 1 kg of TNT is equal to  $0.1 \times 950 \times 427 = 41,000$  kilogram-meters (427 kilogrammeters/kilocal = mechanical equivalent of heat). Within certain allowances with respect to shape and density of the charge, the duration of the explosion can be roughly calculated to one one-thousand of a second. From this point, we can find the power generated in the explosion of 1 kg of TNT (considering that 102 kilogrammeters/second is equal to 1 kilowatt)

$$\frac{41,000}{10^{-5} \times 102} = 40.2 \text{ million kilowatts}$$

It is a well-known fact that there are no machines in existence which can generate such colossal power. This example shows that the high power of explosives is dependent not so much upon the large store of internal energy, as upon the extremely short life of the explosion.

3. Classification and General Characteristics of the Explosive Transformation Phenomenon. The chemical transformation which originates in some part of the explosive propagates in succession. The presence of a transformation front, i.e. a narrow zone of intense chemical reaction which liberates reaction products from the still unreacted initial explosive, is a characteristic feature. The distance which the reaction front traverses in a unit of time, and equal to the layer thickness of the explosive undergoing explosive transformation in a unit of time, is characterized by the propagation rate of the explosive.

The self-propagating chemical transformation of the explosive can take place in accordance with two different methods.

A. The energy liberated in the reaction zone is transferred from the burning products to the nearest layers of the initial explosive in the form of heat in accordance with heat transfer processes. The temperature of the substance in these layers is increased and a reaction sets in. In this particular case, the chemical transformation propagates by atmospheric pressure at a rate of millimeters per second and the propagation rate is strictly dependent upon the pressure under which the process takes place. Such a process is called combustion.



When the combustion takes place out in the open, it is not accompanied by either the characteristic sound effect or mechanical work. In a closed space, however, such as in the powder chamber of a weapon, the process occurs more energetically: the pressure increases swiftly and, as a result, the rate of combustion increases; a very rapid displacement of the shell or bullet takes place under the effect of this high pressure, i.e. a shot accompanied by a sharp sound effect.

The effect, which consists of imparting velocity to the object by means of pushing it forward with its being burst (splitting or breaking up) is called propelling effect.

When black powder burns in a tamped shot-hole,<sup>3</sup> there is also an increase in pressure and corresponding increase in the combustion rate which brings about the demolition of the circumambient medium such as stone, rock, etc. and flight of the broken-up pieces - an explosion occurs.

For burning in a closed space, such as in a weapon's powder chamber or a shot-hole, it is characteristic of the gas pressure to rise more or less swiftly but not sharply, to a value of several thousand atmospheres.

B. The second mechanism for the propagation of the chemical transformation of an explosive consists in the transfer of energy from layer to layer by a compression wave. Speaking more strictly, this is a shock wave, with which we shall become acquainted shortly. In this case, the chemical transformation propagates along the substance with a speed on the order of a thousand meters per second,

whereupon, in contrast to combustion, the propagation rate does not depend on the outside pressure at which the chemical transformation occurs.

Such a chemical transformation is called detonation.

Detonation is characterized by an abrupt jump in pressure up to 200 to 300 atmospheres at the point of explosive transformation, and by a very sharp crushing effect upon the circumambient medium.

Having defined the terms "combustion" and "detonation", we shall use the term "explosion" as the characteristic of the exterior manifestation of the explosive transformation, expressed in a very rapidly proceeding mechanical work.

4. Classification of Explosives.<sup>4</sup> All explosives which are used, or have been used, in practice can be divided into the following groups:

Group I - propelling explosives or powders.

Group II - powerful or high (secondary) explosives.

Group III - initiating (primary) explosives.

Group IV - many pyrotechnic compounds which satisfy the requirements for chemical explosion; as a rule, they are not intended for blasting.

The basic criterion for dividing explosives into these groups are the explosive transformation conditions (combustion or detonation) which is characteristic for each of them, and the conditions of excitation.

Group I. Propelling explosives or powders. The characteristic form of explosive transformation for substances of this group is combustion, not crossing over to detonation even at high pressures which develop in firing. These substances are suitable for imparting motion to a bullet or shell in the barrel of a weapon and for imparting motion to a rocket shell.

By its physical structure, powder can be divided into two classes:

1st Class. Mechanical Mixtures. Potassium nitrate-containing gun or black powder, and various mixtures of the same type with other solid oxides such as mixtures with sodium nitrate, belong to this class.

2nd Class. Colloid powders. Pyroxylin, which has been gelatinized by a solvent, is the preeminent form of colloid powders. Colloid powders can be divided into two categories, depending on the nature of the solvent.

1. pyroxylin powders, produced with the application of a volatile solvent, which is removed from the powder to a great extent during successive phases of production;

2. powders with a slightly-volatile or non-volatile solvent, all of which remains in the powder.

Group II. Powerful or high (secondary) explosives. The characteristic form of explosive transformation of this group of substances is detonation; they are also capable of combustion, but, when the pressure is raised, the combustion becomes unstable and, under certain conditions, it can convert into detonation.

High explosives are used as shell fillers and other kinds of ammunition, as well as for blasting operations.<sup>5</sup> Substances of this group are called secondary explosives because their explosive transformation is difficult to excite by ordinary forms of exterior effect (flame, friction, shock, prick, etc). Secondary explosives are detonated with initiating explosives (see below).

By their chemical nature and composition, the most prevalent high explosives can be divided into the following classes.

1st Class. Nitric esters (nitrates) of alcohols or hydrocarbons. As an example, the following belong to this group:

1. Nitric esters of hydrocarbons. The chief representative of these explosives is pyroxylin or nitrocellulose.<sup>6</sup>

2. Nitric esters of alcohols. The characteristic representatives are:

a. glycerintrinitrate or nitroglycerin,  $C_3H_5(ONO_2)_3$ , which is used for the production of powders and dynamites;

b. diethylene glycol dinitrate or nitrodiglycol,  $(CH_2)_4(ONO_2)_2$ , used for the production of colloid powders.

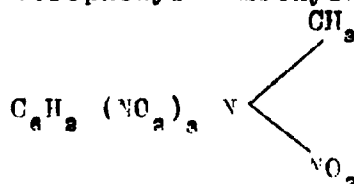
c. pentaerythritol tetranitrate, or PETN,  $C(CH_2ONO_2)_4$ , used as an anti-tank shell filler, for detonators, blasting caps, detonating cord, and other uses.

2nd Class. Nitrocompounds. These are the most important high explosives. They include:

a. Trinitrotoluene or trotyl  $C_6H_2(CH_3)(NO_2)_3$ ;

b. Trinitroxylylene or xylene,  $C_6H(CH_3)_2(NO_2)_3$ .

- c. dinitro benzene  $C_6H_4(NO_2)_2$
- d. dinitro naphthalene  $C_{10}H_6(NO_2)_2$
- e. picric acid  $C_6H_2OH(NO_2)_3$
- f. ammonium picrate  $C_6H_2(OH)(NO_2)_3$
- g. Tetranitrophenyl - methylnitramine or tetryl



- h. cyclo-trimethylene trinitramine or cyclonite



Fusions of nitro compounds, as, for instance, trinitrotoluene with dinitro naphthalene, cyclonite or xylene and some mechanical mixtures of certain nitro compounds or their fusions with powdered aluminum or other substances, have assumed an important meaning.

3rd Class. Explosive mixtures, consisting of a mixture of an oxidizer with the explosive and fuel. These include:

1. ammonium-saltpeter explosives, which contain ammonium nitrate as an oxidizer. An example of this are the amatols 80/20, 60/40, 50/50, 40/60 (the numerator indicates the ammonium nitrate content and the denominator indicates the trotyl content); granulated dinaphtalite - a mixture of 88% ammonium nitrate and 12% dinitronaphtalene processed a special way - as well as others.

2. explosive mixtures on a base of liquid nitric acid (nitroglycerine explosives). The nitric acid ester comes mostly in the form of a gelatine (dynamite), but compositions containing

small amounts of ungelatinized nitroglycerine are in existence. In addition to the nitrate alcohols, oxidizers (nitrates) and combustible materials go into the mixture;

3. chlorate and perchlorate explosives, containing salts of chloric or perchloric acids (chlorates or perchlorates);

4. explosive mixtures on a base of liquid oxidizers, which include liquid oxygen explosives and mixtures on a base of nitrogen dioxide or concentrated nitric acid.

Liquid oxygen explosives are made of a combustion-sorber primer which has been impregnated with liquid oxygen.

Group III. Initiating (primary) explosives. Initiating explosives are characterized by the fact that they can be easily exploded from simple forms of external action such as flames, pricks, and friction, and they can also detonate high explosives. The combustion of initiating explosives is unstable even at atmospheric pressure, and, when they are ignited, detonation occurs almost instantaneously. Similarly to high explosives, they produce a shattering and breaching effect on the closest media.

The most important representatives of initiating explosives are:

1. fulminate of mercury  $\text{Hg}(\text{ONC})_2$ -mercuric salt and fulminic acid  $\text{CNOH}$ ;
2. lead azide  $\text{Pb}(\text{N}_3)_2$  - lead salt of hydrazoic acid  $\text{HN}_3$ ;
3. lead trinitroresorcinate  $\text{C}_6\text{H}(\text{O}_2\text{Pb})(\text{NO}_2)_3 \cdot \text{H}_2\text{O}$ ;
4. tetrazene  $\text{C}_2\text{H}_8\text{ON}_{10}$ .

CHAPTER II

SENSITIVITY OF EXPLOSIVES  
AND THE INITIAL IMPULSE

1. DEFINITIONS

In order that an explosion would initiate, it is necessary to produce an outside effect on the explosive, which would impart a certain amount of energy to it. This outside effect is called initial impulse.

The ability of the explosive to withstand the effect of some kind of outside effect is called the sensitivity of the explosive.

The minimum energy of the initial impulse which is sufficient to excite the explosive is the measure of sensitivity of the explosive to a specific initial impulse.

2. THE NATURE OF THE SENSITIVITY OF EXPLOSIVES

Explosives were previously considered as unstable substances. Molecules of explosives were calibrated with a cone standing on its apex. A slight push was sufficient to throw it out of equilibrium. An even better method seemed to be comparing the explosive with "Prince Rupert's drops" which are produced by pouring molten glass into cold water. Pronounced internal stresses originate in these drops, owing to which they convert into a powder when they are lightly scratched by some solid. However, if such a shape matching is allowed in the case of highly-sensi-

tive substances (nitrogen iodide), not having practical application, and if it is more or less acceptable for certain initiating explosives, then it is not acceptable for high and many initiating explosives.

We shall examine this matter from the point of view of a presentation of the conditions of chemical reaction and molecular stability.

In order that two molecules of different composition react, it is obvious that they must collide. This is a necessary condition, but it is not sufficient by itself. The number of collisions, as experiment bears out, exceeds many times the number of reacted molecules. Consequently, not every molecular collision is accompanied by their reaction.

Reaction occurs only in the collision of reactionable, or activated molecules. The activated molecules are those which contain a store of energy whose magnitude must be not less than that of a specific capacity. The reacting capability of a molecule with an increase in the store of its energy.

This minimum amount of energy which molecules must have so that they could react is called activation energy.

It is quite obvious that the larger is the number of activated molecules in comparison with their overall number, the greater is the rate of reaction.

We shall apply these considerations to the case of a collision between molecules AB and CD, consisting of atoms A, B, C, and D. Let us take the relationship A to C and B to D as greater than A to B and C to D. In order that the regrouping (reaction)



$AB + CD = AC + BD$  would take place, it is first of all necessary to break or greatly weaken the bond between A and B and between C and D. Let us suppose that an energy E is needed to accomplish this. In the collision of molecules having an excess of energy E, a rupture of the bond occurs, as, for example, in the molecules AB and CD in our case.

It is obvious that in the succeeding collision of atoms A and C, B and D, new combinations AC and BD will form, i.e. a combining of those atoms whose force of attraction to each other is the greatest.

But what becomes of the other molecules of the substance? Three cases are possible here.

1st Case. Let us characterize the initial state of the reacting molecules by the point K. In order to convert the system into the activated state L, an amount of heat which is equal to the activation energy E is necessary. Finally, let us characterize the terminal state (reaction products) by the point M. The energy store in the corresponding state is plotted on the ordinate axis of the diagram.

It can be seen from the diagram that, as a result of the reaction, only a part of the activation energy of the molecule is released, and an amount of heat  $Q_1$  is absorbed. The reaction is endothermic, and, therefore, the system is not explosive.

2nd Case. Let the system be characterized by the same states - initial by K and the intermediate by L, but the terminal state by

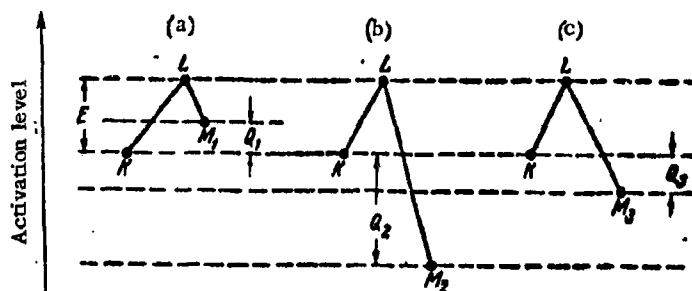


Fig. 1. - Change of energy in the system during chemical reaction (diagram).

$M_2$ . It is evident from Figure 1b that, in this particular reaction, not only all of the systems activation energy  $E$  is released, but, moreover the reaction heat  $Q_2$ . In the transition of the released energy ( $E + Q_2$ ) toward the unreacted molecules, some of them become reactable.

The activation energy of many explosives fluctuates within limits of 30 to 60 kilocal/mole, and the explosive transformation heat fluctuates within 200 to 300 kilocal/mole. Consequently, the amount of heat liberated during chemical transformation of several molecules of an explosive is sufficient to impart activation energy to a new and thereby larger number of molecules of

that substance. It is clear that reactions of this type are capable of self-propagation and the corresponding systems are explosive.

3rd Case. Let the system be characterized by the same states - initial by K, intermediate by L and the terminal state by  $M_3$ .

It is clear from Figure 1c that, in this reaction, in addition to the activation energy  $E$ , only a small amount of heat  $Q_3$  is released. This amount can be insufficient for the activation of new molecules, and the reaction, in spite of its being exothermic, cannot be self-propagating with the result that it will not be explosive.

The examined cases show that it is impossible to explain the sensitivity of an explosive by the instability of their molecules.

A molecule of a substance can be relatively only slightly stable, but, if no heat or an amount of heat which is insufficient to activate several new molecules, is released during its chemical transformation, the reaction will not propagate and explosion will not occur. In another case, the molecules can be stable, but, if a quantity of energy is released in its chemical transformation which is sufficient for the activation of several neighboring molecules, then the reaction is self-propagating and explosion takes place.

The amount of energy which is necessary for the dissociation of a molecule, i.e. activation energy, can serve as a measure of its sensitivity. The activation energy of many explosives is considerable, and, in certain cases, attains 60 kilocal/moles. But

there are also in existence certain explosives whose activation energy consists of only 25 kilocal/moles and even less. During the same period of time, the temperature of explosive transformation for all typical explosives greatly exceeds the activation energy.

### 3. KINDS OF INITIAL IMPULSE

Various kinds of energy can serve as an initial impulse, as, for example:

1. thermal - heating or flame jet;
2. mechanical - shock, bullet shock, friction, and pricking;
3. explosive energy of another explosive.

1. Thermal Impulse. Basic Considerations Concerning Thermal Decomposition. In a manner similar to non-explosive chemical systems, explosives can undergo slow decomposition, which, in contrast to combustion or detonation, take place not in a narrow reaction front, but throughout the entire mass of the substance. In the case of ordinary explosives, the rate of such decomposition at normal temperature is imperceptibly small, but increases sharply with temperature. The majority of explosives undergo slow decay at elevated temperatures (below ignition temperature - see page 28), the speed of which is subject to the law of monomolecular reaction

$$V = \frac{dx}{dt} = K(a-x) \quad (1)$$

where  $V$  = reaction rate;

$a$  = initial concentration of substance;

$x$  = the amount of substance undergoing decay to a given moment;

$a-x$  = concentration of the substance at a given moment.

The coefficient  $k$ , called the reaction rate constant, depends upon the temperature and activation energy.

In many cases of the thermal decomposition of an explosive, the reaction products (nitric acid, nitric oxides, etc) act as catalysts and sharply accelerate the decomposition. Such an acceleration of a reaction by its products is called autocatalysis. It is necessary in this case to introduce one more term into the equation determining the reaction rate, which characterizes the effect of the catalyst

$$V = \frac{dx}{dt} = k(a-x) + k_{cat}(a-x)x^n \quad (2)$$

where  $n$  = the order of the reaction taking place with the participation of a catalyst.

Figure 2 shows the nature of the change in the reaction rate as a function of the duration of the process. Curve I represents a pure monomolecular decomposition (without catalytic effect of reaction products). Its rate decreases on account of a reduction in the amount of the substance.

Curve II represents the process during autocatalysis. At the outset, the reaction proceeds in accordance with the mono-

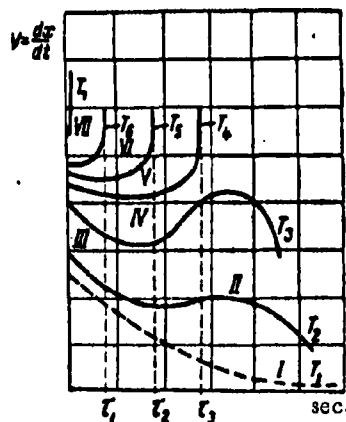


Fig. 2. - Diagram of change in rate of decomposition reaction of an explosive with respect to time at various initial temperatures.

molecular law, after that, as the decomposition products accumulate and act as catalysts, the process is accelerated. Subsequently, in connection with the use-up reacted (initial) substance, the rate decreases once again.

Curve III, plotted at a temperature  $T_3 > T_2$ , lies above Curve II because the reaction rate increases with an increase of the explosive's temperature. Curves IV, V, and VI were plotted at rising temperatures ( $T_3 < T_4 < T_5 < T_6$ ). The unique nature of these curves in comparison to Curves II and III can be explained by

the fact that, at some moment of time, the rate of decomposition, and, accordingly, of the release of the reaction heat, attains values at which the heat intake exceeds the heat output (on account of heat conductivity, vaporization and other possible processes), and the isothermy of the process is disrupted. If a sufficient quantity of the original substance remained up to this moment, then its temperature starts to rise, which leads to a further acceleration of the reaction, terminating with ignition (a phenomenon accompanied by a sound effect and flame). The rate of the process attains a critical value at high temperatures in a shorter interval time, as can be seen from Figure 2: the series  $\tau_3 > \tau_2 > \tau_1$  corresponds to the series  $T_6 > T_5 > T_4$ . In a further increase of the temperature  $T$ , the time intervals  $\tau$ , which are called explosion holdback period, will decrease. A temperature  $T_7$  can be visualized at which the initial rate of the process is equal to the critical value, i.e. the disruption of isothermy and corresponding origination of ignition will take place at an immeasurably small value for the holdback period. It is understood that this should take place with any temperature which is greater than  $T_7$ .

This minimum temperature at which the isothermy is disrupted, i.e. where the heat intake becomes greater than the heat output and the chemical reaction assumes the character of an explosive transformation on account of a sharp acceleration, is called ignition temperature.

Ignition can also occur at relatively low temperatures. In this case, the holdback time depends not only upon the temperature, but also on the particularly important admixtures of certain substances which act as catalysts, as, for instance, mineral acids.

For instance, nitroglycerine in its pure form (thoroughly rinsed from acids during its production) can be preserved for a long time (months, years) at a temperature of  $41^{\circ}$  without any alterations. But this same nitroglycerine with an admixture of 5%  $\text{HNO}_3$  bursts into flames after 320 minutes at the same temperature of  $41^{\circ}$ . A check of the substance's temperature (with a thermocouple) showed that it remains equal to  $41^{\circ}$  for almost all of the stretch of the experiment, and it starts to rise only during the final minutes prior to ignition. This indicates that the holdback is necessary not only for accelerating the reaction by self-heating but also for the accumulation of reaction products which accelerate its progress.

2. EXPERIMENTAL DETERMINATION OF IGNITION TEMPERATURE. The ignition temperature of an explosive can be practically defined as the lowest temperature to which it is necessary to heat the explosive so that a chemical transformation could occur with a speed that is sufficient to obtain a sound effect and flames.

The ignition temperature is not strictly constant for every substance, but depends on a number of causes, first of all on the conditions determining the relationship between heat intake and heat output.



The ignition temperature is determined under strictly defined conditions so that comparable findings could be obtained.<sup>7</sup>

An easily-melted metallic alloy is melted in a special iron tank (Figure 3). After attaining a given temperature which is close to the expectant ignition temperature, a glass or metallic test tube containing a weighed portion of 0.1 g (or 0.05 g) of the tested explosive is placed in the tank. The length of time it takes to the moment of ignition at that temperature is recorded. Repeated tests determine the minimum temperature below which ignition is not observed after a 5 minute exposure. The accuracy is up to 5°.

The ignition temperature for the more important explosives is shown in Table V.

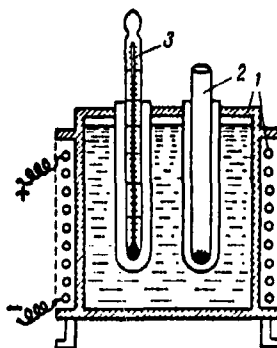


Fig. 3. - Device for determining ignition temperature.

1. Metal tank with electric heater
2. Test tube with weighed portion
3. Thermometer

3. Mechanical Impulse. The action of a mechanical impulse is explained by the conversion of the kinetic energy of shock (friction) into heat. However, this does not produce uniform heating in the entire mass of the explosive, and minute local hot-spots originate, wherein the temperature is raised to several hundred degrees. An explosive transformation originates in these hot-spots, which in a very short period proceeds in the form of combustion, but which quickly hastens to explosion.

In the opinion of the English scientist, F. P. Bowden, and his school of thought, the hot spots can consist of the most minute air pockets which are contained in the explosive (among its crystals). During shock, these air pockets quickly compress and the gas contained in them heats up to a high temperature. The heated air pockets then ignite the circumambient layer of the explosive. The hot spots can also, according to Bowden, originate through friction on surfaces which contain explosive between them, on the particles of extraneous admixtures which contain explosive in it, and through friction on the crystals of the explosive itself. Also, according to the data of N. A. Kholevo, hot spot is possible as the result of the explosive's viscous flow, originating in shock.

The issue of the mechanical origination of heat-up by various mechanical means has not as yet been fully explained. It has been established, however, that a fundamental role is played by not only the stresses originating in the explosive, but also by the transformation of the substance wherein the mechanical

TABLE V  
Ignition Temperature of Explosives

Explosive	Ignition temperature in °C	Explosive	Ignition temperature in °C
Fulminate of mercury	175—180	Tetryl	195—200
Lead azide	340	Picric acid	290—300
Lead styphnate	275	TNT	290—295
Pyroxylin	195	Ammonites	220—240
Nitroglycerine	200	Smokeless powders	180—200
PETN	215	Black powders	290—310
Cyclonite	230		

energy is converted into thermal energy.

There are many varieties of mechanical impulses. Of these, shock, bullet shock, friction, and pricking have the greatest practical significance (for initiating explosives).

The sensitivity of an explosive to shock is determined by testing on an impact tester.

The testing of secondary explosives is carried out on an impact-testing machine (Figure 4), which consists of two guides fastened vertically. A steel weight of 2, 5, or 10 grams slides freely between these two guides. The top part of the weight has a head which is held between the release lugs of the spring breaker. The breaker can be set at any desired height, which can be measured by the scale. The base of the machine, which is made of solid steel, is placed on a solid foundation. A punch device is set on the base (Figure 5) in which steel rollers (for bearings) serve as the anvil and hammer head. The diameter of these rollers is 10 mm. A 0.05 gram weighed portion of the tested explosive is spread out evenly between the surfaces of the anvil and hammer head of the roller device.

Results of the determination of sensitivity can be expressed in three ways:

1. Carry out a specific number of tests at a constant height of fall and weight, and then determine the percentage of explosions (the ratio of the number of tests which terminated in explosion to the number of all the tests which were carried out). Ordinarily, a weight of 10 kg, height of fall of 25 cm,

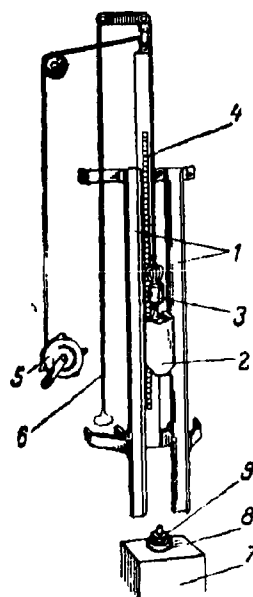


Fig. 4. - Impact-testing machine for testing secondary explosives.

- |   |                              |                   |
|---|------------------------------|-------------------|
| 1. Guides   | 2. Weight                    | 3. Spring breaker |
| 4. Scale  | 5. Device for lifting weight |                   |
| 6. Cord with grip for tripping the breaker release lugs |                              |                   |
| 7. Concrete base  | 8. Steel anvil               |                   |
| 9. Punch  |                              |                   |

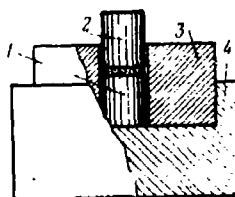


Fig. 5. - Punch

- |                 |                       |
|-----------------|-----------------------|
| 1. Roller-anvil | 2. Roller hammer head |
| 3. Guide sleeve | 4. Machine's anvil    |

**TABLE VI**  
**Sensitivity of high explosives to shock**

Explosive	Percentage of explosions
TNT	4—8
Amatols	20—30
Picric acid	24—32
Tetryl	50—60
Cyclonite	70—80
PETN	100
Smokeless powder	70—80

**TABLE VII**  
**Sensitivity of initiating explosive to shock**

Explosive	Weight in kg	Limits in cm	
		upper	lower
Fulminate of Mercury	0,69	5,5	8,5
Tetrazene	0,69	7,0	12,5
Lead azide	0,98	7,0	23,0
Lead styphnate	1,43	14,0	25,0

and no less than 25 tests, are used. The characteristics of some secondary explosives which were obtained by this method are shown in Table VI.

2. Determine the minimum height of fall of a 2 kg weight which causes even one explosion from a set number of tests. This criterion of sensitivity has been established for commercial explosives.<sup>8</sup>

3. Characterizing the sensitivity of initiating explosives by the upper and lower limits of sensitivity, to wit:

a. by the maximum height of fall of the weight at which not even one explosion occurs from a set number of tests (lower limit);

b. by the minimum height of fall of the same weight at which 100% of explosions are obtained (upper limit).

The upper limit serves as conditional measure of the sensitivity (reliability of the effect) of the initiating explosive and the object containing it. The lower limit serves as a measure of safety in the handling of initiating explosive or objects containing it.

The results of the tests which were carried out by this method are shown in Table VII.

Initiating explosives can be tested on a lever-type impacting testing machine (Figure 6) which consists of a plate with a steel anvil, measuring arc with graduations, and a weight-carrying lever which rotates about a hinge. The weight can be held at a set height by means of a hold-down screw.

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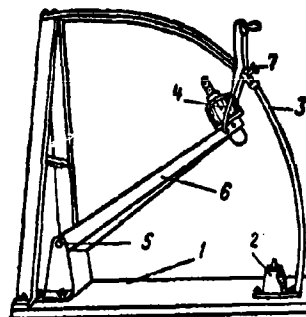


Fig. 6. - Impact Machine for testing initiating substances

- |                          |                |                  |
|--------------------------|----------------|------------------|
| 1. plate                 | 2. Steel anvil | 3. Measuring arc |
| 4. Weight                | 5. Hinge       | 6. Lever         |
| 7. Lever hold-down screw |                |                  |

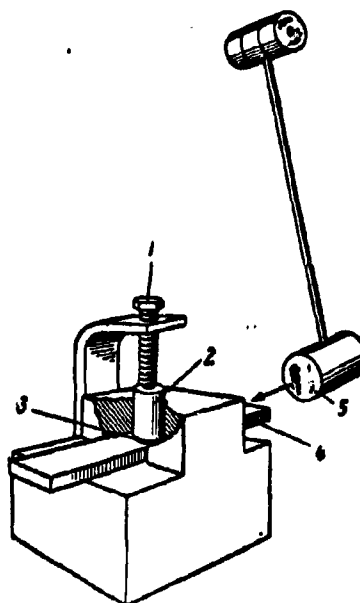


Fig. 7. - Device for determining sensitivity to friction

- |                     |                      |              |
|---------------------|----------------------|--------------|
| 1. Tightening screw | 2. Steel roller      | 3. explosive |
| 4. Sliding plate    | 5. Pendulum striker. |              |



A 0.02 gram weighed portion of explosive is pressed into the cap of a fuse assembly, covered with lead foil, and then placed on the anvil. A hammer head is set on top of the cap which strikes the cap when a weight from 0.5 to 1.8 kg drops on it.

A study of the sensitivity of explosives to shock led to the conclusion that explosions and failures are distributed statistically in accordance with the law of random errors, and, just as in the case of the upper and lower limits, any point on the sensitivity curve (see Figure 34 and its description on page 119) are the result of statistical scattering of the experimental data.

If it would be possible to observe a full identity of all test conditions - full similarity of all tests and nature of shock - during the carrying-out of the tests, then we could obtain a certain critical height of fall for the weight below which no explosions would observe, while the number of explosions above this height would be equal to 100%.

In reality, however, the tests differ from the ideal by form, dimensions, uniformity, etc., owing to which every test has its corresponding critical height which differs from the ideal in one direction or the other. This means that should one part of the test samples explode when a weight is dropped on them from the critical height, while the other part should end in failure.

If we are to consider that the causes leading to explosion or failure are equiprobable, then, where there are a sufficiently

large number of impacts from the critical height of fall, there should be an equal number of explosions and failures, i.e. by 50% of the overall number of tests. Consequently, under test conditions, the critical fall height of the weight corresponds to a 50% probability of explosion.

When the fall height of the weight is changed to some other value, the number of explosions or failures changes correspondingly in accordance with the law of probability.

The sensitivity to a bullet shock is determined by a shot from a rifle into an object filled with the tested substance (such as a hand grenade or aircraft bomb).

The sensitivity of an explosive to friction is determined in various ways. The most prevalent method is the one based on grinding the explosive between two blocks. The block rotates about a vertical axis at a rate of 20 to 150 turns per minute. This method is characterized quantitatively by the weight of the load which presses the blocks to each other and which produces an explosion in the sample of explosive, and by the time elapsed from the beginning of the test to the moment of explosion.

Another device for this same determination, which was used by Bowden, is shown in Figure 7. Here, a thin layer of explosive, compared with a set force between the roller and plate, is subjected to a quick shift when the plate slides after it has been hit by the weight-pendulum, dropping from a predetermined height.

Sensitivity to pricking of initiating explosives is of great importance for capped objects. The methods for determining the sensitivity to pricking are described in Chapter IV.

4. Sensitivity to the Detonation of Another Explosive.

The sensitivity of a secondary explosive to detonation can be characterized by a weight of minimum charge of initiating explosive which assures a sustained detonation of the tested substance under set conditions. Such a charge is called the limiting charge of initiating explosive with respect to a specific explosive (see Table VIII).

TABLE VIII

Sensitivity to detonation of three high explosives which were pressed into the copper jacket of a blasting cap at identical pressures.

Explosive	Limiting charge in g	
	Fulminate of mercury	Lead azide
Tetryl	0,29	0,025
Picric acid	0,30	0,025
TNT	0,36	0,09

The amount of limiting charge depends on the test conditions: material, dimensions and the shape of the jacket into which the initiating explosive has been pressed in; on the density of both charges - initiating and secondary explosives; on the quantity of crystals of both explosives, and on some other conditions.

The charge of initiating explosive which serves for exciting the detonation of the high explosive is called the initiator, and the object consisting of the jacket with the charge of initiating explosive pressed into it is called a blasting cap. Some explosive charges (for example cast TNT) cannot be detonated by a blasting cap. In order to explode such explosives, a blasting cap in conjunction with a booster charge of secondary explosive (such as tetryl) is used. This booster charge is called intermediate detonator or simply detonator.

5. Detonation by Influence. In the detonation of an explosive charge, the second charge can be detonated not only by its being butted up against the other, but also when it is placed at a certain distance from it. Such a transmittal of detonation is called the active charge, and the second charge, which is placed away from the first, is called the passive charge. The spacing distance through which the detonation is transmitted depends on a number of factors, of which we shall mention the chief ones:

a. Brisance, quantity, distribution, and shape of the active charge. PETN and cyclonite transmit a detonation farther than the less-brisant TNT or picric acid; a tightly compressed explosive transmits a detonation farther than the same explosive

which is not as dense; the effect is greater in the direction of the propagation of the detonation than in the opposite or side directions (see pages 86-86); the distance of detonation transmission grows with an increase in the weight of the active charge.

b. Sensitivity to detonation and density of the passive charge. Substances which are more sensitive to detonation deteriorate at a greater distance from the active charge than less sensitive ones do. Because the sensitivity to detonation as a rule decreases with an increase in density, then the transmitting distance of detonation by influence also is reduced with an increase in density of the passive charge. In general, all factors which alter the sensitivity of a passive charge to detonation also alter the transmitting distance of detonation by influence.

c. Ordinary jacket. The transmitting distance is increased by encasing the charges in some kind of jacket, as for instance, a tube.

d. Nature of the medium separating the charges. Detonation can be transmitted best of all through air, worse through water, worse yet through clays, and worst of all through steel and powdery media such as loose soil, sand, etc.

6. Transmission of Detonation from Cartridge to Cartridge. Explosives in the form of cartridges which compose a charge are used in many kinds of blasting operations.<sup>9</sup>

It is obvious that, during the propagation of a detonation by the charge, every preceding cartridge can be considered as a

detonator with respect to the subsequent cartridge. In order to assure a detonation of the complete charge, a sufficient initiating capability of the detonator and a sufficient sensitivity to detonation of the succeeding cartridge are requisite. In the case where the quality of the explosives is lowered (this primarily refers to explosive mixtures) and where cartridges are made out of this explosive, a detonation of the complete charge may not take place.

When testing the reliability of a transmission of detonation from cartridge to cartridge, the maximum distance between two cartridges where a transmission of detonation still takes place is determined.

7. The Effect of Various Kinds of Initial Impulse on an Explosive. Simple Initial Impulse. The described forms of initial impulse, with the exception of the energy of the secondary explosive, are called simple initial impulses. These include a flame, spark, blow, friction, pricking, etc.

In many cases, the absence of equivalence between various forms of the initial impulse can be observed. For instance, black powder is more sensitive to flame than are aromatic nitro-compounds, but it is less sensitive to a blow; lead azide is more sensitive to mechanical action than is trinitroresorcinat, but less stable to thermal effect.

#### 4. FACTORS INFLUENCING THE SENSITIVITY OF EXPLOSIVES

1. Physical Structure and Density of the Charge. As a general rule, when the compressive pressure of a powder-type explosive is increased with a corresponding increase in its density, the sensitivity to shock and detonation decreases. The sensitivity to detonation of a cast explosive is much smaller than that of the same explosive which has been compressed. These relationships can be seen in Table IX.

The influence of the physical structure on the sensitivity to detonation can be clearly seen in the case of pyroxylin and explosive mixtures with solid oxidizers.

Compressed pyroxylin can be readily detonated by a blasting cap; but a compact charge of gelatinized pyroxylin is only slightly sensitive to detonation. It is also equally difficult to detonate a charge consisting of thick powder elements - webs, tubes, etc; a charge consisting of the same powder but which has been thoroughly pulverized can be readily detonated by a blasting cap.

When the density of ammonium nitrate explosives is increased, their sensitivity to detonation decreases; beginning with some value for the density of the charge, the sensitivity decreases to such an extent that detonation can be produced only by a powerful detonator.

A change in the density of certain initiating explosives, particularly in fulminate of mercury, produces an unusual effect. When the density increases, its sensitivity to flame increases,

TABLE IX

Influence of physical structure of charge on sensitivity to detonation.

TNT			Picric acid		
Compression pressure in kg/cm <sup>2</sup>	Density in g/cm <sup>3</sup>	Limiting charge of fulminate of mercury in g	Compression pressure in kg/cm <sup>2</sup>	Density in g/cm <sup>3</sup>	Limiting charge of fulminate of mercury in g
500	1,52—1,54	2	1500	1,58	0,4
3000	1,58—1,60	3	2900	1,68	0,68
Cost	1,5—1,54	Incomplete explosion with 3 g of fulminate of mercury	Cost	1,58—1,60	3



attaining a maximum at a density corresponding to a compression pressure of 250-300 kg/cm<sup>2</sup>. With a further increase in density, the sensitivity gradually decreases, and the fulminate of mercury, which has been compressed under a pressure of about 3000 kg/cm<sup>2</sup>, will burn when ignited, but will not detonate.

The sensitivity of fulminate of mercury to pricking changes analogously, but the optimum density corresponding to the greatest sensitivity to pricking is observed at a compression pressure of 700-750 kg/cm<sup>2</sup>, and the complete loss of sensitivity at a compression pressure of about 2000 kg/cm<sup>2</sup>. Increasing the compression pressure from 750 to 2000 kg/cm<sup>2</sup> and above reduces also the sensitivity of fulminate of mercury to other kinds of mechanical effects, as, for example, to shock.

At the same time, an increase in density has no effect on the sensitivity of fulminate of mercury to detonation. Fulminate of mercury which has been compressed under a pressure of 3000 kg/cm<sup>2</sup> and above infallibly detonates by initiating it with, as an example, a small charge of the same explosive but with a lesser density.

The data which we have at present does not permit us to establish one quantitative characteristic of the influence of a substance's structure and density on the sensitivity which would be applicable to all explosives. As a more or less overall qualitative relationship, it is possible to point out that an increase in the density and a conversion from a porous to compact structure decrease the sensitivity of an explosion, even though it is

not in an identical degree for various kinds of initial impulse.

The following can be pointed out as the probable causes of this phenomenon:

a. with an increase in density, one and the same amount of energy of the initial impulse is distributed on a larger mass of the substance; a less probable cause is the high concentration of energy in specific points;

b. with an increase in density and transition to a compact structure, the possibility of a relative displacement of the crystals decreases, and, consequently, the origination of localized hot spots which lead to ignition and explosion, is also decreased.

c. with a change in density, the quantity and size of the air pockets is changed, which has an effect on the sensitivity;

d. an increase in density and elimination of the air pockets hinder the infiltration of combustion products among the particles of explosives, which produces an effect on the transition of combustion into detonation (see page 63), and it hinders the propagation of the detonation through the "explosive combustion" mechanism (see page 73).

2. Shape and Size of the Crystals. A remarkable difference in the sensitivity of various crystallographic modifications has been established for certain explosives such as lead azide, fulminate of mercury, and nitroglycerine. Thus, the stable form of nitroglycerine (rhomboïd) is more sensitive than the unstable (triclinic) form.

Lead azide can be obtained in two forms - short acicular and needle. Ordinary lead azide is of the short acicular form. It is less stable to a blow and other forms of exterior influences than the needle crystals. The formation of thick crystals of the needle form is sometimes accompanied by a spontaneous explosion.

In the majority of explosives, the sensitivity to mechanical effort increases with an increase in the size of the crystals.

3. Temperature. The number of activated molecules is increased with an increase in temperature. The amount of energy which is needed to induce explosive transformation is decreased accordingly. Therefore, an increase in the temperature of an explosive increases its sensitivity.

Nitroglycerin will explode under certain conditions if the work of the blow consists of 0.2 kg/cm<sup>2</sup> at a temperature of 10°, at 0.1 kg/cm<sup>2</sup> at 94°, and at 182°, it explodes from any slight jar. Celluloid is insensitive at ordinary temperature, but it can be exploded by a blow at 160-180°.

4. Admixtures. Admixtures have an effect on the sensitivity of an explosive to mechanical effort. Particles with a high melting point and whose hardness is greater than the hardness of the explosive (for instance, sand, glass, metallic powders) increase the sensitivity to mechanical effort. Thus, dinitronaphthalene without an admixture of sand will not explode on an impact testing machine when a 2 kg weight drops on it from a height of 2 m; with a 10% admixture of sand, partial explosions are already produced

from a drop height of 70 cm. The sensitivity of TNT to shock is greatly increased with only insignificant admistures of sand (Table X). The cause of this increase of sensitivity in these cases is the localized concentration of shock energy on the sharp edges of the hard particles of admixture.

TABLE X

Effect of an admixture of sand on the sensitivity of TNT to shock

Sand content in TNT in %	Percentage of explosions obtained with a 10 kg weight and drop height of 25 cm .
0,01—0,05	6
0,1 —0,15	20
0,2 —0,25	29

According to Bowden's data, the melting temperature of the admixture's particles plays an essential role in conjunction with the hardness. The admixture increases the sensitivity only in that case where its melting temperature is higher than some certain minimum (400-500°). Admixtures of easily-melted substances which cover the explosive's crystals with a thin film act in a different manner. A part of the heat produced by the hot spots,

which originate during mechanical action on the explosive, is expended in the heating and melting of these admixtures; therefore, when such an admixture is present, the work performed by a blow, which is necessary to induce explosion, is greater than in the case where the admixture is absent.

Substances which in relatively small quantities greatly reduce the sensitivity of an explosive are called phlegmatizers. Conversely, substances which increase this sensitivity are called sensitizers.

5. Chemical Factors. In conjunction with the above-described physical factors, the chemical structure of an explosive also has an effect on the sensitivity of an explosive. The sensitivity of nitrate esters, alcohols and hydrocarbons increases with an increase in the number of nitrate groups into a molecule of an ester.

In the case of a nitrocompound, the sensitivity to mechanical action and detonation is the greater when the quantity of nitro groups in the molecule is greater. For instance, mononitrophenol will not be exploded by a two-gram blasting cap, while only 0.3 g of fulminate of mercury is sufficient to detonate trinitrophenol. The sensitivity to mechanical or thermal initial impulses is increased in the same way.

## CHAPTER III

### STABILITY OF EXPLOSIVES AND METHOD OF ITS DETERMINATION

#### 1. CHANGES IN EXPLOSIVES DURING STORAGE

We shall examine through several examples the phenomena which take place in explosives during their storage.

Purified TNT. Neither the physical nor <sup>the</sup> chemical properties of TNT change in a multiyear storage under normal conditions. After many years of storage, a shell filled with this TNT is suitable for firing, and there is no doubt that it can be further safely stored. TNT is physically and chemically stable.

Unpurified TNT. Raw TNT<sup>40</sup> conducts itself differently in storage than does purified TNT. In the summer time (temperatures of 35° and above), a shell which has been filled with this trotyl exudes a liquid, the so-called trotyl oil. In addition to this, a certain aeration of the charge occurs, but no chemical transformations in the TNT are to be observed.

Unpurified TNT is a substance which is physically unstable, but stable chemically.

Amatol 80/20 humidified when stored owing to the hygroscopy of ammonium nitrate. As a result of the repetitive processes of humidification and drying which take place during its storage, amatol hardens (cakes). Under suitable conditions, the volume

and shape of the charge can change, but no chemical transformations, which could lead to self-ignition and explosion, take place.

Consequently, amatol is physically unstable, but chemically stable.

Blasting gelatin (nitroglycerine gelatinized by a small quantity of nitrocellulose) can undergo various changes during storage. A discharge (exudation) of nitroglycerine is possible. The physical structure of the gelatin changes with time; it becomes transparent and more elastic. Besides this, blasting gelatin undergoes chemical changes which can, under unfavorable conditions, lead to spontaneous combustion and explosion.

Blasting gelatin is not only physically, but also chemically unstable.

Pyroxyline powder also undergoes a number of changes during storage; it loses the volatile solvent contained in it, and this effects a change in the powder's structure. Besides this, chemical transformations occur in the powders just as in the blasting gelatin. The onsetting decomposition can lead to spontaneous combustion of the powder.

Consequently, the powder is physically and chemically unstable.

## 2. PHYSICAL AND CHEMICAL STABILITY OF EXPLOSIVES

The above-mentioned examples make it possible to establish two kinds of stability - physical and chemical.

Physical stability is the capability of an explosive to preserve its physical properties under practical conditions of their storage. A change in these properties can occur either as the result of strictly physical processes (evaporation or absorption of dampness, etc.) or of physico-chemical processes (recrystallization, exudation, etc.).

Chemical stability is the capability of an explosive not to undergo any chemical transformation which could lead to spontaneous combustion under normal storage conditions.

### 3. FACTORS DETERMINING THE CHEMICAL STABILITY OF EXPLOSIVES

The basic factors determining the chemical stability of explosives are chemical structure, the presence of an admixture, and storage conditions.

1. Chemical Structure. The least stable of commercially-used explosives are the nitrate esters in which the  $\text{NO}_2$  group is bonded with an atom of carbon by the oxygen. The nitrocompounds, in which the nitro group is bonded directly with a carbon atom, are very stable. The most stable nitrate esters are much less stable than the nitrocompounds which are used in industry.

The following regularity can be observed in the change in chemical stability of nitrate esters of alcohols and hydrocarbons.

a. the stability of complete nitrate esters of multi-atomic alcohols, generally speaking, is lowered in proportion to the in-



crease of the valence of the alcohols. For instance, dinitroglycol is more stable than nitroglycerine.

b. slightly nitric cellulose esters are more stable chemically than are the highly nitric ones.

2. Admixture of Catalysts and Stabilizers. Various admixtures can greatly change the chemical stability of explosives.

Certain admixtures fulfill the role of catalysts, accelerating the decomposition processes of the explosive. Traces of free acids (strictly speaking, hydrogen ions) have the greatest practical significance of this group of admixtures.

During a slow decomposition of the nitric acid esters, the nitric oxides  $\text{NO}_2$  and  $\text{N}_2\text{O}_5$  are formed, which, in conjunction with dampness (contained in the explosive but also liberated during decomposition) form nitric and nitrous acids. The quantity of the catalyst gradually increases and the decomposition is accelerated accordingly.

Other admixtures (diphenylamine, centralite, aniline, acetone, and others) readily react with the oxides of nitrogen, forming chemically stable nitroso- and nitrocompounds. Thus, one of the most important causes of the acceleration of an explosive's decomposition is eliminated. An admixture of this kind of substance increases the chemical stability of an explosive.

Compounds which, after having been introduced into the composition of an explosive, increase its chemical stability with a corresponding increase in its service life, are called stabilizers. The process of introducing a stabilizer into an explosive or one of removing an admixture catalyzing the chemical decomposition,

is called stabilization.

3. Storage Conditions of Explosives. Chemical stability depends greatly upon the temperature at which the explosives are stored. In turn, the storage temperature depends on the climate and special local conditions (for instance, storing in ships, where the temperature can easily reach  $40^{\circ}$  with an absence of artificial cooling). The higher the temperature, the more rapidly occur the decomposition processes of an explosive.

#### 4. EXPERIMENTAL DETERMINATION OF CHEMICAL STABILITY

The decomposition process of an explosive proceeds extremely slowly at ordinary temperatures, and it is very difficult to evaluate its rate by either the qualitative or quantitative method. An experimental determination of the stability is carried out at elevated temperatures when the decomposition reaction rate is greatly increased.

The starting point of the methods for determining the chemical stability is the assumption that if, under identical test conditions (elevated temperature), one of two explosives proved to be less stable than the other, then the first will also be less stable during prolonged storage at an ordinary temperature.

Several of the simplest tests which are used for determining the chemical stability are described below.

1. Abel Heat Test. This test is based on the mutual reaction of oxides of nitrogen and water with potassium iodide wherein free

iodine is released. This iodine combines with starch to form a colored compound.



Fig. 8. - Test tube containing explosive, prepared for the Abel test.

- |                        |                           |
|------------------------|---------------------------|
| 1. glass test tube     | 2. stopper with glass rod |
| 3. starch iodide paper | 4. tested explosive       |

Sequence of the test (Figure 8).<sup>11</sup> A weighed portion of the tested explosive is placed into a test tube. The test tube is capped with a stopper. A glass or platinum hook is suspended in the tube from the bottom of the stopper. A small piece of starch iodide paper is attached to the hook. One half of the paper is soaked with an aqueous solution of glycerine. The test tube is seated in a water tank whose temperature is kept at a preset level (75° or some other preset temperature). The characteristic of the

chemical stability is the time elapsed from the beginning of the test up to the appearance of a light brown color on the paper where the soaked and dry parts meet.

In the case of dynamite nitroglycerine, this time should be no less than 15 minutes, and for blasting gelatine, this time should be no less than 10 minutes (at 75°).

The Abel Heat Test is the first to be proposed for testing the stability of an explosive, and is distinguished by its simplicity and speed of execution. In conjunction with this, this test has a number of serious defects. The findings depend upon the quality of the employed starch iodide paper, upon the volatility and dampness of the tested substance, upon the experience of the person conducting the test, and other reasons. Therefore, the Abel Heat Test is presently considered as not too reliable, it is used only for the determination of the chemical stability of nitroglycerine and dynamites.

2. Vieille Test (litmus test). Vieille tests are used for pyroxylin and smokeless powders. This test consists in determining the time that it takes the tested substance, which is contained in a hermetically-sealed cylinder placed in a thermostat<sup>12</sup> at a temperature of 106.5°, to change the color of a standard blue litmus paper to red. The change in color is caused by the separation of the nitrogen oxides during decomposition of the powder which, with water, form nitric and nitrous acids.

Pyroxylin and colloid powder should produce the red color no earlier than after a 6 hour lapse.

3. Repeated Vieille Test. The repeated test consists of a successive number of experiments by a simple test with one and the same weighed portion of powder. In every instance, the experiment is carried out to the appearance of the red color, but no longer than of a seven-hour duration, after which the test samples are stored at ordinary temperature. The tests are repeated the next day. The repeated tests extended to the production of the red color for 1 hour from the beginning of heating, but not any longer than 10 days. The sum of the hours of heating characterize the stability of the powder. Stable powders produce the following results:

pyroxylin . . .	60 hours
nitroglycerine . . .	40 hours

The Vieille tests (single and repeated) are also inadequate but they are nevertheless much more reliable than the Abel Heat Test. Their overall defect is the use of an indicator whose reading depends on the observer (sharpness of vision, ability to differentiate intermediate colors, etc.).

4. Weight Test. The determination of chemical stability by the weight test is one of the more precise methods. In this method, weighed portions of powder or explosive are kept in a thermostat at a temperature of  $95^{\circ}$ , and they are weighed after each 24 hour period. The loss in weight of the powder is determined. This loss is expressed in percentage of the original weight. The findings are shown in a diagram (Figure 9).

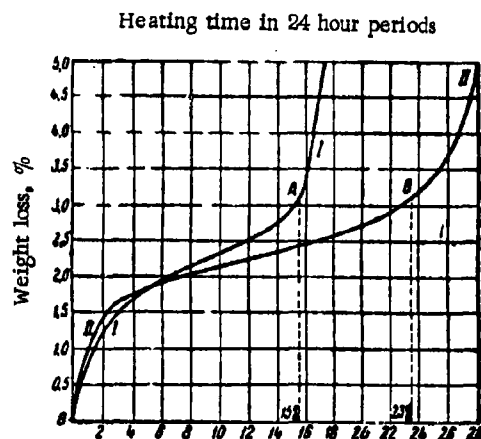


Fig. 9. - Graphical representation of the test results for stability of two powder samples, carried out by the weight test.

The tests are terminated when an inflection is clearly developed on the curve. This inflection indicates the onset of an accelerated decomposition of the powder. The stability is characterized by the time elapsed from the start of the test to the inflection of the curve (points A and B on Figure 9), expressed in 24 hour periods.

The Abel Heat and Vieille Tests enable one to detect only the initial decomposition phase. The weight tests show the progress of decomposition not only at its beginning stage, but also in the

phase where it is more profoundly decomposed.

5. Manometric and Electrometric Tests. Other precise tests are in existence. These tests are based on the measurement of the gas pressures which are formed during the decomposition of a specific quantity of explosive, and determination of the quantity of nitrogen oxides or other principles liberated during the test. In the first case, the decomposition rate of the powder is evaluated by the growth of gaseous products of the dissociation in a sealed volume of pressure. The substance is heated at a preset temperature and the pressure of the decomposition products is measured at equal intervals of time. A curve of the findings is then plotted. The stability is characterized by the time required for obtaining, under predetermined conditions, a certain prescribed pressure.

One of the electrometric tests is the Hansa test. Eight test tubes, each containing 5 g of a substance, are heated at  $110^{\circ}$ . One test sample is taken out every hour and the pH is measured. The curve pH-time characterizes the stability of the powder.<sup>13</sup>

## 5. THE SIGNIFICANCE OF CHEMICAL STABILITY OF EXPLOSIVES

The problem of chemical stability is of particular importance for nitroglycerine explosives and colloid powders. Inasmuch as the storage time for nitroglycerine explosives used in mining is not longer than 1 year, and the storage time of powder is estimated as many years (15-20 years and more), then chemical stability is

of the greatest importance in the case of colloid powders.

During the period when colloid powders were first started to be used, they were only slightly stable and dissociated rather quickly during storage. Another time, the dissociation took place so violently that a spontaneous combustion of the powder took place. Thus the slightly-stable powders were not only unsuitable economy-wise, requiring a frequent renewal of the combat supplies on hand, but also represented a great hazard. Cases are known when spontaneous combustion of a powder was accompanied by fatalities and sometimes assumed the dimensions of immense catastrophes.

In 1907, as the result of spontaneous combustion of powder, an explosion of the ammunition aboard the French battleship "Jena" took place. Another instance took place in France in 1911. An ammunition explosion, having serious consequences, took place aboard the French battleship "Liberté", which was berthed in the port of Toulon.

From the time of the above-described two catastrophes, many great improvements in the production of colloid powders have been made. Powders containing reliable stabilizers, such as diphenylamine and others, are used everywhere.

The safe storage period for a powder containing a stabilizer is more than 20 years, while the period for one without a stabilizer is around 10 years. However, the service reliability period of the powder is sometimes 1-1/2 to 2 times less, owing to losses of ballistic qualities.



## CHAPTER IV

### HEAT AND TEMPERATURE OF EXPLOSION, COMPOSITION SPECIFIC VOLUME, AND PRESSURE OF THE PRODUCTS OF EXPLOSIVE TRANSFORMATION

1. Definitions. The heat of formation of a chemical compound is that amount of energy which is released or absorbed during the formation reaction of simple substances of one mole or one kilogram of that substance.

The heat of combustion of a substance is that quantity of heat which is evolved in the complete combustion of one mole or one kilogram of that substance in oxygen.

The heat of explosive transformation or heat of explosion is that quantity of heat which is evolved in the explosion of one mole or one gram of an explosive of one mole or one gram of an explosive. All three of these enumerated values are expressed in kilocal/gram-mole or kilocal/kg.<sup>14</sup>

2. Hess's law. The thermal effect of a chemical process does not depend on its course (intermediate stages), but only upon the beginning and terminal states of the system under conditions such that the transformation takes place at constant volume.

It is obvious that this law is a partial case of the law of conservation of energy.

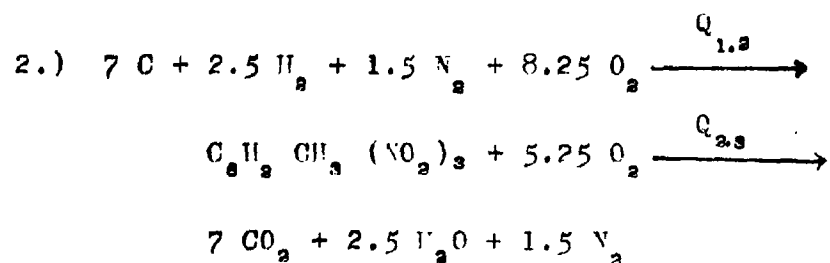
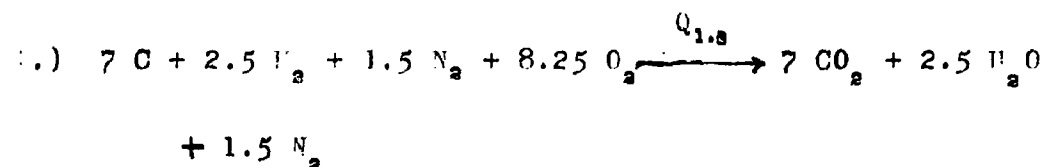
The thermal effects of such transformations, where it is

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difficult or impossible to determine the thermal effect directly by experimental means, can be computed by using Hess's Law. For example, Hess's Law makes it possible to calculate the thermal effects of complex reactions through experimentally-determined thermal effects of much simpler reactions.

3. Determination of the Heat of Formation of an Explosive Composed of Simple Substances by its Heat of Combustion. As an example, we shall show how the heat of formation of TNT is determined.

The system, composed of simple substances, can go over into a state which corresponds to the products of a complete combustion of the TNT by two means:



(the values  $Q_{mn}$  denote the thermal effects which are characteristic of the reaction).

According to Hess's law, we can write

$$Q_{1,2} + Q_{2,3} = Q_{1,3}$$

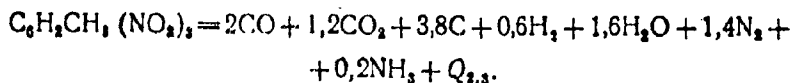
from where

$$Q_{1,2} = Q_{1,1} - Q_{2,1}.$$

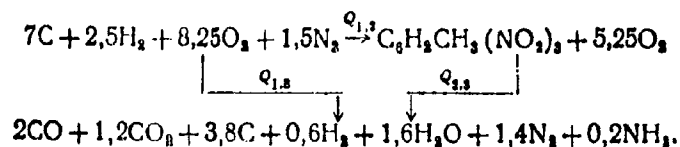
The TNT's heat of combustion  $Q_{2,1}$  is determined experimentally by burning a weighed portion of the substance in a calorimetric bomb in oxygen. The heat of formation of the combustion products  $Q_{1,1}$  is found in thermochemical tables. Thus  $Q_{1,2}$  can be determined in this way.

Consequently, the heat of formation of an explosive is equal to the difference between the heat of formation of the combustion products composed of simple substances and the heat of combustion of the explosive.

4. Computation of the Heat of Explosive Transformation of an Explosive. The reaction of explosive transformation for T T proceeds in accordance with the equation



Just as in the previous example, we can write



According to Hess's Law

$$Q_{1,2} = Q_{1,3} + Q_{2,3} \text{ and } Q_{2,3} = Q_{1,2} - Q_{1,3}.$$

The heat of the explosive transformation is equal to the difference between the heat of formation of the explosion products and the heat of formation of the explosive itself.

5. Experimental Determination of the Heat of Explosive Transformation. The heat of explosive transformation of explosives which are readily ignited by a glowing wire and which burn completely in an inert atmosphere is generally determined experimentally in a device consisting of a calorimetric bomb and calorimeter.<sup>15</sup> Powders, for instance, belong to such substances. Experimental methods for determining the heat of explosion have also been proposed for detonating explosives, but they have not been up to now used on a wide scale.

## 2. Explosion Temperature

The explosion temperature is the maximum temperature which is attained by the products of the decomposition of an explosive during explosive transformation.

In view of the fact that a direct determination of the explosion temperature is difficult and that the findings are not too reliable, this temperature is generally determined by calculation.

The basis of the calculation is the assumption that the ex-

plosive transformation is an adiabatic process taking place with a constant volume and, consequently, that the heat which is evolved during the explosion is expended only in the heating of its products. In conjunction with the foregoing assumption, the following formula can be used for computation

$$Q_v = \bar{c}_v t,$$

where  $\bar{c}_v t$  = average specific heat at a constant volume of all explosion products in an interval from 0 to  $t^0$ .

$t$  = desired temperature of explosion;

$Q_v$  = heat of the explosive transformation at constant volume.

The specific heat itself depends upon the temperature. In rough calculations, this relation can be expressed by the formula

$$\bar{c}_v = a + bt$$

Then

$$Q_v = (a + bt) t$$

from where

$$t = \frac{-a + \sqrt{a^2 + 4bQ_v}}{2b}.$$

The values of the coefficients  $a$  and  $b$  for various gases are listed in Table XI.

TABLE XI

Gases	a cal/gram-mole degree	b-10 <sup>4</sup> cal/gram-mole degree <sup>2</sup>
Bivalent gases	4,8	4,5
Water vapors	4,0	21,5
Carbonic acid gas	9,0	5,3
Tetravalent gases	10,0	4,5
Mercury vapors	3,0	0,0

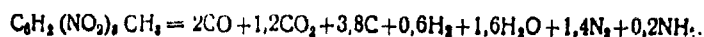
The atomic specific heat of solid substances (simple) is, according to Dulong and Petit, equal to 6.4 cal/deg. gram-atom. The specific heat of solid compounds can be determined by the Joule and Kapp law, according to which the molar specific heat of a solid compound is approximately equal to the sum of the atomic specific heats of the elements which comprise this compound. For instance, the average molar specific heat of potassium carbonate is equal to:

$6.4 \times 6 = 38.4 \text{ cal/gram-mole deg, or}$

$$\frac{38.4 \times 1000}{138} = 278 \text{ cal/kg deg.}$$

(138 - the molecular weight of potassium carbonate).

Example. Calculation of the explosion temperature of TNT. We shall use the following equation for the explosive transformation of TNT:



By making use of thermochemical tables,<sup>1a</sup> we can find the heats of formation of the explosion products:

2 CO	.	.	26.4 x 2 =	52.8 kilocal
1.2 CO <sub>2</sub>	.	.	94.5 x 1.2 =	113.4 kilocal
1.6 H <sub>2</sub> O	.	.	57.7 x 1.6 =	92.3 kilocal
0.2 NH <sub>3</sub>	.	.	11.5 x 0.2 =	2.3 kilocal

The sum of the heat formation of all products of the explosion . . . . . 260.8 kilocal

Heat of formation of TNT . . . . . 13.0 kilocal

Heat of explosive transformation  $Q_v = 260.8 - 13.0 = 247.8$   
kilocal.

We shall calculate the specific heat of the products of the explosion:

$$\begin{aligned}
 \text{CO, H}_2 \cdot \text{N}_2 - 4 \text{ mole} &= (4.8 + 0.00045t)4 = 19.2 + 0.00180t \text{ cal} \\
 1.2 \text{ CO}_2 &= (9.0 + 0.00058t)1.2 = 10.8 + 0.00070t \text{ cal} \\
 3.8 \text{ C} &= 6.4 \times 3.8 = 24.3 \text{ cal} \\
 1.6 \text{ H}_2\text{O} &= (4.0 + 0.00215t)1.6 = 6.4 + 0.00344t \text{ cal} \\
 0.2 \text{ NH}_3 &= (10.0 + 0.00045t)1.2 = 2.0 + 0.00009t \text{ cal}
 \end{aligned}$$

The specific heat of all explosion products is equal to  $62.7 + 0.00603t$  cal/deg. Consequently,

$$t = \frac{-62.7 + \sqrt{62.7^2 + 4 \cdot 0.00603 \cdot 248.000}}{2 \cdot 0.00603} = 3040^\circ.$$

$$t = 3313^\circ \text{ K}$$

Because the values of specific heat are given in small calories, we shall also substitute the expression for  $t$  by  $Q_v$  in small calories.

According to recent opinions (L. D. Landau, K. P. Staninkovich), a large portion of the reaction heat is converted into elastic energy which repulses the molecules of the highly-compressed detonation products. In connection with this, the temperature of the detonation products turns out to be less than the calculated one, and depends on the volumetric density of the explosive. It decreases when the density is increased.



### 3. Equation for the Decomposition Reaction of Explosives

1. Oxygen balance. The relative content of oxygen in an explosive has a direct bearing on the decomposition products of this explosive. The amount of the oxygen balance of an explosive is used for an evaluation of this content. The term oxygen balance means a surplus or deficiency of oxygen in an explosive as against the amount which is necessary for complete oxidation of the hydrogen and carbon which is contained in it into water and carbon dioxide, expressed in percentages of the weight of the substance.

This leads to the conception of explosives with a positive, zero, and negative oxygen balance.

In lieu of the oxygen balance, the oxygen coefficient can be used (proposed by A. A. Schmidt).

The oxygen coefficient is the oxygen content in an explosive, expressed in percentages of the amount of oxygen which is necessary for oxidizing the carbon and hydrogen which is contained in the explosive into carbon dioxide and water.

Examples. The following is needed for a full oxidation of all the carbon and hydrogen which is contained in a molecule of nitroglycerine  $C_3H_5(O_2N)_3$ :

for 3 atoms of carbon - 6 atoms of oxygen  
for 5 atoms of hydrogen - 2.5 atoms of oxygen  
total 8.5 atoms of oxygen

A molecule of nitroglycerine contains 9 atoms of oxygen. Consequently, the oxygen coefficient of nitroglycerine is equal to  $\frac{9}{8.5} 100 = 105.9\%$ , and the oxygen balance is  $\frac{(9-8.5)16}{227} 100 = +3.51\%$  (227 - molecular weight of nitroglycerine).

For a complete oxidation of the carbon and hydrogen contained in nitroglycol  $C_2H_4(OH)_2$  into carbon dioxide and water, 6 atoms of oxygen are required. In this case, the oxygen coefficient is equal to 100%, and the oxygen balance is equal to zero.

For oxidizing TNT  $C_6H_2CH_3(NO_2)_3$  into carbon dioxide and water, 16.5 atoms of oxygen are required, while a molecule contains only 6 atoms. Consequently, the oxygen coefficient of TNT is equal to 36.4% and the oxygen balance consists of -74%.

The equation for the reaction of an explosive transformation is the simplest one of all to understand if the explosive has a positive or null oxygen balance. When the oxygen balance is negative, the corresponding calculation is made more difficult.

2. Equation for the Decomposition Reaction of an Explosive with a Positive or Null Oxygen Balance. Various mutual reactions between the carbon, oxygen, hydrogen and nitrogen which is contained in an explosive are possible. The more important ones are listed in Table XII.

In order to resolve this problem, it is necessary to determine which of these reactions take place during the explosive decomposition of a specific explosion, and in what ratio. It can be assumed that the reaction follows the principle of greatest

TABLE XII

Equations and Thermal Effects for the more-important reactions among carbon, hydrogen, nitrogen and oxygen.

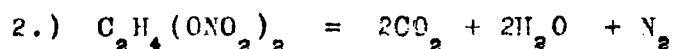
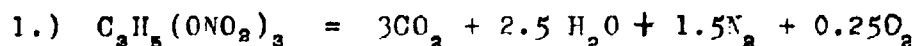
Reaction	Thermal effect kilocal	Reaction	Thermal effect kilocal
$2C + O_2 \rightarrow 2CO$	+52,8	$2H_2 + O_2 + 2C \rightarrow CH_4 + CO_2$	-3,5
$C + O_2 \rightarrow CO_2$	+94,5	$C + 2H_2 \rightarrow CH_4$	+18,4
$2H_2 + O_2 \rightarrow 2H_2O \text{ (vapor)}$	+115,4	$H_2 + 2C \rightarrow C_2H_2$	-57,1
$CO + H_2O \rightarrow H_2 + CO_2$	+9,8	$2C + N_2 + H_2 \rightarrow 2HCN$	-65,8
$2H_2 + CO_2 \rightarrow 2H_2O + C$	+21,6	$N_2 + 3H_2 \rightarrow 2NH_3$	+21,0
$2CO + 2H_2 \rightarrow CH_4 + CO_2$	+59,1	$N_2 + O_2 \rightarrow 2NO$	-43,2
$CO + 3H_2 \rightarrow CH_4 + H_2O \text{ (vapor)}$	+57,8	$2N_2 + O_2 \rightarrow 2N_2O$	-35,4
$2CO \rightarrow CO_2 + C$	+41,2	$N_2 + 2O_2 \rightarrow 2NO_2$	-8,2

work (Berthollet), which states: "of the number of possible chemical transformations for a given system, the most probable is the one wherein the greatest amount of heat is liberated."

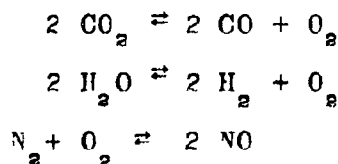
It can be seen from Table XII that, in a reaction among carbon, hydrogen, oxygen, and nitrogen, the greatest amount of heat is evolved in the case of the combustion of oxygen into carbon dioxide and of hydrogen into water. Consequently, in the explosive transformation of an explosive with a positive or null oxygen

balance, it can be assumed, in the first approximation, that all of the carbon is oxidized into carbon dioxide and that all of the hydrogen is oxidized into water, and that the oxygen and nitrogen are liberated in the elementary state.

Examples.



Secondary reactions can take place between the explosion products, as, for instance:



However, the CO, H<sub>2</sub>, O<sub>2</sub>, NO and other secondary components in the explosion products <sup>are</sup> insignificant, and, in many cases, these reactions can be discounted.

3. Explosive with negative oxygen balance - oxygen content sufficient for the transformation of all of the carbon into gases.

CO and H<sub>2</sub> originate in the decomposition products in addition to CO<sub>2</sub>, <sup>H<sub>2</sub>O</sup> and N<sub>2</sub>. In a general case, the equation for the reaction can be represented in the following form:



where the subscripts  $a, b, c, d$  denote the number of atoms of the corresponding molecule of explosive,  $n_{\text{CO}}, n_{\text{CO}_2}, \dots$ , are the number of moles of the corresponding components of the products of the explosive transformation.

It is evident that

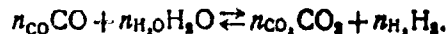
$$2 n_{\text{N}_2} = c;$$

$$n_{\text{CO}} + n_{\text{CO}_2} = a;$$

$$2 n_{\text{H}_2} + 2 n_{\text{H}_2\text{O}} = b;$$

$$n_{\text{CO}} + 2 n_{\text{CO}_2} + n_{\text{H}_2\text{O}} = d$$

A reversible reaction takes place between the decomposition products (the so-called water gas reaction):



Expressing the concentrations of the water gas components through unknown values ( $n_{\text{CO}_2}, n_{\text{CO}}, n_{\text{H}_2\text{O}}, n_{\text{H}_2}$ ) in accordance with the doctrine of chemical equilibrium, we shall obtain<sup>16</sup>

$$\frac{n_{\text{CO}} n_{\text{H}_2\text{O}}}{n_{\text{CO}_2} n_{\text{H}_2}} = K_1$$

where  $K_1$  - equilibrium constant of the water gas reaction.

The equilibrium constant for the given reaction depends only on the temperature. An analytical expression of this dependency is difficult to accomplish. In the calculations, the

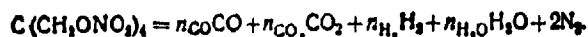
values for the constants, which are found in the appropriate tables, are used.

In order to determine the equilibrium constants by a table, it is necessary to know the temperature of the explosive transformation. On the other hand, in order to calculate the temperature, it is necessary to know the composition of the explosion products. This circle is resolved by the fact that, at the beginning, tentative values are assigned for the temperature  $T$ , the magnitude of  $K_1$  is determined by this temperature and then the equations are solved. Having determined the values  $n_{CO_2}$ ,  $n_{CO}$ ,  $n_{H_2O}$ ,  $n_{N_2}$  and  $n_{H_2}$ , the temperature of the explosive transformation is then computed (see section 2).

If the temperature which is obtained differs from the one that was initially used by more than  $50^{\circ}$ , then a new equilibrium constant is found by this temperature. Next, the calculation is repeated up to the obtaining of a satisfactory approximation between the two temperatures.

For precise calculations, apart from the water gas reaction, other possible reactions between the decomposition products as well as the dissociation of the products are also considered.

Example. To derive an equation for the decomposition of PETN:



We shall set  $4000^{\circ}$  as the decomposition temperature of PETN. At this temperature, the equilibrium constant of the water gas reaction is equal to 8.418. We then have the following system of

equations

$$n_{\text{CO}} + n_{\text{CO}_2} = 5$$

$$2 n_{\text{H}_2} + 2 n_{\text{H}_2\text{O}} = 8$$

$$n_{\text{CO}} + 2 n_{\text{CO}_2} + n_{\text{H}_2\text{O}} = 12$$

$$n_{\text{CO}} n_{\text{H}_2\text{O}} = 8.418$$

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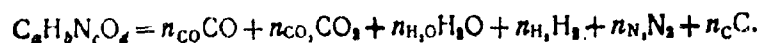

$$n_{\text{CO}_2} n_{\text{H}_2}$$

Solving these equations, we find that  $n_{\text{CO}} = 1.758$ ;  $n_{\text{CO}_2} = 3.242$ ;  $n_{\text{H}_2} = 0.242$ ;  $n_{\text{H}_2\text{O}} = 3.758$ .

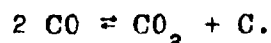
The desired decomposition equation will take on the form:  
 $\text{C} (\text{CH}_2\text{ONO}_2)_4 = 1.76 \text{ CO} + 3.24 \text{ CO}_2 + 0.24 \text{ H}_2 + 3.76 \text{ H}_2\text{O} + 2 \text{ N}_2$ .

The explosion temperature calculated for this equation is equal to  $4303^\circ$ . The approximation is satisfactory.

4. Explosive with a negative oxygen balance - oxygen content insufficient for oxidizing all of the carbon into CO. (free carbon remains in the explosive transformation products. The equation for the decomposition reaction can be written in the following general form:



In addition to the water gas, the so-called blast-furnace gas reaction can also occur in this particular case:



In order to determine the unknown coefficients, we shall use the same equations as in the previous case:

$$n_{\text{CO}} + n_{\text{CO}_2} + n_{\text{C}} = a;$$

$$2 n_{\text{V}_2} = c;$$

$$n_{\text{CO}} + 2 n_{\text{CO}_2} + n_{\text{H}_2\text{O}} = d;$$

$$2 n_{\text{H}_2} + 2 n_{\text{H}_2\text{O}} = b;$$

$$\frac{n_{\text{CO}} n_{\text{H}_2\text{O}}}{n_{\text{CO}_2} n_{\text{H}_2}} = K_1$$

From the equilibrium constant equation for the blast-furnace gas, we shall obtain

$$\frac{n_{\text{CO}}^2}{n_{\text{CO}_2}} \frac{P}{n_2} = \frac{n_{\text{CO}}^2}{n_{\text{CO}_2}} \frac{RT}{v} = K_p$$

where R - gas constant;

T - temperature of the explosion products;

v - volume occupied by the explosion products.

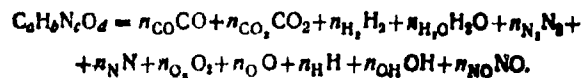
We shall also assign a tentative temperature during the solution of this system of equations, and then we shall solve the problem by the successive approximation method.



5. Equation for Powder Deflagration Reaction. The problem is complicated by the necessity to accurately compute the composition of the deflagration products of the powder, which is particularly important for powder-propellant jet engines. In this case, on account of the relatively low pressures, there is a significant development of secondary reactions and dissociations. It is therefore necessary to determine, in addition to the basic reaction products  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{H}_2$ ,  $\text{H}_2\text{O}$  and  $\text{N}_2$ , the following secondary products (or a part of them):  $\text{O}_2$ ,  $\text{O}$ ,  $\text{N}$ ,  $\text{H}$ ,  $\text{OH}$ , and  $\text{NO}$  which are formed by the reactions:



Retaining the former denotations, we can find the chemical equation for the deflagration reaction of the powder



Obviously,

$$n_{CO} + n_{CO_2} = a; \quad (1)$$

$$2n_{H_2} + 2n_{H_2O} + n_H + n_{OH} = b; \quad (2)$$

$$2n_{N_2} + n_N + n_{NO} = c; \quad (3)$$

$$n_{CO} + 2n_{CO_2} + n_{H_2O} + n_O + 2n_{O_2} + n_{OH} + n_{NO} = d. \quad (4)$$

We shall add seven equations to these four equations of atomic balance of the chemical elements which enter into the composition of the powder and deflagration products, by making use of the expressions for the equilibrium constants of the water gas and reversible reactions (I-VI):

$$\frac{n_{CO} n_{H_2O}}{n_{CO_2} n_{H_2}} = K_1 \quad (5)$$

$$\frac{n_{CO} n_{O_2}^{\frac{1}{2}}}{n_{CO_2}} \left( \frac{P}{n_{\Sigma}} \right)^{\frac{1}{2}} = K_1, \quad (6)$$

where  $n_{\Sigma}$  - the overall mole quantity of all the combustion products, and

P - the pressure under which deflagration of the powder occurs:

$$\frac{n_O^2}{n_{O_2}} \frac{P}{n_2} = K_{II}; \quad (7)$$

$$\frac{n_N^2}{n_{N_2}} \frac{P}{n_2} = K_{III}; \quad (8)$$

$$\frac{n_H^2}{n_{H_2}} \frac{P}{n_2} = K_{IV}; \quad (9)$$

$$\frac{\frac{1}{2} \frac{n_{H_2} n_{OH}}{n_{H_2O}} \frac{P}{n_2}}{n_{H_2O}} = K_V. \quad (10)$$

$$\frac{\frac{n_{NO}}{\frac{1}{2} \frac{1}{n_{N_2} n_{O_2}}}}{n_{N_2} n_{O_2}} = K_{VI}. \quad (11)$$

The equilibrium constants depend on the temperature of the powder gases, which, in turn, depends on the deflagration heat of the powder and conditions of expansion of the combustion products:

$$T = F(Q, P, v) \quad (12)$$

The pressure  $P$  is normally set by the rocket designers.

We obtained a system of 12 non-linear equations, an analytic solution of which is impossible, and, therefore, an inspection or successive approximation method should be used. The latter method is more satisfactory, which we also made use of in this case.

From equation (2) we shall determine

$$n_{H_2O} = \frac{1}{2}b - n_{H_2} - \frac{1}{2}n_H - \frac{1}{2}n_{OH}.$$

By setting  $\frac{1}{2}b - \frac{1}{2}n_H - \frac{1}{2}n_{OH} = A$ , we can write

$$n_{H_2O} = A - n_{H_2}. \quad (13)$$

Substituting the value  $n_{CO_2}$  from equation (1) and  $n_{H_2O}$  from equation (13) into equation (4), we obtain

$$n_{CO} = 2a + A - d - n_{H_2} + n_O + 2n_{O_2} + n_{OH} + n_{NO}.$$

Setting  $2a + A - d + n_O + 2n_{O_2} + n_{OH} + n_{NO} = B$ ,

we then write

$$n_{CO} = B - n_{H_2}. \quad (14)$$

From equation (1) we have

$$n_{\text{CO}_2} = a - n_{\text{CO}} = a - B - n_{\text{H}_2}. \quad (15)$$

From equation (3) we have

$$n_{\text{N}_2} = 1/2 C - 1/2 n_{\text{N}} - 1/2 n_{\text{NO}}.$$

By setting  $1/2 n_{\text{N}} + 1/2 n_{\text{NO}} = D$ , we write

$$n_{\text{N}_2} = 1/2 C - D \quad (16)$$

We treat the values A, B, and D as hypothetical values. We obtained four equations (13) - (16) with five unknowns. In order to solve the system, we also have equation (5) for the water gas reaction constant. We find the value of the constant  $K_1$  by the temperature T which is anticipated in the combustion chamber.

Substituting the values  $n_{\text{CO}}$ ,  $n_{\text{H}_2\text{O}}$ ,  $n_{\text{CO}_2}$  from equations (13), (14) and (15) into equation (5), we obtain

$$\frac{(B - n_{\text{H}_2}) (A - n_{\text{H}_2})}{(a - B - n_{\text{H}_2}) n_{\text{H}_2}} = K_1$$

Hence

$$n_{H_2} = \frac{-[(a-B)K_1 + (A+B)] \pm \sqrt{[(a-B)K_1 + (A+B)]^2 + 4(K_1-1)AB}}{2(K_1-1)}.$$

The sign of the root is selected in such a way that the solution would be positive.

Having determined the value  $n_{H_2}$ , we find the values  $n_{H_2O}$ ,  $n_{CO}$ ,  $n_{CO_2}$  from equation (13) - (15): after this we shall correct the number of moles of the remaining components by making use of the equations for the equilibrium constants (6) - (11). If the obtained values satisfy the selected values A, B and D with the degree of accuracy assumed in the calculation, then the solution is valid. If these values are unsatisfactory, then adjustments are made in the values A, B, and D, and the calculation is repeated until the prescribed degree of accuracy is obtained.

For a check of the validity of the hypothetically selected temperature of the powder gases, it is determined by the previously-described method with the calculation of the expansion of the combustion products in the reaction chamber.

#### 4. Volume of the Gaseous Products of the Decomposition of Explosives.

The volume of the explosion products can be determined by two methods:

1. by calculation after the decomposition reaction of the explosive;

2. by experimental means - measurement of the volume of the gases which are formed during the explosion or combustion of a specific weighed portion of explosive.

1. Calculation of the volume of the products of explosive transformation. We shall write the reaction of the decomposition of an explosive in the general form:



where  $M$  - the molecular weight of the explosive;

$m$  - number of moles of this substance;

$M_1, M_2, M_3$  - molecular weight of the products;

$n_1, n_2, n_3$  - corresponding number of moles of these products.

Then the specific volume of the gases which are formed in the explosion of 1 kg of explosive is:

$$v_0 = \frac{(n_1 + n_2 + n_3 + \dots)}{mM} 22,4 \cdot 1000 \text{ liters/kg at } 0^\circ \text{ and } 760 \text{ mm.}$$

The products of the decomposition, which are gases at explosion temperature, and which are actually found in a liquid or solid state at  $0^\circ$ , are conventionally regarded as gases, and, consequently, are considered in the calculation of the volume. The volume of the substances, which are found in the solid or liquid state at explosion temperature, are disregarded.

Example. To compute the volume of the products of explosive transformation of TNT.

On the basis of the equation for the decomposition reaction of TVT (page 85):

$$v_0 = \frac{(2 + 1.2 + 0.6 + 1.6 + 1.4 + 0.2) \times 22.4 \times 1000}{2 \times 227}$$

$$= 691 \text{ liters / kg.}$$

At 0° and 760 mm Hg (water turns to vapor).

2. Experimental determination of the volume of explosive transformation products. In order to determine the specific volume of the explosive transformation products, the gases which are obtained in the explosion of a weighed portion of explosive in a closed vessel are transferred into a gas meter.<sup>17</sup>

Because water is found in a liquid state under the experimental conditions, whereas it is a vapor at the moment of explosive transformation (and in this state it takes part in the mechanical work produced by the explosion products), then the volume which the water would occupy if it were in a vapor state is determined by calculation, and this volume is added to the measured volume of gas.

## 5. Pressure of the Products of Explosive Transformation

The question of the pressures which originate in the detonation of an explosive are examined in Chapter VI (see pages 74-75 of original). The relations determining the pressure of the explosive transformation products, under conditions when the dynamic effects associated with the propagation of the shock



wave do not occur, are examined below. These relationships are valid for the case of deflagration of powders and explosives.

1. Determinations. In the sequel, it will be necessary to make use of the assumptions concerning several forms of density. The corresponding determinations are listed below.

Density is the mass of unit volume of a compact substance, i.e. without air gaps. It is expressed in  $\text{g/cm}^3$ .

Volumetric or cubic density is the mass of unit volume occupied by the substance, including any gaps which may be found between the particles. It is expressed in  $\text{g/cm}^3$ .

Gravimetric density is the mass of unit volume of loosely poured (i.e. without shaking, tamping, compression, etc.) of a powdery or granular substance, including the gaps between its grains. It is expressed in  $\text{kg/decimeter}^3$  or  $\text{g/cm}^3$ .

Density of loading is the mass of a substance, referred to the volume of space of the explosion, as for instance, a charge chamber. It is expressed in  $\text{kg/decimeter}^3$ .

In the case of a loosely poured substance, the values for the gravimetric and volumetric density are identical.

In the case where the explosive fills up the charge chamber completely, the values for the volumetric and loading charge densities are the same.

2. Computation of the Pressure of the Combustion Products of an Explosive. If the gaseous products of an explosive transformation would be subject to the law of ideal gases, and the

entire taken quantity of explosive would transform evenly into gases, then the pressure produced in the explosion of  $M$  kg of explosive in a volume  $V$  could then be computed by the equation

$$P = n RT \frac{M}{V}$$

where  $n$  - number of gram-molecules of gas formed in the explosion of 1 kg of explosive.

The magnitude  $\frac{M}{V}$  is the ratio of the mass of the explosive charge to the volume in which the explosion takes place, i.e. the charge density, which we shall denote by  $\Delta$ .

$$P = n RT \Delta. \quad (1)$$

The product  $n RT$  is the strength or power of the explosive, and it is denoted by the letter  $f$ . Now, formula (1) assumes the form

$$P = f \Delta \quad (2)$$

We shall determine the physical meaning of the magnitude  $f$ . Let 1 kg of explosive be subjected to explosive transformation, wherein the originating gases are expanded at an atmospheric pressure of  $P_0 = 1.033 \text{ kg/cm}^2$  and at a temperature of  $T = 273^\circ \text{ K}$  to a volume  $V_0$ . It is obvious that the expansion of gases under these conditions is equal to  $P_0 V_0$ .

According to the Clapeyron equation  $n R = \frac{P_0 V_0}{T_0}$ , i.e. the magnitude  $n R$  is the work which the gas would perform at a pressure  $P_0$  while being cooled to  $1^\circ$ . Hence it follows that the

strength of the powder  $f = n RT$  is the work produced by the expansion of 1 kg of gas, while being cooled to a temperature of  $T^0$  at an atmospheric pressure  $P_0$ .

The strength of the powder can be increased by such a change in its composition wherein  $T$  and  $V_0$  would also increase.

Formula (2) is used only in the case of very small charge densities and correspondingly low pressures, when it could be assumed that the combustion products are subject to the equation for the composition of ideal gases.

In the case of large charge densities and high pressures, the combustion products by their characteristics, are far from ideal gases. Their state can be described by the Van der Waals equation

$$(P + a) (V - \alpha) = n RT \quad (3)$$

The magnitude  $a$  is the internal force dependent on the mutual attraction of molecules. This force is slight in comparison with the high pressure of the powder gases. Therefore, equation (3) is used in the following form for the deflagration products of a powder

$$P (V - \alpha) = n RT \quad (4)$$

The magnitude  $\alpha$ , called the co-volume takes into account that portion of the volume of gas which represents the sum of the spheres of activity of the molecular forces and is accessible for the movement of the molecules.

The magnitudes of the co-volume, according to theoretical

computations, is approximately equal to the quadrupled volume of the molecules themselves. A theoretical calculation of the volume of the molecules is difficult, and impractical in many cases. Therefore, an approximate value for the co-volume of the gaseous products is used in determining the explosion pressure. It is taken as 0.001 of the volume which is occupied by the gases under normal conditions.

Equation (4) satisfactorily described the properties of powder gases only at pressures which are no higher than 6000 at.

It follows from equation (4) that

$$P = \frac{nRT}{V - a} = \frac{f \frac{1}{V}}{1 - \frac{1}{V} a} = \frac{f \Delta}{1 - a \Delta}. \quad (5)$$

This is the fundamental internal ballistic formula.

It follows from equation (5) that:

1. the greater the pressure, the greater the force  $f$  and co-volume of the explosive;
2. the greatest pressure is produced by those substances which are capable of forming the largest volume of gases with a low specific heat and thereby capable of evolving a relatively larger amount of heat.

3. Experimental Determination of the Pressure of the Deflagration Products of a Powder. A manometric bomb is used for an experimental determination of the pressure of gases which form during the deflagration of powders in a constant volume.

Not only is the maximum pressure measured in the bomb, but also the influence of the powder's properties and size and shape of the natural elements on the law of growth of pressure in time (relationships  $P, t$ ), and on deflagration rate, as well as other characteristics playing a large role in internal ballistics, are determined.

The bomb (Figure 10) consists of a steel case with two closing plugs: caps: ignition and crusher gage. The ignition closing plug is equipped with a device for igniting the charge which is inside of the bomb. The inside volume of the bomb is from 18 to 400 cm<sup>3</sup>.

The pressure is determined by the amount of contraction of the little copper cylinder called crusher gage. The crusher gage displaces along the sleeve, the assembly of which is shown in Figure 11. A closely ground piston moves back and forth in the sleeve's channel. This piston transfers the pressure from the combustion products to the crusher gage, which is set in the closing plug. A steel pen is attached to the piston head.

The bomb is clamped in special vises (Figure 12) so that the pen could be in light contact with the blackened paper which is fastened to the surface of a revolving drum.

At the beginning of combustion, the pen traces a line on

the paper which is parallel to the base of the drum (1-1, Figure 13). During the process of combustion, the pen traces a curve of the interior pressure gage's deformation which corresponds to the nature of the growing pressure in the bomb, and, after attaining maximum pressure, it once again traces a line which is parallel to the base of the axis. A curve is thus obtained with which the law of rise of pressure in time can be established.

The time rate is determined by a measurement of the sinusoidal wave length, which is obtained on the blackened paper through the contact of another pen, attached to the tine of a tuning fork, vibrating with a known vibration. This sinusoid can be seen in the upper part of Figure 13.

The so-called tare tables are used for determining the pressure by the contraction of the interior pressure gage. They determine the relation between the pressure and contraction of the interior pressure gage.

The interior pressure gauges can be cylindrical (Figure 14, a and b) and conical (Figure 14, c).

A defect of the cylindrical interior pressure gage is that it begins to contract only at a pressure of about  $200 \text{ kg/cm}^2$ . The cylindrical gage, although being entirely satisfactory for determining maximum pressures, are not too satisfactory for determining the course of the rise of pressure. This problem is solved by the use of a conical interior pressure gage, which

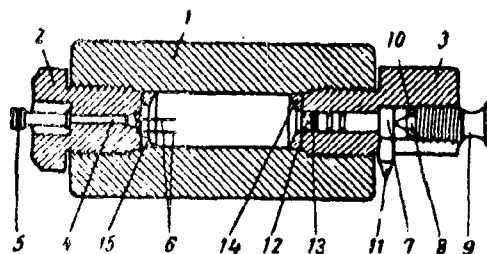


Fig. 10. - Manometric Bomb

- |                            |                     |                                  |
|----------------------------|---------------------|----------------------------------|
| 1. bomb casing             | 2. ignition sleeve  | 3. interior pressure gage sleeve |
| 4. insulated rod           | 5. wire contact     | 6. contact pins                  |
| 7. piston                  | 8. crusher gage     | 9. screw cap                     |
| 10. rubber centering ring  | 11. steel pen       |                                  |
| 12. mastic                 | 13. leather packing |                                  |
| 14. copper obturator rings |                     |                                  |

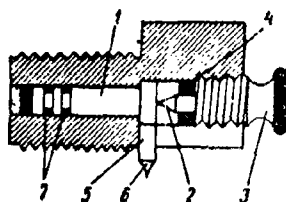


Fig. 11. - Closing plug

- |                               |                           |
|-------------------------------|---------------------------|
| 1. piston                     | 2. interior pressure gage |
| 3. closing plug               | 4. rubber ring            |
| 5. projection for piston head |                           |
| 6. steel pen                  |                           |
| 7. gland packing              |                           |

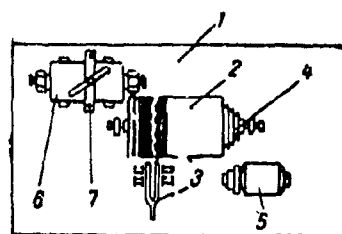


Fig. 12. - Layout of the manometric bomb and recording device

- |  |  |
|--|--|
| 1. plate                                       | 2. drum for recording the reduction in the crusher gage and rate of time |
| 3. tuning-fork with electromagnetic excitation |  |
| 4. step cone                                   | 5. motor   |
| 6. manometric bomb                             |  |
| 7. clamp                                       |  |

begins to contract at 5 to 7 kg/cm<sup>2</sup>. This type of gage was proposed by M. E. Serebryakovi.

If two pressure determinations are made by means of the manometric bomb, as, for instance, at charge densities of  $\Delta_1$  and  $\Delta_2$ , then after obtaining the data, the magnitudes  $\alpha$  and  $f$ , entering into equation (5), can be computed. By knowing these magnitudes the same equation can then be used to find the pressure for any other charge densities.

Other devices, besides interior pressure gages, are used for the measurement of pressure. Of these, the most ideal are piezoelectric manometers with precise and instruments for measuring and recording electric alternating voltages.



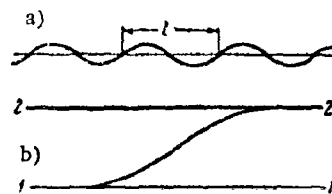


Fig. 13. - Record of a test in manometric bomb

- a. curve for determination of time rate
- b. curve for deformation of interior pressure gage.

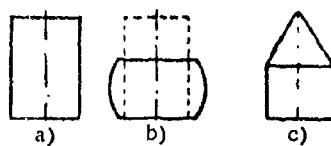


Fig. 14. - Interior pressure gages

- a. cylindrical
- b. cylindrical after contraction
- c. conical

## CHAPTER V

### THE COMBUSTION OF GASEOUS AND CONDENSED EXPLOSIVES

#### 1. THE ORIGINATION AND PROPAGATION OF COMBUSTION IN GASEOUS SUBSTANCES

Gaseous explosives are not used in industry. But the processes of combustion powders and explosives occur through the formation of the gaseous phase; therefore, a study of the combustion in gaseous systems should precede a study of the same phenomenon in condensed explosives. In addition, the formation of muzzle flash in a shot is connected with the combustion of a mixture of powder gases and air.

1. The mechanism of spontaneous combustion of a gaseous mixture. When a gaseous mixture heats up, a reaction between the combustion gases and oxygen originates. Its rate rises rapidly with an increase in temperature. The amount of heat which is evolved in a unit of time increases in accordance with an increase in the reaction rate. The rate of heat elimination into the circumambient medium grows relatively weakly with an increase in the temperature of the mixture.

At low temperatures, the reaction temperature is able to disperse, owing to which the gas, for all practical purposes, retains the same temperature as the circumambient medium. In the heating of the gaseous mixture, the heat intake grows more rapidly than the heat transfer, and becomes greater than the latter after attaining a certain temperature. From this moment, the temperature of the gas rises rapidly, which, in turn, leads to the reaction which terminates in explosion.

The minimum temperature of the gaseous mixture at which the heat intake becomes greater than heat transfer and where the chemical reaction assumes the character of an explosive transformation is called the spontaneous combustion or ignition temperature.

The spontaneous combustion temperature, in a manner similar to the one which has been established above for condensed<sup>18</sup> explosives, depends on a number of conditions determining the magnitude of heat intake and heat outgo. For instance, if the gaseous mixture is contained in a spherical vessel of small diameter, then the spontaneous combustion temperature will be higher than in a vessel of large diameter (heat transfer is proportional to area of surface, i.e. square of the diameter, while heat intake is proportional to the volume, i.e. cube of the diameter). If the gaseous mixture is found under an elevated pressure, then the spontaneous combustion temperature will be lower (the pressure increases the reaction rate but has practically no effect on the heat transfer).

2. Delay of Spontaneous Combustion. Experiment shows that, in heating an explosive gaseous mixture to spontaneous combustion temperature, ignition originates not instantaneously, but after a certain period of time, called the delay period.

The spontaneous combustion period depends on a number of causes, particularly on the temperature and composition of the mixture. Table XIII contains data concerning the length of the delay of certain methane-air mixtures at various temperatures. The spontaneous combustion delay periods for mixtures of air with carbon monoxide or hydrogen are much lower than that of the methane-air mixtures.

TABLE XIII

Spontaneous combustion delay period (in seconds) for methane-air mixtures.

Methane content in volumetric percents	Temperature of the vessel in °C					
	720	775	825	875	975	1075
6	6,4	1,08	0,58	0,35	0,12	0,039
9	—	1,30	0,65	0,39	0,14	0,044
12	—	1,64	0,74	0,44	0,16	0,055

The phenomenon of spontaneous combustion delay is dependent on the same causes as the delay in ignition of condensed explosives.

3. Mechanism of combustion propagation of gaseous mixtures.

In the case where the entire volume of gaseous mixture does not heat uniformly, and where heat sources of a high temperature act on certain of its parts (glowing wire, flame), an intense reaction takes place in a thin layer of the substance which is subjected to direct action of high temperature, and ignition occurs. Thermal energy is transferred from the combustion products of this burning layer to the closest layer of gas by means of heat transfer, and, by heating it, it then causes an intense reaction. If, in addition, the reaction heat of the new gas layers exceeds the heat losses, then the reaction propagates from layer to layer - combustion takes place. There is no propagation of the reaction in a contrary case.

Thus, the mechanism of combustion consists of the propagation of the thermal wave along the gas, accompanied and sustained by a rapid exothermic chemical reaction.

The combustion rate of the gaseous mixtures depends on the pressure, temperature and other factors. In the case of methane-air mixtures, for example, at a normal temperature and pressure, this rate is equal to several meters per second.

## 2. MECHANISM OF COMBUSTION OF CONDENSED EXPLOSIVES

1. Mechanism of combustion of explosives and powders according to Byelyayev. Byelyayev established that the combustion of highly volatile high explosives has a complex character: during the heating of the explosive by a source of heat, melting and vaporization of a thin layer of the substance takes place. The vapors which are formed are heated to a spontaneous combustion temperature with subsequent intensive chemical reaction. The combustion products heat the following layer of explosive undergoing the same physical processes and chemical reactions. Figure 15 shows the Byelyayev combustion mechanism.

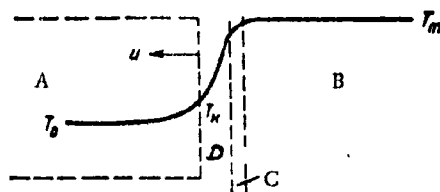


Fig. 15. - Diagram of Byelyayev explosive combustion mechanism

- A. condensed phase region
- B. region of the reaction's combustion products
- C. zone of combustion of vaporous substance
- D. zone of preparation of vapors for combustion

The vapors which are formed by the evaporation of the condensed phase do not deflagrate all at once, but only after the expiration of a certain period time which is necessary for their

heating and development of a reaction in them. As a result, the combustion will take place in zone C, at some distance from the condensed phase A. A preheating and preparation of the vapors for combustion zone D is found between A and C. During the combustion of the explosive, the energy is transmitted by means of heat transfer to the condensed phase through the vapor layer D, preparing itself for reaction.

It is evident that during sustained conditions of combustion, the amount of substance which vaporizes in 1 second per  $1 \text{ cm}^2$  of cross section is equal to the amount of substance which is burned in 1 second per  $\text{cm}^2$ . In other words, the mass rate of vaporization of the condensed phase should be equal to the mass rate of vapor combustion. As concerns the combustion mechanism of the vapor phase, it is obviously identical to the previously-examined combustion mechanism of explosive gaseous systems.

Pyroxylin is the base of colloid powders. It does not have any volatility. Zvel'dovich assumes that decomposition reactions take place in the heated surface layer during the combustion of the powder. The result is that volatile substances, which are capable of reacting, are formed (products of incomplete oxidation). Further, these substances react among themselves in the gaseous phase and form the end products of the combustion ( $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{H}_2\text{O}$ ,  $\text{N}_2$ ) with the liberation of the corresponding reaction heat. The general flow sheet of the phenomenon is thereby close to that shown in Figure 15 for the volatile explosives with the exception

that the role of the vapors is played by the gaseous products of the original reactions.

There is a concept in the recent works of Soviet and foreign scientists that the sole process determining the combustion rate of the powder is without any doubt the reaction in the gaseous phase.

## 2. Conditions of Steadiness of combustion of an explosive.

K. K. Andreyev and A. F. Byelyayev showed the important significance of the ratio between gas intake and gas outgo in their examination of the steadiness of combustion. We shall imagine that an explosive filling up a cylindrical tube is ignited and burns along the face. The originating gases flow off in a direction which is opposite to the direction of the propagation of the combustion, owing to which the pressure above the surface of the explosive rises. The pressure above the surface of the explosive will depend upon the ratio between the gas intake rate (dependent on the combustion rate of the explosive) and the gas outgo rate. Both of these quantities increase with an increase in the pressure, but the rates of such a rise can be different.

The ratio between the gas intake and outgo depends upon the nature of combustion (at a set internal pressure) and its change with rise in pressure.

Depending upon the properties of the explosive and conditions under which the combustion takes place, two extreme cases are possible:



1. The gas outflow rate is equal to the rate of their formation. In this case, we have a steady combustion process, i.e. combustion at a set (constant) rate;

2. the gas intake rate is greater than the gas outflow rate. In this case, the pressure in the front of the combustion will continually rise and the combustion rate will increase.

We shall examine the relations between gas intake and gas outflow for various substances. The relationship of the combustion rate of an explosive to the pressure can be expressed by the formula  $u = a + bP^{\nu}$ . We shall denote the area of the charge along the edge of combustion by  $S$ , and the density of the explosive by  $\delta$ . Then the gas intake is  $m_1 = u\delta S$ . This relation is shown graphically on the diagrams  $m_1$  (Figure 16, a, b, and c). The relationship of the gas outflow to the pressure, determined in accordance with the laws of gas dynamics, is shown in diagrams  $m_2$  of the same figures (dimension of gas intake and outflow are in  $\text{g/cm}^2 \text{ sec}$ ).

In the case where  $\nu < 1$  (Figure 16 a), the pressure rises in the beginning because the gas intake is greater than the gas outflow at  $P_1$ , the gas intake is equal to the outflow. At elevated pressure ( $P > P_1$ ) the gas outflow becomes greater than the gas intake and the pressure is lowered to  $P_1$ . Consequently, a steady burning of the explosive takes place at  $\nu < 1$ .

For the same reasons, the burning along curve I is steady even at  $\nu = 1$  (Figure 16 c, curves  $m_2$  and I). The same holds true for Curve I, Figure 16 c, with the condition that the pressure is

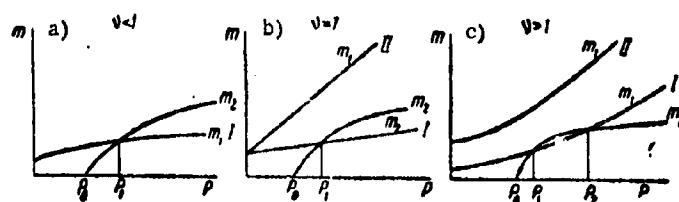


Fig. 16. - Relation of gas intake and outflow to pressure

smaller than  $P_a$ .

Curves II of graphs b and c which correspond to the case where the gas intake is greater than the gas outflow at any pressure, and the upper part of curve I of graph c characterize the unsteady accelerating combustion of the explosive.

It can be deduced from the examined relationship that, if, for a given explosive and conditions of the experiment, the gas intake rate always remains less than the gas outflow rate at rising pressure, then the pressure during combustion will remain steady. Conversely, under conditions when the gas intake rises with the press-

ure at a rate which is greater than that of the gas outflow, the pressure during combustion will rise. A rise in pressure accelerates combustion, i.e. the gas intake increases per unit of time, which, in turn, leads to a new increase in pressure. In this particular case, the gas intake and outflow balance is disturbed, the pressure and combustion rate increase successively, and, under favorable conditions, the combustion is transformed into a detonation.

As experiment bears out, initiating explosives not only have a high burning rate even at low pressures, but they are also characterized by a sharp increase in combustion rate with the growth of pressure. The characteristic capability of initiating explosives to detonate easily upon burning can be explained by: the high burning rate is dependent on the very dynamic rise in pressure above the surface of the burning powder. In turn, the rise in pressure increases the combustion rate to a rate which is of the order of a detonation rate.

Detonating explosives conduct themselves in burning in a manner similar to the initiating ones only in that case where there are factors facilitating the transition from combustion into detonation.

We shall examine the combustion process of an explosive having a porous structure. Burning gaseous products partially penetrate the pores, i.e. deep within the explosive. They then ignite it along inner surface, formed by the pores. As a result of this, the actual burning surface increases in comparison with the

cross section area of the charge. The gas formation rate rises accordingly, i.e. the amount of gases formed in a unit of time per unit of cross section area. On account of this, an accelerating increase in pressure sets in in the the combustion front, the combustion becomes self-accelerating and can, under certain conditions, more or less rapidly convert into detonation.

The process of the combustion converting into detonation, which has been described above for porous explosives, is obviously impossible in the case of liquid explosives. The conversion of combustion into detonation which was observed here can be explained by the fact that, in the burning of the substance, the surface layer of the liquid ceases to be flat. "Waves" appear on this layer. The actual combustion surface becomes much greater than the vessel, and the gas intake rises. In addition, vapor and spatters of the liquid hit into the zone of combustion where they burn up rapidly, and the pressure rises. The combustion becomes self-accelerating and can pass over into detonation.

Cast explosives (cast TNT for instance) have a continuous structure. It is a well-known fact that combustion of such substances takes place only under conditions of heat supply (with burning from without at first, and later on from the combustion heat), which is sufficient for a preliminary melting of the following layer of the substance. Therefore, the phenomenon here can take place analogously to the burning of liquid explosives, i.e. during combustion, vapors and spatters of water get into the zone of burning gases where they burn up and thereby accelerate the

process of a further combustion, bringing it to detonation under favorable circumstances.

The steadiness of burning of colloid powders is dependent, on the one hand, on their homogeneous continuous structure, and, on the other hand, on the fact that the base of the powder is non-melting and non-vaporizing pyroxylin. When this powder burns, the surface of the unburned part of the grain remains solid, and, on account of an almost complete absence of pores, it is not permeable to gases. These properties greatly hinder the transition of burning into detonation.

### 3. Burning of Powders

Three stages are distinguished in the process of burning a powder: ignition, propagation of burning along the surface, and burning within the innards of the powder grain.

Ignition is the origination of combustion in a more or less restricted surface layer of powder.

The stronger the thermal impulse causing ignition, the more readily ignition occurs. In addition the ease of ignition depends on the composition of the powder, sizes of the powder elements, the character of their surface, structure of the powder (porous, compact), and upon other factors.

In view of the fact that the conditions of ignition differ substantially from the conditions at which the deflagration temperature is determined, the connection between the significance

of the ignition temperature and ease of ignition is not always clearly seen. For example, the ignition temperature of gunpowder is equal to  $290 - 310^{\circ}$  while the ignition temperature of colloid powder is  $180 - 200^{\circ}$ . Moreover, gunpowder is ignited more readily than colloid powder. Granular colloid powder is ignited easier than a powder of the same substance in the form of strips, tubes, and sticks, i.e. from coarse powder elements. Equally, a porous grain is easier to ignite than a compact one.

We shall examine the cause of the influence of the physical structure on the inflammability of an explosive by the example of two powder elements produced from one and the same powder block. One of these is porous and the other is compact. These elements differ by the size of specific surfaces (i.e. by the surfaces per unit volume of the substance), large for the porous, and small for the compact. In addition to this, the thermal conductivity of the porous substance is much smaller than that of the compact. An increase in the specific surface and a decrease in the thermal conductivity facilitate ignition of the porous substance by a flame acting on a restricted surface layer of the substance. The conditions at which the ignition temperature is determined are substantially different. A uniform and gradual heating of the entire mass of the substance takes place, the specific surface and thermal conductivity have little effect on the results of the experiment, and the ignition temperature proves to be identical for both the porous and compact substance.

Devices in which the tested powder is subjected to the effect

of flame jet with constant intensity are used for evaluating the ignition capability. The minimum length of time necessary to ignite the powder is determined.

The tests indicated that gunpowder in the powder form (powdery pulp) is ignited more readily than grainy powder; that gunpowder ignites more readily than pyroxylin powder; and that pyroxylin powders ignite with more difficulty than highly-calorific nitroglycerine powders, etc.

The propagation of combustion along the surface, called inflammation, takes place primarily during the burning of the powder in air.

According to Andreyev, the high inflammation rate (in comparison to the rate of combustion within the grain) is dependent on the fact that, the burning substances which are contained in the powder gases will, during burning in air, blend with the air and burn out the oxygen, whereupon the flame temperature rises. For this reason, the surface layers of the powder along the front of the combustion are heated by a flame with a higher temperature. Therefore, the inflammation of the powder occurs faster in air than the propagation of the combustion within the depths of the grain. For instance, according to Andreyev's data, the inflammation rate of one test sample of nitroglycerine powder consisted of 16.7 cm/min, but the combustion rate of the same powder within the depths of the grain amounted to only 4.5 cm/min.

In the closed area of a charging chamber where the powder combustion occurs without air, the accelerated propagation of the

combustion along the surface of the powder does not play such a role, and, so that a practically simultaneous inflammation would take place along the entire surface of all powder grains, it is necessary to make sure that this surface is covered by the flame from the igniter.

Owing to the fact that colloid powder is difficult to ignite at low pressures, hangfires and even misfires were observed during the period when it was first used for firing purposes. Secondary charges, called igniters, were introduced for reliability of ignition. Igniters are made from gunpowder or porous pyroxylin powder. During the combustion of the igniter, the pressure in the bore rises rapidly to 60 - 100 at. and intense flames cover the powder elements (tubes, grains, etc.) of the base charge, which assures its rapid ignition along the entire surface and eliminates hangfires and misfires.

Combustion of the powder, or burning, is the process of the propagation of the decomposition reaction from the surface layers into the depths of the grain.

The combustion rate of a powder depends on its nature, physical structure, internal pressure (i.e. the pressure at which the combustion takes place) and, to a lesser degree, upon the initial temperature of the powder.

Ballistics-wise, the most important appears to be the relation of the combustion rate to the pressure. Various authors proposed formulas for determining this relationship. In ballistics, this relation is generally called principle of combustion rate.



The formula proposed by Vieille has the following form:

$$u = A p^{\nu},$$

where  $p$  - pressure;

$u$  - combustion rate at pressure  $p$ ;

$A$  and  $\nu$  - magnitudes dependent upon the nature of the powder.

Vieille took  $\nu = 1/2$  for ordinary gunpowders. According to M. E. Serel'ryakov's data,  $\nu = 1/5$  for slow-burning gunpowders. G. A. Zabudskiy took  $\nu = 0.93$  for pyroxylin powders.

Nowadays, Soviet scientists recommend the use of various formulas for determining the combustion rate of a powder in different pressure intervals.

For a pressure up to 100 at., the following formulas are proposed:

$$u = a + bp^{\nu} \quad \text{and}$$

$$u = bp^{\nu}$$

where  $\nu$  can be from 0.7 to 0.95 for different powders.

In the case of pressures from 100 to 300 at., the principle of the combustion rate is established.

$$u = a + bp$$

where the magnitudes  $a$  and  $b$  depend on the nature of the powder.

In the case of pressure above 300 at, the principle of combustion rate is generally used:

$$u = u_1 p$$

where  $u_1$  is a coefficient dependent on the nature, and, to a lesser degree, on the temperature of the powder.

The combustion rate of a powder rises with an increase in the specific heat of combustion (caloricity), therefore, the combustion rate of pyroxylin powders increases with an increase of the nitrogen content in the pyroxylin, and the combustion rate of nitroglycerine powders is raised with an increase of the nitroglycerine content, and is lowered with an increase of the content of inert admixtures (stabilizers, plasticizers, etc.).

## SECTION II

### HIGH EXPLOSIVES

#### 1. GENERAL REQUIREMENTS FOR EXPLOSIVES USED AS AMMUNITION FILLERS.

High explosives are used as ammunition fillers (shells, mines, aircraft bombs). Depending on the purpose of the ammunition, standards have been set for blast effect and brisance of the explosive. Standards with respect to the sensitivity of an explosive to mechanical effect are set in relation to the service requirements of the ammunition. In this relation, the most characteristic are artillery projectiles, the bursting charge of which is subjected to a large mechanical effect during the travel of the projectile along the bore and when it is piercing armor (armor-piercing shell).

The stresses developing in the critical cross section during its firing or piercing of armor have been taken as the characteristics of the degree of mechanical effect on the bursting charge.

1. Calculation of the Stresses Originating in the bursting charge during firing. When a projectile travels along the bore, it gains acceleration. Proceeding from Newton's second law, we shall determine the inertia and the stress originating in the bursting charge during its firing.

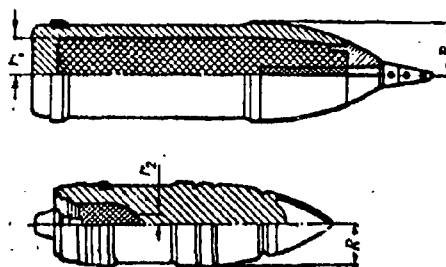


Fig. 26. - Cross sectional view of filled projectiles

We shall use the following denotations (Figure 26):  $p$  - the pressure of the powder gases (variable magnitude);  $p_m$  - the highest pressure of the powder gases originating during firing;

$R$  - half-caliber, i.e. the radius of the projectile body taken along the bourrelet;

$r_1$  - the radius of charge opening at base;

$r_a$  - radius of charge opening at head of projectile (armor piercing);

$w$  - weight of bursting charge;

$G$  - weight of filled projectile;

$g$  - gravitational attraction;

$v$  - displacement velocity of projectile

When it is fired, the projectile travels with accelerated motion under the effect of the force  $p\pi R^2$ . We shall examine the cross section of the projectile at any arbitrary point. The part of the projectile lying to the right of this cross section presses on the opposite part with the force

$$f = \frac{w_1}{g} \frac{dv}{dt},$$

where  $w_1$  - the weight of the portion of the charge lying to the right of the given cross section. The greatest inertia force acts on that layer of the charge butting against the base of the projectile; for this cross section

$$f_m = \frac{w}{g} \frac{dv}{dt}. \quad (1)$$

We shall determine the acceleration of the projectile  $\frac{dv}{dt}$  from the equation

$$p \pi R^2 = \frac{G}{g} \frac{dv}{dt}$$

from where  $\frac{dv}{dt} = p \frac{g}{G} \pi R^2$ .

The greatest acceleration occurs where  $p = p_m$ .

Therefore,

$$f_m = \frac{w}{G} p_m \pi R^2. \quad (2)$$

By dividing both parts of this equation by  $\pi r_1^2$ , we shall find the maximum stress originating in the critical cross section

of the bursting charge:

$$\sigma_m = p_m \frac{w}{G} \frac{R^2}{r_1^2} \quad (3)$$

Formula (3) can have another form

$$\sigma_m = p_m \frac{w}{\pi r_1^2} \frac{1}{\frac{G}{\pi R^2}} \quad (4)$$

where  $\frac{w}{\pi r_1^2}$  - traverse load on the explosive in the critical cross section,

$\frac{G}{\pi R^2}$  - transverse load on the projectile in the same cross section.

2. Calculation of the stresses originating in the bursting charge when the projectile pierces armor. We shall consider these stresses by Brink's approximation method which is based on the following assumptions:

1. during the entire period of piercing the armor, the projectile is subjected to a full force of resistance;

2. the path of the projectile, along which complete piercing of the armor is attained is  $l = H + b$ , where  $H$  is the length of the projectile's head, and  $b$  is the thickness of the armor.

By assuming that all of the projectile's kinetic energy is fully expended in the work of piercing, we can then write:

$$f_c l = \frac{Q}{g} \frac{v_c^2}{2}, \quad (5)$$

where  $v_c$  - the velocity of the projectile before hitting the armor.

According to Newton's second law:

$$f_c = \frac{Q}{g} \frac{dv}{dt}, \quad (6)$$

where  $\frac{dv}{dt}$  - acceleration (negative, i.e. slowing-down of the projectile at piercing of armor.

Substituting the expression for  $f_c$  into equation (5), we obtain

$$\frac{dv}{dt} = \frac{v_c^2}{2l}.$$

The force developed in the critical cross section of the bursting charge is

$$f'_m = \frac{\omega}{g} \frac{dv}{dt} = \frac{\omega}{g} \frac{v_c^2}{2l}. \quad (7)$$

From here, we shall determine the stress in the same cross section:

$$\sigma_{m1} = \frac{\omega}{g} \frac{v_c^2}{2l} \frac{1}{\pi r_2^2}. \quad (8)$$

Because the diameter of the opening of the head part in the critical cross section is small, the stresses can be large.

Example. We shall compute the greatest stresses originating in the bursting charge of a 45 mm armor-piercing projectile at

firing and at piercing of armor.

Initial data:  $m = 0.015$  kg;  $C = 0.8$  kg;  $R = 2.2$  cm;  $r_1 = 1.2$  cm,  $r_2 = 1.0$  cm.

Velocity of projectile prior to hitting into the armor  $v_0 = 500$  m/sec;  $p_m \approx 2500$  kg/cm<sup>2</sup>;  $L = 6$  cm.

The maximum stress at firing is:

$$\sigma_m = \frac{2500 \cdot 0.015 \cdot 2.2^2}{0.8 \cdot 1.2^2} = 158 \text{ kg/cm}^2$$

The maximum stress at piercing is:

$$\sigma_{m1} = \frac{0.015 \cdot 50000^2}{981 \cdot 2.6 \cdot 3.14 \cdot 1^2} = 1015 \text{ kg/cm}^2$$

Thus, the stress in the critical cross section of the bursting charge of a 45 mm armor-piercing projectile at piercing is  $\frac{1015}{158} = 6.4$  times greater than the stress at firing.

The maximum stress attains 1100 kg/cm<sup>2</sup> in many projectiles used in modern artillery. When designing ammunition, it is necessary to know the critical stress of an explosive, i.e. the greatest stress which the projectile's bursting charge can withstand without bursting. This magnitude is determined by test firings with specially-designed knock-down projectiles. The design of such a shell, developed by V. I. Rdylovskiy and used by him for studying the stability of bursting charges at firing is shown in Figure 27. After the critical stresses are obtained experimentally, permitted stresses are then established, which make firing safe.



TABLE XXI

Critical and permitted pressures for some explosives

Explosive	$\sigma_{cr}, \text{kg/cm}^2$	$\sigma_{perm.}, \text{kg/cm}^2$
TNT	1900	1100
Amatol 80/20	1400	1100
Tetryl	850	—
Flegmatized PETN	720	—

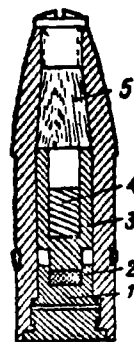


Fig. 27. - Experimental projectile for determining critical stress

1. plug with seat    2. explosive charge  
 3. inert body    4. lead    5. wooden plug

Appropriate values of critical and permitted stresses for some explosives are listed in Table XXI.

It should be mentioned that the critical stress is not absolute, but a conditional characteristic of the sensitivity of an explosive. It is a well-known fact that very large stresses can be produced in a charge by static pressure without any indications of its decomposition. Actually, the magnitude of stress is not important by itself, but the origination of the charges deformation, caused by these stresses, which causes a displacement of the charges particles with respect to each other or with respect to the charge's container, is important. When such a displacement takes place, there is the possibility of a conversion of mechanical energy into thermal energy with a localized heating causing the formation of reaction hot spots. The conditions of the formation of such a hot spot depend not only upon the physico-chemical and mechanical properties of the explosive, but also on the quality of filler, design of the charge and projectile, and upon other factors. The experimental values of the critical stress approximately take into account the effect of these factors for the fixed methods of filling.

3. General requirements for an explosive used as ammunition filler, in relation to the sensitivity to mechanical effect. The strictest requirements in relation to sensitivity to mechanical effect should be set forth for those explosives which are intended for filling armor-piercing projectiles.

Plugs - wooden, cement, or plastic - which increase the area of the explosive in the critical cross section are placed in the head cavity of armor-piercing projectiles to decrease the stresses in the bursting charge.

Strict requirements are set forth for an explosive which is intended as a filler for high explosive projectiles used in large caliber guns. Diaphragms are sometimes inserted into large-caliber projectiles in order to reduce the stresses in the explosive. These diaphragms separate the bursting charge into two separate parts (Italian 149 mm and German 615 mm projectiles).

Lesser sensitivity requirements are set forth for explosives which are used as fillers for medium-caliber howitzer projectiles (122 and 152 mm). These requirements are lesser still for explosives of shaped-charge projectiles, where a relatively light weight of the charge is characteristic for the bursting charges.

Finally, it would seem that the requirements could be even less strict for those explosives which are used as fillers for mines and hand grenades. However, the sensitivity of the explosive to bullet shock assumes an importance here. There is the requirement that the bursting charge would not be triggered by the impact of a bullet.

## 2. NITRIC ACID ESTERS (NITRATES)

1. Pyroxylin. The chemical properties and method of preparation are described in pages

Nowadays, pyroxylin is used only for the production of

colloid powders and dynamites.

2. Nitroglycerine.  $\text{CH}_2 (\text{ONO}_2) \text{CH} (\text{ONO}_2) \text{CH}_2 (\text{ONO}_2)$ . Nitroglycerine is obtained by processing glycerol with a mixture of nitric and sulphuric acids. After the nitroglycerine has been separated from the acids, it is worked to a neutral reaction so that a chemically-stable product is obtained.

Nitroglycerine is an oily, transparent liquid. The specific gravity is  $1.6 \text{ g/cm}^3$  at  $15^\circ$ . Solidification temperature is at  $+13.2^\circ$  (stable form) and at  $+2.1^\circ$  (labile form). 1.8 g of nitroglycerine is dissolved in 1 liter of water at  $20^\circ$ .

The volatility of nitroglycerine at ordinary temperature is very slight, which is of importance for the physical stability of nitroglycerine powders and constancy of their ballistic qualities.

The sensitivity of nitroglycerine to a blow is high; it explodes when a 2 kilogram weight drops on it from a height of 4 cm.

Nitroglycerine is used for the production of nitroglycerine powders and explosives. Nitroglycerine explosives are unsuitable as ammunition fillers on account of their high sensitivity to a blow and friction.

3. Nitroglycol (glycol dinitrate).  $\text{CH}_2\text{ONO}_2 - \text{CH}_2 \text{ONO}_2$ . Glycol serves as a basic product. It is obtained synthetically from ethylene. Glycol is nitrated by a mixture of nitric and sulphuric acids, and nitroglycol is then obtained. It is a liquid with a solidification temperature of  $-22^\circ$ .

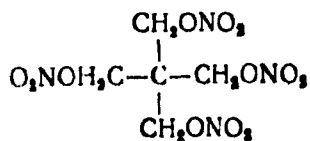
Nitroglycol is used for the production of non-freezing dynamites. On account of its increased volatility, it is unsuitable

for production of powders of the nitroglycerine type.

4. Dinitrodiglycol (diglycol dinitrate)  $\text{CH}_2\text{ONO}_2-\text{CH}_2-\text{O}-$   
 $-\text{CH}_2-\text{CH}_2\text{ONO}_2$ . Diethylene glycol  $\text{CH}_2\text{OH}\cdot\text{CH}_2-\text{O}-\text{CH}_2-\text{CH}_2\text{OH}$ ,  
shortened to dilycol, is a basic product which is also obtained  
synthetically from ethylene. A large quantity of diglycol is ob-  
tained as a by product of certain operations in the chemical in-  
dustry. Dinitrodiglycol is obtained by nitrating diglycol with  
a mixture of nitric and sulphuric acids. It is a liquid with a  
solidification temperature of  $11.3^\circ$ . The specific gravity at  $15^\circ$   
is equal to  $1.39 \text{ g/cm}^3$ .

On account of the slight volatility of dinitrodiglycol and  
a number of properties approximating those of nitroglycerine,  
dinitrodiglycol is used for the production of powders of the  
nitroglycerine type.

5. PETN. The nitric acid ester of pentaerythritol-penta-  
erythritetranitrate, or PETN, has assumed a great importance  
since World War II.



PETN is obtained by nitrating tetravalent pentaerythritol alcohol, which, in turn, is produced by the condensation of acetaldehyde ( $\text{CH}_3\text{CHO}$ ) with formaldehyde ( $\text{HCHO}$ ). These aldehydes, just as the nitric acid used for nitrating, is obtained synthetically from easily-obtained basic substances.

PETN is a white crystalline substance whose density is  $1.77 \text{ g/cm}^3$ . It is easily pressed into a volumetric density of  $1.60 \text{ g/cm}^3$ . It is non-hygroscopic. The melting temperature is  $141^\circ$ , and the ignition temperature is  $215^\circ$ .

PETN is chemically stable in relation to other nitric acid esters. It is more sensitive to a blow than TNT, tetryl or even cyclonite (explosion occurs when a 2 kg weight drops on it from a height of 30 cm, and explosion occurs for all tests where a 10 kg weight and 25 cm drop height are used). The sensitivity of PETN to detonation is somewhat higher than that of cyclonite and other secondary explosives. Expansion in a lead bomb is  $500 \text{ cm}^3$ .

In a standard compression test, PETN produces a complete deformation of the column. The compression is 16 mm at a charge weight of 25 g. The detonation velocity is 7000 m/sec at a density of  $1.60 \text{ g/cm}^3$ . PETN is flegmatized mostly by the addition of small amounts (up to 5%) of paraffin, wax, and similar substances; the sensitivity to shock is thereby greatly reduced, and the working capacity and detonation velocity are slightly lowered.

PETN is used for blasting caps, detonators and primacord. The flegmatized PETN is used as a filler for detonators and for

shaped-charge and other projectiles.

### 3. NITROCOMPOUNDS

1. General Information. Nitrocompounds are the most important class of high explosives. Many representative of this class are characterized by large fugacity and brisance effects at a low sensitivity to mechanical effects in comparison to explosives of other classes. These substances are particularly suitable as fillers for artillery and other types of ammunition. Mixtures of a number of nitrocompounds (for example, TNT, trotyl, dinitronaphtalene) with ammonium nitrate are used as a filler for medium-caliber artillery ammunition.

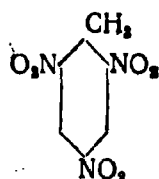
Nitrocompounds are chemically-stable substances. They can be stored for many years without any changes in physical or explosive indexes even under unfavorable conditions.

The basic substances for the production of nitrocompounds of the aromatic series are the aromatic hydrocarbons and their derivatives: benzene  $C_6H_6$ , toluene  $C_6H_5CH_3$ , xylene  $C_6H_4(CH_3)_2$ , naphthalene  $C_{10}H_8$ , phenol  $C_6H_5OH$ , dimethyl aniline  $C_6H_5N(CH_3)_2$  and others.

These substances are obtained from the coking products (by-products) of coal: coke oven gas and tar. In addition, a large quantity of aromatic hydrocarbons are formed during the pyrolysis of petroleum (petroleum benzene, toluene and xylene). Finally, toluene is obtained directly through the fractional distillation of certain kinds of petroleum (toluene-gasoline). Phenol and other aromatic hydrocarbon-derivatives are obtained during a further chemical processing of these substances.

The hydrocarbons or their derivatives are treated with a mixture of nitric and sulfuric acids in order to obtain the nitrocompounds.

2. TNT. The most important representative of the nitrocompound class is trinitrotoluene or TNT



The solidification temperature of chemically pure TNT is 80.85°. The solidification temperature of the commercial product is the criterion of its purity. TNT which is used as ammunition filler should have a solidification temperature which is not lower than 80.2°. During wartime, a temperature of no less than 70° is allowed.<sup>21</sup>

The density of TNT is 1.663 g/cm<sup>3</sup>. The gravimetric density is about 0.9 g/cm<sup>3</sup>; it can fairly easily be compressed to a density of 1.6 g/cm<sup>3</sup>. Density of poured TNT ranges from 1.55 to 1.59 g/cm<sup>3</sup>.

TNT for all practical purposes does not react with metals. The sensitivity of TNT to mechanical effect, and to a blow, in particular, is relatively slight, which is its basic advantage over many other nitrocompounds. When tested on the impact testing machine (10 kg weight and 25 cm drop height), TNT produces 4 to 8% explosions, while tetryl, for instance, produces about 50% explosions.

The sensitivity of cast TNT to detonation is much lower than



that of the pressed type. A booster is necessary to detonate cast TNT, whereas a blasting cap is sufficient for the detonation of pressed TNT. Pressed TNT charges are sometimes used as boosters for cast TNT. Pressed-TNT detonators are used for these purposes more frequently.

The expansion in a lead bomb is  $285 \text{ cm}^3$ . The detonation velocity is 6900 m/sec at a density of  $1.59 \text{ g/cm}^3$ .

The brisance, according to the contraction of lead cylinders in a test, is 16 to 17 mm.

Requirements for TNT used as shell filler. The TNT, which is obtained by washing the product after the separation of acids, has a solidification temperature of  $77-78^\circ$  and is called raw TNT. It contains about 6% of various admixtures, namely isomers of trinitrotoluene and dinitrotoluene. These admixtures worsen the explosive qualities of the TNT. For instance, the sensitivity to detonation is substantially reduced, and, during the summer months, a liquid, the so-called trotyl oil, leaks out of shells filled with this substance.<sup>22</sup>

The efflux of oil from the bursting charge is accompanied by the following phenomena:

1. Loosening of the explosive, which can cause a possible ignition of the charge at firing, and premature explosion.

2. In projectiles with screw-in bases, the trotyl oil, which carries TNT in liquid form, partially remains in the screw threads. At the moment of firing, the metal surfaces hit each other, and the oil which is found between these hitting surfaces can cause an explosion. There is also the chance of an ignition of the charge

by the powder gases. This can be accomplished by the transmission of fire along the oil which is contained in the screw threads of the base.

3. The trotyl oil which separates from the TNT can collect in the recess underneath the fuze (or detonator). In this case, the oil can sometimes get into fuze or booster where it then acts like a flegmatizer. This causes incomplete explosives and duds.

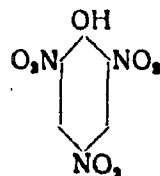
Raw TNT is not used as an ammunition filler. It is cleaned beforehand by washing it with an aqueous solution of sodium sulfite or by other means.

Use of TNT. Trotyl is the basic high explosive which is used as an ammunition filler. Owing to its relatively low sensitivity to mechanical effect under adequate brisance and fugacity effects, TNT is the best explosive for use in projectiles intended for naval and coast artillery guns. Armor-piercing projectiles used by these guns have been filled up to the present with flegmatized TNT, consisting of 94% TNT, 4% naphthalene, and 2% dinitrobenzene.

Large amounts of TNT were used in alloys with other nitro-compounds: with cyclonite for filling shaped charges and small-caliber projectiles; with 20% dinitronaphthalene under the name of K-2, with 5% xylene under the name of Alloy L, and others. TNT was used during the war in mixtures with ammonium nitrate.

Cartridges and charges for blasting work are made out of TNT.

3. Picric acid (trinitrophenol). The chemical formula is:



The solidification temperature of chemically pure picric acid is  $121.6^{\circ}$ . The density is  $1.813 \text{ g/cm}^3$ . It is easily pressed to a density of  $1.63 \text{ g/cm}^3$ .

In testing it on the impact tester with a 10 kg weight dropping on it from a height of 25 cm, picric acid produces a 32% percentage of explosions. Ignition temperature is around  $300^{\circ}$ . The sensitivity to detonation is greater than that of TNT, and lower than that of tetryl. The detonation velocity is 7210 m/sec at a density of  $1.63 \text{ g/cm}^3$ . The expansion in a lead bomb is  $330 \text{ cm}^3$ . The brisance, when tested by the contraction of lead cylinders, is 17-19 mm.

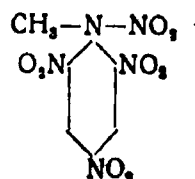
The big defect of picric acid is its ability to form salts upon contact with metals (besides tin) where even a little bit of moisture is present. Some of these salts have a high sensitivity to shock. In connection with this, it is necessary to shield the inner surface of the projectile case so that it would not come in contact with the picric acid. This has been accomplished by varnishing and also by the use of cased fillers (charge in a cardboard container). However, even with these precautions, it was necessary to limit the storage time of these projectiles because

even when the protective coating is used, a slow reaction between the picric acid and projectile casing metal takes place. The use of picric acid, primarily on account of the above-mentioned defect, has practically ceased during the past few years.

Picric acid was used in both the pure state and in alloys, as, for instance, with dinitronaphtalene. Two alloys were used: the "Russian mixture" containing 51.5% picric acid and 48.5% dinitronaphtalene, and a "French mixture" containing 80% picric acid and 20% dinitronaphtalene. <sup>During</sup> the Great Patriotic War, picric acid was used in anti-tank mines which had a wooden case.

4. Ammonium picrate - ammonium salt of picric acid - has a lower sensitivity to shock than even TNT, owing to which the United States started to use it from 1900 for filling armor-piercing projectiles of a 10 inch and larger caliber. Later on, they started to use it also as a filler for aircraft bombs.

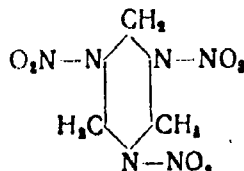
5. Tetryl. The chemical name is trinitrophenylmethylnitramine. Its formula is:



The solidification temperature of the pure substance is 128.7°. The solidification temperature of commercial tetryl should be no less than 127.7°. The specific gravity is 1.78 g/cm<sup>3</sup>.

A density of  $1.68 \text{ g/cm}^3$  can be attained by pressing the tetryl. The ignition temperature is around  $190^\circ$ . The sensitivity to shock is around 50% with a 10 kg weight and drop height of 25 cm. The expansion in a lead bomb is  $340 \text{ cm}^3$ . Brisance, as determined by testing on lead cylinders, is 20 - 21 mm. The detonation velocity is 7770 m/sec at a density of  $1.61 \text{ g/cm}^3$ . The sensitivity to detonation is greater than that of picric acid. At a density of  $1.68 \text{ g/cm}^3$ , tetryl can still be detonated by a blasting cap with 0.54 g of fulminate of mercury. As can be seen from these data, tetryl is more brisant than any of the previously described nitrocompounds. Its sensitivity to detonation and density attained by pressing is greater than that of TNT. On account of these superior qualities, tetryl is particularly suitable for the production of detonators and blasting caps. Owing to the high sensitivity of tetryl to mechanical effect, it is not suited as a shell filler except for small caliber ones, in which it is used in both the pure and flegmatized form. Tetryl alloys with TNT or cyclonite are also used as fillers for some munitions.

6. Cyclonite. The chemical name is cyclotrimethylenetrinitramine. The chemical formula is:



It is obtained by nitrating urotropin.

The melting temperature of cyclonite is  $203.5^{\circ}$ . Its density is  $1.82 \text{ g/cm}^3$ . The ignition temperature  $230^{\circ}$ . The sensitivity to shock is somewhat lower than that of PETN. Expansion in a lead bomb is  $480 \text{ cm}^3$ . In a standard brisance test, cyclonite, analogously to PETN, produces a complete deformation of the lead column. An 18 mm contraction is produced with a 25 gram charge. Its detonation velocity at a density of  $1.70 \text{ g/cm}^3$  is equal to 8370 m/sec.

Cyclonite and the previously-described PETN are the most powerful and most brisant of all the chemically homogeneous solid explosives which are in use today. It is flegmatized by paraffin, wax, ceresin, and other substances, so that its sensitivity to shock and friction would be reduced. It is also flegmatized by di- and trinitrotoluene, as well as by other nitrocompounds. Flegmatized cyclonite can be pressed to a density of  $1.65 \text{ g/cm}^3$ .

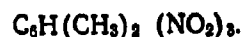
Cyclonite melts with dissociation. In addition, at a high melting temperature ( $203.5^{\circ}$ ) its sensitivity to shock and friction is greatly increased. Therefore, the filling of ammunition by cyclonite is not done by pouring, but only by pressing.

On account of the high sensitivity of the pure explosive to mechanical effect, only flegmatized cyclonite is used for pressing. When used in such form, detonators, shaped charge, and small caliber projectile charges are pressed from it.

Analogously to PETN, pure cyclonite is used only for the production of blasting caps.

Cyclonite has an important use in the form of a mixture with other nitrocompounds, as, for instance, with TNT, as a filler for various ammunition. These mixtures are less sensitive than cyclonite, and they have a greater strength than TNT. They can be poured (in the form of a suspension of cyclonite in melted TNT).

7. Xylyl (trinitroxylenes). The formula is:

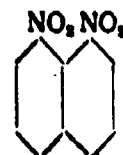


Depending upon the degree of purity, the commercial product contains a greater or lesser amount of various isomeric trinitro derivatives - ortho- and p-xylene. The solidification temperature of purified xylyl is  $170 - 178^\circ$ . Xylyl is a neutral substance which does not form salts with metals. The ignition temperature is around  $330^\circ$ . The sensitivity to shock is greater, and the sensitivity to detonation is markedly lower, than that of TNT. The expansion in a lead bomb is  $270 \text{ cm}^3$ . The contraction of the lead cylinders is 12 - 13 mm. Xylyl is used as an ammunition filler in the form of a mixture with ammonium nitrate and as an alloy with TNT (Alloy L). This alloy contains 95% TNT and 5% xylyl. Its solidification temperature is  $74^\circ$ . Alloy L does not have any explosive properties which are different from TNT, but it is characterized by a much better sensitivity to detonation, which is caused by its finely-crystallized structure.

8. Dinitronaphtalene. The chemical formulas of both isomers of dinitronaphtalene are:



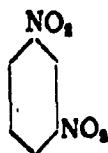
1.5 dinitronaphthalene



1.8 dinitronaphthalene

Commercial dinitronaphthalene consists of a mixture of these isomers. The sensitivity of dinitronaphthalene to detonation is very small. Therefore, it is not used in the pure form, but only in a mixture with ammonium nitrate, called dinaphtalite. This mixture is used as a filler for both ammunition and commercial blasting operations.

9. Dinitrobenzene. The chemical formula is:



The solidification temperature of *m*-dinitrobenzene is 89.9°. The solidification temperature of commercial dinitrobenzene is lower on account of the presence of the isomers contained in it.

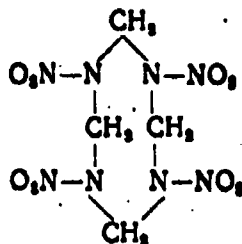


These isomers are ortho- and p-dinitrobenzene. The density is 1.57 g/cm<sup>3</sup>. The detonation velocity is 6100 m/sec, and expansion in a lead bomb is 250 ml.

The use of pure dinitrobenzene for filling shells is difficult, owing to its small sensitivity to detonation. Another drawback of dinitrobenzene is its toxicity. Heretofore, we (Russians) used an alloy of TNT with 2% dinitrobenzene and 4% naphthalene as a filler for armor-piercing projectiles used in naval and seacoast artillery guns. Alloys consisting of large amounts of dinitrobenzene are not suitable as a filler on account of the low melting temperature.

10. New and Powerful Explosives. Tetryl, PETN and cyclonite, which, in strength, greatly exceed TNT and other aromatic nitro-compounds and ammonium-explosives, are referred to as "powerful" explosives. Judging by the present pertinent literary data, new explosives are being found at the present time. The most interesting appear to be octogen, ethylenedinitramine and dinitroxy-diethylnitramine.

Octogen is



is obtained from urotropin by the action of concentrated nitric acid on it in the presence of acetic acid. The stability in heating is greater than that of cyclonite. Its explosive qualities are close to that of cyclonite.



It is equal to tetryl in force of explosion and sensitivity to mechanical action. In comparison with tetryl, it is less toxic and does not have any coloring properties.

Dinitroxydiethylnitramine -  $\text{O}_2\text{N--N}(\text{CH}_2\text{CH}_2\text{ONO}_2)_2$ . Sensitivity to shock is on the order of PETN. It is close to PETN and cyclonite in explosive force. It readily gelatinizes nitrocellulose.

#### 4. EXPLOSIVE MIXTURES

The classification and general characteristics of explosive mixtures were given on page 34.

1. Ammonium nitrate Explosives. Definitions.<sup>23</sup> Ammonium nitrate explosives are those mixtures whose basic component is ammonium nitrate.

The oxidizer in ammonium nitrate explosives is ammonium nitrate. The igniter can be various substances, explosive (TNT, xylyl, and other nitrocompounds) as well as non-explosive (wood meal or some other organic meal, aluminum, pitch, etc). Certain special admixtures such as sodium chloride enter into the com-

position of individual ammonium nitrate explosives. This type of explosive is used in gas wells, etc.

Ammonite is an ammonium nitrate explosive which contains an explosive nitrocompound.

Dynammon is an ammonium nitrate explosive which contains, in addition to ammonium nitrate, only non-explosive combustible materials.

Ammonal is an ammonium nitrate explosive which contains aluminum in its composition.

Ammonium nitrate. The properties of ammonium nitrate explosives depend to a large extent upon the properties of their basic component - ammonium nitrate. It is a white, crystalline substance with a melting point of  $169.5^{\circ}$ .

Ammonium nitrate exists in the form of several crystal modifications. Four of these, which change one into the other at temperature of  $-16$ ,  $+32$ , and  $+87^{\circ}$  (transition points) are the most important by their effect on the properties of ammonium nitrate explosives. Not only the shape of the crystals, but also their size and specific volume are changed during transition.

Ammonium nitrate is very hygroscopic. Water vapors, which are absorbed from the atmosphere, condense on the surfaces of separate crystals and dissolve the surface layer of salt with the formation of a saturated solution. When the vapors evaporate (in the case of a reduction in the relative moisture of the air), crystals are separated out of the saturated solution, which then fasten themselves to the adjoining particle of niter. As

the result of a repeated humidifying and drying, the niter crystals are bonded all the more solidly, and a process of densification and caking of the ammonium nitrate takes place. After prolonged storage at varying humidity, the niter converts into a monolith, and it is then granulated with difficulty.

The sensitivity of ammonium nitrate to detonation is very small. Accordingly a stable detonation of it can occur only with a large diameter of the charge or by enclosing it in a solid case (page 78 of original).

The composition of ammonium nitrate explosives. Numerous compositions (formulas) for ammonium nitrate explosives and some of their valuable properties were known for long time prior to the First World War. In World War I, after a grave defect was discovered in explosives, the suitable ammonium nitrate explosive formulas were quickly put to use and the filling of ammunition with these explosives was adopted. Mixtures of ammonium nitrate with TNT, called amatols, assumed the greatest importance from the very beginning and have been in constant use up to the present day. These mixtures contain from 40 to 80% niter and from 20 to 60% TNT.

Filling by the screw-in method, which was developed after World War I, made it possible to widen the assortment of ammonium nitrate explosives suitable for ammunition. In addition to the amatols, it was possible to use other ammonium nitrate explosives for fillers, particularly some of those which were produced for commercial blasting operations.

Table XXII lists some of the typical ammonium-nitrate ex-

plosives intended for blasting operations.

Safety explosives, a representative of which is shown in Table XXII, are used for operations in coal mines which are gas and dust hazardous. Their formula is selected in such a way that no inflammation of the gas-air and dust-air mixtures would occur. This is accomplished by reducing the brisance and fugacity effect and explosion temperature by the insertion of sodium chloride into the composition. There is a requirement in safety as well as in other explosives which are permitted for underground operations that the amount of toxic gases ( $\text{NO}_2$  and  $\text{CO}$ ) which are formed at explosion does not exceed the prescribed norms.

The production of ammonium nitrate explosives. Amatols with a content of 40 to 60% TNT are obtained by mixing melted TNT with heated, preliminarily dried and pulverized ammonium nitrate. The TNT does not form any alloys with the ammonium nitrate, but a gruel-like suspension of the ammonium nitrate particles is obtained in the molten TNT, which is then in a suitable condition to be poured as ammunition filler. After this pasty mass cools, a conglomerate is formed which consists of the solidified TNT containing the ammonium nitrate particles within it.

If the amatol contains less than 40% TNT, it then does not form a mixture of gruel-like consistency which is suitable for pouring into ammunition. Such mixtures fill ammunition by means of a mechanical method (pressing, screwing-in).

Powdered ammonium nitrate explosives are obtained by grind-

TABLE XXII

Typical representative of ammonium nitrate explosives which are used for commercial blasting operations.

Name of explosive	Composition in %		Density under conditions of the explosive's use, in g/cm <sup>3</sup>	Expansion in lead bomb in ml	Brisance according to contraction of lead cylinder, in mm	Detonation velocity in m/sec
	Ammonium nitrate	Other components				
Ammonite No .6 , powdered	79	TNT 21	1,0—1,15	360	14	—
Ammonite No .6 , pressed	79	Same	1,25—1,35	360	20	3800
Ammonite No .7	81	TNT 14 , pine bark meal	1,0—1,1	350	13	4070
Granulated dinaphtalite	88	Dinitronaph-talene 12	1,0—1,25	320	15	—
Alumite No .1	80	Trotil 12 , aluminum 8	0,95—1,05	400	16	—
Dinamon	90—88	Organic meal 10-12	0,9	330	11	2500
Safety ammo-nite	68	TNT 10 , sodium chloride 10-12 , oil-cake or pine tar meal, 2 .	1,0—1,15	240	11	2870

<sup>1</sup> pulverized pine bark or peat , etc .

Note: Comma represents decimal point.

ing previously-dried ammonium nitrate and combustible materials with subsequent intermixing of them in drums (spherical grinders). The mixing is sometimes done under millstones, through which a finer pulverization is attained at the same time. This increases the density, detonation velocity and brisance.

Properties and use of ammonium nitrate explosives. The presence of ammonium nitrate in the composition predetermines the hygroscopy and caking tendency of ammonium nitrate explosives, this being their intrinsic defect. Niter, covered by a thin film of water-repellent substances is used in order to reduce the hygroscopy. Caking can be lowered by inserting certain loosening admixtures such as oilcake meal, pitch, etc. into the explosive's composition.

The explosive properties of ammonium nitrate explosives depend upon the nature of the components, weight relation among them, method of production of the explosive, degree of pulverization, and intermixing (see Table XVII on page 79 of original), density of the charge, and degree of caking.

When ammonium nitrate is added to TNT, the brisance is somewhat reduced, but the fugacity effect is somewhat increased. The fugacity increases with an increasing content of ammonium nitrate in the mixture. Therefore, where earth, wood-earth and analogous fortifications are to be destroyed, and requiring a large fugacity effect, the use of amatol is possible. Conversely, in direct fire against a solid mass such as an armored object where brisance effect is needed, it is necessary to use projectiles

filled with TNT or some other more powerful explosive.

The sensitivity of ammonium nitrate explosives to detonation is reduced in proportion to their caking tendency. Therefore, it is necessary to prepare ammonium nitrate explosives for a prolonged storage (multiyear), and munitions are filled with these explosives only during time of war, when they are rapidly used up.

In comparison with other explosive mixtures, ammonium nitrate explosives are characterized by a lower sensitivity to mechanical effects. On account of this and also on account of their low cost and satisfactory fugacity and brisance effects, they are widely used as a filler for many types of munitions. For those very same reasons, they find a wide application, and, in the Soviet Union a practically exclusive application, for commercial blasting operations.

During the Great Patriotic War, the largest amounts of ammonium nitrate explosives were consumed for medium-caliber projectiles. Heavy-caliber projectiles (besides armor-piercing for naval and coast artillery guns), aircraft bombs and marine obstacle mines were filled with amatols 40/60, 50/50 and 60/40 by the pour method.

When filling ammunition with ammonium nitrate explosives, a density of 1.45 to 1.55 g/cm<sup>3</sup> is effected. This greatly lowers the sensitivity to detonation. Therefore, it is necessary to initiate this explosive by a more powerful detonator than one that is used for initiating a TNT charge. This feature is taken



into consideration when selecting fuzes for ammunition which has been ~~filled~~ with nitrate explosive in wartime.

2. Chlorate and Perchlorate Explosives. Chlorate and perchlorate explosives consist of a mixture of chloric or perchloric acid salts with a combustible. The most widely used are  $\text{KClO}_3$ ,  $\text{KClO}_4$  and  $\text{NH}_4\text{ClO}_4$ .

Chlorate explosives draw attention to themselves, because the oxidizer contained in them, Berthollet's salt, can be readily obtained in large quantities from abundant raw materials. However, their capability to be used as ammunition fillers is strictly limited on account of the great sensitivity to mechanical effects. They were used in World War I in France, England and Germany for filling mortar and bomb-thrower projectiles, which are characterized by a low initial velocity and corresponding low stresses in the bursting charge.

3. Explosives on a base of liquid oxidizers. Oxyliquits and mixtures on a base of nitrogen dioxide or nitric acid belong to this category of explosive mixtures.

Oxyliquits are cartridges of a combustible component - absorber - which has been impregnated with liquid oxygen. The impregnation of oxyliquit cartridges for military-engineering or commercial blasting operations is done immediately prior to their use. Such cartridges, as the result of a vigorous vaporization of the liquid oxygen, lose their explosive properties relatively quickly. In relation to the cartridge size and conditions of use

its "life span" consists from several minutes to 1-1½ hours. This singularity of oxyliquits precludes their use in munitions.

Explosive mixtures on a base of nitrogen dioxide have great strength, but on account of a high sensitivity, volatility, and pronounced toxicity, their use is limited. They were used in France during World War I as an aircraft bomb filler. Nitrobenzene, liquid hydrocarbons and other organic substances were used as the combustible. Both components were inserted separately, and they were intermixed by means of a special mechanism after they were dropped from the aircraft.

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## SECTION V

### COLLOID POWDERS

#### 1. General Information

Combustion is a characteristic form of explosive transformation of powders. It is a well-known fact that the rate of combustion of a powder is increased with an increase in pressure. Nonetheless, even upon firing from a weapon, where the pressure can go up to 3000 at, an increase in the combustion rate does not present any danger with respect to damaging the barrel.

It would turn out differently if the weapon were to be loaded with an equal amount of high explosive instead of powder. In this case, a rapid rise in the pressure would take place, and the combustion would convert into detonation, whereupon the barrel of the weapon would burst.

The ability to have steady combustion at high temperatures is determined by the physical structure of the powder elements - their density, stability, and absence of pores (or by a small quantity of them). In connection with this, the combustion proceeds only along the surface of the powder, which burns in parallel layers. This makes it possible to control the powder combustion process in the weapon by a suitable selection of the sizes and shapes of the powder elements. Figure 50 shows the curves for changes in pressure, developing in the bore of a weapon at firing. The x-axis shows the travel of the projectile and the y-axis the pressure in the bore.

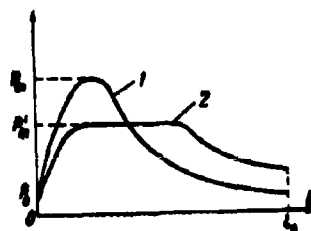


Fig. 50 - Curves for the pressure developing in the bore at firing

At the origin, the coordinate corresponds to the initial position of the base of the projectile. As the combustion develops, the pressure in the initial air-space will begin to rise, and at a certain moment, it will cause the projectile to be set in motion along the bore, overcoming inertia and bite of the rotating band in the rifling.

A rapid rise in the pressure occurs in the initial period of the projectile's travel, attaining a certain maximum  $P_m$ . From this moment, the pressure begins to fall on account of the fact that the volume of the initial air-space grows more rapidly than the influx of the powder gases. After completion of combustion of the powder, the velocity of the projectile continues to rise under the action of the expanding powder gases.

The work of the expansion of the powder gases, upon which the muzzle velocity of the projectile depends, is equal to the work of

the force propelling the projectile along the tube, i.e.

$$L = S \int_0^{L_0} p dl,$$

where  $S$  - the cross section of the projectile upon which the powder gases press;

$L_0$  - bore length (distance from beginning of rifling to muzzle face).

The same work can be accomplished for different values of the maximum pressure  $P_m$  in relation to the law of gas formation during the combustion of powder. This can be readily seen from a comparison of curves 1 and 2 in Figure 50. Curve 2, for which the value  $P_m$  is minimum at a constant value  $L_0$ , is the ideal pressure curve.

One of the fundamental needs set forth for a powder is that it should burn in parallel layers; only in this case is it possible to control the gas influx by a selection of the size and shapes of the powder elements, and to make sure that the necessary ballistics firing indexes are obtained. It is obvious that, with random combustion rates which change from one round to another, it is necessary to obtain uniform ballistics results. Colloid powders fully satisfy this requirement, while black powder does this only at a density of 1.8 g/cm<sup>3</sup> and above. However, the preparation of such a powder is difficult.

## 2. Classification of Colloid Powders

Cellulose nitrates - nitro-celluloses (see below) - are the basic colloid powders. Depending on the solvent used for gelatinizing the pyroxylin, colloid powders are divided into two basic groups:

1. Pyroxylin powders on a volatile solvent which is almost completely removed from the powder during production.

2. Powders on a difficult-to-volatilize solvent, all of which remains in the powder.

Nitroglycerine and diglycol powders are the most important representatives of powders on the difficult-to-volatilize solvent.

Nitroglycerine powders are, in turn, divided into ballistites and cordites.

Ballistites are powders produced on a base of nitroglycerine-dissolved pyroxylin with a low nitrogen content, called colloxylin.

Cordites are powders which are produced on a base of pyroxylin with high content of nitrogen, or containing a large amount of colloxylin. In both of these cases, the nitroglycerine entering into the composition of the powder does not assure a complete gelatinization of the nitro-cellulose. A supplementary volatile solvent, which is removed from the powder during later stages of production, is used for complete gelatinization. Acetone is used as the volatile solvent for high-nitrogen pyroxylin, while an alcohol-ether mixture is used for colloxylin.

Beginning with World War II, many countries started to use

diglycol powder, added to the nitroglycerine ballistites in composition and properties, but containing diethyleneglycol-dinitrate instead of nitroglycerines.

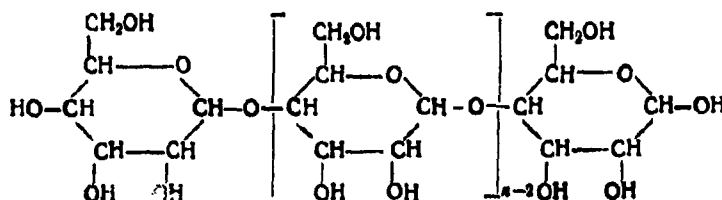
### 3. MATERIALS USED IN THE PRODUCTION OF COLLOID POWDERS.

The properties and method of obtaining nitroglycerine and dinitroglycol were described on

1. Pyroxylin is a nitric acid ester, or cellulose nitrate, which is also called nitro-cellulose.

Cellulose is used for the production of pyroxylin. It is found in cotton, wood, flax, hemp, straw, etc., in amounts varying from 92-93% (cotton) to 50-60% (wood). Pure cellulose, which is obtained from the plant raw material by a special chemical treatment, is used for the production of high-quality pyroxylin.

A molecule of cellulose consists of a large number of identically formed and interlinked glucose radicals  $C_6H_{10}O_5$ :



Therefore, the general formula for cellulose has the form  $(C_6H_{10}O_5)_n$ , where  $n$  is the number of glucose radicals. Cellulose does not

consist of identical molecules of a specific length, but of a mixture of molecules with varying amounts of glucose radicals, which, according to the data of various researchers, fluctuate from several hundred to several thousand. In writing the chemical reactions, it is conventional to express cellulose by the formula for the glucose radical  $C_6H_{10}O_5$ .

Every glucose radical contains three hydroxyl groups OH. Namely, these hydroxyl groups react with nitric acid according to the equation:



where  $m$  is 1, 2, or 3.

As a result of this reaction, the OH groups are replaced by  $ONO_2$  groups, called nitrates. Depending on the conditions, not all of the OH groups can be replaced by the nitrate groups, but only a part of them. For this reason, not one, but several pyroxyline with various degree of esterification, are obtained.

Cellulose is not nitrated by pure nitric acid, but with a mixture of this acid with sulfuric acid. The reaction of the cellulose with the nitric acid is accompanied by the separation of water. The water dilutes the nitric acid, which weakens its nitrating action. However, the sulfuric acid takes up the water, which then cannot impede esterification.

The more concentrated the acid mixture, i.e. the lower the water content, the greater is the degree of the cellulose esterification. Pyroxylin with a prescribed degree of esterification



can be obtained by a suitable choice of the composition of the acid mixture.

Forms of nitrates of cellulose. The structure of cellulose should be expressed by some definite formula, because it is not homogeneous with respect to amount of molecules. This pertains to a still greater degree to nitrates of cellulose which consist of molecules which are not homogeneous in degree of esterification.

Therefore, nitrocellulose is characterized by the nitrogen content in it, determined by chemical analysis or by the degree of esterification (number of nitrate groups found, on the average, in the glucose radical).

For practical reasons, the following forms of nitrocellulose which are used in powder production, are differentiated:

- a. Colloxylin. Nitrogen content is 11.5-12.0%. Completely soluble in ether-alcohol mixtures.
- b. Pyroxylin No. 2. Nitrogen content is 12.05-12.4%. At least 90% of it is dissolved in ether-alcohol mixtures.
- c. D. I. Mendeleev Pyroxylin. Contains 12.45% nitrogen. Solubility is at least 95% in ether-alcohol mixtures.
- d. Pyroxylin No. 1. Nitrogen content is 13.0-13.5%. Solubility in ether-alcohol mixtures is from 5 to 10%.
- e. Blended pyroxylin. These consist of a mixture of Pyroxyline No. 1 and No. 2, and contain from 12.7 to 13.1% nitrogen. The solubility in ether-alcohol mixtures is 25 to 50%. The propagation between the two types of pyroxylin in the mixture

various for different powders.

**Pyroxylin Production.** The production of pyroxylin consists of the following operations: nitration of the cellulose, washing and stabilization, composition of aggregates, finishing treatment.

**Nitration of Cellulose.** The cellulose is immersed in a mixture of nitric and sulfuric acids and it is stirred in this mixture for a predetermined time at a prescribed temperature.

**Washing and stabilization of nitro cellulose.** After the nitration is finished, the acid is removed from the formed pyroxylin in a centrifuge. Generally, a quantity of spend acid, which is approximately equal to the pyroxylin by weight, remains in it after centrifuging.

The biggest part of this acid is removed by washing in cold water. After this, the pyroxylin contains the following residues:

- a. an insignificant amount of sulfuric and nitric acids (around 1%):
- b. various slightly stable admixtures which were formed during nitration (sulfuric acid esters of cellulose and nitric acid esters of saccharine substances).

The process of removing these admixtures, called stabilization, consists of the following:

- a. Hot washing in vats. An acid bath is performed at first. A 0.5% solution of sulfuric acid is used in order to accelerate the disintegration of the slightly-stable admixtures, and after that, by an alkali (with soda admixture) in order to neutralize the acid. All of these washings are done through boiling.

b. Pulverization in a hollander. Pyroxylin consists of separate fibers, being narrow capillaries, which, during nitration, are occluded with acid. This acid is very difficult to remove from the fiber by washing. In order to remove this acid, it is necessary pulp the fibers so that their inner cavities could be exposed. In addition, pulped pyroxylin can be more readily processed in powder production, and the powder which is obtained is more homogeneous.

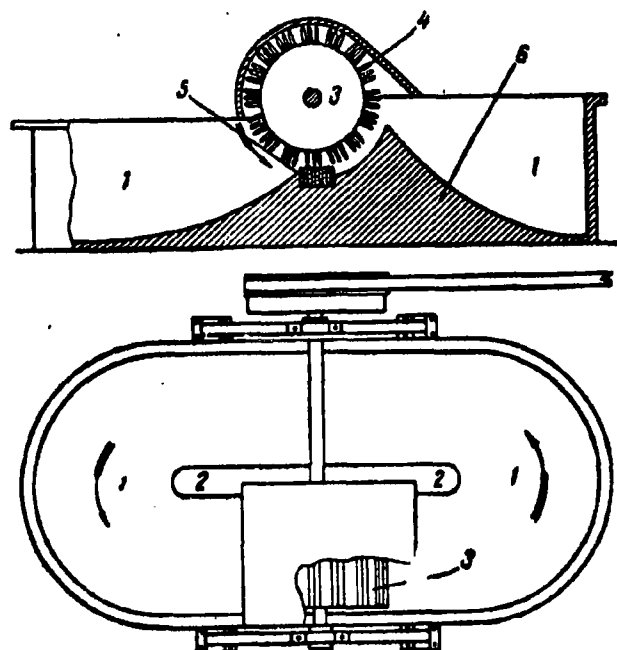


Fig. 51 - Diagram of Hollander

- |                      |                                     |
|----------------------|-------------------------------------|
| 1. hollander trough  | 2. longitudinal baffle              |
| 3. drum              | 4. drum knives                      |
| 5. stationary knives | 6. inclined trough bottom (hillock) |

The pyroxylin is pulverized in hollanders between the knives which are fastened to the revolving drum and the stationary knives which are mounted in the hollander trough. The construction of a hollander is schematically shown in Figure 51.

c. Poaching in scrubbers. When the cellulose is pulverized in the hollanders, not only acid residue, but also the slightly-stable admixtures which were not disintegrated in the hot workings are separated out of the fiber. The pulped pyroxylin is therefore subjected to poaching in a scrubber. Figure 52 shows the construction of a scrubber.

The above-described complex and lengthy process of washing, pulverizing and poaching is necessary for obtaining a chemically stable pyroxylin, which is one of the basic conditions for subsequently obtaining a chemically stable powder which is suitable for prolonged storage.

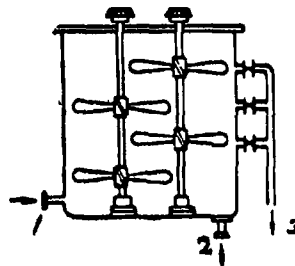


Fig. 52 - Scrubber (diagram)

1. steam 2. pasty mass 3. water

Composition of the aggregate batch. Individual batches of pyroxylin are somewhat different in properties. So that a homogeneous material could be obtained, it is necessary to intermix several batches into one big one, called the aggregate batch. In addition, such an intermixing is necessary for obtaining blended pyroxylin from the various forms of nitrocellulose (for instance, from pyroxylin Nos. 1 and 2).

The pyroxylin batches are mixed in iron or iron-concrete mixers.

Finishing treatment of pyroxylin. After mixing the pyroxylin, the random admixtures and large quantity of water have to be removed from it. This is done in the following manner:

a. the water-soaked pyroxylin is passed through a screen so that it could be separated from the non-metallic admixtures, and through an electromagnetic field so that iron filings and chips could be removed.

b. the batch coming from the electromagnets contains up to 90% water, which is removed at first by wringers or, more frequently, by means of settling the pyroxylin and then decanting the water, and then centrifuging, where the water content in the pyroxylin is reduced to approximately 30%. The pyroxylin is then ready for powder production.

2. Nitrocellulose Solvents. Nitrocellulose solvents are substances which form plastic, colloidal systems with the nitrocelluloses. Ethyl alcohols and simple ethers are not solvents

for nitrocelluloses used in the powder industry - they only cause them to swell up.

A mixture of ethyl alcohol with diethyl ether (ether-alcohol mixture) proves to be a good solvent for colloxylin, pyroxylin No. 2 and collodion. This mixture is widely used in the powder industry.

Acetone is the most effective solvent. It gelatinizes all nitrocelluloses, from colloxylin to pyroxylin, with the highest degree of esterification.

Nitroglycerine and diglycol dinitrate are solvents for colloxylin.

3. Stabilizers. Diphenylamine ( $(C_6H_5)_2NH$ ) is used as a stabilizer in pyroxylin powders.

The stabilizing effect of diphenylamine is based on the fact that it readily reacts with the initial products of the decomposition of nitrocellulose - nitrogen oxides and nitric and nitrous acids - forming chemically stable nitroso- and nitrocompounds.

Diphenylamine acts in a saponifiable manner on nitrocellulose, even more intensely on nitroglycerine and dinitrodiglycol. It is allowed in pyroxylin powders in an amount not exceeding 2%, while it is not at all permitted in powders on a difficult-to-volatilize solvent.

Derived ureas - centralites - are used as stabilizers in powders on a difficult-to-volatilize powder. They can also readily react with the nitrogen oxide and nitric and nitrous acids, forming chemically-stable nitroso- and nitrocompounds. Centralites

are white, crystalline substances, soluble in nitroglycerine.

4. Plasticizers. Supplementary solvents, which accelerate the gelatinization process and which remain in the ready powder, are generally used in the production of powders with a difficult-to-volatilize solvent. Such substances are called plasticizers. Non-volatile substances such as dinitrotoluene, dinitroanisole and others are used as plasticizers. Centralites is a simultaneous plasticizer and stabilizer.

5. Flegmatizers. These are substances which reduce the combustion rate of a powder. Camphors, for instance, are used as flegmatizers.

Camphor is a solid, volatile substance with a characteristic odor. It is difficult to dissolve in water, but dissolves readily in alcohol.

6. Graphite. Finely-granulated and laminated powders are covered with a thin film of graphite so that electrification of the powder and blocking of the grains would be eliminated. In addition, graphiting increases the gravimetric density. For instance, graphiting made it possible to increase the gravimetric density of rifle-cartridge powder from 0.5 to 0.7 kg/decimeter<sup>3</sup>; thereby the capacity of the cartridge case was increased from 2.5 to 3.48 g of powder.

#### 4. Production of Pyroxylin Powders

The production of pyroxylin powders consists of the following

operations (for cannon powders):

1. dehydration of the pyroxylin,
2. mixing the pyroxylin with solvent,
3. blocking,
4. preliminary sun-drying,
5. cutting,
6. second sun-drying,
7. separating (sorting),
8. soaking,
9. drying,
10. composing small batches,
11. composing aggregate batch,
12. packing,
13. physico-chemical and ballistics tests.

In the production of rifle-cartridge powders, flegmatization, graphiting, separation of the graphited powder, second drying, mixing of small and aggregate batches, packing, and physico-chemical and ballistics tests are carried out after it has been dried.

Dehydration of pyroxylin. Water hinders the swelling of pyroxylin; it is therefore necessary to reduce its content to some definite limit (no more than 4%). In this case, it is necessary to directly dry by hot air on account of the danger of inflammation and explosion. Pyroxylin can be dehydrated by alcohol, which dislodges the water easily.

The role of alcohol during dehydration of pyroxylin is not



limited to the dislodgement of water. Alcohol dissolves the low-nitrogen cellulose nitrates and the unstable admixtures, which increases the nitrogen content in the pyroxylin and increases its chemical stability.

Mixing the pyroxylin with the solvent and pressing. The basic phase of production, where the pyroxylin is converted into powder, is the gelatinization process which takes place during the mixing of the pyroxylin with solvent and blocking.

In the first stage, the pyroxylin particles soak up the solvent and swell up. This operation is carried out in special blenders into which the alcohol-dehydrated pyroxylin, a corresponding amount of ether (in the case of necessity, alcohol is added), and stabilizer are loaded. A more or less homogeneous, jelly-like block is formed.

The block is then placed into a steel die where it is extruded into powder tubes, strips, ribbons, cords, etc. of a given size. The pressure of pressing is within limits of 300 - 500 kg/cm<sup>2</sup>. The gelatinization process of the powder block terminates during the pressing. The block becomes compact and transparent.

A powder blocking die for a tubular grained powder (Figure 53) is a steel cylinder which contains a recess for the needle holder in the upper part. The recess has a conical passage which is attached to the cylinder mouth. The needle is positioned along this axis.

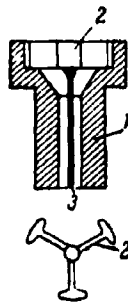


Fig. 53 - Powder blocking die for tubular-grained powder

1. steel cylinder      2. needle holder      3. needle

The die for blocking powder with 7 perforations (Fig. 54) has seven needles instead of one. The cross sectional area of the opening through which the powder block enters the conical area should be much larger than the cross sectional area of the cylinder mouth of the die. In a contrary case, the powder block will not be sufficiently compressed. The block will not hold together after it has been disunited by the needles, and the powder will then be of a dissimilar mechanical stability.

The blocked powder is subjected to shrinkage in further operations, i.e. the initial sizes are decreased. The amount of shrinkage depends primarily upon the solvent content. It also depends on the quality of the pyroxylin, blocking conditions, etc. It has been established by practice that thickness shrinkage is, on the average, equal to 30 - 35%. The die sizes are selected with a consideration for subsequent shrinkage of the powder.

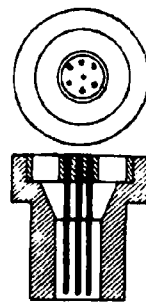


Fig. 54 - Powder blocking die for powder with 7 perforations

Preliminary sun-drying and cutting of the powder. The powder coming out of the die contains around 40% of the ether-alcohol solvent, and it is therefore easily deformed. When cutting it, it is necessary to give it some mechanical stability by a partial removal of the solvent, which is done by the so-called sun-drying.<sup>24</sup> After solvent recovery, a large amount of solvent still remains in the powder, which is needed so that burrs, chips, cracks, etc. would not appear during cutting. The cutting of cords or tubes for powder elements is done on special machines.

A particle element is a particle of powder of a prescribed form and size (tablet, cord, tube, etc.). Powder elements which are friable are called grains.

Second sun-drying and separation of powder. The powder still contains a lot of solvent after cutting, which is reduced to approximately 15% by a second solvent recovery operation, and, after that, it is separated (sorted); thereby dust, powder elements of irregular shape or size, etc. are removed.

Soaking. The solvent content in the ready powder should be reduced to 0.5 - 5% (depending on the web thickness). However, this is very difficult to do by drying, because when the solvent content is less than 15%, the drying rate drops rapidly. The external layers of the powder dry quicker, the pin holes are covered up, and it becomes more difficult for the solvent to get out of the layer. Therefore, water soaking is used. In soaking, the pin holes in the surface layers are not covered over and the

solvent is removed quickly. When the powder is not soaked thoroughly, it has a decreased density, which worsens its ballistic quality.

Drying. After the powder has been soaked, it is dried at a temperature of about  $50^{\circ}$ , so that the moisture absorbed during soaking can be removed.

Finally, after drying, where the powder is generally over-dried, the powder is lightly humidified (keeping it in a damp atmosphere) so that the moisture content could be brought to the norm prescribed by technical conditions.

Composition of the Aggregate Batch. The dry powder which has been obtained in separate apparatus is then intermixed so that a homogeneous aggregate batch could be formed. The ready batch is packed into hermetically-sealed cases (galvanized iron chest), so that a constant content of the residual solvent and moisture could be preserved in the powder. This is necessary in order to maintain unvarying ballistic properties.

#### 5. Powders on Difficult-To-Volatilize Solvent

Table XXVIII shows, in the nature of an example, the compositions of four brands of powders on a solvent which is difficult-to-volatilize.

Powder elements on a difficult-to-volatilize solvent are produced in the form of tablets, cords, tubes, rings, disks, or ribbons without perforations.

TABLE XXVIII

Examples of powders on a difficultly-volatile solvent

Name of components	Content of components in %			
	Cordite	Ballistite	Diglycol powder	Nitroguanidine powders
Blended pyroxylin	65	—	—	—
Colloxylin	—	58,5	66	42
Nitroglycerine	29,5	30	—	—
Dinitrodiglycol	—	—	23,0	18,5
Nitroguanidine	—	—	—	30,0
Centralite	2	3	5,7	1,1
Other stabilizers	—	—	1,5	0,5
Other plasticizers	—	—	4,1	7,7
Dinitroderivatives	—	7,5	—	—
Vaseline	3,5	1	—	—
Acetone (above 100%)	1,5	—	—	—
Moisture (above 100%)	0,5	0,5	—	—
Graphite (above 100%)	—	—	0,1	0,1
Potassium sulfate	—	—	1	—
Magnesium oxide	—	—	0,1	0,1

Note: Comma represents decimal point.

1. Nitroglycerine powders of the ballistite type. The powder components of the ballistite type are blended in warm water. This causes a swelling of the cellulose nitrates in the solvents.

After the water has been squeezed out, the powder block is repeatedly passed through hot rolls. A further, almost complete, water removal occurs, and the powder block gelatinizes and densifies. It is then rolled into rolls and extruded through an appropriate die into tubes or cords. The tubes and cords are then cut to the required sizes.

If the powder is desired in tablet form, it is passed through rolls (calenders) with a closely regulated clearance. The thin sheets which are obtained are then cut up into tablets of the desired size.

2. Diglycol powders of the ballistite type. The method of production is analogous to the ballistite-type nitroglycerine powders. By imbedding nitroguanidine into the composition of the glycol powder (see Table XXVIII), the combustion rate can be increased. This type of powder was used in the base charge of some multisection charges in the German Field Artillery Arm (see page 202).

3. Nitroglycerine powders of the cordite type. According to one of the methods for producing cordite powder, nitrocellulose and nitroglycerine are blended under water; then the water is squeezed out by rolls, the squeezed-out block is then transferred to the blender where acetone and other powder components are added.

After being processed in the blender, the powder block is rolled and blocked through dies into cords and tubes, which are then passed on to the cutters. Then the powder elements are dried so that the acetone can be removed.

## 6. Properties of Colloid Powders

1. Physical properties. The density of a powder, which is of great practical importance, depends primarily upon the composition. This density fluctuates from 1.56 to 1.65 g/cm<sup>3</sup> for various types of powders. Nitroglycerine powders have a density from 1.54 to 1.62 g/cm<sup>3</sup>.

The gravimetric density of granulated pyroxylin powders fluctuates from 0.6 to 0.9 kg/decimeter<sup>3</sup>. It depends upon the density of the powder, and sizes and shapes of the powder grains. The maximum possible charge at prescribed sizes of the shell case or powder chamber in the tube depends upon the gravimetric density.

Ungranulated powders (cords, tubes, etc.) are not firable, in their case, the maximum seating capacity, rather than the gravimetric density, is determined. This is the largest weight of cord or tube powder increments placed in a unit of volume (decimeter<sup>3</sup>) of the shell case without being forced in. The maximum seating capacity for monoperforated or cord powders attains 0.8 kg/decimeter<sup>3</sup>.

2. The content of moisture and residual solvent. The content of volatile substances in pyroxylin powders is of great



importance. The same is true of water in nitroglycerine powders. The volatile substances in pyroxylin powders are the residual solvent (alcohol, ether) and water. The water content in pyroxylin powders is usually from 1 to 5%, and the residual solvent content is from 0.5 to 5%, depending on the size of the powder grain.

Because it is difficult to determine the residual solvent and water separately, the overall volatile substance content, and the content of volatile substances which were removed by a six-hour drying of the powder at 95°, are determined. During this six-hour powder drying period, all of the water and a small amount of the residual content in nitroglycerine powders is 2 to 3 times lower than in pyroxylin powders.

3. Ballistic properties of powders. The ballistic properties of powders are evaluated by the muzzle velocity<sup>28</sup> of the projectile, maximum pressure of the powder gases, and the probable deviations of the muzzle velocities in a series of firings.

The ability of a powder to preserve the constancy of these three qualities during its prolonged storage is called the ballistic stability of a powder.

The probable deviations of the muzzle velocities of a projectile upon being fired from one and the same weapon depends upon the quality (homogeneity) of the powder, upon the accuracy of weighing and arrangement of the charge. Consequently, with accurate weighing and correct charge arrangement, the probable deviations characterizes the ability of the given powder to assure

uniformity of muzzle velocities, i.e. accuracy of fire.<sup>26</sup>

4. Electrification of colloid powders. The ability of powder grains to become easily electrified during blocking, where the static electricity voltage can reach 10,000 volts, is of practical importance from the point of view of safety engineering. An electric spark can originate at such a high voltage. This spark will not inflame the powder grains on account of the brevity of the electric charge, but it can ignite the powder dust. The burning of the dust can ignite the powder.

The hazard which is associated with electrification can be removed by grounding the metal parts of the devices with which powder operations are conducted, by removal of the powder dust from the work chamber or from the very powder itself (by screening), and by graphiting the powder grains.

5. Comparison of the properties of powders on a volatile and difficult-to-volatilize solvent.

a. pyroxylin powders can alter the moisture content and lose a part of the residual solvent to a much greater extent than nitroglycerine powders. Both of these factors lower the ballistic stability of pyroxylin powders in comparison with the nitroglycerine ones.

b. the production process of pyroxylin powders is quite long, which, in the case of granulated powders, is from 6 to 10 days, and in the case of some shapes of powders with a big web thickness, it can be more than a month. Conversely, in the

case of ballistite-type powders, fast production is characteristic (on account of the elimination of volatile solvent removal, sun drying and soaking processes, the production time is around 6 hours).

c. The shrinkage of powder elements on a volatile solvent is much greater than that of ballistite-type powders. Therefore, the shape of ballistite powder elements is more regular than of pyroxylin powders.

d. The powder elements of a ballistite type powder can be produced with a bigger web thickness than pyroxylin powder elements.

e. The calorific value of nitroglycerine powders can be changed within limits from 650 to 1300 kilocal/kg by an appropriate selection of the formula, whereas the heat value in pyroxylin powders can be changed within the relatively narrow limits of 700 - 1000 kilocal/kg.

f. The strength of some of the ballistite-type powders and of all the cordite powders is greater than that of the pyroxylin ones.

g. The cost of ballistite-type powders is 20 to 30% less than the cost of pyroxylin powder.

h. An intrinsic defect of some formulas for some ballistite-type powders and all cordite powders is the increased barrel erosion.

i. Nitroglycerine can, under certain conditions, ooze out

of the powder (this is called exudation), whereupon the ballistic properties are changed, and handling of the powder can become dangerous. The exudation of cordite powders occurs more readily and vigorously than that of ballistite-type powder. The production time of cordite powders is the same as that of pyroxylin ones.

j. A defect of nitroglycerine powders is the great danger during production in comparison with pyroxylin powder: the glycerine nitration and powder blocking operations are explosion-hazardous, and rolling of the powder block is sometimes accompanied by ignition.

## 7. Characteristics of powder elements and powder brands.

1. Shape of powder elements. Depending on the firearm, powders are prepared for them which are different from each other by composition, shape, and size of the powder element. With respect to shape of the powder elements, there are granulated, cord, monoperforated, rings, and those in the form of spirals.

The web thickness, perforation diameter, outside diameter, and length of the powder element are important characteristics of a powder element. The web thickness is the smallest wall thickness of a powder element: this is fixed this way so that a complete combustion of the powder charge would take place upon firing. The web thickness is the wall thickness in monoperforated powders or the thickness of the tablet in laminar powders, and,

in the case of grains with seven perforations - the distance along the diameter between the outside cylindrical surface of the grain and circumference of the perforation, and also by the circumferences of the perforations along the diameter, and along the straight lines which connect the centers of the perforations (Figure 55).

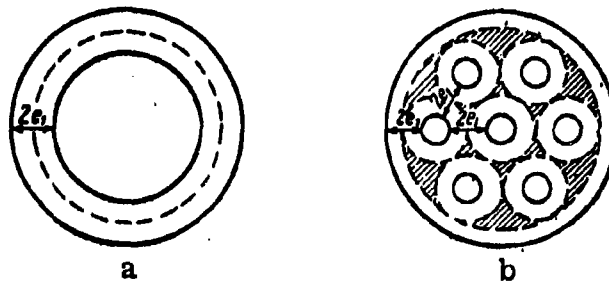


Fig. 55 - Cross sections of powder grains

- a. grain with one perforation (tube)
- b. grain with 7 perforations
- $2 e_1$ . web thickness

Depending on the shape of the powder element, its burning can be progressive or degressive.

Progressive burning is such a combustion where the rate of gas formation grows in proportion to the combustion of the powder. Progressive burning provides the best conditions for utilizing the energy of the powder in the gun by making it possible to get the highest muzzle velocity of the projectile at the lowest maximum pressure of the powder gasses in the gun. This last fact makes it possible to reduce the wall thickness of the tube and to

lighten the mount.

Conversely, degressive burning is that combustion when the rate of gas formation decreases in proportion to the deflagration of the powder.

In degressive burning of the powder, the maximum pressure in the gun has a much greater magnitude, but the work performed by the powder gases is reduced with the result that the live force of the projectile upon leaving the tube also decreases.

Progressiveness of burning can be obtained in colloid powders by choice of the shapes of the powder elements. The shapes of the powder elements, the surface of which is reduced during burning of the powder, is called degressive. When the surface of the powder is increased during burning, then the shape of the powder elements is called progressive.

It is quite obvious that, in the combustion of a powder which has a spherical, cubic or prismatic shape, the amount of gases being formed in a unit of time will be reduced in proportion to the burning of the powder. This is due to the continuous reduction of the burning surface. These are degressive.

During the burning of powder having the shape of long tubes (Fig. 55a), the outside surface of the tubes decreases, but the inside surface increases, thus compensating for the loss of the outside surface (the sum of the inside and outside diameters at any moment of the powder's burning is a constant value). Owing to the small effect of a decrease in the length of the tube, the burning surface of these powders remains practically constant.

This form of powder is on the borderline between progressive and degressive.

Strip-type powder (with a large value for the ratio of the length to the thickness) approximates a powder with a constant burning surface.

Finally, the grain with seven perforations (Fig. 55b) is characterized by an increase in the surface in proportion to burning of the powder, i.e. it is of the progressive type. The center perforation compensates the decrease of the outside surface of the grain, and, on account of burning in the remaining six perforations dispersed along the circumference, the burning surface increases. However, when the powder burns through, the grains fall apart and form 12 slivers: six smaller internal ones and six exterior ones of a larger size (in Fig. 55 these slivers are shaded by diagonal lines). Evidently, these parts, consisting of about 20% of the grain, burn degressively.

The shape of the powder elements for small arms (revolvers, pistols, rifles, machine guns) should provide for automatic cartridge loading; therefore, the powder should possess a satisfactory friability. With small dimensions of the cartridge and a need for long range fire, the powder should have a high gravimetric density (no less than  $0.7 \text{ kg/decimeter}^3$ ).

In the case of short-barreled weapons (revolvers, pistols, sub-machine guns), powder grains with a thin web (thin tablets) are used, which assure a quick deflagration of the powder. In the case of long-barreled firearms (rifles and machine guns), single-perforated flegmatized grains are used (see page 196).

which assure progressive burning.

Thin-webbed (thin tablets) grains are most frequently used for short-tubed trench mortar charges. In the case of a longer tube, single-perforated grains are suitable.

Grains with one or seven perforations are used for mortars and howitzers. These shapes enable a convenient matching and suitable filling of the increments.

Grains with one or seven perforations are suitable as charges for both fixed and separate-loading ammunition ranging from 20 to 76 mm.

In the case of guns and howitzers which are above 76 mm, the monopерforated form of powder grain is used primarily. This shape assures simultaneous inflammation and rigidity of the charge. These are necessary in the fairly long powder chambers in cannon of this type.

We shall mention that the granulated shape of the powder elements for semi-fixed ammunition presents the disadvantage that it is necessary to use powder bags (containers) made from calico, silk, nitrocellulose, etc. In cases, where it is possible to have progressive burning of the powder, rings, strips and tubes are used. Powder charges composed of these elements can be tied together with cord. The defect of such a form of powder elements is that their filling cannot be automated.

In the case of rocket-firing systems, monopерforated powders with a large web thickness are widely used.



2. Powder Marking. Every powder has a mark assigned to it so that it could be distinguished from other types.

Formerly, the powder was primarily marked in accordance with the first letter of the cannon or weapon for which it was intended. For instance, a powder intended for light-weight rifle ammunition was marked as "VL"; powder used in heavy-weight rifle ammunition was marked as "VT" etc. These markings of rifle powders have been retained up to the present time.

At the present time, the characteristics defining its ballistic qualities are primarily used in its marking. These characteristics are the composition and shape of the elements, and web thickness. In this system, the brand of a granulated powder is denoted by a fraction. The numerator indicates the web thickness in tenths of a mm, and the denominator shows the number of perforations in the grain. For instance, 9/7 indicates a grain of seven perforations with a web thickness of 0.9 mm. We list some powder markings: 4/1, 7/1, 7/7, 9/7, 12/7, 14/7, 15/7.

For marking monopерforated pyroxylin powders, the initials TR are added after the fraction indicating those same characteristics as for granulated powder. For instance, 10/1 TP signifies that the powder is monopерforated with a web thickness of 1 mm.

The letters TR are not added when marking nitroglycerine powder because they are not produced in grains of cylindrical shape, even if the production of such grains is entirely feasible. Therefore, the marking 10/1 N denotes a monopерforated nitroglycerine powder with a web thickness of 1 mm.

Tablet-shaped powders are marked by the letters PL with two

numerals separated by a hyphen. The first number shows the thickness of the tablet in 1/100 mm, and the second number shows the width in 1/10 mm.

Strip-type powders are marked by the letter L with a number showing the web thickness in 1/100 mm.

Powders for use in naval and coast artillery are primarily monoperforated; their marking is denoted by a fraction in which the numerator shows the caliber of the gun in mm, and the denominator shows the length of the rifled part of the tube in calibers. Example: 75/50 is a powder for a 75 mm cannon of 50 caliber length.

A lot of ready powder is given a conventional marking which includes the powder brand, year of production, and name of factory. For example, the conventional marking VT 2/49 F means rifle powder for heavyweight bullet, 2nd batch produced in 1949 by factory F.

#### 8. Use of colloid powders.

Pyroxylin powders were until recently widely used in a number of countries for all calibers with the exception of trench mortars. Nitroglycerine powders were used more frequently in trench mortars on account of the insufficient potential energy of pyroxylin powders.

The area of application of nitroglycerine and diglycol powders, possessing a number of advantages over pyroxylin powders (see Section 6), has been greatly expanded within the past 6 years.

Powder on a volatile solvent is not used in rocket-firing systems because it is practically impossible to remove the solvent

from the thick-walled charges of rocket powders, and the dimensions of the charges cannot be maintained with sufficient accuracy owing to shrinkage.

### 9. Special forms of pyroxylin powders.

1. Quick burning powders. Quick powders can be obtained by two methods:

a. by producing powder grains of a very small thickness (around 0.1 mm) with a small content of volatile substances. Such a powder is made from pyroxylin with a large content of nitrogen;

b. by producing porous powders. Saltpeter is added to batch during processing in the blenders in order to obtain porous powders. This salt is removed from the powder (after cutting) by soaking it in hot water. After the saltpeter has been dissolved, a large number of fine pinholes remains in the powder. Depending on the desired combustion rate, the saltpeter is imbedded into the powder batch in amounts from 45 to 220 parts by weight per 100 parts by weight of the pyroxylin.

Quick powders are intended for use in short-barreled guns and for blank artillery rounds. The shorter the barrel, the quicker the powder must burn in order to attain the necessary pressure at firing and complete burnout of the powder.

2. Flegmatized powders. Progression of burning of a powder can be attained by the introduction of flegmatizers into the outside layer of a powder grain. The powder is treated with the flegmatizer solution in revolving drums. The flegmatizer solution is sprayed in by a force pump at a pressure of 2 to 2.5 at.

This wets the powder grains uniformly with the solution as well as a corresponding uniform distribution of the flegmatizer in the surface layers of the powder grains.

With such a treatment of the powder grain, the flegmatizer impregnates the wall of the powder to a depth of 15% of the web thickness whereupon the concentration of the flegmatizer decreases gradually from the outside layers within the grain. Accordingly the combustion rate of the powder rises in proportion to the displacement of the combustion front from the outside layer into the inner parts of the grain.

TABLE XXIX

Effect of flegmatization on the ballistic qualities of rifle cartridge powder

Condition of powder	Charge, g	Muzzle velocity, m/sec	$P_m$ kg/cm <sup>2</sup>
Unflegmatized	2.52	786	28 0
Flegmatized	3.25	840	2840

It is clear from Table XXIX that flegmatization of rifle-cartridge powder makes it possible to increase the weight of the charge by 30% and the muzzle velocity by 8% without increasing the maximum pressure in the bore. The flegmatization effect can also be seen by the example of a flegmatized monopercorated powder

which in progressiveness is equivalent to powder grains with seven perforations.

Only rifle-cartridge powders and, in exceptional cases, cannon powders with a thin web thickness (for small caliber artillery) are flegmatized.

3. Flashless powders. A large amount of combustion gases are contained in the combustion products of colloid powders. These are primarily carbon and hydrogen, which after escaping from the bore, intermix with air. The temperature formed by the combustible mixture is higher than the ignition temperature. Therefore, the mixture ignites and a bright flame appears in front of the muzzle, which gives away the battery position at night. This flame is called muzzle flash.

In order to eliminate this defect, special flashless powders are used. The powders are obtained by the insertion of admixtures into the powder composition which increase the ignition temperature of the gaseous mixtures or which reduce the combustion temperature of the powder.

Admixtures which increase the ignition temperature of the gaseous mixture have the greatest importance. Potassium salts,  $KCl$ ,  $K_2SO_4$ ,  $K_2CO_3$ , and  $KHC_2O_4$  are used for these purposes. Flashless, flash-damping and flash-reducer powders are produced on a base of these salts.

Example of flashless powder:

pyroxylin (13.5% nitrogen)	. . . . .	85 parts by weight
dinitrotoluene	. . . . .	10 parts by weight

dibutyl phthalate	. . . . .	5 parts by weight
diphenyl amine	. . . . .	1 part of weight
potassium sulphate	. . . . .	0.3-0.5 parts by weight

In this particular composition, dinitrotoluene and dibutyl phthalate lower the temperature of the combustion products, and the potassium sulphate raises the ignition temperature of the mixture of powder gases and air. In addition to this, dibutyl phthalate reduces the hygroscopicity of the powder.

Flash-damping powders contain up to 50% of inert salts such as potassium chloride in their composition. This flash-damping powder is added to the regular powder in amounts from 10 to 20% of the regular powder's weight when the charge is prepared.

Flash-reducers consist of inert substances which increase the ignition temperature of the combustible mixtures. Potassium salts are primarily used for this purpose. These flash reducers are placed in the charge prior to loading the gun. They can be used only in guns firing separate-loading ammunition or in guns equipped with special unfixed shell cases.

A defect of the flash-damping media is the smoke escaping from the muzzle which gives the battery position away during daylight.

4. Flareback. During a rapid tempo of fire, the so-called flareback is observed sometimes, especially in heavy-caliber guns. This flareback escapes from the breech when it is opened and it can burn the breech detail serving the piece.

The cause of flareback is the presence of burning gases in

the powder chamber, which form an explosive mixture with air. These can flare up on account of insufficient cooling during heavy fire, or they can flare up because a smoldering fragment of a powder bag or the strap remains in the bore after firing. This second cause can be eliminated by using a nitrated cloth in the charges which burns up completely upon firing.

## 10. Charges and Igniters

1. Definitions and classification. A charge for firing from an artillery piece or small arm is that amount of powder assembled in a set sequence and intended for firing one time only.

The mark of the powder and weight of the charge is selected in accordance with ballistics calculations and fired in such a way that the required muzzle velocity would be attained with the greatest powder gas pressures which have been set for a given weapon.

According to the kind of fire for which they are intended, charges are divided into propelling, practice blank, and special charges which are used in test firings.

2. Propelling charges. Propelling charges are divided into unitized and multi-section charges.

Unitized charges have a constant service weight and are intended for imparting one prescribed muzzle velocity to the projectile.

Multi-section charges consist of several previously-weighed parts which are packed in separate sacks, called powder bags,

namely: of a weighed portion of powder called base charge, or simply base and supplementary weighed portions of powder, called increments. The base charge makes certain that the minimum range of fire for the given artillery system is attained. The complete charge, consisting of the base and all increments, makes certain that the highest muzzle velocity is attained for the given system. Multi-section propelling charges make it possible during firing to change the weight of the charge by adding or taking away increments, which then changes the muzzle velocity, trajectory, and range of fire.

Propelling charges are subdivided into three types: fixed, semi-fixed, and separate loading.

Fixed charges are constant as a general rule. They are placed in the shell case loosely or in a paper bag (Figures 56 and 57). If the powder does not fill up the entire volume of the case, then packing is generally put in so that the powder would not move around in the case. The packing consists of stops in the form of distance washers or trihedral prisms which are inserted between the charge and base of the projectile.

Propelling charges which consist of long tubes, rods, or strips are generally tied in one (Figure 56b) or two (Figure 57c) bundles which are then inserted into the case. They are put in loosely very rarely (Figure 57a). Fixed charges are equipped with a standard cardboard cover (obturator) which is placed between the projectile and propelling charge. The obturator is intended to eliminate the passing of powder gases past the



rotating band into the rifling at the initial moment of ignition.

Multisection propelling charges are very rarely used for firing ammunition. In this case, it would be necessary to be able to have access to the inside part of the shell which means that either the shell or complete round would have to be taken apart. This would complicate their production and handling during firing.

Charges for semi-fixed ammunition in the overwhelming majority of cases are multi-section; fixed propelling charges for use in semi-fixed ammunition are used only for firing armor-piercing and shaped-charge projectiles.

An example of a propelling charge for a semi-fixed round is shown in Figure 58. The weight of the charge is changed during firing by the removal of the required number of increments from the shell case. The increments can be of identical or dissimilar weights. Increments of aliquot parts are widely used in the Soviet Army, while the German army uses increments of different weights.

Propelling charges for semi-fixed ammunition which are inserted into the shell case are covered with a standard reinforced cardboard cover with the rims turned to the inside of the case. The obturator serves for the uniform sealing of the charge in the case and for obturating the powder gases. The cord wads or cap reinforcements serve to make the charge air-tight in the case. When the charge is assembled, it is sealed on the outside with a hermeticizer.

Separate-loading ammunition charges are multi-sectioned in

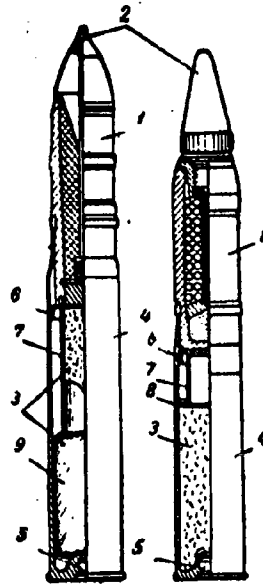


Fig. 56 - Fixed rounds

- |                 |                   |                               |
|-----------------|-------------------|-------------------------------|
| 1. projectile   | 2. fuze           | 3. propelling (powder) charge |
| 4. case         | 5. primer cup     | 6. obturator                  |
| 7. distance wad | 8. cardboard disk | 9. powder bag                 |

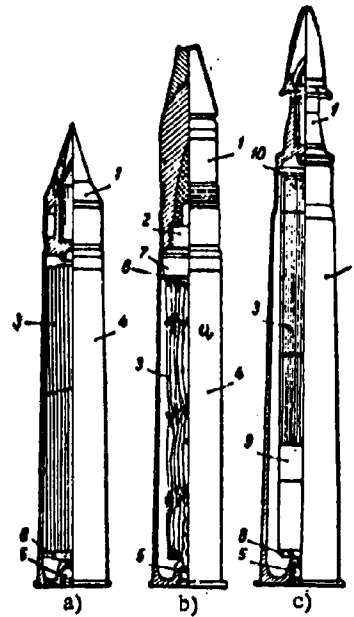


Fig. 57 - Fixed rounds used by the former German Army

- |                    |               |                      |
|--------------------|---------------|----------------------|
| 1. projectile      | 2. fuze       | 3. propelling charge |
| 4. case            | 5. primer cup | 6. obturator         |
| 7. distance wad    | 8. igniter    | 9. powder bag        |
| 10. copper remover |               |                      |

the overwhelming majority of cases. In addition to strength, the powder bag must be burned up completely together with the charge upon firing (see paragraph 4 of section 9).

The base charge and increments are tied together by the straps which are of the same material as the powder bag. An example of an arrangement of a separate loading charge is shown in Figure 59.

Propelling charges are made up of a powder of one mark or from the powders of several marks. In the latter case, the propelling charges are called combination charges. The powders of various marks in a combination charge are always put into separate bags, whereupon the base charge is made up of a powder with a smaller web thickness or from a faster burning powder as compared to the increment powder.

The following basic requirements are set forth for a propelling charge:

- a. assuring the required muzzle velocity at a maximum pressure not exceeding the set limit;
- b. a potency of the explosive to be able to perform the work required;
- c. the lowest possible bore erosion;
- d. stability during prolonged storage.

3. Special, practice and blank charges. Special charges are used for the testing of artillery pieces and ammunition. Their weight is determined by the technical conditions in use for the appropriate artillery piece.

Practice charges are used in heavy-caliber naval and seacoast

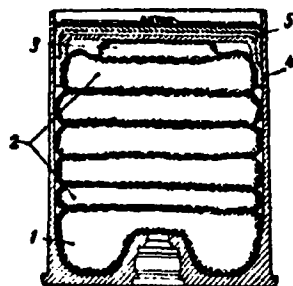


Fig. 58 - Stacked multi-section propelling charge for semi-fixed round.

- |                |                    |                  |
|----------------|--------------------|------------------|
| 1. base charge | 2. increments      | 3. top increment |
| 4. obturator   | 5. reinforcing cap |                  |

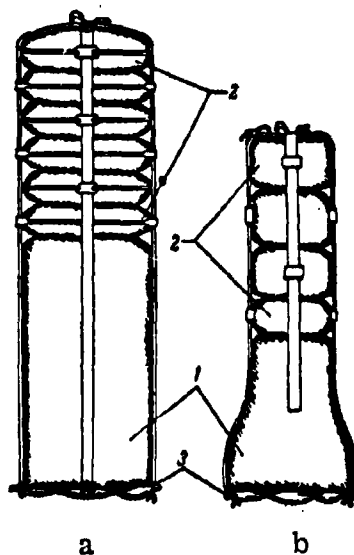


Fig. 59 - Multi-section propelling charges for separate-loading round

- |                |               |            |
|----------------|---------------|------------|
| a. full        | d. reduced    |            |
| 1. base charge | 2. increments | 3. igniter |

guns during practice (training) firings. These charges are of smaller weight than the propelling charge, and they produce a lower pressure upon firing, which reduces bore erosion.

Blank charges (Figure 60) are used primarily in guns of medium caliber for blank firing during maneuvers, for cannon salutes, and for signalling.

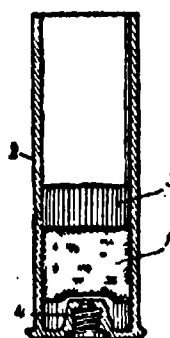


Fig. 60 - Blank Round

- |                  |         |                 |
|------------------|---------|-----------------|
| 1. powder charge | 2. case | 3. closing plug |
| 4. primer cup    |         |                 |

4. Igniters. Special devices are used for igniting the charge. Detonating caps are used in separate-loading charges, while primer cups are used in cased charges. However, the flames which originate through the action of the detonating cap or primer cup in the majority of cases are not sufficient to produce a rapid and simultaneous ignition of all the grains of the charge. Ignition is made sure of by the use of an igniter made out of

black or porous pyroxylin powder, easily ignited from the flame produced by the cap or primer cup.

The igniter is positioned in the charge in such a way that the flame from the cap or primer cup would hit it directly. In the case of long charges for heavy-caliber guns, additional igniters can be used, which are spaced among the charge components.

The weight of the igniter is from 0.5 to 2.5% of the total weight of the propelling charge.

#### 11. Barrel erosion.

Shortly after the transition from black to colloid powder, a destructive action of the powder gases on the bore was noted (pitting).

At first, the pitting effect will noticeably lower the accuracy of fire, and later on, after a specific number of rounds had been fired, the gun will become completely unfit for further service.

The first signs of pitting are dull spots on the polished surface of the bore. These spots are primarily in the powder chamber. These spots are caused by the appearance of hundreds of fine and shallow cracks in the metal. When the gun is fired further, the separate cracks elongate with a simultaneous increase in their width and depth. Those cracks whose directional orientation coincides more or less with the direction of the axis of the bore, hence, with the direction of travel of the powder gases, are increased in size especially rapidly.

When these longitudinal cracks become sufficiently elongated, the powder gases and unburned particles of powder start to pass through the rotating band of the projectile and burned-out section of the bore surface. Then a wearing-away of the metal and stripping of the bands occurs.

In a pronounced case of abrasion, the rifling in the forcing cone is completely obliterated, owing to which, in guns firing separate-loading ammunition, the projectile can be rammed in further into the tube during loading than in the case where the tube is not worn. This advance of the projectile during loading increases the volume of the powder chamber, which causes a reduction in muzzle velocity and range. In conjunction with this damage to the rifling, accuracy of fire is decreased.

The above-described phenomena, known as barrel erosion, take place slowly at the beginning, but, as the number of rounds fired increases, the pitting increases all the more. The rule of thumb in this case is that if the velocity of a projectile drops by 10% on account of pitting, then this particular bore is no longer fit for further service.

Barrel erosion is the result of a number of causes.

Effect of heat on the surface layer of the metal. According to D. K. Chernov, the powder gases are able to heat the thin surface layer of the bore walls to a high temperature during firing. This layer has a tendency to expand, which is prevented from doing so by the adjacent cool layer of metal. Stresses occur in the heated layer which cause the inside surfaces of the wall to crack.

The origination of the cracks is made possible by the hardening of the surface layer, which takes place on account of a rapid cooling of the heated layer after firing. The cooling rate is increased even more by the cold air entering the bore when the breech is opened for loading the next round. A change in the mechanical properties of the inner layer metal, similar to quenching takes place.

Nitroglycerine powders cause greater erosion than pyroxylin powders, even with equal calorific values. On the other hand, blended pyroxylin powders are more erosive than nitroglycerine powders. Powders with the lowest possible combustion temperature must be used so that the heat effect of the powder gases can be reduced.

Mechanical effect of powder gases on the walls of the bore (erosion). A conclusion, based on a number of tests, was also drawn concerning the effect of mechanical effect of powder gases escaping from the powder chamber through the slit between the rotating band and bore walls. The wear of the bore is increased with a rise in the powder gas pressure, and the most pronounced burning of the bore occurs where the rifling starts, i.e. in that place where the rotating band is not completely gripped by the rifling, and where, consequently, the gases can escape more readily.

The work of the gases can be compared with washing by a stream of water. Calculations show that gases travel along the bore at a velocity of approximately 600 m/sec. It is natural



that, at such a high velocity, the glowing particles of gas hitting the metal will damage it and form winding channels which, basically, follow the path of the bore's generatrix. These channels deepen gradually, and even encroach into the forcing cone. As the number of rounds fired increases, the zone of the channels gradually elongates from where the rifling begins to the muzzle. In badly worn bores the width of this zone attains several calibers. During the initial periods of wear of the bore, these channels distribute themselves exclusively along the bottom of the grooves, but, as the wear increases, they begin to get into the side walls and lands.

The erosion rate of the bore can be reduced by any measure which eliminates the escape of powder gases between the rotating band and bore surface.

Experiment showed that obturators of even the most rudimentary kind, in the form of small cups of sufficiently stiff pasteboard, and seated in the case, can decrease barrel erosion. Obturators for fixed rounds are of particular importance to guns because the position of the shell in them becomes invariable upon loading with any degree of bore wear. Being rigidly crimped to the case, the projectile assumes one and the same position in the loaded gun, the position being dependent on the length of the case, and the advance of the projectile is limited by the centering slope. In guns firing separate-loading ammunition, as the bore wears away, the rifling at the forcing cone deteriorates; thus the projectile is forced home up to the stop in the rifling,

even if it is damaged. In the case of guns firing fixed ammunition which have a worn bore, the projectile does not build up against the rifling. This causes an extremely large gas escape in the initial moment.

In addition to cardboard obturators, the rotating band is smeared with a special lubricant in order to eliminate gas escape. When the round is fired, the lubricant fills up the headspace and, by greasing the bore, protects it from the direct action of the gases.

Occlusion of Powder Gases. An increase in the pressure in the tube leads to an increase of erosion in the bore not only in conjunction with an intensification of the mechanical effect of the gas streams, but also under the effect of powder gas occlusion.

Occlusion is the retention of gases by a metal. The gas is absorbed by the metal, forming a solid solution in it (variable composition phase), and which sometimes partially enters into a chemical combination. The rate of occlusion and depth of penetration of the gases into the metal are increased with an increase of temperature and pressure.

When the tube assumes its normal state after firing, the gases which have penetrated into it remain as if they were corked up in the pores, and, by exerting pressure on the walls, they damage the metal.

Bores (particularly in sporting rifles) rust after a certain period of time after firing in spite of the fact that they were

cleaned and oiled immediately after being fired. This can be explained by the fact that the occluded gases gradually come out from the pores of the metal in which they were imbedded after firing. Gases of an acidic character are found in the combustion products of smokeless powder. These gases react with moisture and form acids which then cause rusting of metals.

Occlusion not only rusts metals, but also damages the surface layer of the bore.

In order to reduce the effect of occlusion, measures can be taken wherein the requisite muzzle velocities can be obtained at a lower bore pressure in the piece. Such a pressure reduction, as we have seen, can be attained by the use of progressive-burning powders.

#### Chemical effect of the combustion products of the powder.

The chemical action of some combustion products of a powder also has an effect on the bore on a par with the mechanical and thermal effects. It has been discovered that the carbon content is increased in the surface layers of the metal, which is due to the carbon being separated out as the result of the dissociation of the combustion products when they are pushed up against the very hot walls of the bore. Therefore, the layer of metal becomes harder and more brittle, and, on the other hand, its melting temperature is lowered.

The influence of the chemical factors increases with rapid rates of fire, when the tubes heat up to 300 - 500°.

Effect of the size of the powder charge. The amount of gases which are formed during the deflagration of powder also has an effect on the wear of the bore. This can be verified by the fact that barrel erosion decreases when firing with reduced charges. Erosion grows quicker than the weight of the charge, as can be seen by the following data showing the effect of the size of the charge on bore wear of English howitzers with an identical number of rounds fired:

number of increments in the charge	1	2	3	4	5	6
bore wear in %	6	9	14	27	48	100

Effect of caliber. The bore wear of sister pieces increases rapidly with an increase of the caliber. This is evident from the following data concerning the bore life of long-barreled guns which are part of the ordnance of the U. S. A.

gun caliber in mm	. . . . .	120	152	208	254	305
bore life (no. of rounds fired)	. . . . .	200	166	125	100	83

It may be added that a piece whose caliber is less than 100 mm can be fired a thousand times, and the bores of machine guns of less than 10 mm can fire more than 10,000 rounds.

Where one and the same caliber is used, the bore of relatively short range pieces (howitzers) have a longer service life than bores of long range pieces (long-barreled guns).

Barrel erosion can be reduced by the use of certain special steels, and also by a sensible design of the rifling.

## SECTION VI

### BLACK POWDER

#### 1. Composition and Components of Black Powder

The average composition of black powder is: 75% saltpeter (mostly potassium nitrate), 15% carbon, and 10% sulfur.

Potassium nitrate. Potassium nitrate is only slightly hygroscopic. This valuable property assures physical stability (absence of humidification) of the powder which is made out of it. The melting temperature is  $334^{\circ}$ .

Chile Saltpeter is not suitable for the production of military gunpowders on account of its high hygroscopicity.

Sulfur is a solid crystalline substance of pale yellow color, not soluble in water, and having a melting temperature of  $114.5^{\circ}$ .

Charcoal. Charcoal from soft types of wood is used for the production of powder. More often than not, it is from buckthorn or alder. The method of the charcoal production, primarily its degree of roasting, has an important significance on the quality.

The degree of roasting has an effect on the inflammability of the powder. The powder ignites the more easily when the degree of roasting of the charcoal is lower. Conversely, the heat-producing ability of the charcoal rises with an increase in the degree of roasting, i.e. with an increase in the carbon content. Consequently, the hygroscopicity of the charcoal and of the powder produced from it decreases with an increase of the degree of roasting of the charcoal.

Three basic types of coal are used in powder production:

Kind of Charcoal	Ignition Temperature in °C	Carbon Content in %
cherry	350 - 450	80 - 85
Lignite	280 - 320	70 - 75
Chocolate	140 - 175	52 - 54

Nowadays, coal with a carbon content of 74-78% is chiefly used.

The mechanism of explosive transformation of black powder.

A reaction between solid substances takes place very slowly. Bowden's study showed that, in the initial stage of the ignition process for black powder, melting of the sulfur occurs. The close contact of the liquid sulfur with the potassium nitrate and other organic substances which are contained in the charcoal leads to an acceleration of the reaction to a point which is characteristic for an explosive transformation. After the powder attains a normal rate of combustion, a quantity of heat is evolved with which a direct oxidation of the carbon by the potassium nitrate becomes possible.

The more difficult ignition of a sulfur-free powder can be explained by the fact that the liquid phase in this kind of powder can originate only under conditions of melting of the higher-melting saltpeter (melting temperature of potassium nitrate is 334°).

## 2. Properties of Black Powder.

Black powder has a slate-gray color and dull luster. The larger grains very often can be from a blue-black to a grey-black color with a metallic luster.

The density of the powder grains fluctuates from 1.5 to 1.93 g/cm<sup>3</sup>. The gravimetric density of rifle powder is from 0.900 to 0.980 kg/decimeter<sup>3</sup>.

A powder which has been produced satisfactorily will not soil the hands, no dust will remain on paper, and it is resistant to mashing between the fingers.

The moisture content in accordance with technical conditions should be no more than 1%. When the moisture content is above 2%, the powder is difficult to ignite.

With respect to sensitivity to shock, black powder belongs to that number which are safe in handling (duds with a 10 kg weight dropping on it from a height of 35 cm, explosives when some weight drops on it from a height of 45 cm).

A chest containing black powder can be exploded by the impact of a rifle bullet.

The sensitivity of black powder to flame or even a small spark, which can originate when two metal objects strike each other is the cause of the great hazard associated with its handling.

The ignition rate of a black powder charge (i.e. the rate of propagation of the flames from grain to grain), according to Bowden, is equal to 60 cm/sec at atmospheric pressure, and, under a

pressure of 30-50 at., the ignition rate rises to 2000 cm/sec. The combustion rate of a powder grain is equal to 0.4 mm/sec, and, under a pressure up to 30 - 50 at., it rises to 9 cm/sec.

According to Andreyev's data, the combustion rate of a time fuze (in which the black powder grains are impressed as alike as possible along the length of the fuze) at atmospheric pressure is 0.5 cm/sec, and at a pressure of 31.3 at., it is 2.4 cm/sec.

The nature of burning of black powder depends upon its density. Powder elements which are made out of black powder, and having a density of  $1.65 \text{ g/cm}^3$  and below, do not burn in parallel layers. During firing with a charge of this powder, the grains are scattered, and, for this reason, the burning time in the bore of equal charges from identical elements can fluctuate greatly.

The sensitivity of black powder to flame and good ignition abilities are dependent, on the one hand, upon a high temperature of the flames, and, on the other hand, the presence of solid or liquid particles in amounts up to 50% in the combustion products. The ease of blocking black powder into time ring fuzes in the shape of powder trains - delay or booster elements - the combination of these properties in many cases makes black powder indispensable even today.

### 3. THE PRODUCTION OF BLACK POWDER

The production of black powder consists of a number of operations, which have as their purpose:

a. a fine pulverization and an intimate blending of the black powder components;



b. obtaining grains of the desired size and shape out of the blend which has been prepared in this way. This particular blend is called mealed black powder.

The pulverization and blending of the components is attained by a prolonged processing of the components in a number of machines - in disintegrators, tubs (spherical grinders), by millstones, etc.

The mealed black powder is pressed under millstones or in presses. The powder press cakes are grained in special graining machines; they are then buffed in drums so that sharp edges could be removed and a smooth surface obtained. The powder is then sifted and grains of uniform size are obtained.

#### **4. Grades of Black Powder**

Black powders are subdivided into ordinary, irregularly shaped, fuze, cord, sporting rifle, and powders for mining purposes.

Ordinary powder includes coarse-grained artillery (rifle no. 1) rifle (shrapnel, or rifle no. 2), fine (rifle no. 3), and sulfur-free. These powders, with the exception of the sulfur-free, differ from each other mainly by the grain size.

The composition of sulfur-free powder is 80% potassium nitrate and 20% charcoal.

Irregularly-shaped powders consists of prismatic (with one perforation) and cubical.

Fuze powders. At the beginning of the 20th century, black powder was used as a filler for time fuzes. By composition, it was analogous to the ordinary brands, but it was distinguished from the other in that it had additional requirements with respect

to the quality of the components and method of production. This powder was given the name of ordinary fuze powder. The maximum burning time of this powder was 22 seconds in the double-decker time fuze used at that time.

However, in association with an increase in the range of fire, it was necessary to increase the burning time of the time fuze, which, with retention of the double-decker fuze, could be attained by using a powder which burned slower than the ordinary fuze powder. This type of powder was called slow-burning fuze powder.

Retarding the burning rate of a powder can be done in several ways. Included are: the covering of the surfaces of the powder grains by a flegmatizing film, inserting substances into the powder which lower its combustion rate, and the use of low-wasted charcoal.

Some of the substances which reduce the burning rate are shellac, paraffin, rosin, synthetic resins such as phenol-formaldehyde resin, bakelite, and others.

The common defect of all fuze powders is that their burning rate depends upon the atmospheric pressure. This is particularly manifested in antiaircraft fire. The effect of the atmospheric pressure upon the burning rate is the lesser when the formation of the gaseous products is the lesser. The burning rate of the compositions which burn up without forming gases for all practical purposes does not depend upon the pressure. In connection with this, compositions were developed which burn up with the formation of only a small amount of gases. These compositions are characterized by a small dependence of the burning rate on the ex-

terior pressure, and by a small sensitivity to the initial temperatures. They are used in time fuzes, antiaircraft artillery fuzes, and in the production of delay elements.

Fuze powders should satisfy the following basic requirements:

- a. uniformity of the separate lots and constancy of the burning time in the fuzes during firing;
- b. non-extinction upon being fired;
- c. high stability, i.e. the ability to retain the constancy of the burning rate after a more or less prolonged storage under varying atmospheric conditions (heat and moisture).

Cord powder is used for the production of safety fuzes. It is composed of 80% potassium nitrate, 10% sulfur, and 10% charcoal.

#### 5. Uses of Black Powder

Black powders are used nowadays:

- a. for filling time fuzes (fuze powders);
- b. for making the powder trains serve to transfer fire to the bursting charge in shrapnels;
- c. for bursting charges which are used in shrapnel, incendiary, and illuminating shells;
- d. for making delay elements and flame boosters in powder trains and fuzes;
- e. for making powder tablets used in primer cups;
- f. for making igniters for charges of colloid powders, and for making pyrotechnic devices;
- g. for making safety fuses.

In addition, black powder is used in sporting rifles and for certain types of mountain operations (making block rubble).

## SECTION VII

### PYROTECHNICS

Substances and mixtures which produce illuminating, thermal, smoke or sound effects during burning, and which are used for military purposes or in the national economy, are called pyrotechnics.

In military science, pyrotechnic compositions are used for the production and filling of illuminating, photo-illuminating, signal, tracer, incendiary, camouflage and simulation devices. These devices are used as ammunition fillers. Ammunition which has been filled with pyrotechnic devices bears the general name of pyrotechnic media.

The science in which the above-mentioned compositions and media are studied is called pyrotechnics.<sup>27</sup>

#### 1. Components of pyrotechnic compositions

Pyrotechnic compositions are mechanical mixtures; they consist basically of oxidizers and combustible substances, and they contain admixtures which impart supplementary special properties to the compositions. These properties include a coloring flame which forms a colored powder, reducing the sensitivity of the composition (flegmatizers), increasing the mechanical stability of the pressed composition (binders), as well as others.

Oxidizers. Nitrates, chlorates, perchlorates, oxides and peroxides of metals and certain chloro derivatives are used as oxidizers.

Nitrates of barium, potassium, sodium and strontium with the salts of nitric acid are used most frequently. The salts of potassium and barium  $\text{Ba}(\text{ClO}_3)_2 \cdot \text{H}_2\text{O}$  are used with the salts of chloric acid in pyrotechnics. The salt of potassium (potassium perchlorate  $\text{KClO}_4$ ) is used with the salts of perchloric acid. Of the oxygen compounds of metals, those are used which are capable of giving up oxygen fairly easily: barium peroxide  $\text{BaO}_2$ , manganese dioxide ( $\text{MnO}_2$ ), lead dioxide ( $\text{PbO}_2$ ), minium ( $\text{Pb}_3\text{O}_4$ ), cinder ( $\text{Fe}_3\text{O}_4$ ), as well as some others. Hexachloroethane ( $\text{C}_2\text{Cl}_6$ ) is used as an oxidizer in addition to the oxygen-containing substances.

Combustibles. Organic as well as inorganic substances are used as combustibles in pyrotechnics.

Of the number of inorganic substances, highly-calorific metals such as aluminum, magnesium, alloys of aluminum and magnesium, as well as others, are used as combustibles. In burning of aluminum, 7000 kilocal/kg is released. 6000 kilocal/kg are released when magnesium is burned. The combustion temperature of these metals and their alloys is higher than the combustion temperature of other combustibles, organic as well as inorganic. Magnesium has a high reaction capability. It ignites readily and burns faster than aluminum.

Aluminum is used in incendiary and illuminating compositions, while magnesium is used in illuminating, photoilluminating, and

tracer compositions. Sometimes a small amount of magnesium is added to signal compositions in order to increase the brightness of the flame.

Aluminum has a high ductility and this greatly hinders its pulverization. Aluminum-magnesium alloys containing 30 to 70% magnesium can be easily pulverized. An aluminum-magnesium alloy, containing 50% magnesium, is corrosion-resistant in comparison to other alloys and has a high degree of brittleness, which enables it to be pulverized easily. The specific gravity of this alloy is  $2.15 \text{ g/cm}^3$ . Aluminum-magnesium alloys which contain no less than 90% magnesium are called electronates, and are used for the production of light-duty aircraft-bomb bodies. With a content of 8-10% aluminum, the mechanical processing of the aluminum-magnesium alloys is facilitated.

The organic combustibles include hydrocarbons (gasoline, benzene, kerosine, petroleum, fuel oil, turpentine, etc), carbohydrates (starch, sugar, sawdust and others), and resins (rosin, shellac, bakelite, phenol-formaldehyde resin, drying oil) which serve as binders at the same time. The role of combustibles is also very often fulfilled by some smoke-formers (naphtalene and others). The combustibles are selected in such a way that they produce the maximum special effect required from a given pyrotechnic composition.

For instance, in incendiary, illuminating, tracer, and photo compounds, the best effect is attained with high temperatures of combustion. Therefore, combustibles with a high heat-producing capability are used in them. Conversely, in the case of smoke-producing compositions, a high temperature is not required, and,

very often, it is not even desired. Combustibles are put into these compositions which have a low heat-producing ability (Carbohydrates, charcoal). Aluminum and magnesium are not used in this instance, or else they are used in very small amounts.

Binding Agents. Binders serve to hold the composition together. They also give mechanical stability to the composition or to the semi-finished products which are made out of it (spiders, segments). Binders have an effect on the combustion rate, and the properties and performance of the compositions. For this reason, various binders and in varying amounts are added for various compositions. Many binders protect the compositions from humidification at the same time.

Drying oils, dextrin,<sup>28</sup> and natural and artificial resins are used as binders.

Shellac and rosin belong to the natural resins.<sup>29</sup> Of the artificial resins, phenol-formaldehyde resin, bakelite, and polyvinyl chloride are used.<sup>30</sup>

Flame-Coloring Substances. The bright flame is obtained when certain elements (such as Na, Ba, Sr, and Cu) color the flame to a specific color at a high temperature.

Strontium compounds color the flame to a red hue. A green color is obtained with barium, while a blue color is obtained with copper compounds. Certain sodium salts dissociate at a temperature of 1000° and above, whereupon a nascent radiation of the sodium vapors takes place, which is used to get yellow light.

Colored Smoke-Formers. Intermediate products and coloring

materials are used to get colored smokes. These are colored organic compounds which transform into a vaporous state upon burning. On occasion, inorganic coloring substances are used.

Flegmatizers. Flegmatizers are substances which lower the sensitivity of pyrotechnic compounds to mechanical effects. As a rule, they also reduce the burning rate. Resins, paraffins, and oils are used as flegmatizers.

## 2. GENERAL REQUIREMENTS FOR PYROTECHNIC COMPOSITIONS AND MEDIA

The following general requirements have been set for pyrotechnic compositions:

- a. the assigned pyrotechnic effect (signalling, illuminating, incendiary, etc);
- b. minimum sensitivity to mechanical effect and safety in handling and use;
- c. sufficient physical and chemical stability during prolonged storage;
- d. stability with respect to internal thermal effects (spark non-inflammability, etc.);
- e. simplicity of the production process;
- f. availability of the initial products and availability of a source of raw materials.

The following basic requirements have been set for pyrotechnic media:

- a. producing the desired pyrotechnic effect:



- b. safety in handling and storage;
- c. not sensitive to bullet shock;
- d. unchangeability of the pyrotechnic effect during prolonged storage of the media (on the order of several years);
- e. simplicity and safety of production.

### 3. PROPERTIES AND TESTING OF PYROTECHNIC COMPOSITIONS

1. Properties of Pyrotechnic Compositions. The greater part of pressed pyrotechnic compositions is characterized by steady burning. In many cases, oxygen from the air can take part in the burning, and, for that reason, the majority of the compositions has a negative oxygen balance which provides for a better pyrotechnic effect with the given weight.

The burning rate of pyrotechnic substances is of great importance. It depends upon the nature of the oxidizer and combustible, upon the degree of grinding of the components, density of the composition, and upon others. The greater part of chlorate compositions burns faster than the nitrate compositions. Conversely, nitrate compositions which contain magnesium burn faster than the chlorate and perchlorate ones.

The volume of the combustion products, heat, and combustion temperatures can be determined by calculation just as in the case of explosives. The combustion temperature can be established experimentally (thermocouple, optical pyrometer, spectroscopy) only in certain compositions.

Gases or vapors are formed in many pyrotechnic compositions

when they are burned, with the result that these compositions will then possess explosive properties, and, in a manner similar to explosives, they are capable of exploding or detonating through the effect of one or another kind of impulse.

In addition, pyrotechnic compounds have inherent special properties such as a bright light, colored flame, incendiary, capability, smoke formation, etc.

2. Testing Pyrotechnic Compositions. Sensitivity to mechanical effect. The sensitivity to shock and friction is determined analogously to that for high explosives (see pages 51-56).

The chlorate compositions have the greatest sensitivity to shock. The perchlorate ones have a lesser sensitivity, while the nitrate compositions have the least sensitivity.

The greatest sensitivity to friction is possessed by those compounds which contain chlorates together with sulfur and antimony ( $\text{Sb}_2\text{S}_3$ ) and many of the organic substances. Blends containing nitrates are relatively little-sensitive to friction.

Sensitivity of pyrotechnic compositions to initial heat impulse is characterized by three values: spontaneous combustion temperature, ignition temperature, and combustibility from flame.

The physical nature and method of determination of the spontaneous combustion temperature of pyrotechnic compositions are analogous to those which were described in the chapter entitled "Theory of Explosives" for the ignition temperature of explosives.

According to Zhironov, the ignition temperature is the limit

value of the spontaneous combustion temperature at which the delay period is equal to zero (see page 46 ). It is found by extrapolation of the delay periods which were determined for various spontaneous combustion temperatures, as can be seen in Figure 61.

TABLE XXX

Sensitivity of pyrotechnic compositions to flame  
(according to data of I. I. Vyernidub and V. A. Sukhikh)<sup>1</sup>

Composition	Upper limit in cm	Lower limit in cm
Gunpowder No. 1	2	15
Incendiary	3	13
Red-colored fire	0	2
Illuminating	0	3

<sup>1</sup>Copied from A.A. Shidlovskiy's book "Fundamentals of Pyrotechnics", Oborongiz, 1954. page 94.

The flammability of a pyrotechnic composition from a flash of fire is characterized by the greatest distance between the section of the time fuze and surface of the composition at which steady inflammation (upper limit) takes place, and by the smallest distance between the section of the time fuze and surface of the composition at which 100% failure occurs (lower limit). Approximate data concerning the sensitivity of certain compositions to flame are cited in Table XXX.

Stability is of great importance in the storage of the ready products. If the components of the composition react with the evolution of heat, the composition will be capable of spontaneous combustion. If the composition contains components which can

absorb moisture from the circumambient air, then it is capable of humidification and will turn out to be physically unstable, and, sometimes, chemically unstable also.

In order to determine the hygroscopicity of a composition, a hygrometer is used, which is most often in the form of a desiccator, into whose bottom a saturated solution of salt is poured in. This solution contains a certain amount of the crystals of the same salt. Generally, a saturated solution of potassium nitrate or common salt is used. A constant relative humidity (at a given temperature) is established in the space above the saturated solution. The tested substance is placed into the desiccator over the layer of liquid.

In relation to the conditions, the testing of the composition for hygroscopicity can last from 1 to 10 days up to 1 to 2 months. The tested substance is periodically weighed during the course of this time. After the testing is finished, a curve of the dependence of the degree of the composition's humidification upon the holding time of the composition at a given relative humidity is plotted.

3. Computation of the density of a compressed composition. Sometimes it is necessary to know the density of a pressed pyrotechnic composition when designing pyrotechnic media. In the event there are no corresponding experimental data, then an approximate value can be obtained by the following calculation.

We shall determine the theoretical value of the actual density of the composition, i.e. the compact substance, without gaps,

by the following formula:

$$d_{\text{actual}} = \frac{100}{\frac{a_1}{d_1} + \frac{a_2}{d_2} + \dots + \frac{a_n}{d_n}},$$

where  $d_1, d_2, \dots, d_n$  - actual densities of the components,

$a_1, a_2, \dots, a_n$  - percentage content of these components  
in the composition.

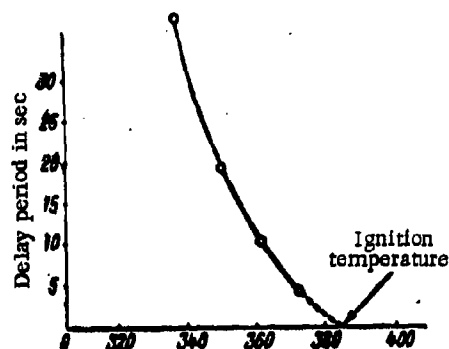


Fig. 61 - Graph for determining ignition temperature

The obtained magnitude  $d_{\text{actual}}$  has to be multiplied by the coefficient of density, which is a ratio of the magnitude of the practically attainable (i.e. unknown) density of the composition to the magnitude  $d_{\text{actual}}$ .

The coefficient of density for the majority of pyrotechnic compositions fluctuates within limits of 0.7-0.8, while the fluctuation is 0.9-0.95 for tracer compositions.

#### 4. ILLUMINATING COMPOSITIONS

1. Luminous characteristics of illuminating compositions and media. Illuminating media, which are filled with articles (illuminants, stars) made out of illuminating compositions, are used to light up positions. A high power is required from the illuminants and stars.

The light which is radiated during their burning had to provide for, in addition to a sufficient distinctness of observation, also an accurate discrimination of the color. The latter can be possible if the radiation of the burning substance approximates that of the sun's radiation to which the human eye can become accustomed and adapted.

In addition to the requirements for a high illuminating power and a specific spectral radiation, a third basic requirement is set for these articles: the linear burning rate should be a unit of millimeters per second. The luminous intensity and burning rate are important characteristics of illuminating compositions and articles which are made out of them.

The illuminating compositions are characterized by the specific light sum, i.e. the amount of light energy, which is evolved in the combustion of 1 gram of the illuminating composition:

$$L_0 = \frac{I t}{m} \text{ candle sec/g}$$

where  $m$  - weight of the article in grams;

$I$  - luminosity in candles;

$t$  - burning time of the article in seconds.

Example. A star, pressed out of an illuminating composition and weighing 50 grams burns 9 seconds, generating a luminosity of 100,000 candles. The specific light sum of the composition is:

$$L_0 = \frac{100,000 \times 9}{50} = 18,000 \text{ candles sec/g}$$

Illuminating media are characterized by the luminosity which is radiated upon their burning, and which is obtained by the illumination of a locality. Luminosity is determined by a photoelectric photometer, consisting of a photocell and device for measuring the photoelectric current. A direct proportionality exists between the luminosity and magnitude of the photoelectric current (upon observing the rules established for photometering illuminating compositions). The required illumination of a locale by illuminating media should be on the order of 1-2 meter-candles, and duration of illumination should be no less than 10 seconds.

2. Choice of illuminating composition components with high luminous indexes. When selecting the components for an illuminating composition satisfying the requirements of a high specific light sum, the well-known physics assumption that the radiation

of solid and liquid particles which are heated to a high temperature will basically conform to the law of the radiation of an absolutely black body, is used as a guide. The intensity of radiation of an absolutely black body, according to the Stefan-Boltzmann law, is directly proportional to the fourth power of the absolute temperature. Such a radiation, dependent on the oscillatory movement of electrons and ions which is accompanied by the movement of the molecules of solid or liquid bodies, heated to  $500^{\circ}$  and above, is called temperature or heat radiation.

In comparison with solid or liquid substances, the temperature radiation of gases and vapors is very insignificant.

The mechanism of the origination of temperature radiation consists of the following. Constant collisions and interactions of solid and liquid particles, which are obtained as the result of a rapid and disorderly oscillating movement, lead to continuous and irregular changes in the velocity of movement of the electric charges (electrons and ions) entering into the composition of the substance's particles. The oscillations of the charges in turn produce electromagnetic waves of every kind of frequency, which in turn are the cause of the formation of a dense spectrum (concerning radiation which are close to monochromatic, see page 245).

For getting the greatest intensity of radiation during the burning of illuminating compositions:

- a. they should contain components which, upon burning, will form either solid or liquid substances at combustion temperature.
- b. the highest possible combustion temperature of the com-



position is required.

These requirements are satisfied by compositions containing aluminum, magnesium, or its alloys as the combustible. While burning, the metals form oxides, which are either in the solid or liquid state at combustion temperature. A large amount of heat is evolved, owing to which a high combustion temperature is obtained.

Because the human eye is most sensitive to the yellow-green portion of the spectrum, the illuminating compositions are chosen in such a way that a green or yellow light would be primarily radiated during their burning. This is obtained through the use of barium nitrate as an oxidizer. Barium nitrate decomposes fairly easily at an elevated temperature. The barium oxide which is formed during the decomposition of the barium nitrate produces a dense spectrum with the yellow-green part being predominant (also see page 246).

Salts of sodium, decomposing during combustion and releasing sodium atoms which radiate yellow rays, increase the light power of the illuminating compositions which contain barium nitrate.

3. Sensitivity of illuminating compositions to mechanical effect and choice of oxidizer. Illuminating compositions have particular requirement with respect to the sensitivity to mechanical effects, which are the result of the service conditions of the illuminating media. The employment of artillery-type illuminating shells (primarily in medium-caliber howitzers) imposes requirements which limit the shock sensitivity of the compositions to the per-

mitted stresses which have been set for explosives upon firing. Also, the employment of flare bombs and photo bombs makes it necessary to restrict the sensitivity of the compositions which are used in them to blows, bullet shock, and penetration of the bomb by fragments.

These circumstances exclude the possibility of using chlorate compositions in the above-listed munitions, and led to the necessity of using less-sensitive compositions on a base of barium nitrate.

4. Effect of binders on the properties of illuminating compositions. Binders reduce the brightness of flames; for that reason, their content in a composition is limited within limits of 5 to 6%. Substances which provide a sufficient mechanical stability for the pressed article when used in an insignificant quantity, are used as binders. These substances include phenol-formaldehyde resin, bakelite, and a solution of rosin in drying oil.

The binders also play the role of a delay element. If the combustion rate still remains high with a 6% binder content, then a part of the combustible in the form of a coarse-grained metallic powder is inserted. This will also delay burning. In case of necessity, the burning rate is reduced by an increase in the blocking pressure (i.e. by an increase in the density of the object).

5. Formulas for illuminating compositions. Examples of illuminating compositions are shown in Table XXXI.

TABLE XXXI

## Illuminating Substances in %

Components	I	II	III	IV
Barium nitrate	66	68	75	80
Aluminum	—	28	18	15
Magnesium	30	—	4	—
Idiol or shellac	4	4	—	—
Drying oil	—	—	3	6 (over 100%)
Mealed black powder	—	—	—	5

The composition listed in the last column of Table XXXI was used in Pogrebnyakov's shell. The mealed black powder in it was intended for facilitating ignition.

6. Conditions of blocking illuminating compositions. Illuminating compositions, which are used as fillers for pyrotechnic media, are generally blocked into jackets under a pressure of 500-1000/kg/cm<sup>2</sup>. Illumination "stars" are blocked under a pressure of 2000-3000 kg/cm<sup>2</sup>. The blocking pressure is selected in relation to the properties of the composition and requirements of burning rate. Generally, the object is blocked into a cylindrical-shaped form, and one face has a flammable composition added to it during blocking. A quickmatch for ignition is also inserted into this face.

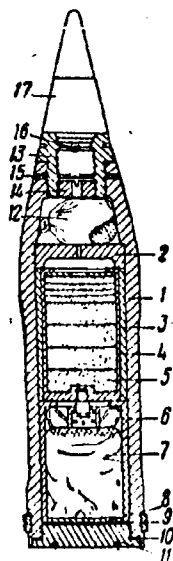


Fig. 62 - 122 mm long-range illuminating howitzer projectile

- |  |                       |
|--|-----------------------|
| 1. shell case                          | 2. upper diaphragm    |
| 3. illuminant half-cylinders           |                       |
| 4. illuminant jacket                   | 5. illuminating torch |
| 6. parachute half-cylinders            | 7. parachute          |
| 8. felt gasket                         | 9. cardboard gasket   |
| 10. load obturator ring                | 11. base              |
| 12. burster                            | 13. screw top         |
|  | 14. sleeve            |
| 15. hold-down screw for attacking head |                       |
| 16. time-fuze hold-down screw          |                       |
| 17. time fuze                          |                       |

7. Example of illuminating projectile. Figure 62 shows a 122-mm illuminating howitzer projectile, which lights up an area of up to 1000 meters for 50 to 55 seconds at a bursting height of about 500 meters. The luminosity is up to 500,000 candles.

During the projectile's flight, the gases of the burster charge, which have been ignited by a flash of flame from the time fuze, eject and ignite the torch. The torch and parachute are placed into half-cylinders which protect them from damage at the moment of ejection. After flying out of the projectile's case, the half-cylinders fall apart and free the parachute upon which the burning torch is suspended. To prevent the parachute shroud lines from twisting, the torch is equipped with a pivot yoke, rotating on ball bearings.

#### 5. PHOTO-ILLUMINATION COMPOSITIONS (PHOTO BLENDS)

Special pyrotechnic compositions - photo blends - are used to light up an area for night-time aerial photography purposes.

The requirement of a photo blend is to produce a large amount of light in the course of a short period of time, on the order of hundredths of a second. When aerial pictures are taken from a plane flying at an altitude of 1000 meters or higher, the required luminosity is obtained from a candle power of hundreds of millions or from several billion candles.

Photographic materials possess a varying sensitivity to the rays of different length waves. Therefore, the photo blends upon burning should radiate the light of a spectral composition which

is correspondent to the sensitivity of the photo film.

On the basis of what has been mentioned above, the following basic requirements are necessary for photo blends:

a. the photo blends upon burning should emit a large amount of light energy;

b. they should burn up very fast;

c. the combustion products which are formed during the deflagration of these blends should have a large amount of high-melting solid or difficult-to-volatilize liquid particles which emit light well;

d. the flame should have the highest possible temperature.

These requirements are satisfied to the highest degree by blends of magnesium powder or aluminum-magnesium alloys with various oxidizers. Aluminum without an admixture of magnesium is not used in photo blends because its combustion rate would not be sufficient.

Nitrates, but not chlorates, are used as oxidizers for the same reasons as in the selection of an oxidizer for illuminating compositions.

Most of all, photo blends which are composed of magnesium powder, strontium or barium nitrate are used.

## 6. TRACER COMPOSITIONS

Tracer compositions are used for marking the flight path of a bullet or projectile (formation of a trail, track).

Heretofore, burning tracer compositions (night operations),

and smoke compositions (daylight operations) were used. Experience showed that smoke tracer compositions did not assure the necessary visibility of the flight trajectory of a bullet or projectile along its entire path. Therefore, only burning tracer compositions are used today.

The fundamentals of assembling tracer compositions (white tracers especially) and their properties are very close to that of the illuminating compositions. This stems from the requirements set forth for them which, in many respects, coincide with the requirements for illuminating compositions. Tracer compositions should:

- a. release the maximum attainable quantity of light energy upon burning;
- b. burn at a set rate;
- c. have great stability and be able to be compressed under large pressure (from 3000 to 8000 kg/cm<sup>2</sup>). This precludes the possibility of a partial or complete burn-out in the bore;
- d. unfailing ignition from the ignition composition;
- e. to leave the maximum possible amount of slag in the seat of the bullet or projectile. This is necessary for a minimum change in the weight of the bullet or projectile, which has an effect on the rigidity of the trajectory. Such a requirement is set for those munitions in which the weight of the tracer element is quite large in comparison to the overall weight.

Barium nitrate is primarily used as an oxidizer in white tracer compositions, while strontium nitrate is used for red tracers.

Table XXXII shows some examples of burning tracer compositions.

TABLE XXXII

Tracer Compositions		
Components	White fire	Red fire
Barium nitrate	55	—
Strontium nitrate	—	60
Magnesium	35	30
Resins	10	10

Tracer compositions, consisting of a blend of nitrates with magnesium and resins, and blocked under high pressure, are not reliably ignited by the powder gases upon being fired. Flammable mixtures are used to ignite them. These mixtures burn under high pressures during the travel of the projectile or bullet along the bore. So, in order to avoid rapid burning, slightly gaseous compositions such as a blend of barium peroxide, barium nitrate and magnesium with a minimum amount of binder, are used. The addition of barium peroxide to these blends increases their sensitivity to initial thermal impulse and provides for an unfailing ignition from the powder gases at the moment of firing. We shall cite two examples of flammable compositions for tracers:

1. 80%  $\text{BaO}_2$ , 18% Mg and 2% binder



2. 48%  $\text{Ba}(\text{NO}_3)_2$ , 30%  $\text{BaO}_2$ , 13% Mg and 9% phenol formaldehyde resin.

Uses of Tracer Compositions. Tracer compositions are used as fillers for tracers in highexplose, high-explosive-incendiary, armor-piercing and shaped-charge projectiles, and for armor-piercing and ball tracer small-arms ammunition.

The tracer composition is ignited upon firing either directly by the powder gases or by means of a percussion cap, which is set off by a percussion mechanism.

The advantage of the first type of tracer is the simplicity of the arrangement. The defects are: the possibility of a corrosive effect on the bore by the combustion products; giving away the firing position; the tracer charge can be deformed during its travel along the bore by the pressure of the powder gases, which can cause a fast burn-out with resultant "short tracer"; and an insufficient hermetization of the tracer charge.

Tracers with a percussion cap are devoid of these defects, but, on the other hand, they are more complex, owing to which they are rarely used.

A tracer of the first type is composed of a metallic body, into which the tracer composition is forced. This is illustrated in Figure 63. The body is capped with a celluloid disk in order to make the composition air-tight. The tracer is inserted into a screw-on plug which is attached to the fuze or inserted directly into the body of the projectile. Figure 64 shows a tracer com-

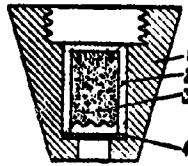


Fig. 63 - Tracer for MD-5 fuze

- |                       |                   |
|-----------------------|-------------------|
| 1. screw-on plug      | 2. tracer holder  |
| 3. tracer composition | 4. celluloid disk |

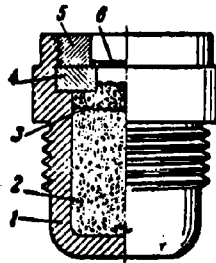


Fig. 64 - Tracer

- |                         |                       |
|-------------------------|-----------------------|
| 1. tracer body (steel)  | 2. tracer composition |
| 3. ignition composition | 4. ring               |
| 5. nut                  | 6. celluloid disk     |

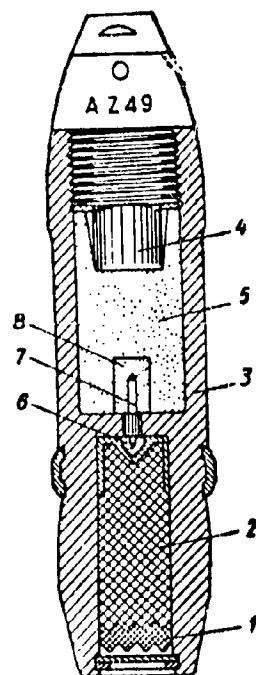


Fig. 65 - High-explosive self-destruction tracer projectile

- |                         |                       |
|-------------------------|-----------------------|
| 1. igniting composition | 2. tracer composition |
| 3. projectile case      | 4. fuze               |
| 5. bursting charge      | 6. suppressor         |
| 7. pin                  | 8. detonator          |

posed of a solid metal sleeve into which the tracer composition is pressed. Figure 65 shows a high-explosive self-destruction tracer shell. After the expiration of a certain period of time, the tracer composition ignites the fuze and causes an explosion of the projectile, so that the unexploded anti-aircraft projectile would not fall on the ground.

A tracer with a percussion mechanism is shown in Figure 66. At the moment of firing, the percussion plunger heats up the friction primer, a flash of flame goes through the powder delay element into the tracer composition, and the gases which are formed eject the sleeve, thus opening up an orifice of the exit of the flame. The visible flame (trace) appears at a distance of about 150-200 meters from the weapon, which thus does not disclose the firing position to the enemy.

## 7. NIGHT SIGNALLING COMPOSITIONS

1. General information concerning signalling media. Signalling media are used for communications by means of giving off signals which are seen at a distance. They are subdivided into day and night signalling devices.

Night signalling devices give off colored flames. Three, four, or five-colored systems are used for signalling. The best is the three-color because its colors - yellow, red, and green - are the easiest to distinguish by the eye. When the four and five-color systems are used, blue or white color is used in addition to the other three. These two colors are difficult to make out at a fairly long distance.

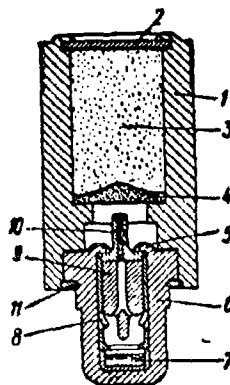


Fig. 66 - Tracer with percussion mechanism

- |                                      |                 |                       |
|--------------------------------------|-----------------|-----------------------|
| 1. tracer body                       | 2. steel gasket | 3. tracer composition |
| 4. ignition composition              | 5. gasket       | 6. primer cup         |
| 7. friction primer                   | 8. safety case  | 9. percussion plunger |
| 10. sleeve with powder delay element |                 |                       |
| 11. lead ring                        |                 |                       |

## 2. Light-producing characteristics of signal compositions.

Signal devices are filled with articles (stars) which have been made out of signalling compositions. The basic requirements of signalling compositions with respect to the character of emission of the flames differs from the corresponding requirement for illuminating compositions; the emission should be as close to monochromatic as possible. The most important characteristic of compositions which are used for making signal stars is the purity of the flame's color, which is evaluated by the ratio of the intensity of monochromatic emission to the intensity of the entire

visible emission. This ratio is ordinarily expressed in percents, and should be no less than 70% for the human eye to make a clear distinction between the flame's colors.

### 3. Selection of the components for signalling compositions.

The sharpest colored flame of the burning composition is obtained owing to the illumination of the gaseous phase; the atoms and molecules of this phase emit energy in a narrow region of the visible spectrum. For example, yellow rays are obtained during the atomic radiation of sodium. During the burning of compositions containing barium nitrates or strontium nitrates as well as chlorine-containing substances (polyvinylchloride, hexachloroethane, chlorates), the oxides of strontium and barium convert into easily volatilized monochlorides  $\text{SrCl}$  and  $\text{BaCl}$ . The first one emits red color, while the second one emits green light.

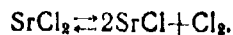
We shall note that the vaporous oxides of barium and strontium also emit rays - the first one green and the second one emits red rays. However, the concentration of the vaporous oxides in the flame is very small on account of the small elasticity of their vapors. Therefore, the intense light of solid and liquid oxides of barium or strontium, and having a compact spectrum, damps the weak light of the vaporous oxides. The emission of solid substances (oxides of metals), which produce a compact spectrum, should not take place in signalling compositions, or else it should be insignificant in comparison with the emission of the gaseous phase.

Chlorates and nitrates are used as oxidizers in signalling

compositions. Blends of potassium chlorate with the combustible burn more intensely than blends with nitrates.

The specific light sum of signalling compositions should be expressed by a value which is no less than several thousand candles sec/g. The luminosity which is emitted by the flames of the burning star should be expressed in thousands, and even more preferably, in tens of thousands candles. The burning of the pressed substance should take place with a speed of several millimeters per second.

4. Compositions for red fire. Strontium compounds, primarily in the form of carbonates or oxalates, are inserted into the compositions in order to obtain a red color of the flame. Berthollet's salt is used as an oxidizer. When these substances burn, strontium chloride is formed, which, at an elevated temperature, dissociates according to the reaction:



Strontium monochloride emits red rays. One example of a composition for red fire: 60%  $\text{KClO}_3$ , 25%  $\text{Sr}(\text{C}_2\text{O}_4)$ , 15% phenol formaldehyde resin.

Compounds which contain strontium nitrate are also used. In this particular case, magnesium is added in addition to an organic combustible. In order to transform the oxides of strontium which are formed during burning, chlorine-containing substances are inserted into the monochloride.

5. Green fire compositions. Barium compounds are used to get green flames. The most favorable is barium chlorate, which is an oxidizer at the same time. A defect of compositions containing barium chlorate is their great sensitivity to mechanical effect.

When a compound containing barium chloride burns,  $\text{BaCl}_2$  is formed which then dissociates with the formation of  $\text{BaCl}$ , emitted green rays. The compositions for green fire are shown in Table XXXIII.

TABLE XXXIII  
Examples of green fire compositions in %

Components	I	II
Barium chlorate	89	85
Phenol formaldehyde resin	11	—
Shellac	—	15

Barium chlorate can be substituted by nitrate; this lowers the sensitivity of the composition to mechanical effect, but at the same time, the color of the flames worsens somewhat. The following is related to this type of signalling composition: 63%  $\text{KClO}_3$ , 25%  $\text{Ba}(\text{NO}_3)_2$ , 12% phenol formaldehyde resin. Green fire compositions are also made on a base of barium nitrate and chloro-organic compounds.



6. Yellow fire compositions. Sodium salts - sodium oxalate, sodium fluoride, and some others - are used to get yellow fires. The salts should be non-hygroscopic and should dissociate easily at elevated temperature.

An example of a yellow fire composition is: 60%  $\text{KClO}_3$ , 25%  $\text{Na}_2\text{C}_2\text{O}_4$ , 15% phenol formaldehyde resin.

A small quantity of aluminum (up to 5%) or of an aluminum-magnesium alloy is sometimes inserted into the colored flame compositions so that the brightness of the flames could be increased.

7. Uses of night signalling compositions. Night signalling compositions are used in 26 mm shells, rifle grenades, and high-power signals.

26 mm signal shells are used for night signalling up to a range of 7 km. Their construction is shown in Figure 67. The burning time of the signal "stars" is about 6.5 seconds. The luminosity is no more than 10,000 candles.

8. Daylight signalling Compositions. The so-called daylight compositions are used for signalling during the daylight hours. These produce tinted (colored) smokes during burning. Colored smokes are also used in artillery projectiles in the form of a small charge which colors the explosion products for facilitating fire correction.

Smoke is a colloid system consisting of finely pulverized solid particles (dispersed phase) which are suspended in air (dispersion medium). If the dispersed phase is a liquid substance,

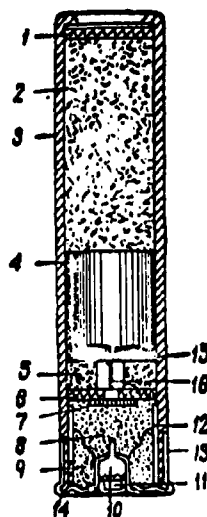


Fig. 67 - 26 mm night signalling shell.

- |                           |                           |
|---------------------------|---------------------------|
| 1. cardboard closing plug | 2. felt packing           |
| 3. paper shell case       | 4. signal star            |
| 5. felt wad               | 6. cardboard closing plug |
| 7. gauze disk             | 8. burster                |
| 9. paper ring             | 10. anvil                 |
| 11. friction primer       | 12. iron tube             |
| 13. brass head            | 14. flange                |
| 15. ignition              | 16. quickmatch            |

then the system is called fog. Smoke which has five colors is used. These colors are: red, yellow, blue, green, and black.

In order to obtain these colored smokes, semi-products and coloring agents are used, which convert into a vaporous state on account of the reaction heat.

Berthollet's salt is used as the oxidizer in smoke compositions. Sodium chlorate is used less often, and, sometimes, nitrates are added in.

The burning temperature of the colored smoke composition with organic coloring substances should be sufficient to vaporize the smoke-former and, at the same time, not that high wherein its decomposition would come about. Therefore, metallic powders are not satisfactory as combustibles in this case. For instance, mixtures of Berthollet's salt with milk-sugar are used. They are calculated to burn the combustible only to carbon monoxide. Even though the combustion temperature of this mixture is within the limits of 800-1200<sup>0</sup>, the smoke former does not decompose but only sublimates, owing to the fast burning rate.

An example of blue smoke is: 35%  $KClO_3$ , 25% milk sugar, and 40% indigo.

Uses of daylight signalling devices. Daylight signalling media by construction and operation are analogous to those of the above-described night media. The difference is that the "star" in the daylight devices is a little bag of unbleached cloth which is filled with the colored smoke composition. When the composition burns, the cloth bag obstructs the passage of air and incomplete combustion takes place within the bag, which provides for vaporization of the smoke-former.

When the 26 mm daylight shell is fired, the "star" is lifted to a height of 70 meters. The cloud of smoke can be distinguished for a distance of up to 2 km for 10 seconds on a windy day and for 30 seconds on a calm day.

## 9. MASKING SMOKES

Masking smokes are used for the formation of a smoke screen, which is used to blind the firing positions of the enemy's batteries, his emplacements, observation and command posts. Smoke screens are also used to mask friendly troops and rear area objects.

White smokes cover the outlines of objects better than do the black ones. Substances which form white smoke are used most often as fillers for smoke shells. These substances include white phosphorous, sulfur trioxide, and chloric tin.

When the phosphorous burns, phosphoric anhydride is formed, which reacts with the moisture in the air and forms meta- and orthophosphoric acids, which form white smoke (fog).

Sulfur trioxide, being a very volatile substance, easily transforms into the vaporous state and reacts with the moisture in the air, forming sulphuric acid.

The sulphuric acid vapors, possessing a very slight buoyancy at ordinary temperature, supersaturate the area. At the same time, the moisture in the air reacts vigorously with the sulphuric acid, forming hydrates. Upon condensation, the individual molecules, combining themselves, form colloid particles, which constitute the dispersed phase. White fog is formed.

Stannic chloride in a finely pulverized state reacts with the moisture in the air according to the formula:

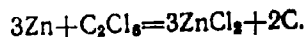


The orthostannic acid forms white smoke in conjunction with the hydrogen chloride.

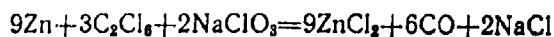
Yershov's compositions (20%  $\text{KClO}_3$ , 10% carbon, 50%  $\text{NH}_4\text{Cl}$ , 20% naphthalene) are smoke producers. When the Yershov composition burns, a volatilization of the ammonium chloride and a part of the naphthalene takes place, which then form white smoke.

Mixtures of the Yershov type are designed for incomplete combustion, and the products of their combustion contain a lot of the oxides of carbon, hydrogen, carbohydrates and other combustibles. Flash eliminators (carbonates - soda, chalk, magnesium carbonate) are put into the smoke compositions in order to prevent them from flaring up when mixed with air. A large amount of heat is used up in their composition, owing to which the temperature of the combustion products is lowered. Besides this, the carbon dioxide which is formed rarifies the combustion products, thus raising the combustion temperature of the latter. Ammonium chloride also fulfills the role of flash eliminator.

During World War II, smoke compositions on a base of hexachloroethane and zinc dust were used. They formed gray smokes, because black carbon particles were liberated together with the white zinc chloride particles according to the equation



A supplementary oxidizer such as sodium chlorate is put into the mixture in order to eliminate the formation of carbon. In this case, the combustion proceeds according to the reaction



and white smoke is formed.

## 10. INCENDIARY SUBSTANCES AND COMPOSITIONS

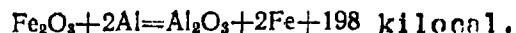
1. Classification. Incendiary substances and compositions are divided into two groups: oxidizer-containing compositions and incendiary substances without oxidizers.

The compositions of the first group can be further divided into the following groups:

- a. thermites and thermite compositions which contain oxides of metals as oxidizers and metals as the combustibles;
- b. compositions in which the oxidizer is an oxygen-containing salt.

The incendiary substances of the second group include electron, organic combustibles and spontaneous-combustion substances. Substances of the second group can burn and effect an incendiary action only in the presence of oxygen and with the free access of the air's oxygen.

2. Thermites and Thermite Compositions. For instance, the combustion of an iron-aluminum thermite (containing oxide of iron and powdered aluminum) takes place according to the following equation:



Thermite reactions are distinguished by the following singularities:

- a. high combustion temperature ( $2400-2800^{\circ}\text{C}$ );
- b. the combustion is flameless because practically no gaseous products are obtained;
- c. liquid slags are obtained which are heated to a high temperature. Their flow increases the radius of the incendiary effect.

Oxides of iron are the best of the possible oxidizers for practical use. They contain a relatively large quantity of oxygen; they have a high specific gravity, are inexpensive and readily attainable. Iron scale ( $\text{Fe}_3\text{O}_4$ ) rather than  $\text{Fe}_2\text{O}_3$  is generally used.

Thermite normally consists of a mixture of 25% aluminium and 75% ferric oxides. The combustion temperature of such a composition is  $2500^{\circ}$ .

The defect of thermites is that their incendiary effect is limited by the small radius directly around the focus of burning. In addition, thermites are difficult to ignite. Therefore, rather than thermite, thermite compositions containing a number of admixtures such as saltpeter and organic combustibles, facilitating ignition and increasing incendiary action (owing to the formation of flames) are generally used as fillers for incendiary media.

Sometimes magnesium is used in thermite compositions. It increases their incendiary effect (on account of magnesium's low boiling temperature -  $1107^{\circ}$  - it evaporates in burning of the composition and burns up in flames).

As an example, the following incendiary composition is used

for filling 76 mm projectiles: 44%  $\text{Ba}(\text{NO}_3)_2$ , 6%  $\text{KNO}_3$ , 21%  $\text{Fe}_2\text{O}_3$ , 13% Al, 12% Mg and 4% binder. For filling incendiary aircraft bombs, a thermite composition was used which contained a supplementary oxidizer - barium nitrate. This composition consisted of 24% Al, 50%  $\text{Fe}_3\text{O}_4$  and 26%  $\text{Ba}(\text{NO}_3)_2$ .

Thermite compositions are used for setting objects on fire which are difficult to ignite. They are also used to knock out metal objects (cannon, tanks, etc.).

### 3. Incendiary compositions with oxygen-containing salts.

These compositions produce a high combustion temperature and catch fire fairly easily. Nitrates and chlorates serve as oxidizers while metals such as magnesium, aluminum-magnesium alloys and others are the combustible.

Incendiary compositions on a base of oxygen-containing salts are used primarily for filling small-caliber projectiles and bullets intended chiefly for igniting liquid combustible materials (easily ignitable materials). The burning of incendiary compositions with oxygen-containing salts takes place in a fraction of a second, in comparison to other forms of incendiary compositions or substances.

4. Incendiary substances not containing oxidizers. The aluminum-manganese alloy, electron, which contains no less than 90% magnesium, was used during World War II for making small caliber incendiary aircraft bomb bodies. These bombs were filled with thermite. Such bombs were devoid of dead load. When the electron bomb body burns up, a flame is formed which promotes a



good incendiary effect. The combustion temperature is around  $2000^{\circ}$ .

Organic combustibles such as petroleum, kerosene, gasoline, pitch, and others possess a high heat-producing ability. For instance, when 1 kg of kerosene burns in air, around 10,000 kilocal are evolved, whereas only 800 kilocal are liberated in the burning of 1 kg of thermito. When petroleum products are burned, a larger flame is obtained, therefore the radius of incendiary effect of such substances is much greater than in the case of thermito compositions. But, on the other hand, the combustion temperature of the petroleum products is low ( $700-1000^{\circ}$ ). Some of the drawbacks of the petroleum products are the excessively large mobility and spreading out as well as the too-fast evaporation rate.

Organic combustible substances are used for action against easily-flammable objects and for anti-personnel purposes.

Hardened combustibles. The defects of the organic substances can be greatly reduced or even eliminated by using a combustible in hardened form, in combination with thermito, or in a thickened form.

In hardening, the combustible is gelatinized by soaps, i.e. by the salts of higher organic acids of the aliphatic series. When a petroleum product is preheated to a temperature of  $75-80^{\circ}$ , the organic acid is dissolved, and then an equivalent amount of an alcoholic solution of caustic soda or some other base is added in.

After cooling, this mixture hardens, assuming the consistency of a hard soap. It can be cut by a knife and retains its shape.

Hardened combustibles are used in combination with thermito in aircraft bombs. The head part of the bomb contains the thermito charge. A metal diaphragm is then put in, and then the hardened combustible is put in.

Figure 68 shows the construction of an incendiary bomb with a combination combustible. The weight of the combustible is 50 kg. When the bomb burns, the flames reach a height of 5 meters.

A thickened combustible is a viscous, fluid, colloid paste. Tackiness is sometimes imparted to this paste by means of special admixtures. On account of this, when the burning paste falls on some object, it will cling to the object. A thickened combustible is obtained by means of blending a liquid combustible with aluminum salts of naphthenic and highly molecular aliphatic acids. Such a blend obtained the name napalm.

Napalm acquired infamy from the time of its barbaric application by the U. S. forces in heavyweight aircraft bombs against the peaceful people of Korea. This napalm contained burning metallic powders, magnesium primarily, owing to which an elevated combustion temperature was obtained with the result that the incendiary effect was increased.

5. Spontaneous-combustion incendiary substances. Of the spontaneous combustion substances, the most important is white phosphorous which readily bursts into flames in air. The incon-

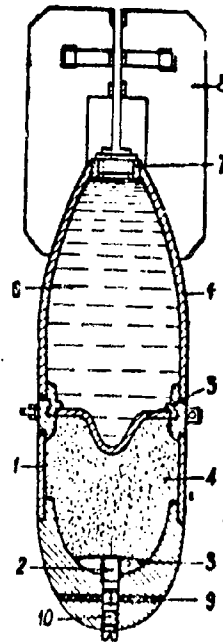


Fig. 68 - Incendiary bomb with combination combustible.

- |                             |   |
|-----------------------------|---|
| 1. bomb body                | 2. ignition spider                      |
| 3. intermediate composition | 4. thermite incendiary base composition |
| 5. diaphragm                | 6. hardened combustible                 |
| 7. base plug                | 8. fin                                  |
| 9. gas-escape aperture      | 10. hole below fuze                     |

diary effect of phosphorous is not large. Its combustion temperature is around  $1000^{\circ}$ , therefore it ignites only objects which can be set afire easily - hay, straw, gasoline, etc.

Hand grenades and mines which were filled with phosphorous were used in trench warfare. When they exploded, a large amount of smoke was formed. The burning droplets of phosphorous burn through clothing and inflict serious skin diseases which are difficult to cure. Combustible substances such as petroleum oils, tars, etc. are added to phosphorous in order to improve its incendiary properties.

6. Uses of Incendiary Compositions and Substances. Incendiary compositions are used in aviation munitions, in field and anti-aircraft artillery, and in small arms ammunition.

## 11. IGNITION COMPOSITIONS

Some pyrotechnic compositions can be quickly and readily ignited by a quickmatch. But many compositions are set on fire with difficulty, and special ignition compositions are used to set them afire. In the case of substances which are ignited with even greater difficulty, intermediate compositions are necessary.

Those mixtures which contain chlorates and organic combustibles or nitrates in conjunction with magnesium ignite the easiest of all. These compositions in powder form should be ignited by a quickmatch. But the same compositions in a pressed form require a special igniter for ignition.

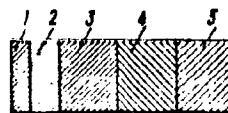


Fig. 69 - Diagram of inflammation of pyrotechnic substances which are difficult to ignite.

1. Mealed black powder
2. igniting composition
3. first intermediate composition containing 15% igniting composition and 25% base composition
4. second intermediate composition containing 50% igniting composition and 50% base composition
5. base composition

Thermites are ignited with great difficulty. Increments from the ignition composition are insufficient in this case, and the use of an intermediate composition, consisting of a mixture of flammable and ignition compositions is required. If this is insufficient, one more intermediate composition with a large content of the ignition composition is put in and distributed as shown, for instance, in Figure 69.

The number of components in the intermediate composition and their ratio is established experimentally for each case.

Examples. For igniting illuminating compositions which contain magnesium, an igniting composition of the gunpowder type is used (the sulfur is substituted by phenol formaldehyde resin): 75% potassium nitrate, 15% charcoal and 10% phenol formaldehyde resin.

For compositions which are more difficult to ignite and which contain aluminum, the charcoal is replaced by magnesium in the ignition composition. Finally, in the case of pyrotechnic substances which are still harder to ignite, intermediate compositions are used.

---

## FOOTNOTES

<sup>1</sup>In the arbalest, the arrow travelled along a trough when fired. In the arquebus, the trough was replaced by a tube which made it possible to fire bullets as well as arrows.

<sup>2</sup>Alfred Nobel - Swedish engineer, and A. Noble - English artillery scientist.

<sup>3</sup>The term "shot-hole" means a man-made cylindrical depression in rock. The diameter of this shot-hole can be up to 75 mm and the depth can be down to 5 meters. The shot-hole serves as a receptacle for explosive in blasting operations. The free part of the shot-hole above the charge is packed with an inert material, called "tamping".

<sup>4</sup>The classification shown here includes only those practically employable explosives. For this reason, it does not include such explosives as gaseous mixtures, supersensitive substances, etc.

<sup>5</sup>Two different terms for analogous concepts are used in the pertinent literature. "Demolition" work is used by the military and the term "blasting" operations is used for national economy purposes. The latter term is used for all cases in this book. This is in accordance with the recommendations of the Committee on Technical Terminology of the Academy of Sciences, USSR.

<sup>6</sup>Nitric esters or nitrates of hydrocarbons and alcohols, for reasons associated with the historical development of their structural representation, have been erroneously named "nitrocellulose", "nitroglycerine" etc., instead of "nitrate of cellulose", "glycerintrinitrate", etc. However, from the point of view of the irregular structure of these compounds, the names have been preserved up to the present time in scientific and technical literature.

<sup>7</sup>All-Union State Standard 2040-43 defines the test conditions for pyrotechnic compositions.

<sup>8</sup>For a detailed description of a method for determining the sensitivity to shock, see All-Union State Standard 4545-46. "Explosives." A method for determining the sensitivity to shock".

- <sup>9</sup> A charge is a quantity of explosive which is used for effecting one explosion..
- <sup>10</sup> This is the name for TNT which is obtained after the nitration of toluene and washing away of acids from the products. It contains a certain amount of dinitrotoluene and other substances.
- <sup>11</sup> For layout of the apparatus for Abel test, see All-Union State Standard 3566-47.
- <sup>12</sup> For construction of the thermostat, see All-Union State Standard 7367-55.
- <sup>13</sup> For a detailed description of manometric and electrometric tests, see G. F. Klimenko, Test Methods for Powders. Oborongiz, 1941.
- <sup>14</sup> As is well known, the thermal effect of a process which is taking place with the participation of gases or vapors can be distinguished in relation to the fact that the process either proceeds or does not proceed in a constant volume. In the calculation of detonation processes, it is assumed that the reaction can run its course before the expansion of its products begins. Accordingly, for this particular case, the thermal effect is computed at a constant volume (denoted by  $Q_v$ ). Conversely, in examining the combustion process, the thermal effect is computed at a constant pressure (denoted by  $Q_p$ ). Proceeding further, if condensing substances (water, for example) are formed in this reaction, then the magnitude of the thermal effect will be changed in relation to the state in which these substances are obtained - liquid or vaporous. In the calculation of explosive transformations, it is generally assumed that water and analogous substances are obtained in the form of vapors.
- <sup>15</sup> For a description of a calorimetric bomb and calorimeter, see K. K. Snitko, Explosives, Publication of the Artillery Academy, 1939, as well as courses in the theory of explosives.
- <sup>16</sup> For the derivation of these and subsequent expressions, see a chemical textbook. We shall only mention that the equilibrium constants can be expressed through the equilibrium concentrations of reacting substances (denoted by  $K_c$ ) or through their equilibrium partial pressures (denoted by  $K_p$ ). The second of these methods is used here. If we are to consider the products of the explosive transformation as an ideal gas, then, for the reaction  $aA + bB = cC + dD$ , the following relations can be readily derived:



$$K_p = \frac{P_A^a \cdot P_B^b}{P_C^c \cdot P_D^d} = \frac{n_A^a \cdot n_B^b}{n_C^c \cdot n_D^d} \left( \frac{P}{n} \right)^{\Delta n} = \frac{n_A^a \cdot n_B^b}{n_C^c \cdot n_D^d} \left( \frac{RT}{v} \right)^{\Delta n},$$

where P is the overall pressure of the explosion products;  $n_{\Sigma}$ , v, and T are the corresponding number of moles, volume, and temperature of these products; and  $\Delta n = (a+b)-(c+d)$ .

17 For a description of the gas meter and method for determining the volume and composition of the explosion products, see K. K. Snitko, Explosives, Publication of the Artiller Academy as well as in courses devoted to the theory of explosives.

18 In contrast to gaseous ones, solid and liquid substances are called condensed substances.

19 The mass rate of combustion (or vaporization) is equal to the mass of substance which is burned (or vaporized) in 1 sec per 1 cm<sup>2</sup> of cross section. The dimensions of mass rate are g/sec·cm<sup>2</sup>.

20 There is a distinction between the melting and solidification temperatures. The temperature at which the test sample, slowly heated in a capillary tube, melts completely is called the melting temperature.

The solidification temperature is determined differently. For this determination, about 15g of the substance is heated above the melting temperature and then the melt is cooled, and the drop in temperature is observed. At the beginning, an even drop in the temperature of the cooled substance is observed. After that the temperature settles and then rises. Finally, the temperature drops once more. This maximum temperature which is attained after the first period of temperature drop is called solidification temperature.

Theoretically, the melting and solidification temperatures should coincide. Under experimental conditions, however, the melting temperature is approximately 1 to 1.5° higher than the solidification temperature.

<sup>21</sup>For details, see the commercial requirements of TNT as contained in All-Union State Standards 3471-46 and 4117-48 (TNT for ammonites).

<sup>22</sup>Trotyl oil is a mixture of TNT with asymmetric isomers of trinitrotoluene, dinitrotoluol, and other substances. The melting temperature of this mixture is around 30-35°.

<sup>23</sup>Collection of recommended terms of the Committee on Technical Terminology, Academy of Sciences, USSR. Terminology of blasting operations. Publication of Academy of Sciences, USSR. Moscow, 1953.

<sup>24</sup>Drying the powder at low temperature (20-30°) in an atmosphere containing the solvent vapors. If this operation is carried out in air not containing the solvent vapors, it will then form a crust on the surface of the powder on account of rapid evaporation, which will then slow down a further removal of the solvent from the deep-seated layers.

The length of the process is approximately 24 to 48 hours, depending on the thickness of the powder element.

<sup>25</sup>Muzzle velocity is that velocity which a projectile has upon coming out of the weapon at that moment when the base of the projectile passes the muzzle face of the tube.

<sup>26</sup>For determining the probable deviation of muzzle velocities of a projectile, 5 to 10 rounds are fired, and the muzzle velocity is determined each time.

The probable deviation is computed according to the formula:

$$r_v = 0.6745 \sqrt{\frac{\sum (v_i - v_{av})^2}{n-1}},$$

where  $r_v$  = probable deviation of muzzle velocity;

$v_i$  = muzzle velocity of every separate round;

$v_{av}$  = average value of muzzle velocity for a series of rounds fired.

$n$  = number of rounds fired in the series.

<sup>27</sup>The word pyrotechnics comes from two Greek words "piros" (fire) and "texnos" - the art also means "the ability to produce fire".

- <sup>29</sup> A defect of resin is its low softening temperature (60-80°). Therefore, the reaction product of resin and caustic lime (calcium resinate) is used in certain compositions. Its softening temperature is 120-150°. The shellac separates out in the form of an incrustation which is found on the branches of tropical plants. The softening temperature of shellac is generally around 70-100°.
- <sup>30</sup> Phenol-formaldehyde resin is a synthetic resin obtained by the condensation of phenol with formaldehyde in the presence of an acid catalyst. The softening temperature is not lower than 90-97°. It is not soluble in water. Bakelite is another form of synthetic resin. It is obtained from the same substances as phenol-formaldehyde resin but under other reaction conditions. Bakelite gives pyrotechnic compositions a higher mechanical stability than many other binders. Polyvinyl chloride, or, as it is otherwise called, polyvinyl chloride resin, is a product of the polymerization of vinyl chloride. It is inserted into compositions whose flames require the presence of chlorine.
- <sup>31</sup> For a description of the instrument and method of determining the luminosity of illuminating compositions, see 1) A.A. Shidlovskiy, Fundamentals of Pyrotechnics.

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