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INTERIOR BALLISTICS

VNUTRENNYAYA BALLISTIKA

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VNUTRENNYAYA BALLISTIKA

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The manual contains the theoretical principles of interior ballistics and the contemporary methods of solution of its main problems. The course includes investigations and studies accomplished in recent years in various branches of this science. Also, a short historical description is given of the development of interior ballistics. The latter emphasizes the leading part played by Russian scientists prior to the October revolution, and particularly after it.

Considerable attention is given to the practical aspects of a series of problems. Reference is made to a sizable quantity of test data, examples and problems helpful in mastering the method of basic ballistic calculations.

FOREWORD

"Military science and research institutes, as well as our cadres of designers should constantly and persistently improve the standards of the Soviet military technical thought, perfect our war materials and develop new and better specimens of it."

(From the speech of the marshal of the Soviet Union, N.A. Bulganin, on the 23rd of February 1948

Interior ballistics appear to be a basic aspect of artillery, closely related to a large number of complex branches of artillery sciences which insure the formation of the modern artillery system and related ammunition problems.

The power characteristics of the weapons, their efficiency and conformance to the tactical and technical requirements, depend to a significant degree upon the power and rational solution of interior ballistics problems.

The demands on artillery weapons increased rapidly prior to the second world war, and particularly during the hostilities.

"Mechanized Warfare" required the creation of entirely new types of artillery weapons, an increase in the power of existing types of weapons, and an extensive complexity of materials. Quantitative variations of the basic fire parameters caused definite qualitative modifications of artillery materials.

Therefore, the problems confronting interior ballistics at the present time cannot be compared in any way with interior ballistics problems of the first quarter of the twentieth century, with respect to their complexity and variability.

The domestic interior ballistics, comparably to all other related branches of artillery sciences, progressed and developed along outlines peculiar to themselves. Artillery sciences and techniques, among them interior ballistics, constantly expanded and developed during the years of Stalin's Five Year Plans. This created types of artillery systems which were markedly superior, as respects quality, to those of foreign armies, as proves by the practice of the Great Homeland War (World War II).

Artillery technology continued to develop after the war, and the demands on it are increased. Thus, the tasks and scope of problems which interior ballistics has to cope with and solve are widened.

In order to solve these tasks successfully, it is first necessary to have an advanced theory supported upon a modern experimental basis. Secondly, we need personnel familiar with this theory and the related experiments, who are capable of following the guiding instructions expressed by Comrade A.A. Zhdanov in a philosophical discussion, that "the basic task of all science appears to be its further progress, the derivation of new rules, the testing of its theses in practical application, and the replacement of outdated assumptions by new ones."

The volume of problems confronting interior ballistics has widened significantly from the time of the 1939 edition of the standard study manual "Interior Ballistics," written by M.E. Serebriakov, G.V. Oppokov and K.K. Greten. Solutions were also worked out for a series of new problems.

In connection with this, consideration was given to the publication of a new study manual on interior ballistics, which would be adequate for the increased demands of modern artillery technology and which would offer materials and methods for the further development of this branch of science.

The proposed manual differs greatly from the textbook published in 1939. It contains a series of newly written sections and chapters, which present solutions of problems in complex cases resulting from the development of artillery technology.

The manual reflects an extensive methodical study, carried out in the Interior Ballistics Department of the Artillery Academy during the years of the Great Homeland War (World War II) and subsequently to it.

Basically, the course was put together from studies and investigations of our Soviet scientists, including lecturers of the Interior Ballistics Department of the Artillery Academy.

Studies of foreign authors are utilized only for the purposes of clarification of the history of one problem or another. Those relate mainly to studies on investigations of powder combustion, and on some others conducted prior to 1925.

The course is designated as a basic study manual for students of the engineering departments of the Artillery Academy and other institutions of higher education. Also, for the guidance of employees of design offices, factories, institutes and laboratories active in processing, investigating and creating new types of artillery weapons and ammunition. The book should also be of use to a wide circle of scientific workers, engineers and students in advanced courses of institutions of higher education.

The course is composed of the introduction and three sections. For the most part, the introduction is newly written. Special emphasis is placed on the relation of interior ballistics to the design of artillery types and ammunition. A new chapter entitled "From the History of the Development of Interior Ballistics" was written, stressing the leading part of Russian scientists prior to and after the October revolution.

The first section entitled "Physical Principles of Interior Ballistics", presents an account of the physical principles of interior ballistics and of the phenomena taking place during firing, from the start of powder combustion to the end of the period of the after-effects of gases on the projectile and on the gun barrel.

The basic course is preceded here by the first chapter, containing information on powders and their basic characteristics.

Disregarding the opinions of some specialists, to the effect that the terms pyrostatics and pyrodynamics are outdated at the present time, the manual continues to utilize these expressions because of their clarity and brevity.

The composition and arrangement of the material contained in Chapter II, "General Pyrostatics," was changed considerably. Chapter III, "Ballistic Analysis of Powders on the Basis of their Physical Combustion Principles," was expanded and supplemented. Chapters on the criterion of the propriety of this or another law of combustion speed were introduced in conformance with the modern status of problems of the theory of powder combustion.

New material was added to Chapter IV, "Physical Principles of Pyrodynamics," including a new treatment of some problems (the effect of chamber expansion, the dependence $p_{dn} - p_{st} - p_{sn}$).

Chapter V presents material on phenomena connected with the escape of gases, on the duration of the after-effects of gases on the projectile, on the maximum recoil speed and projectile velocity, and on the conception of the forces acting on the barrel when using a muzzle brake.

Section 2, entitled "Theory and Practice of Solving Interior Ballistics" Problems (theoretical and applied pyrodynamics), presents analytical, empirical, tabular and numerical methods of solving problems in interior ballistics. The most important practical task of interior ballistics, the ballistic design of weapons, is discussed in the last chapter of this section. In this connection, a series of studies conducted by Russian scientists during the past ten years was utilized.

The introduction to the second section considers the tasks, and gives a classification of the methods of solution. The precise method of Professor N.F. Drozdov, first published in world literature in 1910, is referred to in Chapter IV as a basic example. Similarly, a simpler approximate solution of the basic problem of interior ballistics is also discussed. Theoretical solutions are accompanied by detailed solutions of examples. The methods of solution of Professor I.P. Grave and Professor G.V. Oppokov are explained. The chapter on the investigation of basic relations for a simple case is rewritten and rearranged. It offers explanations of the principal types of elements of ballistic curves (p, v, ψ, T/T_1 as functions of l).

A new chapter is introduced on the solution of the problem, on the basis of the physical principle of combustion, in accordance with the method of Professor N.E. Serebriakov.

Chapter VII, "Numerical Methods of Solution," was kept without much change.

Chapter VIII, discussing empirical methods and tables, was considerably abbreviated, because the former lost their importance with the existence of precise tables composed on the basis of analytical formulas. At the same time, the correction tables of Professor V.E. Slukhotzki were added.

In Chapter IX, "Tabular Methods for the Solution of Interior Ballistics Problems," the fundamentals for the compilation of tables were re-written, and material was added on the new tables GAU 1942.

The idea of the method of relative variables and a reduced number of parameters, evolved during recent years by Professor B.N. Okunev, Professor N.F. Drozdov, Lecturer M.S. Gorokhov and L.I. Sviridov, is introduced in the course for the first time.

The theory of similarity is so arranged that its principles follow inherently from formulas used as a basis for the compilation of ballistic tables.

Chapter X, "Ballistic Design of Weapons," is completely re-written, offering new methods for solving this problem. It includes the theoretical substantiation and new criteria relating to tactical and technical requirements. The "directional diagram," especially developed by the author, permits a considerable reduction of the number of variants in calculations. In this connection, an evaluation of gun life by the method of Professor V.E. Slukhotzki is introduced.

The third section, "Solution of Interior Ballistics Problems in Complex Cases," gives solutions of interior ballistics problems for certain special cases of great interest in practical applications. For instance, Chapter XI includes:

1) The solution of problems for combination projectiles; which are analytical and apply the GAU 1942 table.

2) The solution of problems for mortars, with consideration of the partial escape of gases through the clearance, and with reference to a detailed example of calculation.

3) The solution of interior ballistics problems relating to progressive acceleration, treated by Professor G.V. Oppokov.

The 12th and last chapter clarifies peculiarities of ballistic weapons having a conical bore, and offers ideas on the design of those types.

In this way, the course covers the greater part of the basic problems of modern interior ballistics.

The major portion of the study was written by Professor M.E. Serebriakov, Doctor of Technical Sciences, Active Member of the Academy of Artillery Sciences, Major-General of Artillery Engineering Services. About six pages of print were written by Professor G.V. Oppokov, Doctor of Technical Sciences, Major-General of Artillery Engineering Services.

The authors express deep gratitude to the corps of lecturers of the Department for criticism in reviewing the manual, and to Professor D.A. Ventsel for a review of the study and for a series of valuable comments.

The authors also express gratitude to the junior scientific

collaborator P.I. Liserkin, who made a series of basic calculations and provided examples; and to the editor, Colonel-Engineer B.V. Smirenskii, for his great services in the preparation of the manual for printing.

M. Serebraikov
G. Oppokov

INTRODUCTION

THE OBJECT AND TASKS OF INTERIOR BALLISTICS

Artillery - the main striking fire power of the Soviet Army.

The basic mission of artillery in combat consists of striking targets with projectiles fired from weapons with one or another initial velocity. These targets are often located at a great distance away on the ground, or at a given point in space (firing at aerial targets). In addition, it is required at times that the projectile strike the target at a given angle of impact or with a given velocity (i.e., in the penetration of armor).

The projectile is transmitted to the target by firing from a weapon. Accurate fire appears to be the basic element of artillery effectiveness.

The discharge imparts motion to the pistol bullet, as well as to the heavy projectile of battleship guns or to the armor piercing shell of an anti-tank gun.

Ballistics, one of the principal specialized, technical branches of artillery sciences, is concerned with the study of the laws governing the projectile's motion in the bore of the weapon and in the air.

Two principal periods may be distinguished in the motion of a projectile.

1) Motion within the bore of the weapon during the discharge, when the projectile moves at a constantly increasing velocity as a result of the pressure of powder gases, and leaves the bore of the weapon with a given, so-called muzzle velocity v_0.

2) Motion or flight in the air of a projectile discharged from a weapon with a muzzle (maximum) velocity, and undergoing the effects of gravity and of air resistance until the moment of impact with the target.

In connection with those two periods of motion, ballistics are divided into two basic sections: interior ballistics, and exterior ballistics. This is done on the basis of the characteristics of the phenomena and processes studied.

Exterior ballistics are a study of the flight of a projectile from the moment of its departure from the bore, or from the end of the period of after-effect, when it has its highest velocity, to the moment of impact with the target. By determining the principle of air resistance to the motion of the projectile, exterior ballistics permit determination of the angle to the horizon, and velocity, with which a projectile of a given caliber, weight and form should be fired in order for it to strike a target at a given distance, at a given angle of fall and with a given velocity, or to pass through a given point of space (firing at aerial targets).

Interior ballistics are a study of phenomena and processes taking place during the discharge, and, particularly, the motion of the projectile in the bore, the characteristics of its acceleration, and the principles of the powder gases' pressure growth (see figs. 1 and 2). The discharge itself represents a process of the very rapid conversion of the initial chemical energy of the powder into thermal, and then into a kinetic energy of motion of the projectile - charge - barrel - gun carriage system.

The conveyor of energy, imparting motion to the projectile and to the entire artillery system, is the powder and the gases formed during its combustion.

The discharge process lasts hundredths or thousandths of a second. The maximum pressure reaches 3000 atmospheres and more. The temperature of the powder gases at the moment of their formation during the powder combustion reaches nearly 3000°; while at their emergence from the bore it is around 2000°. Nevertheless, the process of discharge is uniform, controllable and stable from one discharge to another.

The principal and very valuable characteristic of modern smokeless colloid powders, that they burn ~~regularly~~ in parallel layers at a comparatively low speed, constitutes the basis for this uniformity and stability of the discharge process. Using this characteristic, interior ballistics teaches how to make rational use of the powder energy at the time of discharge. It facilitates control of the discharge phenomenon i.e., of regulating the influx of gases into a bore during powder combustion, in relation to charge conditions, in a manner which will produce the required pattern of pressure development and the desired muzzle velocity of the projectile.

The discharge phenomenon clearly shows the interdependence between the elements and factors. For instance, the motion of the projectile depends on the pressure of powder gases, while the pressure itself depends on the combustion of the powder (accelerated with an increase of pressure) as well as on the increase of space behind the projectile, the latter factor depending on the velocity of the projectile.

As a result of experimental and theoretical investigations of the uniformity of discharge, interior ballistics permits the solution of the following fundamental practical problems.

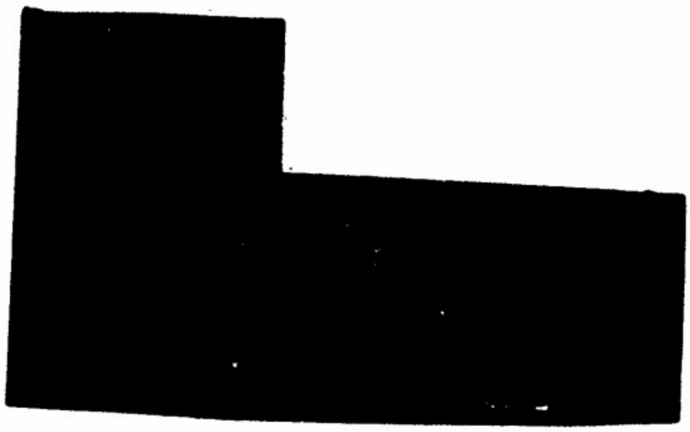

Fig. 1 - Gas Pressure and Projectile Velocity Curves as a Function of Time
1) period of after-effect

Fig. 2 - Gas Pressure and Projectile Velocity Curves as a Function of Shell's Trajectory

The first fundamental problem of interior ballistics is to determine a method of measuring the powder gases pressure and the projectile velocity in a given weapon, for given charge conditions and in particular to determine the maximum pressure p_m and the muzzle velocity v_0 of the projectile.

The second fundamental problem of interior ballistics is the problem of the ballistic design of weapons. This problem consists of a determination of the design factors of the barrel of a gun and of the loading conditions (weight of charge, volume and form of powder) which will give a projectile of a given caliber and weight with a given muzzle velocity, at a certain maximum gas pressure.

The first problem is incorporated in this more general task, as the final step.

In addition to these fundamental problems, interior ballistics serve to solve a considerable number of related problems of an experimental and theoretical nature, which permit more accurate definition of our concept of the discharge phenomenon.

The scope of interior ballistics covers the investigation and analysis of conditions and factors controlling the characteristics of gas pressure and projectile velocity variations in the bore, the determination of general rules controlling the discharge phenomenon and processes occurring in this phenomenon, the treatment of methods for solving theoretical and experimental problems arising in the investigation process, the treatment of special equipment for investigating phenomena occurring during a discharge and the methods of utilizing such equipment; and the exploration of ways leading to the further development of interior ballistics.

With respect to its scope, interior ballistics offers an unusually wide and variable field. In the process of investigating its numerous interdependent processes and phenomena, one will have to deal with a large number of parameters, variable values and characteristics of weapons, projectile and charge.

Therefore, in a determination of relations between various values characterizing a discharge, as well as in solving problems of interior ballistics, it is necessary to approach the phenomenon initially through its basic characteristics, to simplify it and give a schematic solution for some not quite precise assumptions; then to proceed to a clarification of the effects of secondary factors; and having found these, to include them into the elementary schematic functions, thus expanding the latter and making them more complex. Of course, this type of complex arrangement of the various processes, when expressed mathematically, results at times in quite complex functions representing relations between the basic values.

The following basic processes are distinguishable in the discharge phenomenon:

1) The process of powder combustion and the production of high-temperature gases, strongly compressed and containing a large reserve of energy. The rate of powder combustion, or the rate of its explosive conversion, depends basically on the pressure and temperature of the gases, and on the temperature and characteristics of the powder.

2) The process of the conversion of the thermal energy, contained in the heated and strongly compressed gases, into kinetic energy of motion of the projectile - charge - barrel system.

3) The processes of projectile motion, barrel recoil, and motion of gases of the charge, all overcoming a number of different resistances.

All these processes are interrelated, take place simultaneously and exert complementary effects.

For the purpose of studying the first series of processes, it is necessary to be familiar with the principles of physics, physical chemistry, thermo-chemistry and the theory of explosive substances, because powder is a propulsive explosive substance. General physical principles for gases are also applicable to powder gases, while the rules of chemical kinetics apply to the combustion of powder.

For the purpose of investigation and calculation of the energy conversion process on the basis of thermodynamics, a balance of energy in a discharge is compiled, with a calculation of heat accumulation and of its expenditure for the performance of various external functions and the heating up of the gun bore wall. In this connection, the first principle of thermodynamics is utilized.

Principles of theoretical and applied mechanics and of gas dynamics are applicable, and are utilized for an investigation of the projectile, gas and barrel motion, and for the calculation of resistance forces.

All these processes are expressed by definite mathematical functions and formulas, which permit interrelating the elements of the discharge and conditions of charging, and which yield solutions to a whole series of problems arising in an analysis of the phenomena of a discharge.

It is clear from the above statements that interior ballistics utilizes the following branches of science in the molding of its fundamentals: physics, physical chemistry, theory of explosives, thermodynamics, theoretical and applied mechanics, and mathematics.

Because the discharge of weapons is the object of its investigations, interior ballistics shows their specilized technical artillery character, in conformance to their tasks, on the basis of a complex application of all those general technical branches of science.

An artillery ballistic specialist should detect conditions which permit the most advantageous exploitation of the weapon and its charge, and the best possible perfection of discharge control. He can exert influence on the type, volume and form of the powder, the design and weight of the projectile, the design of the weapon and the relation between chamber volume and bore. Combining all these factors, he should attempt to modify the results of the discharge process to conform to practical requirements.

BREAKDOWN OF INTERIOR BALLISTICS INTO BRANCHES

Interior ballistics investigates the most complex artillery phenomena, the discharge, and teaches how to control it. That is, how to calculate the design of the bore, and to regulate the efflux of gases, in a combustion of powder, in a manner insuring the attainment of a given initial velocity of the projectile at a given value of maximum gas pressure.

The experimental investigation of the phenomena of a discharge and the combustion of powder considers the simultaneous effects of the following factors, distinguishing the phenomena of discharge from the common physico-chemical processes:

1) Higher value of pressure (2000-3000 atm. and more).

2) High temperature of powder gases (2500°-3500°C).

3) Short duration of the phenomenon (0.001-0.060 sec).

4) Combustion of the powder in a varying space, with the performance of various types of functions by the gases.

Powder plays a decisive part in the phenomena of discharge. Therefore special consideration should be given to the investigation of the principle of gas formation in a combustion of powder in the bore at the time of discharge.

The principles of gas formation are first studied under simpler conditions, in an invariable space, by igniting charges of powder in special, so-called manometric bombs. The latter permit bringing the pressure up to 3000 atm. and more. The increase of pressure in this type of bomb during the ignition of a given charge of powder is registered by means of special devices.

Because the volume of a manometric bomb, in which the combustion of powder occurs, remains constant and the gases do not perform any work, it is easier to investigate the principles of gas formation. Knowing the principles of powder gas formation in a constant space, it is possible to calculate the changes for a variable space where gases propelling the projectile perform work and cool off.

In connection with this method of investigation, interior ballistics is usually divided into two basic branches: pyrodynamics and pyrostatics.

Pyrostatics investigates principles of powder combustion, gas formation and pressure development in simpler cases, in a constant space, as for instance with an immovable projectile (statics). Having determined those rules, we utilize them to control the process of powder combustion during a discharge from a weapon.

Pyrodynamics, using pyrostatic data on the principles of gas formation, investigates the phenomenon of discharge in all its complexity, where a conversion of energy occurs together with the combustion of the powder and the inception of the motion of the projectile (dynamics). At the same time, the gases perform a series of mechanical functions and cool off.

Gas dynamics investigates phenomena connected with the motion and escape of gases, such as the escape of gases from the bore during the period of after-effects, their escape through openings in muzzle brakes, through the clearance in mortars, through nozzles of reactive projectiles, etc.

The theoretical assumptions of pyrostatics and pyrodynamics are based on and verified by experiments conducted in special laboratories, as well as on firing ranges, by firing conventional or specially adapted weapons.

Ballistic equipment for the investigation of phenomena occurring in a discharge is very extensive and varied. Its design, principles of functioning and methods of utilization are contained in a special course, entitled "Experimental Ballistics."

THE IMPORTANCE OF INTERIOR BALLISTICS IN THE DESIGN OF ARTILLERY

The theoretical and experimental investigation of the phenomenon of discharge facilitates the solution of problems of the ballistic design of weapons. In a ballistic design, the design factors of the bore, the weight of the charge and quantity of powder are determined for a given caliber and weight of the projectile and for its muzzle velocity. Subsequently, the principles of gas pressure variation inside of the bore and the principle of projectile acceleration in its motion along the bore are calculated. In addition, calculations are made on the gas pressure variations and velocity of projectile during the period of the after-effects of gases on the projectile and the gun carriage.

The results of the calculations are represented in the form of curves p, ℓ and v, ℓ being a function of the trajectory, the curves ρ , t and v, t as well as V, t (where V is the recoil speed) as a function of time (figs. 1 and 2).

These data, obtained by a solution of interior ballistics problems for a selected variant of the ballistic design of the weapon, are elementary, and basic for the subsequent calculations of the barrel, carriage, projectile, charge, fuze and shell case.

On the basis of these data, obtained in a solution of interior ballistics problems, the gun designer calculates the barrel (thickness of wall, weight of barrel, design of breech block assembly, location of center of gravity). He calculates the form, depth and width of lands and grooves in the bore, and treats the design of the counter-recoil facilities, as well as the gun mount in general. The ammunition designer calculates the body of the projectile and its drive collar for strength, calculates the charge of explosive substance, the shell case and the primer cup; he designs the fuse mechanism and time fuzes. The technologist at a powder factory calculates and designs pressing dies and determines the technological process of powder preparation on the basis of a given form and grain size of powder.

In this manner, a series of branches of artillery sciences are used for the design and building of new weapons and ammunition for them. These sciences are interior and exterior ballistics, strength of weapons, the theory of gun mounts, the theory of fuze and projectile design, the technology of powder and explosive substances, and metal working. In this connection, interior ballistics provide the principal and fundamental information.

The design of a rather complex aggregate, such as the modern artillery weapon with its attached fire control devices, and of its ammunition, is a product of the results of prolonged calculations. Each of the component parts of that aggregate requires for its manufacture a complex and prolonged technological process.

THE HISTORY OF THE DEVELOPMENT OF INTERIOR BALLISTICS

The history of the development of interior ballistics is inseparably connected with the general development of artillery.

The origin of firearms and the history of the development of artillery up to 1860 is presented in the well known article of Engels entitled "Artillery" [1]. Without reference to the earlier stages of this development and the conversion from a home industry to the factory methods of weapons and ammunition production, we quote an extract from that article on the development of ballistics as a science:

"The end of the 17th and the beginning of the 18th centuries comprised the period when artillery was finally incorporated into the military organizations of a majority of countries, the elimination of its medieval guild character, and its recognition as a special military branch, promoted its adaptation to normal and rapid development. This resulted in an almost instantaneous and quite appreciable progress. The diversity and irregularity of calibers and types became apparent, along with the unreliability of all existing empirical rules and the complete lack of precisely determined principles. It became impossible to endure these conditions any longer. Therefore large-scale tests were conducted everywhere, in order to clarify the problems of caliber, the relation of caliber to charge, as well as of the length and weight of the gun, the distribution of metal in the gun, the range of fire, the effects of recoil on the gun carriage, etc.

The result of this was a significant simplification of calibers, better distribution of metal in the gun, and a very considerable reduction of the charge, which then amounted to from one-third to one-half of the weight of the projectile."

In Russia, Peter I exhibited a great deal of interest in the development of artillery. He personally wrote the "Guide to the Utilization of Artillery." During the reign of Peter I, the Russian artillery became one of the best in Europe.

The progress of artillery science, mainly in the field of investigation of projectile flight and air resistance (Galileo, Bernouilli, Euler and others), ran parallel to the organizational and tactical improvements of artillery.

In his classical study entitled "Hydrodynamica," Daniel Bernouilli gave the basic knowledge about gases, introduced to science the conception of an expansion of gases in consequence of their buoyancy, and showed how on the basis of this expansion to calculate the motion of a projectile in the bore of gun.

The famous mathematician Euler, member of the Russian Academy of Sciences, gave considerable attention in his studies to the investigation of processes occurring in the bore of a weapon. However, as a result of the lack of means for experimental investigation at that time, his studies were limited to the setting up of problems.

In the middle of the 18th century, Robins submitted the first instrument for determinations of projectile velocity. Called the "ballistic pendulum," it was used up to the 1860's. In Robins' study, entitled "New Principles of Artillery Science" and written in 1742, ballistics were first divided into exterior and interior ballistics. In this connection, the scope of interior ballistics was defined as follows: "Knowing the length and caliber of the gun, the weight of the cannon ball, the powder charge and the elastic force at the first moment of ignition, to determine the velocity with which the projectile will depart from the gun."

The technical reorganization of the artillery proceeded parallel to the theoretical and experimental investigations. This embraced the reduction of the number of calibers, improvement in charging and mechanisms, and increasing combat qualities.

The period 1750-1760 witnessed a great step in the development of the Russian artillery. At that time, a number of new artillery types ("unicorns") were introduced under the leadership of Count P.I. Shuvalov. Also, the loading of the guns was modified by the introduction of powder bags for the charges; and new organization of the artillery was effected. Shuvalov's "unicorns" exhibited superior combat properties not only during the Seven Year War (1756-1763, when the Russian armies occupied Berlin), but also during the Homeland war of 1812, particularly in battle of Borodino. These artillery types lasted for nearly one hundred years, up to the introduction of rifled guns. The basic personalities active in the reorganization of artillery in other countries (Friedrich II of Prussia, Gribeval in France) to all intents followed in Shuvalov's footsteps.

Fundamental theoretical and experimental ballistic investigations, which produced proper assumptions about the phenomenon of discharge and its uniformity, were conducted beginning with the second half of the 19th century, on the basis of the general development of technicology and a series of related branches of science.

The first theory of powder combustion, published abroad in 1857, was written by the Russian chemist Shiphov and the German chemist Bunsen. In 1860, Captain A.P. Gorlov wrote an article on the motion of the projectile in the bore of a rifled gun. An abstract of this article was contained in the reports of the Paris Academy of Sciences in 1862. In 1865, Colonel N.P. Fedorov determined the effect of powder combustion conditions on the composition of the products, by firing a pistol and a four-pound cannon. These studies laid the foundation for the development of proper hypotheses on the combustion of powder in a discharge, and were used in much later studies by numerous researchers.

Significant progress of experimental ballistics, expressed in the appearance of two basic instruments which are still widely used in our times (the chronograph of Le Boulanger for measurements of projectile velocity and Nobel's crusher gage for measurements of powder gas pressure), occurred in the 1860's.

The crusher gage, which permits estimating gas pressure on the basis of the compression of a copper column, laid the foundation for the development of a special branch of experimental ballistics, "manometry," and promoted the production of manometric bombs. The latter facilitated investigations of the principles of powder combustion at high pressures.

From 1863 to 1875, Nobel and Abel conducted experiments on the ignition of black powder in a manometric bomb. They determined the quantitative and qualitative composition of combustion products, their thermal capacity, the amounts of emissible heat, combustion temperature, and also the dependence of the maximum pressure on the power of the powder and uniformity of charging.

These investigations were based on studies of the properties and characteristics of powder combustion products in a discharge, made earlier by Shipkov, Bunsen and Fedorov.

During the second half of the 19th century, the general principles of a knowledge of heat and of the kinetic theory of gases, as well as the fundamentals of chemistry and other branches of science, developed parallel to the above investigations. They permitted obtaining a scientific theoretical basis for the process of powder combustion, and for the conversion of the energy of powder gases into the kinetic energy of the projectile and of the gases.

The differential equation was introduced in 1864. On the basis of the first law of thermodynamics, this equation served to determine the equilibrium of the energy emitted during the combustion of the powder charge and the energy expended for the performance of numerous functions (Rezal).

The French scientist Cappo used this equation in 1876 for solutions of problems occurring in artillery practice. Cappo's formulas were the basic functional ballistic formulas, in almost all countries. In our country they were replaced by the formulas of A.F. Brink, and later by the formulas evolved by Professor N.F. Drozdov from 1903 through 1910. (See details farther on).

A great contribution to the development of not only interior ballistics, but also of artillery in general, was made by the invention of smokeless powder: the pyroxylin powder of Vel (French scientist, chemist, powder specialist, 1884), the nitroglycerin powder of Nobel and Abel in England (1888-1889), and the pyrocolloid powder of D.I. Mendeleev in this country (1890).

After improving the manometric bomb and equipping it with registration of the pressure increase as a function of time, Vel determined the difference between the practically instantaneous combustion of black powders and the uniform gradual combustion of smokeless colloidal powders. This permitted regulation of the gas supply by varying the dimensions of powder elements.

A new type of powder was prepared as a result of numerous theoretical and laboratory studies. It was smokeless, colloidal on a pyroxylin basis, and was obtained by an ethyl alcohol compound treatment of pyroxylin explosive substance. Vel projected and prepared a strip-type, pyroxylin powder for a 65 mm gun. By firing, he obtained results fully verifying calculated data. The new powder proved to be almost three times as powerful as black powder, and produced a significant increase of projectile velocity, with a lower pressure of powder gases in the bore.

Aside from the elimination of smoke on battlefields and a considerable increase of the range of fire, the introduction of smokeless powders also caused a modification of battle tactics.

In Russia, a specimen of the French pyroxylin powder was obtained. Experiments toward its production began in 1887 at the Okhtensk gunpowder factory; while firing tests with it were conducted by the research committee of the same factory.

The famous Russian chemist D.I. Mendeleev in the 1890's developed a special pyroxylin powder, which offered numerous advantages in a comparison with Vel's powder. However, the Artillery Committee rejected the powder of D.I. Mendeleev for armament purposes, under the influence of the at that time customary neglect of the prominent personalities of Russian science, and the worship of all that was foreign. The value of this powder was properly recognized in the U.S.A. where it was adapted for armament purposes. During the period of the first world war, 1914-1918, the Russian army obtained considerable quantities of the pyrocolloid powder from the U.S.A.

Disregarding the fact that the technology and industry of Tsarist Russia were at a lower level than the foreign standards, our ballistics scientistics frequently surpassed foreign researchers from the theoretical point of view, and played a leading part in the treatment of numerous problems. Many of their studies were immediately sent abroad and utilized. We have already mentioned the outstanding studies of Shipkov, Gorlov and Fedorov from 1857 to 1868.

The first course of interior ballistics in Russia was written by Colonel P.M. Albitzki in 1870, and read at the Artillery Academy.

In 1879, Colonel Kalakutzkii, a pupil of the Artillery Academy, published a study on tests conducted to determine conditions of the development of abnormal pressures in firearm bores, which long before Vel, touched on the problem of the propagation of undulatory gas motion. His studies were transferred the following year to France.

Colonel V.A. Pashkevich, a very skilled and talented artillery man, became successor to Albitzkii. From 1885 to 1891, he wrote a course in interior ballistics: Part 1, theoretical; Part 2, experimental. In 1892, these books were translated into English in the U.S.A. His instructions on experimental ballistics were used at the Artillery Academy, for many years afterwards.

From among the most distinguished scientists active during the second half of the 19th century and at the beginning of the 20th century in the development of theoretical and experimental ballistics in Russia, it is proper to mention the founder of world-wide interior ballistics, Professor of the Artillery Academy N.V. Manevskii (born in 1823, active from 1850 to 1892,) and his pupil and follower N.A. Zabudskii (born in 1853, active from 1880 to 1917).

Although these two scientists acquired their fame through studies in the field of exterior ballistics, they have made great contributions to the development of interior ballistics.

For example, prior to the design of a 60-pounder smooth-bore gun, and before the investigations of Nobel, Manevskii submitted in 1856 an original method of determining the powder gas pressure at various cross sections of the bore of artillery weapons.

The gun calculated by Manevskii was built, and, when tested, showed considerably better results than the guns competing with it and built from the designs of other people, including English scientists.

In 1867, N.V. Manevskii organized special tests for the experimental determination of the projectile travel in the bore of a four-pounder gun as a function of time. From this information, curves of powder gas pressure in relation to projectile travel and time were plotted by means of calculations.

This study was of great importance to the development of interior ballistics and the design of guns.

N.V. Maievskii

In 1878, N.V. Maievskii was elected corresponding member of the Academy of Sciences, ("People of Russian Science," published by the Academy of Science of the USSR, 1944, volume 11).

Professor of the Artillery Academy N.A. Zabudskii, a pupil and successor of N.V. Maievskii, was greatly and successfully active in the theoretical direction, as well as in the field of the development of artillery technology.

In 1911, the French Academy of Sciences elected N.A. Zabudskii to corresponding membership of its department of mechanics, in recognition of his scientific accomplishments in ballistics. In the field of interior ballistics, N.A. Zabudskii completed in 1904 a study on investigations of pressure in the bore of several guns, and gave numerous empirical formulas for muzzle velocity and maximum pressure.

Later, in 1914, he published his main study on the experimental determination of pressure and velocity curves as a function of projectile travel in the bore of 300 mm field gun, applying for the first time to this purpose the original method of progressive shortening of the gun barrel.

On the basis of these investigations, he gave empirical formulas for the dependence of muzzle velocity of the projectile and of the maximum pressure of powder gases on the variation of numerous conditions of charging (weight of charge, weight of projectile, volume of chamber, size of powder).

This fundamental study of N.A. Zabudskii had a major share in the evolution of proper assumptions on the dependencies in the bore of a weapon during a discharge, and is used in part up to the present time.

In 1892, Colonel A.F. Brink began to lecture in the course of interior ballistics at the Artillery Academy. In 1901, he wrote a complete course of interior ballistics. For this purpose, he used the formulas of Cappo, and new expressions for coefficients and exponents for pyroxylin powders. These appeared for the first time in literature. In addition, he submitted his own empirical formula for the pressure curve.

N.A. Zabudskii

At the time, this course was the most complete among all systems of instruction known abroad, as then noted by Professor N.F. Drozdov.

This course of instruction was transferred to Germany and the U.S.A.

In 1903, Colonel N.F. Drozdov, lecturer at the Artillery Academy, submitted an article, contained in the Artillery Journal. It was the first mathematically precise solution in world literature of a basic problem of interior ballistics. It had none of the simplifications used prior to that time. In 1910, this study was considerably enlarged, and published in a separate edition. It was offered by him as a dissertation toward the attainment of a degree.

The tables compiled by him in 1920, on the basis of his solution, contributed greatly to the simplification and speeding up of ballistic calculations, and to the solution of a series of varied problems relating to the ballistic design of guns. Also, they served as a prototype for a whole series of detailed tables compiled later on. (Science and Research, Institute of Artillery, GAU).

The first dissertation study on interior ballistics in Russia was written and defended in 1904 by Captain of the Guard I.P. Grave, instructor at the Artillery Academy. This study dealt with the experimental and theoretical investigation of the principle of powder combustion rate and pressure development in the combustion of powder in a constant space. The study was of considerable scientific interest, and was translated in France in a somewhat abbreviated form.

In 1908 appeared the study by Charbonne (France) entitled

"Interior Ballistics." He proposed the division of interior ballistics into the fundamental branches: pyrostatics and pyrodynamics. He defined more precisely the conceptions of pressure propulsion, and the calculation of secondary functions in a discharge. While criticizing the geometrical principle of combustion evolved by Vel, he presented his own method of determining the principle of powder combustion on the basis of tests in a manometric bomb. This principle was also used by him in the solution of the basic problem of pyrodynamics.

The French ballistics specialist Siugo, who wrote a course of instruction for interior ballistics in 1926, should be counted among the circle of followers of Charbonne who developed his solution and rendered it more precise.

Parallel to the theoretical school of thought of Charbonne and Siugo, there existed in France an empirical approach by Gosso and Liubill who submitted solutions to the problem of interior ballistics on the basis of utilizing the results of a very large number of discharges (1922).

The studies of the German ballistics specialist Kranz can be mentioned among the experimental activities of the beginning of the 20th century. He published a "Course of Ballistics" in three volumes (exterior, interior and experimental. 1920 through 1926). Kranz organized a special ballistic laboratory at the Technical Military Academy in Berlin, and invented a number of new instruments for the investigation of discharge phenomena.

From among Italian authors, mention should be made of Bianci, who gave the solution to a problem of interior ballistics (1917). With certain modifications introduced by Professor I.P. Grave, this solution was accepted and taught at the Academy of Artillery for many years afterwards.

Having given due recognition to the studies of several foreign scientists, it would be improper to pass up in silence the disregard of the works of our national scientists by the foreign literature on ballistics. For example, one of the recent theoretical courses of interior ballistics of the French ballistics specialist Vinter (1939) discusses widely and in detail the French school of interior ballistics as fundamental in character. It discusses the accomplishments of the Italian school of interior ballistics as a branch of the French school of ballistics, and refers to the names of English, German and American scientists. However, it entirely fails to mention representatives of our national Soviet school of interior ballistics. Also, nothing is said of the studies of the distinguished scientist, Professor N.F. Drozdov, who had between 1903 and 1910 already given the first, mathematically precise solution in world literature, of the fundamental problem of interior ballistics. Meanwhile, it is well known that Professor N.F. Drozdov is one of the founders of the Soviet school of ballistics, which contributed quite a few valuable and pioneer studies to many fields of interior ballistics. This disregard of Soviet scientists undoubtedly has a political character, in spite of the statements of burgeois scientists as to the non-political nature of science. Even during the pre-revolution period, Russian artillery scientists, using development tests of national artillery and artillery technology, as well as the ideas of leading foreign artillery scientists, successfully treated and independently solved the main theoretical and practical problems of artillery science in general and of ballistics in part. The research of N.V. Maievskii, N.A. Zabudskii, V.M. Trofimov, N.F. Drozdov, I.P. Grave and others are outstanding contributions to the science of artillery, and have retained their value even to the present time. The major part of these investigations were printed in the older and widely known "Artillery Journal," which appeared for the first time in 1808. Artillery and interior ballistics underwent a still greater development after the Great October Revolution.

A new era in the development of artillery and artillery science in the new Soviet state began with the victory in October of 1917. The Bolshevik Party and the Soviet Government headed by Lenin and Stalin have enthusiastically supported artillery scientists from the very beginning of the existence of the Red Army, and have revised their task and goals to the present mission of universal strengthening of the armed forces of the Soviet Union for the purpose of preserving it from capitalist encirclement.

In response to the appeal to the Party and the government, to selflessly prevent the conquest of the Soviet Republic, patriotic artillery scientists urgently undertook the task of organization and improvement of Soviet artillery, using the best traditions of Russian artillery science for the purpose of fullfilling this mission.

There were many difficulties at the beginning of this course:

collapse of the economy, a poor material and technical foundation for the development of artillery science and technology. However these difficulties were surmounted, and artillery science continued to work on the further development and the increase of the power of the artillery of the Red Army.

In this connection, a significant part was played by the activities of the Commission for Special Artillery Research, 1919 through 1926, under the leadership of the famous Russian artillery scientist V.M. Trofimov.

V.M. Trofimov

V.M. Trofimov was born in 1864. He graduated with top honors in 1892 from the Academy of Artillery and gave 25 years of his life to scientific and practical study at the Main Artillery Range. He was director of this range from 1910 to 1917, and has done much for the development and improvement of its equipment and organization, particularly during the time of the war from 1914 to 1918.

During his stay at the range, V.M. Trofimov conducted a large number of scientific investigations. Many of his studies were incorporated in firing manuals, while some were translated into foreign languages.

For his study entitled "The Effects of Shrapnel from the 300 mm Gun" (1903), V.M. Trofimov was awarded the Maseskasov and the greater Mikhailov medals.

The period of particularly intensive activities of V.M. Trofimov is connected with the studies of the Commission for Special Artillery Research (KOSARTOP), which was formed through his initiative in 1919 for the purpose of working on problems connected with firing over very long distances.

After obtaining data on the shelling of Paris by the Germans over a distance of about 120 km, V.M. Trofimov undertook to obtain equal results in Russia, and began his efforts in 1918, in disregard of the difficult materials conditions.

He recruited the aid of several young employees of the range, and conducted a number of preliminary investigations in order to find ways of attaining the designated goal.

Using recent material, V.M. Trofimov submitted his principle of air density variation with altitude. Because firing over very long ranges involves variations of air density over a very wide range, Trofimov utilized, for the first time in ballistics, the method of numerical integration of the differential equations of exterior ballistics to calculate the trajectory (similarly to the system of Euler: breakdown into small portions and solution of each portion). For this purpose, he used the study of Academician A.N. Krylov, entitled "On an Approximate Numerical Solution of Common Differential Equations" (1918).

After conducting a number of investigations, he determined conditions under which this type of firing is possible, and demonstrated the feasibility of firing over ranges up to 140 km.

Extensive preliminary studies had to be made in order to obtain a practical solution to a problem of this type. It was namely necessary to determine the most advantageous design of the bore and conditions of loading, to make the projectile streamlined and stable in flight, obtain a fast and uniformly burning gun powder to improve the life of the bore, etc. The КОСАРТОП (Commission for Special Artillery Research) was formed under the leadership of V.M. Trofimov for the purpose of dealing with all these problems.

The activities of the Commission for Special Artillery Research started during the period of blockade and full isolation from foreign countries. Nevertheless, the work of this commission between 1919 and 1926 (the year of death of V.M. Trofimov) progressed successfully, and played a major part in the development of Russian artillery thought. For a certain period of time, the Commission for Special Artillery Research became the central point of the project.

"The period of activities and studies of the Commission for Special Artillery Research, from 1919 to 1926, is a period of animated and intensive activity which cannot be compared with any given analogous period of the years preceding the war of 1914 to 1918. The large quantity of scientific research studies conducted at that time, touching on practically all important and pressing artillery problems of a theoretical character, were of decisive importance." (I.P. Grave, News of the Artillery Academy, volume

XXXI).

In addition to problems directly connected with super-long range firing, the Commission for Special Artillery Research processed the technical and tactical requirements for new artillery types, as well as for self-propelled artillery, mortars, problems of gas dynamics, etc. These activities provided the foundation for the modernization of the artillery of the Red Army, which was accomplished several years later.

V.M. Trofimov recruited not only all leading artillery scientists of the Artillery Committee (*) for work with the Commission, but also all professors from the Artillery Academy (**) and a number of leading civilian scientists (***) active in fields related to artillery.

At the same time, V.M. Trofimov used the freshman workers in science, who, under the guidance of leading scientists, attended the School of Science at the Commission for Special Artillery Research. Subsequently, many of them became leading specialists

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(*) Professor G.A. Zabudskii (gun powder); V.I. Rdultovskii (projectiles, fuses); N.F. Rozenberg and A.G. Matiusin (technology, manufacture of guns); G.P. Kisnemskii (gunpowder); V.V. Makeladze (firing and tactics); V.A. Pashkevich (ballistics, mathematics); P.A. Durliakhov (gun carriages) and others.
(**) Director of the Academy, Professor S.G. Petrovich (mechanics and exterior ballistics); Professors: N.F. Drozdov (strength of guns, interior ballistics); I.P. Grave (interior ballistics); V.V. Mechnikov (exterior ballistics); A.V. Sapozhnikov (chemistry, gunpowder and explosives); I.A. Krylov (metallurgy); lecturers F.F. Lender (gun carriages); O.G. Fillippov (gunpowder, interior ballistics) and others.
(***) Academician A.N. Krylov (mathematics, mechanics); Professor N.E. Zhukovskii (mechanics, aerodynamics); S.A. Chaplygin (hydromechanics); N.N. Bukhgoltz and V.P. Vetchinkin (gas dynamics); N.P. Molchanov (meteorology) and others.

in various fields of artillery activities (D.A. Venttsel, B.N. Okunev, V.E. Slukhotskii, M.E. Serebriakov).

In addition to the personal recruiting of leading scientists and specialists, the Commission for Special Artillery Research maintained close relations with a number of national scientific and technical institutions.

About 150 monographs relating to scientific and research studies conducted by the personnel of the Commission for Special Artillery Research, as well as about 80 design treatments, were published during the period of its activities.

The studies of the Commission for Special Artillery Research were of great importance for the assembling of a number of outstanding research people around problems of artillery materiel. After the death of V.M. Trofimov, the direction of the Commission was transferred to the hands of the outstanding specialist in the field of super-long range firing, Professor E.A. Berkalov, who has also obtained a great deal of experience in this field.

Due to the attention given by the party, the government, and particularly by Comrade Stalin to this problem, the efforts to improve the artillery of the Red Army, and to scientifically insure its development, continued to expand during the following period of time.

During the years of Stalin's Five-Year Plans, our country created the material and technical foundation necessary to provide the armed forces with modern combat materiel and, among those, artillery. Material conditions necessary to a fruitful development of scientific and technical artillery thought were created, parallel with the development of our industry and economy.

A number of designing offices were established under the direction of Heroes of Socialist Labor V.G. Grabin, I.I. Ivanov, F.F. Petrov and other designers, which produced many samples of artillery types. These showed superior combat and technical qualities during the period of the Great Homeland War. All these activities were personally supervised by Comrade Stalin, who examined test specimens of new artillery types and issued instructions on the course of their further development.

Comrade Stalin's anxiety in connection with the development of scientific artillery thought found its expression in the establishment of the Academy of Artillery Sciences in 1946, for the purpose of processing basic scientific problems confronting the artillery.

A new generation of Soviet artillery scientists and ballistics specialists grew up during the 30 years of existence of the Soviet government. The first to be counted among those are: Academician A.A. Blagonravov, president of the Academy of Artillery Sciences; N.F. Vasiliev, member of the governing body of the Academy of Artillery Sciences; K.K. Snitko, A.A. Tolochkov,. D.A. Venttsel, N.E. Serebriakov, V.E. Slukhotskii, Ia. M. Shapiro, active members of the Academy of Artillery Sciences; and Professors B.N. Okunev, G.V. Oppokov. These are followed by the younger generation of science workers: M.S. Gorokhov, M.A. Mamontov and others.

It can be definitely stated that, in our Union, we have established a leading Soviet scientific school of artillery designers and ballistic specialists, who are making their way in the field of artillery science and technology.

Like V.M. Trofimov, two leading scientists of our country, who became the instructors and educators of numerous generations of Russian ballistic specialists and designers, had a major share in the formation of this scientific school. These were the distinguished worker in science and technology of RSFSR (Russian Soviet Federative Socialist Republic), Colonel General of Artillery Nikolai Fedorovich Drozdov, laureate of Stalin's medal, member of the Presidium of the Academy of Artillery Sciences; and Major General of Artillery Engineering Services Ivan Platonovich Grave, laureate of Stalin's medal and active member of the Academy of Artillery Sciences.

As already stated, N.F. Drozdov submitted the first mathematically precise solution in world literature of the fundamental problem of interior ballistics, without any of the approximations utilized by foreign authors.

Since 1911, he has lectured for many years at the Artillery Academy in the course of weapon design, and from 1920 in the course of interior ballistics of the Naval Academy.

Professor N.F. Drozdov has written a number of studies toward the expansion of his method, and has compiled special tables for solution of problems in interior ballistics.

These tables were of great importance for the efforts on acceleration of ballistic design and improvement of our artillery systems, since the calculations of the latter were considerably simplified by the existence of these tables.

During very recent times (1947-1948), N.F. Drozdov has written two more studies. One pertains to the properties of highest power artillery weapons. The other presents solutions of the interior ballistics problem in relative variables for simple and combination charges, with appended tables which considerably expedite computations.

Professor N.F. Drozdov is the founder of the Russian School for the Ballistic Design of Guns, which created a number of outstanding artillery types.

Professor I.P. Grave lectured for many years (from 1911 till 1934) on interior ballistics at the Artillery Academy, and wrote the most complete course of theoretical interior ballistics in world literature. With respect to its variety of included material and the completeness of exposition, this study may be justly named an encyclopedia of theoretical interior ballistics. This course is composed of four volumes of pyro-dynamics (1932-to 1937) and pyrostatics (1938). The course contains extensive material, and presents a criticism of Russian and foreign articles and studies. All those are analyzed, and cite reference literature. For the first time in our literature, problems of gas dynamics and ballistics of an incompletely enclosed space are submitted to particular consideration in this study.

Aside from this, I.P. Grave had contributed largely to the development of an experimental base, at the Artillery Academy by organizing a ballistics laboratory in 1926.

After 1938 and during the period of the Great Homeland War, Professor I.P. Grave held the chair of interior ballistics at the Artillery Academy, conducted a series of investigations, and wrote several studies on current problems of interior ballistics.

The Soviet School of Ballistics, whose cadre grows constantly, successfully solves all of the more complicated practical problems that occur, and lays out new paths of development for interior ballistics.

In the past, as well as particularly during the period of Soviet development, our national science of ballistics kept ahead of foreign thought with respect to many more important problems.

The following facts may be quoted by way of examples:

A mathematically precise solution of the fundamental equation of interior ballistics was offered, for the first time in world literature, by Professor N.F. Drozdov in 1903 in our country.

The problem of solving a series of questions relating to combination charges is completely untouched in the world literature. In our country, these problems were solved by N.F. Drozdov, I.P. Grave, V.E. Slukhotskii and others, who also presented tables for the solution of problems for the case of combined charges.

An analytic solution of problems for mortars, with calculation of partial escape of gases through the clearance, was submitted in this country in 1940 by M.E. Serebriakov, K.K. Greten, and in more detail by G.V. Oppokov.

Ballistic design and its methodology has been treated most completely, thoroughly and rationally, as a result of the studies of our scientists.

The problem of highest power weapons, or weapons with smallest volume, is solved in this country differently than in French literature. A solution is given which is more economical and advantageous from the standpoint of design.

A new method of ballistic analysis of gunpowder, which permits the test determination of the actual principle of powder combustion and recognition of the influence of a whole series of factors previously disregarded (physical principle of combustion), was developed by M.E. Serebriakov in this country between 1923 and 1937.

Also, the solution of ballistic problems through the methods of numerical integration was developed very thoroughly in this country. This method was used for the first time in ballistics by V.M. Trofimov in 1918, in exploitation of the studies of Academician A.N. Krylov.

The methods of numerical solution of problems were developed and expanded in particular details by Professor G.V. Oppokov in a series of his studies.

This incomplete account of the accomplishments of our scientists already permits recognition of the fact that interior ballistics has reached a high theoretical level in our country and progresses along the proper paths. In order to fulfill the mission assigned by Comrade Stalin, "to exceed the accomplishments of foreign science within a short period of time," it is necessary, by means of continued and persistent work, to raise still further the scientific level of our investigations.

Artillery technology develops with each passing year; while the problems confronting interior ballistics widen and become more complex. New methods of solution come into existence. Outdated hypotheses are eliminated, and are replaced by new ones. New experimental methods and more precise equipment are introduced, providing research scientists with new material and new methods of investigation.

Interior ballistics will progress as a result of the expansion of our knowledge of the discharge and of phenomena accompanying it, the establishment of new rules, the replacement of outdated hypotheses by new ones, the improvement of our ability to direct the discharge along the desired course.

The mission confronting the students of a course in interior ballistics is to become familiar with the modern status of this branch of science and with the theoretical fundamentals of interior ballistics, and to learn to apply them to solution of numerous practical problems arising in the design of various types of artillery and the ammunition for them.

LISTING OF NOMENCLATURE, SYMBOLS AND DEFINITIONS IN THE FIELD OF INTERIOR BALLISTICS

A. BASIC PROPOSITIONS

1) The following listing specifies only the most characteristic values used in interior ballistics as one of the branches of artillery science.

2) Individual terms relating to variables associated with certain characteristic instants are properly designated by adding the following subscripts to the symbol of the variable value:

0 - for the instant of commencement of projectile motion.

m - for the instant of maximum pressure of gases.

s - for the instant of decomposition of the powder grains.

k - for the instant of the end of powder combustion.

d - for the instant of the projectile leaving the bore.

3) As is proper, interior ballistics utilizes the following system of units: decimeter-kilogram (force)-second.

4) The term "powder grain" is construed as a separate element of the powder charge (strip, fluted cylinder, rod, cube, etc.).

5) The initial dimensions of powder grain are the sizes of the grains prior to the commencement of combustion (explosive conversion).

6) Numbers in parentheses contained in the text correspond to the item number in section B of this listing.

7) Nomenclature standardized as technical terms is printed in heavy type.

B. NOMENCLATURE, SYMBOLS AND DEFINITIONS

Item No.	Nomenclature	Symbol	Definition
	I. Characteristics of the Barrel, Projectile and Charge		
1	Caliber of barrel (cylindrical)	d	Diameter of bore at groove "lands"
1a	Caliber of barrel (tapered)	d_0 d_d	Entrance caliber Exit caliber
2	Cross section of bore (grooved)	s	Area of cross section of bore in the part where rifling grooves have full profile (grooves included).
3	Length of bore	L_{kn}	Distance from breech end of the bore to the muzzle face of the barrel
4	Length of the rifled portion of the bore	L_{nr}	Distance from the beginning of grooves in the bore to the muzzle face of the barrel
5	Gun chamber		Initial air space in the chamber portion of the barrel with a properly loaded projectile

Item No.	Nomenclature	Symbol	Definition
6	Volume of gun chamber (5)	W_0	
7	Weight of projectile	q	
8	Weight of gunpowder charge	ω	
	II. Properties of Powder and Powder Gases		
9	Heat of formation	Q_w	The quantity of heat emitted by one kilogram of powder burning in a constant space and when cooling the gases down to the temperature of 18°C (water vapor)
10	Specific volume of powder gases	w_1	Volume occupied by gases of one kilogram of powder at a temperature of 0°C and a pressure of 760 mm of mercury column (water vapor)
11	Temperature of powder at the time of firing	T_1	Temperature of powder combustion (heat of formation) measured from 0°K (absolute scale)
12	Energy of powder charge	f	$f = \frac{p_a w_1 T_1}{273}$ (10;11), where p_a - one physical atmosphere
13	Covolume of powder gases	α	A coefficient representing the effect of the volume of gas molecules on the pressure of gases
14	Rate of burning (a variable value)	u	Linear velocity of propagation of combustion reaction of powder towards the center of the powder grain
15	Rate of burning under pressure equal to unity.	u_1	

Item No.	Nomenclature	Symbol	Definition
	III. Dimensions of Gunpowder Grain		
16	Depth of the burnt layer of a gunpowder grain (variable value)	e	
17	Initial thickness of powder grain	$2e_1$	
18	Surface of powder grain (variable value)	S	
19	Initial surface of powder grain	S_1	
20	Volume of powder grain (variable value)	Λ	
21	Initial volume of powder grain	Λ_1	
22	Relative thickness of burned layer of powder grain (variable value)	z(z)	$z = \frac{e}{e_1}$ or $z = \frac{\ell}{\ell_k}$ (16, 17, 32, 33, 34, 15)
23	Relative surface of powder grain	σ	$\sigma = \frac{S}{S_1}$ (18, 19)
24	Specific volume of burned powder grain (variable value)	ψ	$\psi = \frac{\Lambda_1 - \Lambda}{\Lambda_1}$ (21, 20)
	IV. Travel, Velocities and Pressures		
25	Instant of departure		The instant of passage of base of projectile past muzzle face of barrel.
26	Relative travel of projectile.	ℓ	Displacement of projectile in relation to the bore, measured from the location of projectile base at the commencement of motion.
27	Total travel of projectile in the bore	ℓ_g	Travel of projectile in relation to the bore (26) at the instant of departure (25)
28	Relative speed of the	v(v)	Speed of projectile in its

Item No.	Nomenclature	Symbol	Definition
	projectile (variable value)	v(v)	movement relative to the bore (26)
29	Muzzle velocity	v_d (v_d)	Relative velocity of projectile (28) at the instant of departure (25)
30	Pressure of powder gases (variable value)	p	Mean value of partial pressures of powder gases in the initial air space, at the given position of the base of projectile (at a given instant)
31	Mean pressure of powder gases	p_{sr}	$p_{sr} = \frac{\varphi q v^2}{2gs\ell}$ (37, 7, 28, 2, 26), where g - acceleration of gravity
32	Impulse of pressure of powder gases (variable value)	I	$I = \int_0^t p dt$ (24, 30), where t - time
33	Impulse of pressure powder gases at the end of powder combustion	I_k	$I_k = \int_0^{t_k} p dt$ (24,30), where t - time
	V. Special Values and Coefficients		
34	Density of loading	Δ	$\Delta = \frac{\omega}{W_0}$ (8:6), where ω is in kg, and W_0 in dm^3
35	Gravimetric density of powder		Ratio of weight of powder placed freely in a container of a given shape and volume to the weight of water at 4°C (density equal 1) occupying a container of the same volume Remark: The gravimetric density of powder depends on the volume and shape of the

Item No.	Nomenclature	Symbol	Definition
			container, and on the method of placing the powder in it. These factors are specific in each given case.
36	Reduced length of chamber	ℓ_0	The length of a straight cylinder whose volume is equal to the volume of the gun chamber (6), and whose base area corresponds to the area of the cross section of the bore (2)
36a	Actual length of chamber	ℓ_{km}	Distance from the base of the bore to the base of the projectile
37	Factor determining secondary functions	φ	A coefficient for evaluating the secondary functions of powder gases (rotation of projectile, gun recoil, friction, etc.)
38	Coefficient of weight of projectile	c_q	$c_q = \frac{q}{d^3}$ (7;1), where q is kg and d in dm.
39	Coefficient of charge utilization	η_ω	$\eta_\omega = \frac{qv_0^2}{2g} \frac{1}{\omega}$ (7; 29; 8) where g- acceleration of gravity
40	Coefficient of projectile location at the instant of total combustion of charge	η_k	$\eta_k = \ell_k/\ell_d$ (27) where ℓ_k is travel of projectile (26) at the instant of total combustion of the powder
41	Relative weight of charge	$\frac{\omega}{q}$	
42	Power factor of weapon	C_E	$C_E = \frac{E_d}{d^3} = c_q \frac{v_d^2}{2g}$
43	Efficiency of the charge	r_d	$r_d = \frac{E_d \theta}{f\omega} = \eta_\omega \frac{\theta}{f}$

Item No.	Nomenclature	Symbol	Definition
44	Charging parameter of Professor N.F. Drozdov	B	$B = \frac{s^2 I_k^2 g}{f \omega \varphi q}$
45	Coefficient of chamber expansion	X	$X = \frac{l_0}{l_{km}}$ (36; 36a)

PART ONE
PHYSICAL PRINCIPLES OF INTERIOR BALLISTICS

SECTION ONE
GUNPOWDER AS THE SOURCE OF ENERGY

CHAPTER I - GENERAL INFORMATION ON GUNPOWDERS

I. TYPES OF POWDERS

Modern gunpowders belong to a group of smokeless colloidal powders. Black powders, used at the time of the invention of gunpowder, are now used in artillery only in the capacity of igniters, in primer cups, in rings of time fuses, and also in shrapnel.

Smokeless powders, which appeared almost simultaneously in France (Vel) and England (Nobel) during the 1880's and 1890's, were rapidly adopted in all countries. Their introduction greatly modified all artillery materiel and combat tactics.

The basic properties of smokeless powders are: considerably greater energy, and an ability to burn in parallel layers, which permits regulation of the influx of gases forming during the combustion of powder.

The main base of all smokeless powders is pyroxylin, or nitrated cellulose. In this connection, a division is made, as respects the degree of nitration, into highly nitric pyroxylin or No. 1 (nitrogen content 12.9 to 13.3%); lower nitric pyroxylin or No. 2 (nitrogen content 11.9 to 12.3%), and collodion ($\sim$11%).

Pyroxylin No. 1 is also called insoluble, because it is practically insoluble in a mixture of alcohol and ethyl ether. Pyroxylin No. 2 is called soluble, because it dissolves almost completely in the same mixture.

In many countries, a mixture of pyroxylins No. 1 and No. 2 is used for the production of gunpowder (for example, in our country and in France).

In the U.S.A., powder is manufactured with a so-called pyrocollodion base. The latter ranks between No. 1 and No. 2 with respect to nitrogen content (12.5 to 12.75%). It is however entirely soluble in an alcohol-ethyl ether mixture.

Developed by D.I. Mendeleev as early as 1890, pyrocollodion gelatinizes very well, and provides a more homogenous powder substance than the powder containing insoluble pyroxylin.

When subjected to the action of an alcohol and ethyl ether mixture of a given ratio, the pyroxylin will gelatinize under pressure and become a colloid.

A mixture of pyroxylin with a solvent, so as to form a paste, can be given any form (strip, tube, rod, etc.) through extrusion.

Pure pyroxylin powders are prepared:

a) From a mixture of pyroxylin No. 1 and No. 2 (mixed pyroxylin);

b) From a pyrocollodion;

c) From one pyroxylin No. 2 (for special purposes).

In addition to pure pyroxylin powders, there are the so-called nitroglycerin powders. The latter contain from 25 to 60% of nitroglycerin, the remainder consisting of pyroxylin and a small quantity of various admixtures.

Up to the first imperialistic world war of 1914 to 1918, the nitroglycerin powders were divided into two basic groups: the ballistites and the cordites. They differed in their contents of the elements, the quality of the pyroxylin, as well as the solvent gelatinizing the powder.

Ballistites are prepared with a soluble pyroxylin, mainly a colloid with a small nitrogen content. Nitroglycerin is used as the gelatinizing agent. In the preparation of the powder, the substance is flattened out under hot rollers and cut into cubes or rectangular strips.

Cordites are prepared with an insoluble (highly nitric) pyroxylin, with acetone serving as the solvent. It is extruded in the form of cords or tubes.

The first specimens of cordite contained up to 58% of nitroglycerin (cordite M-1); while later specimens contained from 25 to 30% (cordite MD - modified).

Smokeless powders have a significantly higher energy as compared with black powders. At the same time they have one substantial disadvantage. Being prepared with an ethyl ether-alcohol solvent or with acetone, they contain some quantity of this free solvent. In this connection, depending upon atmospheric conditions, the solvent can evaporate from the powder, or, vice versa, the powder can absorb moisture from the air. Such variations in the content of volatile substances are reflected quite sharply in the ballistic qualities. These properties, volatility and hygroscopicity, of common pyroxylines prepared from a volatile solvent and, to a lesser degree, nitroglycerin powders, make it necessary to store the powder in waterproof packing and, whenever possible, at a constant temperature.

Beginning with the first world war and subsequent to it, there appeared a powder prepared without a solvent or with a non-volatile solvent. Among powders of this type we count a powder prepared from a mixture of pyroxylin and tretyl. This powder, when heated and subjected to high pressure, will gelatinize and can be well pressed. A powder consisting of pyroxylin, nitroglycerin and an admixture of nitro derivatives of the aromatic series (di-nitro-toluol, di-nitro-benzene, centralite and others) also belongs to this type.

These powders are non-hygroscopic, non-volatile, and have a comparatively low ignition temperature. They are much simpler to produce, and therefore find increasing utilization in numerous countries.

Di-nitro-glycolic and nitro-guanidine powders appeared in Germany during the period of the Great Homeland War (World War II), because of the existing shortages of raw materials.

Insofar as pyroxylin is obtained by the nitration of cotton with a mixture of nitric and sulfuric acids, and the free acid remaining in the pyroxylin gradually decomposes it, a complete refining of the latter, for the purpose of eliminating the acid, comprises one of the main operations in the production of pyroxylin. However because traces of acids will remain after the preparation of the powder, and will affect its keeping qualities, about 1 to 2% of a stabilizer is suitably mixed into the powder for the purpose of neutralizing the action of the acids. This stabilizer combines with nitric oxides and neutralizes them. The most commonly used stabilizers are di-phenyl-amine and centralite (di-ethyl-di-phenyl-urea).

2. GENERAL PROPERTIES OF POWDERS, THEIR FORM, DIMENSIONS AND TYPES

Smokeless powder is a colloidal substance, a gel, and is similar in its external appearance to celluloid. It is semi-transparent or opaque, depending upon the composition of the powder and the thickness of the material. The usual color of pyroxylin powders is grayish green. The color of the nitroglycerin powders is brown. Stabilizing admixtures stain them into various colors (yellow, red, black). Pyroxylin powder is harder than nitroglycerin powders, the latter being more soft and elastic as a result of the presence of liquid nitroglycerin.

The surface of a powder may be rough, dull or polished. Fine-grain powders for small arms are for the most part coated with graphite to increase compacting and to reduce electrification of the powder as a result of friction. In this way, their surface takes on a shining black color resembling by its appearance black gunpowder.

The form of powders is usually varied: strips, rectangular sheets, blocks, cubes, short and long tubes, grooved grains, etc.

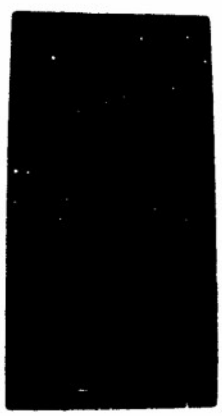
Powder in the form of thin square flakes, or beads with a hole through them are used for small arms. The ratio of a side of the square of a flake to the thickness varies from 5 to 10. The length of a bead with a hole through it is 5 to 10 times its wall thickness, while its inner diameter is from half to the entire wall thickness. Powder for weapons of small or medium calibers with cartridge loading have the form of long tubes (macaroni), with a ratio of the length to wall thickness from 100 to 300, or they may be in the form of short cylinders with either one or seven holes through them (see further for details). Both of the two latter forms are called granular powders. Their length is 8 to 15 times greater than the wall thickness. (Grains of rifle powders are appropriately shorter.) Powders in the form of long tubes, either for the entire length of the gun chamber or in two semi-charges for half of the gun chamber, are used almost exclusively for weapons of larger caliber with individual loading. Since the loading of those weapons is performed individually and automatically, and the weights and volumes of the charges are larger, it is important to have a sturdy, inflexible charge. This requirement is fully satisfied by a bundle of tightly bound tubes.

The quantity of gases formed during burning of the powder, and the rate of their formation, depend on the weight of the charge and the numerical value for the surface of the powder. The latter depends on the thickness of the powder and its form. The smaller the grains of the powder, the larger their surface is in a given weight of the charge; the larger the quantity of gases forming in unit of time, the higher is the rate of powder combustion. The larger the caliber of the weapon and its length, the longer should the action of gases on the base of the projectile last in order to provide it with a given velocity, and the coarser should the powder be. The wall thickness varies from 0.1 mm for pistol powders to 6 mm for powders for the 354 mm (14 inches) guns. A porous fine powder is used for pistols.

<u>Processing powder</u>. In order to obtain a given form of powder,

the substance is forced through perforations (of a die) by means of a press. Strip powders are made either by flattening under rollers and subsequent cutting, or by forcing through a flat slot. In order to illustrate the preparation of powders with channels, a schematic drawing is shown below of a die, through which tubular powder is pressed (figs. 3 and 4).

The powder mass is contained in the space between the plunger A and the plate die BB. Under the pressure of the plunger, the mass is forced through the openings in the die BB and surrounds the attached pin C. The holes in the die are symmetrical relatively to the pin, and are designed in a manner such that their total area is larger than the cross-sectional area of the cylindrical portion d-d.



Figs. 3 and 4 - Diagram of Die for Pressing Powder

1) Bottom view at d-d; 2) top view of the die plate.

In view of the fact that the plunger A moves downward, the mass is extruded in the shape of tubes, which are broken off from time to time.Later, the latter are dried in the open air to eliminate the excess of the solvent and cut into sections of the desired length.

Tubular powder is thus obtained. Powder with seven holes in it is also obtained in an analogous process.

It was agreed to designate powders by conventional symbols indicating the dimensions (gage) of powder, form of grains, lot, year of production and factory at which the powder was produced.

Powders for small arms are designated in this manner: (Пл) Pl - flake, (P) R - revolver powder, (В) V - rifle powder, (ВЛ) VL - rifle powder for small caliber bullets, (ВТ) VT - rifle powder for large caliber bullets. For instance, V $\frac{2}{43}$ R denotes rifle powder, 2nd lot of 1943, Rozhal factory.

Gunpowder is designated by a fraction, whose denominator indicates the number of holes in the grain and the numerator shows the thickness of the wall in tenths of a millimeter. For instance, 7/1 - a grain with one hole and wall thickness of 0.7 mm; 15/7 - a grain with seven holes and a wall thickness of 1.5 mm.

Tubular and strip powders are usually designated by the caliber of the weapon for which they are used. For instance: 75/50 - powder for a 75-mm weapon with a 50-caliber length.

CHAPTER II - BASIC CHARACTERISTICS OF POWDER

1. CHARACTERISTICS OF THE COMPOSITION OF POWDER

Powders used in our country are for the most part pyroxylin.

The composition of these powders is basically determined by two characteristics, on which depend all physical-chemical and fundamental ballistic properties. These characteristics are the nitrogen content in the pyroxylin powder and the content of volatile substances.

Nitrogen Content

To characterize a powder with respect to nitration, it is necessary to know the nitrogen content in 1 gram of pyroxylin powder. This is usually expressed in percent or in cm^3 NO (nitric oxide) corresponding to 1 gram of pyroxylin powder.(*) The nitrogen content affects the energy of the powder, as well as its rate of combustion. The greater the content of nitrogen is, the stronger is the powder and the more intensively it will burn. On the average, the nitrogen content in pyroxylin fluctuates within the range of 11.8 to 13% (K = 188.5–208 cm^3 NO/g of powder).

Content of Volatile Substance in the Powder, Expressed in Percent

In a physical chemical analysis of powder, not only the total content H of volatile substances is determined, but also its component parts, namely: volatile substances removable by means of 6 hours of drying at a temperature of 95°C (h%), which are usually considered to be the humidity contained in the powder, and then those inseparable by six hours of drying (h'%) which are attributed to the alcohol-ethyl ether solvent remaining in the powder mass and gelatinizing the powder.

The value H is usually related to the thickness of the powder, and the thicker the powder the higher will H be. In thin powders H

(*) Relation between the nitrogen content N% and the volume NO is given by the formula $N\% = K \times 0.0006257 \times 100$, where K is the number of cm^3 in 1 gram of powder at 0° and a pressure of 760 mm.

$$(0.6257 \sim \frac{5}{8}), \text{ or } N \sim \frac{5}{80} K = \frac{K}{16}$$

equals 2.0 to 2.5%; in powders with a strip thickness of about 1 mm, $H \sim 4.0\%$; in very thick powders, with a thickness up to 6 mm, H reaches up to 7%.

The value H mainly affects the rate of combustion of a powder. The higher H is, the slower the powder burns. The variation of moisture content in a powder, because of atmospheric conditions, is one of the main defects of pyroxylin powders having a volatile solvent.

2. PHYSICAL-CHEMICAL PROPERTIES OF POWDERS

Powder is a low explosive; therefore, all physical-chemical properties of explosives and their characteristics are also applicable to powders. Those characteristics are:

Quantity of Heat (Q, Cal/kg) emitted in the combustion of 1 kg of powder, and in cooling the gases to the temperature of 15°C. This characteristic is the most essential one, insofar as at the instant of discharge the chemical energy is converted into thermal energy, and the latter into mechanical energy. Also, the larger Q is, the higher is the temperature of powder gases, and the greater is the mechanical work which they can perform.

As a rule, Q is determined by a test in a calorimetric bomb. In this connection, the following must be taken into consideration.

The calorimetric bomb is immersed in water at a temperature of 15°C. The temperature of water rises at the instant of ignition by only a few degrees, under the effect of heat emitted in the bomb, and after that it begins to drop.

The test is conducted for a period of 5 to 10 minutes. Consequently, if water vapors are present in the products of the explosion, then they will proceed to condense and, in this manner, the quantity of heat determined in the test will relate to water in the liquid form rather than vapor form. Actually, the water is in a vapor state at the instant of ignition or explosion, and the equation

$$\underset{H_2O\ \text{vapor}}{Q_w} = \underset{H_2O\ \text{liquid}}{Q_w} + 620\,\frac{a}{100}$$

is used for its determination (where a represents the percentage content of water in the decomposition products of the powder, 620 is the quantity of kilocalories absorbed in the condensation of 1 kg of water vapors and reducing their temperature to 15°C).

Because the water is in a vapor state at the instant of explosion or discharge, the actual quantity of heat emitted in this connection is expressed in this way:

$$\underset{H_2O\ \text{vapor}}{Q_w} = \underset{H_2O\ \text{liquid}}{Q_w} - 620\,\frac{a}{100}.$$

If we convert all the quantity of heat Q_w·, emitted in a combustion of 1 kg of powder, into mechanical energy by multiplying by the mechanical equivalent of heat E = 4270 kgdm/cal, then the resultant value $P = EQ_w$ will represent the potential energy of the powder, or the work it could perform if all its emitted heat would convert into mechanical work. This value is called the <u>potential</u> of the powder.

<u>Volume of Gases</u> w_1, dm^3/kg, formed in the combustion of 1 kg

of powder, and occupied by them at a pressure of 760 mm and temperature of 0°C.

After the combustion of powder in a calorimetric or manometric bomb, gases may be conducted into the gasometer, and their volume may be measured at atmospheric pressure and a temperature of 15°C. The latter may then be reduced to 0°C. Then the water present in a vaporous state will condense into a liquid and the volume of gases measured in the gasometer will be smaller than the actual volume, if the water was in the form of a vapor. Therefore, the volume of gases determined in the gasometer refers to liquid water

$$\left(w_{1\,H_2O\ \text{liquid}} \right)$$

For conversion to the gas volume which they would occupy if the water were in the form of a vapor, the formula

$$w_{1\,H_2O\ \text{vapor}} = w_{1\,H_2O\ \text{liquid}} + 1240\,\frac{n}{100}$$

is used (where n is the percent of water vapor content in the gaseous mixture, 1240 dm^3 is the volume which would be occupied by one kg of water vapor at atmospheric pressure and 0°C). The volume of gases w_1 has great significance, because the greater it is, the greater is the amount of work which can be performed by the gases in the gun.

<u>Temperature of explosive decomposition</u>, or the temperature of the powder at the time T_1, of firing, i.e., temperature possessed by powder gases forming during the combustion at the instant of their formation. It is measured on the absolute scale. The higher the temperature of the gases is, the greater is the amount of mechanical work which they can perform in a discharge.

The value T is usually not determined directly during a test, in view of its large magnitude and the short duration of powder combustion. It is determined indirectly. This requires knowledge of the quantity of heat

$$Q_w$$

$$H_2O \text{ vapor},$$

the composition of the gases, their heat capacity, and their variation with the temperature.

Composition of gases and their heat capacity. An analysis of the gases after powder is ignited in a calorimetric bomb shows that the main bulk of gases from pyroxylin powders is composed of the diatomic gases CO, H_2, N_2, triatomic CO_2 and H_2O (in the form of vapor), and also a small percentage of metane CH_4 and ammonia NH_2. The ratio of these component parts varies somewhat, depending upon the compactness of loading. It is necessary to state that an analysis of gases is not made at the moment of combustion, but later, when the gases cool off. Therefore, the composition of the gases also depends on secondary reactions between the basic gases, while these secondary reactions may themselves depend on the compactness of loading and the conditions of cooling.

Knowing the composition of the gases, it is also necessary to know the heat capacity of gases c_p and c_w, as well as their variation with the temperature(*), in order to make computations of the temperature.

It was determined on the basis of experiments conducted by Malliar and Lechatel, as well as subsequent investigations, that

(*) c_p and c_w - heat capacity of gases at a constant pressure and a constant volume: $c_p - c_w = AR$

the dependence of the heat capacity of gases c_v on temperature t may in a first approximation be expressed by a linear function

$$c_v = a + bt,$$

where a and b are constant values. These have the same fixed values for all diatomic gases, and others for triatomic gases.

At the present time, a series of very new and accurate formulas are available for the heat capacity. They are based on the quantum theory of heat capacity and take into consideration the oscillatory motion of atoms. In this connection, numerical characteristics in the formulas are determined spectroscopically (Einstein's formulas).

Professor A.N. Shelest submitted a logarithmic dependence for the molecular heat capacity in the form of

$$\mu c_v = z \cdot 0.9925 \left(\ln \frac{T1}{98.1} + 1 \right)$$

All these formulas show abrupt variations of heat capacity at low temperatures, which cannot be expressed by linear factors. However, under the conditions of a discharge, gases as a rule cool off to a temperature of about 1800-2000°K, between the instant of gas formation at a temperature $T_1 \approx$ 2500-3000°K to the instant of the projectile's passage through the muzzle face. In this range of temperature variations, all empirical and theoretical dependencies can be expressed to a satisfactory degree of accuracy by the common linear equation

$$c_v = a + bt = A + bT,$$

which we also shall adopt farther on in the manual. (For more details, see the energy equilibrium equation)

To determine the temperature, we utilize the equality

$$dQ = c_v \cdot dt$$

Substituting $c_v = a + bt$, we obtain

$$dQ = (a + bt)\ dt.$$

By integrating we obtain

$$Q = \int_0^t (a + bt)\ dt = at + \frac{bt^2}{2}.$$

From this quadratic equation, we determine t:

$$\frac{b}{2}t^2 + at - Q = 0;$$

$$t = \frac{-a \pm \sqrt{a^2 + 2bQ}}{b}.$$

We select the plus sign before the radical, since minus results in a negative temperature.

Here we have exemplified the method of determining the temperature for given values of a and b, pertaining to any one gas. However, for a mixture of gases the values a and b will be individual for each gas, and may be determined as follows.

Assume that the values of coefficients a and b for each gas will be:

$$a_1,\ a_2,\ a_3, \ldots\ldots,\ a_i \ldots\ldots$$

$$b_1,\ b_2,\ b_3, \ldots\ldots,\ b_i \ldots\ldots$$

The relative parts by weight for each gas are

$$m_1,\ m_2,\ m_3, \ldots\ldots,\ m_i \ldots\ldots,$$

while

$$a_1 + a_2 + a_3 + \ldots + a_i + \ldots = 1.$$

Then

$$a = a_1 a_1 + a_2 a_2 + a_3 a_3 + \ldots + a_i a_i + \ldots = \sum_1^k a_i a_i,$$

$$b = a_1 b_1 + a_2 b_2 + a_3 b_3 + \ldots + a_i b_i + \ldots = \sum_1^k a_i b_i,$$

and these values must be substituted in the equation for computing t.

Values of the mean molecular heat capacity from 0 to t are listed in Table 1(*).

Table 1

t, °C	N_2, O_2, CO	H_2	H_2O	CO_2
100	6.96	6.95	8.04	9.08
500	7.07	7.02	8.32	10.34
1000	7.30	7.15	8.83	11.33
1500	7.52	7.38	9.46	11.92
2000	7.70	7.56	10.27	12.29
2500	7.84	7.70	11.38	12.55
3000	7.96	7.83	12.98	12.74

(*) Professor D.V. Alekseev, "Fizicheskaya Khimiya" (Physical Chemistry), page 60.

Since various authors submit different values for a and b, the temperatures computed by the aid of the listed formula vary up to 10%.

More accurate equations are obtainable by an application of the quantum theory.

In view of the fact that interior ballistics equations also include the weight of powder charges, as well as their volumes, one of their physical characteristics, is the specific weight or <u>density of powder</u> δ . The density of powder varies within very narrow limits, from 1.63 to 1.56; and on the average it is assumed in approximate computations to be equal to 1.6. The density of powder depends little on the type of powder. It is equal to 1.6 for both the pyroxylin and nitroglycerin powders. For pyroxylin powders, the density depends on the content of volatile substances H (the higher H, the smaller δ). Powders with a non-volatile solvent have $\delta \approx 1.62$, with δ dependent on the conditions of pressing: the greater the pressure of pressing, the greater is the δ.

For black powders, δ varies between 1.50 and 1.80. In extreme cases it reaches 1.90.

<u>Table 2 - Values for Several Physical Chemical</u>
Characteristics of Powders

Characteristic	For Pyroxylin Powders	For Nitroglycerin Powders
Calorific value Q_v cal/kg (water in vaporous state)	900-800	1100-1200
Volume of gases w_1, dm^3/kg (water in vaporous state)	900-970	860-800
Temperature of combustion T_1, ^oK	2800-2500	3000-3500

Table 2 - (Cont'd.)

Characteristics	For Pyroxylin Powders	For Nitroglycerin Powders
Content of volatile substances H, %	2.0-7.0	0.5
Density of powder δ, kg/dm^3	1.62-1.56	1.62-1.56

The famous Russian gunpowder specialist G.P. Kusnenskii (died in 1923) submitted the following empirical formulas for the fundamental physical-chemical and ballistic characteristics of pyroxylin powders (N = nitrogen content in percent):

$$w_1 = 1515 - 48.72N; \quad T_1^0 = 273 + 34.7N^{5/3}$$

Calculations based on those formulas give the following values for w_1 and T_1 (table 3):

Table 3

N, %	11	12	13	14
w_1	979	931	882	833
T_1°	2165	2456	2750	3096

During recent years investigations were conducted to determine the experimental dependence of the fundamental physical-chemical characteristics Q, w_1 and T_1 on the composition of the powder.

For our powders, these dependencies were submitted by Lecturer V.G. Shekloin (1943).

If we designate the percentage content of nitrogen in pyroxylin as N, and correspondingly designate the content of nitroglycerin in gunpowder as n, while designating centralite (di-ethyl-di-phenyl-urea) as c, di-butyl-phthalate as d, vaseline as v, separable volatiles as h, inseparable volatiles as h', di-phenyl-amine as s, camphor as ϕ and graphite as g, then the formulas of Sheklein will yield:

$$Q_w = 730 + 148.5\ (N - 11.8) + 9.41\ a - 28.5\ c - 24.3\ d - 37.5\ v -$$

$$- 13.8\ h - 26.7\ h' - 31.0\ s - 32.5\ \phi - 42.0\ g,$$

where 730 represents the heat of explosive decomposition of pyroxylin having a nitrogen content of 11.8%.

$$v_1 = 944 - 47.3\ (N - 11.8) - 2.45a + 14c + 12d + 23v + 3.4h +$$

$$+ 16.9h' + 14.6s + 17.4\phi + 10g.$$

where 944 represents the volume of gases forming during the combustion of pyroxylin having a nitrogen content of 11.8%.

$$T_1{}^{\circ}K = 2790^{\circ} + 375\ (N - 11.8) + 22\ a - 71\ c - 50\ d - 100\ v - 54\ h -$$

$$- 82\ h' - 88\ s - 92\ \phi - 125g.$$

where 2790° corresponds to the temperature of the explosive decomposition of pyroxylin having a nitrogen content of 11.8%.

9. BALLISTIC PROPERTIES OF GUNPOWDER

Ballistic properties of gunpowder is the term applied to values governing the maximum pressure p_m of powder gases and to the rate of pressure increase $\frac{dp}{dt}$ during combustion of the powder inside a constant space.

One of them depends on the nature of the powder, and is related by a definite pattern to the latter's physical-chemical characteristics. The others are governed by the geometrical data of the powder grains composing the charge.

Ballistic properties dependent on the nature of the powder are determined experimentally through combustion inside a manometric bomb.

In the combustion of powder in the bore during a discharge, the pressure of the gases and the rate of its variation depends not only on the characteristics of the powder, but also on several other values and parameters related to the design of the bore of the gun and projectile, and characterizing the entire artillery system (for example p_m, $v_д$). These values may be termed the ballistic characteristics of the gun and projectile.

For the time being, only a short definition of ballistic properties will be presented at this place. A more detailed discussion of these properties will be given later, in the chapter on pyrostatics.

<u>The "Energy" f of the powder</u> represents the work which the gases can perform during the combustion of 1 kg of powder, if we heat these gases up to the temperature T_1° and permit them to expand at constant atmospheric pressure.

This <u>work</u> depends on the specific volume of gases and the temperature of the explosive decomposition of powder. It is expressed in kg-m/kg

$$f = RT_1 = \frac{p_a v_1}{273} T_1,$$

where p_a = 1.033 kg/cm^2 and represents atmospheric pressure;

v_1 is the specific volume of gases at 0°C and atmospheric pressure; and

T_1 is the temperature of explosive decomposition (combustion) of powder.

By modifying the proportion of the powder in a manner increasing w_1 and T_1, it is possible to also increase the energy of the powder.

The term "energy" appears to be a sort of historical survival, and does not truly define the amount of work. However, since it has been maintained in ballistics, we shall continue to use it in our treatise.

Covolume α in dm^3/kg. In the presence of great pressures, such as develop in the combustion of powder in bombs and weapons, gas densities become so great that the gaseous molecules by themselves occupy a liberally significant part of the space in which the combustion occurs. In physics, this is explained by the introduction of a value, proportional to the volume of gas molecules and equal to the sum of volumes of spheres of influence of each molecule, in the equation for the state of the aggregation of gases. Van-der-Vaals assumed that the volume of these spheres of influence is equal to the quadruplicated volume of the molecules themselves.

This value is called the "covolume." It is specific for a given type of powder, proportional to the volume of gas molecules, and exerts influence on the value for pressure.

We will assume that covolume is a volume proportional to the volume of molecules of gases forming during the combustion of 1 kg of powder. (It is expressed in dm^3/kg.)

The ratio of the covolume of a given gas to its volume at $0^\circ C$ and at a pressure of 760 mm, $\alpha : w_1$, varies within narrow limits for various gases. Namely:

Nitrogen	0.001380
Methane	0.001001
Oxygen	0.000890
Hydrogen	0.000887
Carbon dioxide	0.000886

Usually it is assumed that $\alpha \sim 0.001\ w_1$.

Kisnemskii gave for pyroxylin powders the formula $\alpha = 5.7/N^{0.7}$, i.e., $\alpha = 0.00108\ w_1$.

Krantz writes in his study [2]: "In all probability, the adjustment from volume to covolume is not a constant value, but a function of the volume. The commonly accepted proposition that $\alpha = 0.001\ w_1$ constitutes an approximation, with the error increasing for an increase of pressure. It is most expedient and accurate to accomplish a determination of the covolume on the basis of pressure measurements."

Information gained in recent years provides the foundation for the assumption that the covolume becomes smaller with an increase of the pressure of gases above 10,000 kg/cm^2. The covolume may be considered as a constant value, under normal conditions and pressures up to 4000 kg/cm^2.

Rate of powder combustion u_1 at a pressure $p = 1$. Similarly to f and α, this value is a derivative of the physical-chemical properties of powders. Variations of the chemical composition of the powder are reflected very strongly in the value for the rate of combustion. For instance, the rate of combustion u_1 for nitroglycerin powders possesses values from 0.070 to 0.180 mm/sec at $p = 1\ kg/cm^2$, depending mainly on the content of nitroglycerin.

The rate of combustion u_1 for pyroxylin powders possesses values from 0.060 to 0.090 mm/sec at $p = 1$ kg/cm², depending on the content of volatile substances.

In the combustion of powder within a constant space, the energy f and the covolume α exert influence on the value of the pressure and on the rate of its intensification. The rate of combustion u_1 influences only the rate of pressure increase.

The value u_1 of the rate of combustion, when related to the pressure $p = 1$ has a compound magnitude dm/sec: kg/dm².

All these characteristic f, α and u_1 depend upon the nature of the powder.

Table 4 - Values f, α and u_1 for Various Powders

Powder	f in kgdm/kg	α in dm³/kg	u_1 in dm/sec: kg/dm²
Pyroxylin powders	770,000-950,000	0.90-1.1	0.0000060-0.0000090
Nitroglycerin powders	900,000-1,200,000	0.75-0.85	0.0000070-0.0000150
Black powders	280,000-300,000	~0.5	---

The last ballistic characteristic depends upon the geometrical data of the powder. This characteristic is the "Dimensions and form" of powder grains, and the related "specific surface of the powder," the ratio of the initial surface of the powder to its volume. The principle of gas formation and the rate of pressure increase in the combustion of powder depend upon these values.

Chief importance is attributed to the smallest dimension, the thickness of the strip or the wall. Because the combustion of the powder grain (strip, tube) occurs from two sides, the thickness is usually designated by $2e_1$ (e_1 corresponding to the half of the thickness which burns in one direction).

Apart from the ballistic characteristics of the powder, the density of loading Δ also affects the value and character of the pressure increase. It is a characteristic of the conditions of charging. The density of loading represents the ratio of weight ω of charge to the volume W_0, in which the combustion of the powder takes place:

$$\Delta = \frac{\omega}{W_0} \ \text{kg/dm}^3.$$

In this sense, if we fill the entire space W_0 with powder, then the density of loading will become a gravimetric density.

The gravimetric density characterizes the degree of compactness of the charge. At a given density δ of powder, it will be greater for a fine powder with rounded edges and less for a rectangular grain with protruding edges. In this connection, for instance, a granular powder with seven holes proved to be more "suitable for packaging" than the strip type powder. By the same token, a shell for a field gun will house 1100 kg of strip powder, and up to 1380 kg of the powder grains having seven holes.

In this manner, we have four ballistic characteristics: the energy f, the covolume α, the rate of combustion u_1 at $p = 1$, the dimensions and form of the powder, and the characteristic of the charging conditions, the density Δ of loading.

With a given composition of the powder, we can regulate the process of pressure increase and the magnitude of the pressure by varying Δ, the dimensions and the form of powder. The dimensions and form of powders are varied because it is necessary in each case to select the dimensions of the powder and the weight of the charge for the gun, in order to obtain the required muzzle velocity of the projectile, under conditions in which the pressure will not exceed a given fixed value governed by the strength of the barrel wall.

The ballistic characteristics will be discussed in greater detail in Section II.

SECTION TWO
GENERAL PYROSTATICS

BASIC RELATIONS AND PRINCIPLES
OF GAS FORMATION DURING THE
COMBUSTION OF POWDER IN A
CONSTANT SPACE

CHAPTER I - COMBUSTION OF POWDERS

1. THE MANOMETRIC BOMB

Pyrostatics investigate the combustion of gunpowder in a constant space. It is one of the fundamental branches of interior ballistics. A familiarity with it is necessary for a clear comprehension of phenomena occurring during a gun discharge.

The combustion of powder is investigated in this connection under simplified (static) conditions, where the motion of the projectile is disregarded, the variations of volume do not exist, and gases do not perform exterior mechanical work. The mechanical work of the gases consists of a certain pressure, which the walls of the space in which the combustion takes place are subjected to from within.

On the basis of the experimental investigation of the development of the pressure of the gases during a combustion of powder within a constant space, pyrostatics form the theory of powder combustion and establish principles of formation for gases containing the energy which is expended for the performance of various exterior functions under the conditions of a gun discharge.

In this connection, investigation is made of the influence of physical-chemical properties of powder, of ballistic characteristics and conditions of charging on the development and process of gas pressure. The latter is in itself a very important factor, affecting the rate of formation of gases.

Pyrostatics presents the methodology of the ballistic analysis of gunpowders, i.e., the methodology for determining the ballistic characteristics of the powder.

Knowing the ballistic characteristics of a powder and the principles of its combustion in a constant space at a given process of pressure, it is possible to account for the principles of gas formation and pressure development under the even more complicated conditions of a discharge, with an occurrence of projectile motion (pyrodynamics), and a variation of the volume and performance of exterior functions by the gases.

In this manner, pyrostatics offers a source of knowledge and fundamental data necessary for a comprehension and study of the more complicated phenomena occurring during a discharge.

Instruments in which the principles of gas formation during a combustion of powder in a constant space are investigated, are called manometric bombs. In view of the fact that in the course of the subsequent exposition of pyrostatics it will be necessary to take experimental materials as a basis, a description of the design of the most typical manometric bomb is included here for the purpose of lending clarity to statements on obtaining such material.

The manometric bomb is a laboratory instrument serving for the purpose of determining the magnitude and character of the increase of pressure developed by gases formed during the combustion of gunpowder or explosives inside a constant enclosed space. Making it possible to determine all ballistic characteristics of gunpowder, (energy of the powder, covolume of the powder gases, duration of combustion and its rate, as well as several other characteristics), the manometric bomb at the present time constitutes one of the fundamental instruments of an interior ballistics and powder laboratory.

Fig. 5 - Manometric Bomb for the Investigation of Powder Combustion

Up to the present time, the Vel bomb, designed in the 1880's appears to be the most widely used. In this bomb, the pressure is determined from the compression figure of a copper cylinder, called "crusher." (English word "crush" means to crush or compress.)

The bomb (fig. 5) consists of a cylinder A, made of high-grade steel, which has a screw thread in each end of its inner surface. The igniter cap B is screwed in at one end, while the cap C with the crusher manometer is screwed into the other end. In the igniter cap, there is an insulated rod which conducts the electric current igniting the fuse, while a second conductor is connected directly to the body of the bomb. A thin wire connects the points c and c', and passes through a shell made of tissue paper which contains a given amount of igniter (pyroxylin, black powder). This wire is ignited by the current.

The rod p moves within the duct of the crusher cap C, and transmits the pressure of the powder gases to the crusher column k. The latter is made of electrolytic copper. Its other end is placed against the head of a screwed-in plug which serves as an anvil. A small centering rubber ring a is placed on the crusher to obtain coincidence of its axis with that of the rod. The head of the rod r, adjacent to the crusher, has an outwardly protruding extension r' which moves in a lateral guide slot in the head of the rod cap. A light steel pen point n is fastened to the extension. It registers the travel of the rod as a function of time on smoked paper glued to the drum of the chronograph.

The copper obturating rings, d, d, serve to prevent the escape of gases between the walls of the bomb and the screwed-in caps, while the portion of the duct e which borders with the rod is filled up with a mastic to protect the rod from the immediate effects of high temperature gases.

The bomb 6 is fastened in a special clamp 5 near the drum 2 (fig. 6), in order for the pen point to touch the smoked paper only lightly, and when the drum revolves, to mark on the latter a thin straight line parallel to the base of the cylinder (mm on fig. 7).

The tuning fork K is located on the other side of the drum 2. It is caused to vibrate by the opening and closing of electromagnets e,e, which attract the arms of the tuning fork. A thin pen point ℓ is fastened to one of the latter's arms, recording its oscillations on the same smoked strip of paper.

Prior to the experiment, the drum of the chronograph is put into rapid rotation by means of an electric motor M or a time mechanism. When the rotation becomes uniform, the current is turned on and burns the wire going through the fuse. The fuse itself ignites the charge of powder located in the bomb.

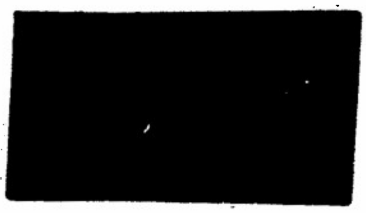


Fig. 6

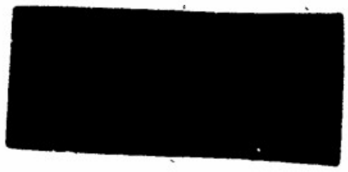


Fig. 7 - Curve of the Compression of the Crusher in the Manometric Bomb

The pressure produced during the combustion of the powder gases is transmitted through the rod to the crusher, compresses it, and the pen point of the rod plots the compression curve aa (fig. 7) in accordance with the process of pressure increase. After the end of the combustion and the attainment of maximum pressure, the rod stops, and the pen point draws a straight line bb parallel to the initial line. Here, the distance between both of these straight lines is equal to the full compression of the crusher.

Simultaneously with the turning on of the current, the vibrating tuning fork is placed near the drum for a short period of time by the aid of an automatic mechanism, and its pen point, draws a wave-like curve "sine curve" about the center line. Because the number of tuning fork oscillations per second is already known, and having measured the length of one wave by means of a comparator microscope, we can determine on the circumference of the drum the length corresponding to 0.001 second at a given speed of drum rotation. In this way we obtain a time scale for measuring the crusher compression curve.

After completion of the test, the paper with the sinusoidal curve and the crusher compression curve is taken off and coated with lacquer. After the drying process, the curve is measured under a comparator microscope.

The pattern of the curve and of the sinusoid is shown in fig. 7.

After measuring the compression curve obtained at suitable time intervals, the compression of the crusher is determined as a function of time.

Then, in a given test, the dependence of powder gas pressure increase on time (curve p as a function of t) is obtained on the basis of the dependence of crusher compression on the magnitude of the pressure, the latter having been previously determined experimentally in a press.

In this way we can determine not only the maximum pressure developed by the gases of a charge of given weight (for a given density of loading), but also the pressure increase relatively to time. That is, just those values which depend on the ballistic characteristics of a gunpowder.

Consequently, if we knew the equations relating the ballistic characteristics to the law of gas pressure increase, and had the bomb test data for any given powder, we could determine the numerical values of its ballistic characteristics.

In pyrostatics, relationships are also known between the ballistic characteristics of a powder, the condition of the test and test data obtained.

Even now, the manometric bomb forms the basic apparatus of pyrostatics. Sometimes an elastic manometer is used in place of the crusher cap.

The previously mentioned cylindrical crusher began to compress and registered the increase of pressure at approximately 300 kg/cm^2. The initial phase of powder combustion remained unexplored.

In order to obtain the entire law of pressure increase from the beginning of ignition to the end of the total combustion of the powder, one can use a crusher shaped so that, having a low resistance at low pressures in the first phases of the combustion process, it gradually increases in resistance as the pressure increases.

The conical crusher developed by the author in 1923, and obtained by machining a part of a cylindrical crusher into a cone, possessed that property. This type of crusher registers pressures from 5 to 7 up to 3000 kg/cm^2. In this way, it permits not only the investigation of powder combustion from the very beginning to its end, but also a study of the burning of the igniter itself and the process of powder ignition.

The conical crusher was widely applied in our country in laboratory tests of powder combustion, as well as in determinations of the low pressures of powder gases in tests conducted on the firing range.

At the present time, piezoelectric manometers based on modern achievements in electrotechnology and radiotechnology are also used. Still, the main aspect of the business remains thus: the process of pressure increase is registered by one or another method. Then, knowing what type of powder we deal with and the conditions of its combustion, on the basis of the pressure increase, we can determine the rate of gas formation and its dependence on various factors.

2. PRINCIPAL PHASES OF COMBUSTION

In the combustion of powder we can distinguish the following three phases.

Ignition of the powder. In order for the powder to become ignited, it must be heated up in such a manner as to obtain, at any given point of the charge, a temperature higher than its ignition temperature. The ignition of smokeless powder occurs at a temperature of about 200°C. Black powder with an ignition temperature of the order of 300°C, however, ignites and burns more vigorously. After the powder is ignited, even though only at one point, the combustion reaction proceeds by itself as a result of the heat emitted in the combustion of the powder. Two processes take place simultaneously: ignition of the powder, and the combustion proper.

Ignition is the process of the propagation of the combustion reaction over the surface of the powder grain.

Combustion is the process of the propagation of the reaction into the interior of the powder grain.

The above two processes differ one from the other. The figures characterizing them and relating to the rates of ignition and combustion of smokeless and black powders are listed below, in Table 5.

3. COMBUSTION OF POWDERS AT ATMOSPHERIC PRESSURE

<u>Black powders</u>. After the ignition of black powders in the open air and at any given point, the flame spreads very rapidly in all directions over the surface. Then the grain continues to burn from all sides, by concentric layers toward the center of the grain. In accordance with the experiments of Piober, ignition in identical grains will occur the slower, the more carefully the grains are polished, the greater the density of the powder, and the less burned is the charcoal used for the manufacture of the powder.

In the open air, the speed of ignition of black powder placed in the form of a path over corrugated iron varies from 1 to 3 m/sec, depending upon the circumstances.

The rate of combustion of black powders in open air was determined in experiments by igniting powder demolition blocks, with the lateral surface covered by grease. It proved that the rate of combustion, or the speed of the transmission of the flame from layer to layer, does not depend upon the cross-sectional area of the burning block, but that the speeds of combustion are inversely proportional to the density of the blocks. It was proved that for an identical composition of the powder mass, brown charcoal reduces the rate of combustion, and the rate of combustion is lowered with an increase of powder humidity.

The rate of combustion of black powder in open air is on the average around 0.01 m/sec = 10 mm/sec., i.e., many times less than the rate of ignition.

Smokeless Powders ignite and burn in the open air considerably slower than the black powders.

If we fasten a strip of pyroxylin powder (or a stick of nitroglycerin powder) vertically and ignite an upper corner of it, the strip will burn calmly with a yellowish flame, while the propagation of flames over the surface of the strip will proceed comparatively slowly.

In addition to this, the burning grains will form an angle some time after the beginning of the combustion. This angle will remain constant to the end of the combustion (figs. 8a and b). The magnitude of this angle depends on the ratio of the combustion rate of powder to the rate of ignition.

Assume that the rate of combustion equals u, the rate of ignition u', while $u' > u$.

If we ignite a strip of powder at one corner (at the point a), then it will burn inside at the rate u, and on the surface at the rate u', for various intervals of time. Assume $u' = 2u$. Then the strip will have sequential burning surfaces of the type shown in fig. 8, i.e., 1-1-1; 2-2-2;...;5-5-5; 6-6-6. Beginning with the surface 5-5-5, the angle at the top maintains its magnitude and equals two times $\angle cde = \angle \varphi$.

Now, the ratio of rates is $u/u' = \sin \varphi$. In this manner, having measured the angle φ, we can determine how many times the rate of ignition is larger than the rate of combustion. It is of interest to note that after reaching the constant angle (surface 5-5-5), the further shortening of the strip proceeds in unit time not at u (rate of combustion), but at u' (rate of ignition). Therefore, noting the time for the total combustion of a stick of a given length, we can determine the rate of ignition but not of combustion.

The rate of combustion of smokeless powders in open air is about 1 mm/sec., i.e, significantly less than in the case of black powders.

The rate of ignition is two to three times greater. Therefore, the strip burns in air for a sufficiently long time. However, if we heat up the entire surface of the strip at one time, so that it will ignite simultaneously (for instance by casting a strip of powder into the flames of a melting oven), then the entire surface of the strip will burst simultaneously into flames, and the powder will be consumed rapidly, because it is thin.

Table 5 - Rate of Ignition and Combustion of Powder in Open Air

Gunpowder	Black	Smokeless
Rate of ignition u' mm/sec	1000-3000	2-5
Rate of combustion u mm/sec	10	1-2

If larger quantities of smokeless powder are ignited, individual strips and grains are carried away as a result of the formation of a larger quantity of gases and may be projected a certain distance, while tubes burning over their interior surface become comparable to rockets, and fly at a higher velocity in various directions, sometimes exploding to the accompaniment of a piercing sound.

Fig. 8 - Combustion of a Strip of Powder in the Open Air

1) Front view; 2) side view.

4. COMBUSTION AT A PRESSURE LOWER THAN ATMOSPHERIC PRESSURE

The first observations and experiments were conducted with black powder. They have shown that powder burns less vigorously in rarefied atmosphere on high mountains than at the foot of the same mountains. Experiments on the combustion of powder fuses at various altitudes and at various barometric pressures verified this conception. These experiments retain their significance even at the present time, because the combustion of powder in time fuses, during antiaircraft firing at aerial targets, takes place much slower than in flat trajectory firing.

5. COMBUSTION IN A VACUUM

The significance of pressure becomes even more clearly evident in the event of great rarefaction. It was proven by experiments that if the powder is placed in a vacuum under the bell of an air pump, it will completely fail to ignite, regardless of bringing it into contact with a red hot wire.

A platinum container filled with black powder was heated until red, in a greatly rarefied atmosphere under the bell of an air pump. After some time passed, the powder began to burn slowly. However it did not explode, as in the open air. If a platinum wire is conducted through the powder and heated up, the grains surrounding it will begin to melt; however, combustion will not commence immediately. If the heating up is continued, then grains in contact with the wire will burn only after the passage of some time, while the others will remain intact.

And, combustion occurs easily only when pressure is increased to 1/10 atm.

In this manner, the heating up of the powder, even by a red-hot body, is by itself insufficient. It is necessary that a certain minimum of atmospheric pressure exist. The higher the initial pressure, the more vigorously will the powder ignite.

The same concepts apply to smokeless powders also.

6. COMBUSTION OF POWDERS AT INCREASED PRESSURES

The rate of powder combustion depends very largely on the pressure. Although this fact was known for a long time, experiments determining the relations between the rate of combustion and the pressure were first conducted by Vel at the end of the 19th century.

It should be of interest here to show how he arrived at the determination of a characteristic for parallel layer combustion of powder on the basis of these experiments, and by also utilizing additional observations on the form of the incompletely burned grains projected from the gun during firing.

Black powders. After making observations on the incompletely burned grains which were projected from a gun when it was discharged, Kastan found that for densities of black powder $\delta \leq 1.64$ there are no residues; for $\delta \approx 1.72$ the residues had an irregular form; while at $\delta > 1.81$, the form of the residues was very similar to the original grains. (In fig. 9, residues are represented by the shaded areas.)

Vol prepared, from one and the same mixture of black powder, tablets and small cylinders of similar shape but of varying dimensions a_1 and a_2, and ignited them in a bomb, using the same charging density. Thus, the maximum pressure p_m was the same (for both). The times τ_1 and τ_2 for total combustion were determined by the aid of crusher pressure recordings.

In the first instance, at $\delta \leq 1.64$, the time of combustion of the powder was not governed by the dimensions; $\tau_1 \approx \tau_2$, regardless of the significant difference in dimensions.

In the second instance, at $\delta \approx 1.72$, the time increased with an increase of the thickness of the explosive block; but not however proportionally to the dimensions. This corresponded to the irregular residues in the experiments by Kastan.

Fig. 9 - Incompletely Burned Grains of Black Powder

At $\delta \approx 1.80$, the result was a direct proportionality of the combustion times to the linear dimensions of the blocks:

$$\frac{\tau_2}{\tau_1} = \frac{a_2}{a_1}$$

At this density, the incompletely burned grains projected from the gun were similar to the original ones.

This condition, as well as the others, can occur only in the event of parallel layer combustion.

The table lists comparative data on results of experiments involving firing from guns and ignition in a bomb of powders of the same form and characteristics, but with varied dimensions (Table 6).

Table 6

Item No.	δ	Experiments by Firing	Experiments in the Bomb
1	<1.64	Residues did not result	$\tau_1 \approx \tau_2$
2	~ 1.72	Resultant residues had an irregular form	$\tau_1 < \tau_2$, but not proportional to a_1 and a_2
3	>1.80	Resultant residues had a regular form	$\frac{\tau_2}{\tau_1} = \frac{a_2}{a_1}$

These tests showed the direct dependence of the combustion time on the density of loading. Black powder is a mechanical mixture of sulphur, saltpeter and charcoal. The less the density of the powder ($\delta \approx 1.64$) and the lower the pressure of the pressing process, the more porous is its mass. Therefore, when the pressure is increased, the powder disperses, and the time of combustion does not depend on the dimensions.

At an increased density of loading ($\delta \approx 1.70 - 1.72$), its particles fit closer one to another, the interstices become smaller, and the dispersal under pressure occurs later. Only a very dense mass ($\delta > 1.80$) does not disperse under pressure, and burns in concentric layers.

In this way, the character and rate of combustion of black powders at higher pressures depends on the density δ , and even to a greater degree on pressure. The rate of combustion increases with an increase in pressure.

The following characteristic of parallel layer powder combustion, which became known as Vel's characteristic, was determined on the basis of the experiments listed above.

If two powders, identical with respect to chemical composition and having a similar form of grain, but of different dimensions, are burned in a closed space with the same density of loading, and if their times of total combustion are related to each other as their smallest dimensions, or as their coefficients of similarity $\tau_2/\tau_1 = a_2/a_1$, then this is a characteristic of powder combustion by parallel layers.

For instance, if in the first instance the charge is composed of laminas with dimensions 3 x 30 x 30 mm, and in the second instance of 1 x 10 x 10 mm, then the ratio of their times of combustion $\tau_2 : \tau_1$, will be equal to 3:1.

If we change the time scale of one of the pressure increase curves obtained in a combustion of such powders in a bomb so that its beginning and its end coincide with the beginning and the end of the other, then all intermediate points of the curves will coincide - they will become congruent.

Smokeless powders. Experiments conducted in a bomb with specimens of smokeless powders have shown that the latter satisfy this characteristic. Therefore, it can be assumed that they burn in parallel layers.

Although the rate of combustion of smokeless powders in open air is considerably lower than the comparable rate for black powders, their combustion in an enclosed space proceeds unusually fast. This is indicated by the short duration of the discharge phenomenon and by experiments in a manometric bomb, where the process of combustion lasts only thousandths of a second. Because tablets of smokeless powders are very strong and elastic, they do not break down during combustion (as in the case of black powder), but burn in concentric layers.

Strips of powder which are at times projected from guns in an incompletely burned state, and are extinguished in the air, practically retain their shape, except for the fact that their surface becomes rougher. In disagreement with the combustion in open air, the strip retains the form of a regular parallelopiped. Angular combustion, which results in air by virtue of a small difference between the rates of combustion and ignition, is not present at higher pressures. This points to the fact that ignition in an enclosed space takes place considerably faster than in the open air, as a result of heated igniter gases producing a sufficiently high pressure.

If a strip is heated up in open air by throwing it into fire, then it will burst into flames instantly, practically in its entity, and will burn out rapidly. During the combustion of powder in bombs and weapons, ignition is accomplished by auxiliary igniters made of pyroxylin or black powder.

These instantly produce a larger quantity of high temperature gases, which raise the pressure to 10-50 atmospheres. Under such conditions, the powder begins to burn practically simultaneously over its entire surface, and the further combustion process proceeds by concentric layers. That is why the powder retains its initial form.

Conducted observations served as a basis for the formation of Vel's law of combustion for smokeless powders. The assumption that the mass of the powder is homogenous in all directions, and that the grains of the charge are exactly alike in their dimensions and form, was accepted as a basis for this principle. The basic assumptions of this law are as follows:

1) The ignition of powder in an enclosed space is instantaneous.

2) The combustion of smokeless powders proceeds by parallel layers, at a rate identical from all sides.

The quantity of gases forming during the combustion of powder is characterized by variations in the volume of the burning powder grain. With the assumptions set forth, and on the basis of purely geometrical considerations, one can determine the relations between the thickness of the powder burnt from all sides at any given moment and the burnt volume of the powder. These assumptions are often called the geometrical law of combustion.

The geometrical law of combustion expresses only the superficial geometric aspects of the combustion process, and considers the powder to be homogeneous as respects its mass, and to be identical in dimensions. This law is a formulization of the unusually complicated process of combustion of the entire charge, which consists usually of grains or elements differing with respect to dimensions and having a not entirely homogeneous mass as a result of its manufacture. For instance, a strip pressed through a slot shows a different strength when sawed downward or perpendicular to the direction of pressing (analogous to the different strength of wood along and perpendicular to its fibers).

In addition to this, the ignition of the charge in the presence of a large number of grains in the chamber (of the gun) may also fail to be simultaneous and instantaneous for the igniter pressures of 15-50 atm usually applied.

Consequently the combustion of the entire charge differs from the scheme submitted for the individual grain of powder.

Still, by explaining the influence of a series of geometrical factors on the law of gas formation and the rate of gas generation, the geometrical law of combustion provides a basis for the comprehension and evaluation of the effects of the form and dimensions of powder grains on the development of gas pressure in the bore of guns. The shape and dimensions of the powder grains (together with weight of charge) namely form the factors by whose aid it is possible to regulate within a wide range, the process of gas formation, and, by the same token, to regulate the phenomenon of discharge.

The subsequent studies of the twentieth century defined the geometrical principle of combustion more precisely, and introduced consideration of the influence of factors, inexplainable in the light of the basic assumptions.

The geometrical law was originated on the basis of an investigation of pyroxylin powders in a simpler form (strip, tablet, tube). Later, powders in a more complex form made their appearance. These were powders with a multitude of holes (American grain with three, seven and nineteen holes; in our country the grain of Kisniemskii with 36 holes), flegmatized powders with an uneven distribution of the flegmatizer over the depth of the powder mass, nitroglycerin powders, in which the nitroglycerin distributed itself unevenly over the powder in storage. Also introduced was the process of graphite covering the surfaces of certain powders, which retarded the ignition process.

The appearance of these new factors demanded a more precise definition of our ideas on the actual character of powder combustion, and required the introduction of corrections to the perfected scheme of combustion.

7. THE THEORY OF POWDER COMBUSTION

In 1908, the French research scientist Charbonne presented in his study, entitled "Interior Ballistics" [3], a criticism of the basic assumptions of the geometrical principle of combustion, and expressed doubts as to their correctness.

By examining more closely strips of coarse powder projected in an incompletely burned state from small caliber guns during discharges, one can find a large number of strips burning practically in parallel layers. However, some of the strips burn irregularly. The thickness fails to remain identical, and the surface of powders shows the appearance of grooves. The latter become larger and unite, and in this manner break down the powder into fine tablets, which cover the ground before the gun in large numbers. The cause for these irregularities of combustion, as well as for the crumbling of the strips, is partially located in the imperfection of powder manufacture. However, an artillery specialist who uses powders for firing guns and who wishes to form a theory of their performance, should operate on the basis of powders as they are in reality, and not on the basis of ideal powders perfect in form and homogenous in their combustion. Even if we disregard the manufacturing defects and accept the principle of combustion by parallel layers, can we assume that ideal principles evolved for one grain can be applied without modification to an entire bundle of powder present in the chamber of a gun, or to a charge composed of several such bundles? Certainly not, for it is easy to show the basic reasons influencing deviation from the elementary principle of combustion of one grain.

Ignition and Combustion. It was commonly accepted in interior ballistics that the ignition of the entire charge is instantaneous in character, i.e., that the rate of transmission of fire is infinitely high as compared with the rate of combustion. This stipulation is entirely wrong, and is not verified under any conditions in open air. It is prohibitive to assume that at higher pressures, the rate of ignition will become infinitely higher in comparison to the rate of combustion.

It is by far more probable that the first bundle, located adjacent to the igniter, will ignite and burn somewhat ahead of the last one, which is located at the bottom of the projectile.

Propagation of ignition. Ignition propagates for the most part in the holes in and interstices between the powder grains. It will proceed more advantageously if the grains are distributed in the direction of chamber axis, than if they were placed irregularly.

The closeness of the grains to one another and to the wall of the gun increases the possibility of the occurrence of causes which result in the failure of the powder to burn by parallel layers.

These considerations were at one time of significance to the improvement of ideas on the actual combustion of powder.

However, Charbonne could not prove experimentally a number of the very probable assumptions on ignition which he put forth.

Considerably more complete investigations of the combustion of powder were conducted in the experiments of M.E. Serebriakov [4] (1924-1929), who developed the conical crusher of high sensitivity to small pressures, which permitted the registration of pressure increase beginning with 5 to 7 kg/cm^2.

The use of a conical crusher, providing a complete pressure curve from the beginning of ignition to the end of the combustion, and the methodology of combustion analysis, developed by the author, by evaluating the experimental pressure curve obtained in the combustion of powder in a bomb, made it possible to investigate and to prove, on the basis of a series of experiments, the non-instantaneousness of powder ignition and its dependence on the magnitude of the igniter gas pressure, as well as on the properties of the igniter itself.

By providing a graphic representation of the intensity of gas formation, this methodology permitted the discovery of a series of deviations from the geometrical law of powder combustion, and permitted explaining them and showing that the process proves to be actually more complex than it appears on the basis of the assumptions of the geometrical law.

It was discovered that the mass of powder is not homogeneous from layer to layer, and that the exterior layers burn at a higher rate than the interior ones.

It was proven by special experiments that the character of combustion depends not only on the form of the powder grains, but also on the reciprocal situation of burning surfaces: the nearer they are situated to each other, the more intensively does the combustion proceed.

The peculiarities of the combustion of flegmatized powders, as compared with common powders, were shown on the basis of the developed methodology. A method was also submitted for determination of the depth of flegmatizer penetration into the powder mass.

The peculiar character of the combustion of powders having narrow and long holes, in which an increased pressure develops and is reflected in the general intensity of gas formation, was determined by experimental investigation. An analysis of these experiments resulted in the establishment of a special theory of irregular combustion of such powders, which took into consideration the influence of the varied intensity of combustion of individual elements of the charge.

The theory of irregular combustion shows that the difference in intensity of gas formation in the interior of powder holes, and on the exterior surface of the powder, depends on the density of loading, and varies during the combustion of powder in a gun in accordance with the motion of the projectile.

Since the discovered anomalies were not explainable by the assumptions of the geometrical law, but were caused by peculiarities of the physical-chemical properties of the powder or physical properties of powder gases, the sum total of data representing the actual law of gas formation were called the "physical law of combustion" [5]. For details see Section III.

Mieraur [6] approached the process of combustion from the standpoint of physical chemistry, and introduced the following assumptions as a basis for a scheme of powder combustion:

1) Powder burns as a result of attaining its temperature of decomposition by virtue of the impact of previously formed gas molecules.

2) In the gaseous layer directly adjacent to the burning surface of the powder (contact layer), the reactions are still incomplete (presence of NO, which still fails to react with CO and H_2). The temperature of this contact layer is lower than the temperature of explosion obtainable by way of calculation. The rate of powder combustion depends on the temperature of this particular layer at a given pressure.

3) The reactions end in layers of gas more distant from the surface of the powder, and the layers of gases become increasingly warmer.

4) Upon contact with the cool wall of the bomb, the gases transfer a portion of their heat and their temperature decreases.

The same author attempted to determine the influence of the radiant energy of powder gases on the heating up of powder at low densities of loading and pressures.

During recent years (from 1939 on), a number of studies of our science professors Ia. B. Zeldovich, A.F. Beliaev and D.A. Frank-Kamenetski [8] were devoted to the problems relating to the mechanism of the combustion of powders and other explosive substances.

Beginning with the investigation of volatile liquid explosives, and having evolved a theory of their combustion, Professor Zeldovich applied that theory to the combustion of powders [9].

This so-called "thermal" theory considers the combustion of powder to be the result of the heating of its surface to the temperature of decomposition, with a consequent conversion of the powder into gases, and an increase of the temperature of these gases to the temperature of combustion.

In this connection, the rate of combustion depends on the temperature to which the powder is heated by the action of the hot gases surrounding it, while the depth of the heating and the increase of temperature depend on the rate of combustion, which is itself dependent on the pressure of the gases.

A characteristic of this theory is the detailed chart of thermal energy distribution between the gases and the powder, and the extensive explanation of the significance of the initial temperature of decomposition, of the heating value and heat conductivity of the powder.

Even though this theory cannot be considered entirely complete, it still remains of interest, in view of the fact that it gives details on and perfects our ideas on the process of powder combustion.

8. THE MODERN THEORY OF POWDER COMBUSTION

(According to Ia. B. Zeldovich)

In accordance with contemporary views, the combustion of powder occurs as follows.

The nitrocellulose in the surface layer of the powder decomposes. The products of the decomposition come out on the surface (process of gasification) and react in the gaseous phase, increasing the temperature of the gases greatly. The temperature on the surface of the powder is now relatively low, and corresponds to the primary decomposition of nitrocellulose. The temperature distribution in the mass of the powder and in the gases forming during its combustion, is shown by the diagram of fig. 10.

T_0 - the temperature in the interior of the powder.

T_p - the temperature on the surface of the powder.

T_g - the temperature of combustion (temperature of the gases).

Chemical reactions occur in the shaded areas. In zone 1, gasification; in zone 2, reaction of gases liberated from the powder (reaction of combustion).

The burning surface of the powder has a heated layer (x_g), whose thickness depends on the temperature conductivity of the powder and its rate of combustion. The decomposition reaction proceeds in a portion of this layer x_r. One of the fundamental tasks of the theory of powder combustion is to determine the relations existing between the rate of powder combustion and the kinetics of the chemical reaction.

The surface layer temperature value is important not only for determining the relations existing between the kinetics of gasification and the rate of combustion, but also for the investigation of problems connected with the ignition of the powder, unstable combustion etc.

In the tests of O.I. Leipunskii and V.I. Aristovain, the following results were obtained in combustion of powder at atmospheric pressure:

For pyroxylin powder T_p = 252 ± 48°C = 525 ± 48°K

For nitroglycerin powders T_p = 330 ± 48°C = 603 ± 48°K

Fig. 10 - Distribution of Temperatures During Combustion of Powder (Zeldovich)

1) Powder; 2) gases.

The decomposition of pyroxylin does not occur in the entire surface layer, but only in that part of it where the temperature approaches T_p. The thickness of its x_r comprises only about 8% of the thickness of the heated-up layer x_g.

Below, certain characteristics of powders are listed in accordance with the data of O.I. Leipunskii (Table 7).

Table 7

Specimen of Powder	Calorific Value of Powder cal/g °C	Temperature Conductivity cm^2/sec.	Heat Conductivity cal/cm-sec. °C	Rate of Combustion at p = 1 kg/cm^2 mm/sec.
Pyroxylin	0.29	$1.2 \cdot 10^{-3}$	$5.5 \cdot 10^{-4}$	0.51
Nitroglycerin	0.34	$0.87 \cdot 10^{-3}$	$4.8 \cdot 10^{-4}$	0.45

CHAPTER 2 - CHARACTERISTIC EQUATION OF POWDER GASES

(Dependence of Powder Gases' Pressure on the Conditions of Loading)

During the combustion of powder, a large quantity of gases is formed. They have a high temperature and exert high pressure on the wall of the gun in which the combustion occurs. The general principles of physics and thermodynamics are applicable to these gases. Therefore the characteristics equation expressing the relations between pressure, temperature and specific volume of gases should also be valid for this case.

For "ideal" gases, whose molecules do not have a volume and fail to attract each other, or for sufficiently rarefied gases, the physical form of the equation for unit weight is expressed by the Klapeiron formula:

$$pw = RT,$$

if p is the pressure of gases;

w is the specific volume at t = 0°C and a pressure of 1 atm;

$T^{\circ} = 273 + t^{\circ}$ - absolute temperature of gases;

R is the gaseous constant.

Since in a combustion of powder in the manometric bomb, the gases have a very high density, then the following Van-der-Vaals equation for real gases should serve as the equation of their state of aggregation:

$$\left(p - \frac{a}{v^2}\right) (v - b) = RT,$$

where b is the characteristic of molecule volume,
and a is the characteristic of cohesion of gas molecules.

The latter force (of cohesion) may be disregarded at higher temperatures, so that the equation will then be written in this simplified form:

$$p (v - b) = RT.$$

In this latter form, the equation is accepted in interior ballistics. This equation pertains to a unit of weight of gases.

If ω kg of powder is burned in the space W_0 and is converted entirely into gases whose temperature is equal to the temperature of combustion T_1, then the preceding equation will be written in this manner:

$$p\left(\frac{W_0}{\omega} - b\right) = RT$$

or

$$p (W_0 - \omega b) = \omega RT_1,$$

whence

$$p = \frac{\omega RT_1}{W_0 - b\omega} \tag{1}$$

The formula of Van-der-Vaals was evolved theoretically in the 1870's as a result of the assumptions of the kinetic theory of gases.

Investigations of powder combustion, and of gases forming during such process, were begun by Gay-Lussac (1824), and were continued by Bunsen and Shipkov (1850). These investigations were conducted at pressures around 1 atm. However, combustion in guns occurs at higher pressures. Therefore, studies began in the second half of the 19th century on the investigation of powder combustion at higher pressures in manometric bombs.

Detailed experimental investigations (initiated in 1868 and completed in 1880) were conducted in England by Nobel and Abel.

Some data of these experiments are quoted in the "Interior Ballistics" of A.F. Brink [10], and also in the study of I.P. Grave entitled "Pyrostatics" [11].

The experiments were conducted in manometric bombs, with a limitation of the maximum pressure by means of a cylindrical crusher, and included measurements of the volume of gases and an analysis of their composition. Black powders which were at that time used for military purposes, formed the object of investigation at loading densities $\Delta = 0.10-0.90$.

The experiments clarified the composition of the products of powder combustion, the quantity of gaseous products and their volume at $0^{\circ}C$ and 760 mm, the quantity of non-gaseous products and the physical form in which they are found at the moment of explosion, the quantity of heat Q_w, the mean heat capacity of decomposition products in a constant space, the temperature of decomposition products, the relations between the pressure and density of loading, the variations occurring in the products of decomposition with a change in the density of loading, the influence of the chemical composition of the powder on the resultant products of decomposition, heat and pressure, and also the effects of grain dimensions, their consistency and humidity content, etc.

Experiments on the clarification of the dependence of the maximum pressure on the density of loading, formed an object of special interest for interior ballistics.

1. THE FORMULA FOR THE MAXIMUM PRESSURE OF GASES

After conducting a large number of experiments, plotting the values for maximum pressure p_m and density of loading Δ in a diagram, drawing the curve p_m, Δ through the points obtained, and fitting an equation to this curve, Nobel and Abel established the following empirical relation between the density of loading Δ and the maximum pressure p_m:

$$p_m = \frac{f\Delta}{1 - \alpha\Delta}. \qquad (2)$$

In this formula, f and α are constant coefficients determined as a result of a number of experiments at various Δ.

Assuming $\Delta = 1/1 + \alpha$, we obtain:

$$p_m = \frac{f\,\dfrac{1}{1+\alpha}}{1 - \dfrac{\alpha}{1+\alpha}} = f.$$

At the first glance, we conclude that the value f has the dimensions of pressure. That type of dimension may be encountered in older courses of interior ballistics, under the theory of explosive substances. Actually, as it will be shown later, they express the work capacity of the powder gases.

The value f was termed the "energy" of the powder.

The value α represented the volume of liquid and solid residuals in the combustion products of black powder.

The proper physical meaning of the coefficients f and α is clarified by a comparison of formula (2) and a simplified formula (1).

In formula (2) we substitute in the place of Δ its meaning ω/W_0, and convert it by multiplication of the numerator and denominator by W_0. We obtain:

$$p_m = \frac{f\Delta}{1 - \alpha\Delta} = \frac{f\omega}{W_0 - \alpha\omega}.$$

Formula (1) has the following form for ω kg of gases:

$$p_m = \frac{\omega R T_1}{W_0 - b\omega}.$$

By comparing two formulas obtained experimentally and theoretically, we find that they are identical at $f = RT_1$ and $\alpha = b$. In formula (2), the value α represents the volume of gas molecules, as does value b in formula (1).

The physical meaning of the value f, the so-called energy of the powder, is explained by the expression

$$f = RT_1.$$

It is known from thermodynamics that the value R represents the work which the gas performs, if we heat it 1° at atmospheric pressure $p_a = 1.033$ kg/cm^2:

$$R = \frac{p_a w_1}{273}.$$

Since 1/273 is the coefficient of gas expansion when it is heated 1°, then $w_1/273$ is the expansion of the volume w_1 when the gas is heated 1°, while the product of p_a by $w_1/273$ is the work that is done by 1 kg of gases when heated up to T_1^0 at a constant pressure $p_a = 1.033$ kg/cm².

Consequently, $f = RT_1 = p_a w_1 T_1/273$ expresses the work which can be performed by 1 kg of powder gases, expanding during heating up to T_1^0 at a constant pressure $p_a = 1.033$ kg/cm².

Substituting values f in kg-dm/kg, α in dm³/kg, and $\Delta = \omega/W_0$, kg/dm³ in formula (2), we obtain the value of the pressure:

$$p_m = \frac{f\,\Delta}{1 - \alpha\,\Delta} = \frac{\frac{\text{kg-dm}}{\text{kg}}\,\frac{\text{kg}}{\text{dm}^3}}{\text{abstract}\ \frac{\text{dm}^3}{\text{kg}}\,\frac{\text{kg}}{\text{dm}^3}} = \frac{\text{kg}}{\text{dm}^2};$$

the values f and α depend on the characteristics of the powder; f on w_1 and T_1, and $\alpha \approx 0.001 w_1$.

The Nobel formula, evolved on the basis of experiments with black powder, was further verified by other research scientists, for smokeless powders and for a number of explosives.

<u>Analysis of Nobel's formula</u>. The formula was established empirically for pressures $p_m \leq 6000$ kg/cm².

An analysis of it shows that at $\Delta = 0$, $p_m = 0$. If we increase the value of Δ, then p_m will increase quicker than Δ (since $f\Delta$ divides into the diminishing fraction $1 - \alpha\Delta$). Equation (2), which gives the dependence of p_m on Δ, represents a portion of a hyperbola, since upon elimination of the denominator it has the form $p_m - \alpha \Delta p_m - f\Delta = 0$ and the discriminant $a_{11}a_{22} - a_{12}^2 = -\alpha^2 < 0$.

If we assume that the formula is correct for points obtained further on in the experiment, then the curve p_m, Δ goes out into infinity, having approached an asymptote parallel to the axis $y(p_m)$ at $\Delta = 1/\alpha$.

Then

$$1 - \alpha \Delta = 0 \text{ and } p_m = \infty .$$

If we show the dependence of p_m on Δ in a graph, by plotting Δ on the axis of the abscissa and p_m on the axis of ordinates, then we obtain a curve p_m, Δ (fig. 11) passing through the origin of coordinates and having an asymptote in the form of a straight line running parallel to the axis of ordinates at a distance of $1/\alpha$ from the origin. Negative values are not discussed, in view of the fact that they do not have a physical meaning.

Since α is approximately equal to unity for pyroxylin powders, the critical value of Δ, at which p_m should be equal to infinity, is equal to one. For nitroglycerin powders, $\alpha \approx 0.8$ and, consequently, critical $\Delta = 1/0.8 = 1.25$.

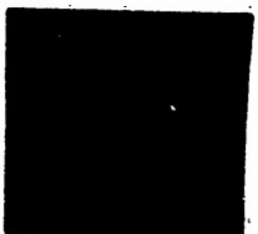


Fig. 11 - Dependence of p_m on Δ, in Accordance with Formula (2)

In practice, densities of loading not higher than 0.25 are selected for combustion of powder in a bomb, because the resultant pressure in such a case is 2000 to 3000 atm. In extreme cases Δ up to 0.40 are selected, where p_m = 5500 atm. The gravimetric density of the most "pachagnaia" rifle powder, in the form of small cylinders with one hole through them, amounts to 0.85-0.90, i.e., less than the required critical value. In this case, the calculated pressure would amount to about 50,000 kg/cm^2.

It is possible to obtain this type of density of loading, and even higher, in practice, by pressing the powder in the form of one compact cylinder fitting to the shape of the vessel in which the combustion occurs. In this instance, the density of loading $\Delta = \delta$ = the specific weight of the powder. At a density of loading higher than Δ, the process will change into an explosion even prior to the end of the powder combustion.

The dependence p_m, Δ can be represented in the form of a straight line, which can be used advantageously to determine two basic ballistic characteristics: the energy of the powder f and the covolume α.

By converting the equation (2), we obtain:

$$\frac{p_m}{\Delta} = f + \alpha p_m. \qquad (3)$$

If we accept p_m for x and p_m/Δ for y, then in the new system of coordinates formula (3) will be expressed by the lineal equation

$$y = f + \alpha p_m.$$

where f represents the segment intercepted on the axis of ordinates by the straight line, α is the angular coefficient of this straight line or the tangent of the angle φ, formed by this line with the axis x.

Conducting a series of experiments with several Δ, and having obtained corresponding magnitudes of p_m, we find the ratio p_m/Δ, and we plot the points corresponding to each density of loading on axes p_m/Δ, and p_m of the graph (fig. 12). These points should be located on one straight line. Prolonging this straight line 1-1 to its intersection with the axis of ordinates, we find the energy f. The tangent of the angle formed by this straight line with the axis Δ gives the value of covolume α. Vel conducted experiments with a whole series of explosive substances and powders, and has constructed typical straight lines for them.

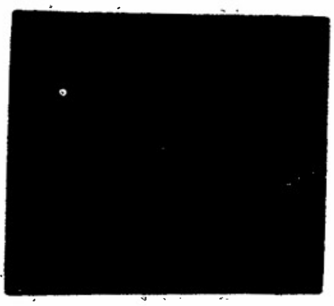


Fig. 12 - Dependence of p_m/Δ on p_m, in Accordance with Formula (3)

Fig. 13 - Characteristic Straight Lines of Three Basic Powders

If we take mean values of f and α for the common powders, then we obtain three characteristic straight lines on the graph p_m/Δ, p_m (fig. 13):

1) Pyroxylin powder: f = 900,000; α = 1.

2) Nitroglycerin powder: NG:f = 1,050,000; α = 0.8.

3) Black powder: f = 280,000; α = 0.5.

Similar straight lines were also obtained for a number of other explosive substances.

2. DETERMINATION OF THE ENERGY OF POWDER AND OF THE COVOLUME OF POWDER GASES

The magnitudes f and α can be determined analytically and graphically.

We have a linear equation with two constant coefficients f and α:

$$\frac{p_m}{\Delta} = f + \alpha p_m. \tag{3}$$

In order to determine f and α by the aid of this equation, it is necessary to conduct experiments with two densities of loading. Then, the values p_m and p_m/Δ will be known.

If in an experiment, at a density of loading Δ_1, the resultant pressure was p_1, while at a density of loading Δ_2, the pressure was p_2, we have a system of two equations:

$$\frac{p_2}{\Delta_2} = f + \alpha p_2; \tag{a}$$

$$\frac{p_1}{\Delta_1} = f + \alpha p_1. \tag{b}$$

Subtracting the terms of one equation from the other, we obtain:

$$\frac{p_2}{\Delta_2} - \frac{p_1}{\Delta_1} = \alpha\,(p_2 - p_1),$$

then

$$\alpha = \frac{\dfrac{p_2}{\Delta_2} - \dfrac{p_1}{\Delta_1}}{p_2 - p_1} \tag{4}$$

and

$$f = \frac{p_1}{\Delta_1} \cdot \frac{p_2}{\Delta_2} \frac{\Delta_2 - \Delta_1}{p_2 - p_1}. \tag{5}$$

In place of this equation, it is simpler to determine the value of f by substituting the obtained numerical value for α in equations (a) and (b). Obtaining an identical magnitude of f from either of the two equations serves as a verification of the correctness of calculations of f and α:

$$f = \frac{p_1}{\Delta_1} - \alpha p_1 = \frac{p_2}{\Delta_2} - \alpha p_2. \tag{6}$$

The diagram on fig. 14 gives a graphical illustration of the application of derived equations (4) and (5) for the determination of f and α:

$$oa = p_1;\ ob = p_2;$$

$$ae = \frac{p_1}{\Delta_1};\quad bg = \frac{p_2}{\Delta_2};$$

$$gf = \frac{p_2}{\Delta_2} - \frac{p_1}{\Delta_1};\ ef = p_2 - p_1;$$

$$\alpha = \frac{gf}{ef} = \frac{\frac{p_2}{\Delta_2} - \frac{p_1}{\Delta_1}}{p_2 - p_1};$$

$$ec = \alpha \cdot p_1;\ gd = \alpha \cdot p_2;$$

$$f = oh = ae - ec = \frac{p_1}{\Delta_1} - \alpha p_1;$$

$$f = oh = bg - dg = \frac{p_2}{\Delta_2} - \alpha p_2.$$

Thus, formula (4) for α and formula (6) for f both have a simple graphic interpretation.

In this manner, in order to determine the energy of powder f and the covolume α, it is necessary to conduct powder combustion experiments in a bomb at two densities of loading, and then to determine f and α either by use of formulas (4) and (6) or graphically. In this connection, it is not permissible to select densities of loading very close to each other, because the results would be less reliable and a larger error is possible. The best conditions exist when $\Delta_2 - \Delta_1 \sim 0.10$. For instance, for determining f and α for pyroxylin powders, it is advisable to conduct experiments at $\Delta = 0.15$ and 0.25, and for stronger nitroglycerin powders at $\Delta = 0.12$, and 0.20 or 0.22.

At densities of loading below 0.10, it is also possible to obtain unreliable results, because the linear dependence fails at pressures $p_m < 1000$ atm, and the points p_m/Δ, p_m are situated below the straight line: the lower they are, the smaller p_m is. This occurrence is explained by greater losses in heat emission through the walls of the bomb, because the combustion of powder takes place slowly at low loading densities. For the same reason, the resultant pressures are lower than in the case where loss of heat through the walls did not occur.

It will be shown below how losses through heat transfer are calculated in a determination of f and α.

Fig. 14 - Graphic Determination of the Powder Energy and of the Covolume

In addition to determination of the values f and α on the basis of experimental data, the Nobel and Abel formula is also applicable to the following cases:

1) Knowing f and α, a calculation of p_m is undertaken by the aid of the value Δ.

$$p_m = \frac{f\Delta}{1 - \alpha\Delta} = \frac{f}{\frac{1}{\Delta} - \alpha} .$$

2) Knowing f and α, we undertake to calculate, by the aid of p_m, the Δ at which a given pressure would result.

Solving the equation for Δ, we obtain:

$$\Delta = \frac{p_m}{f + \alpha p_m} = \frac{1}{\frac{f}{p_m} + \alpha} .$$

The formula cited is used for solutions of a number of practical problems. For instance, at a given f and α, it can be determined what Δ should be in order to obtain a given magnitude of pressure (assume ~ 3000), so that we may know the densities of loading for which powder may be burned in a bomb with an effective pressure of 3000 atm. Or, for instance, to calculate the pressure produced by an igniter of a given weight in a chamber of a given volume, containing a charge of a given weight.

3. NUMERICAL EXAMPLES

In order to better explain the method of determining f and α, the following examples are given.

In solving examples, it is necessary to express all magnitudes by consistent units. The most used system of units: kilogram - decimeter - second.

Example 1. To determine f and α on the basis of the following data:

$$\Delta_1 = 0.15;\ p_1 = 1{,}470 \text{ kg/cm}^2 = 147{,}000 \text{ kg/dm}^2;$$

$$\Delta_2 = 0.25;\ p_2 = 2{,}750 \text{ kg/cm}^2 = 275{,}000 \text{ kg/dm}^2$$

We find the ratios $\frac{p_1}{\Delta_1}$ and $\frac{p_2}{\Delta_2}$.

$$\frac{p_2}{\Delta_2} = \frac{275{,}000}{0.25} = 1{,}100{,}000 \text{ kg-dm/kg}$$

$$\frac{p_1}{\Delta_1} = \frac{147{,}000}{0.15} = 980{,}000 \text{ kg-dm/kg}$$

$$\frac{p_2}{\Delta_2} - \frac{p_1}{\Delta_1} = 120{,}000;\ p_2 - p_1 = 128{,}000.$$

We determine α:

$$\alpha = \frac{\frac{p_2}{\Delta_2} - \frac{p_1}{\Delta_1}}{p_2 - p_1} = \frac{120,000}{128,000} = 0.938.$$

f may be determined from the basic equation, by substituting in it the expression found for α.

$$f = \frac{p_1}{\Delta_1} - \alpha p_1.$$

$$\frac{p_1}{\Delta_1} = 980,000; \ \alpha p_1 = 0.938 \cdot 147,000 = 137,900.$$

$$f = 980,000 - 137,900 = 842,100 \text{ kg-dm/kg}$$

However, if we determine it in accordance with the general equation, then we obtain:

$$f = \frac{p_1}{\Delta_1} \cdot \frac{p_2}{\Delta_2} \frac{\Delta_2 - \Delta_1}{p_2 - p_1} = 980,000 \cdot 1,100,000 \frac{0.10}{128,000} = 842,100 \text{ kg-dm/kg}$$

Example 2. Given is $f = 850,000$ kg-dm/kg; $\alpha = 0.96$ dm^3/kg. To determine the Δ, at which the resultant $p_m = 3,200$ kg/cm^2 = 320,000 kg/dm^2. From the basic equation, we find the expression for Δ:

$$\Delta = \frac{p_m}{f + \alpha p_m}$$

We substitute:

$$\Delta = \frac{320,000}{850,000 + 0.95 \cdot 320,000} = \frac{320,000}{850,000 + 304,000} = \frac{320,000}{1,154,000} = 0.2772$$

Exercise. A bomb withstands $p_m = 4000$ kg/cm^2. Determine the maximum permissible density of loading for each type of powder, pyroxylin, nitroglycerin and black, using data in the table for fig. 13.

4. THE EFFECT OF ERROR, IN DETERMINING PRESSURES p_1 AND p_2, ON ERRORS IN DETERMINING f AND α

Assume that errors δp_1 and δp_2 were made in determining the values for pressures p_1 and p_2. We will find the corresponding errors δf_1, and δf_2, also $\delta\alpha_1$ and $\delta\alpha_2$.

a. Errors in Determining f

For the purpose of investigation, we will take the equation

$$f = \frac{p_1}{\Delta_1}\,\frac{p_2}{\Delta_2}\,\frac{\Delta_2 - \Delta_1}{p_2 - p_1} \qquad \text{(a)}$$

$$\alpha = \frac{\frac{p_2}{\Delta_2} - \frac{p_1}{\Delta_1}}{p_2 - p_1}\,. \qquad \text{(b)}$$

We differentiate the expression (a) with respect to p_1, regarding all other values as constants:

$$\delta f_1 = \frac{p_2}{\Delta_2}\,\frac{\Delta_2 - \Delta_1}{\Delta_1}\,\frac{p_2}{(p_2 - p_1)^2}\,\delta p_1; \tag{c}$$

Dividing (c) by (a), we obtain

$$\frac{\delta f_1}{f} = \frac{p_2}{p_1}\,\frac{\delta p_1}{(p_2 - p_1)} = \frac{p_2}{(p_2 - p_1)}\,\frac{\delta p_1}{p_1}. \tag{7}$$

Similarly:

$$\delta f_2 = \frac{p_1}{\Delta_1}\,\frac{\Delta_2 - \Delta_1}{\Delta_2}\,\frac{-p_1}{(p_2 - p_1)^2}\,\delta p_2; \tag{d}$$

$$\frac{\delta f_2}{f} = -\frac{p_1}{p_2}\,\frac{\delta p_2}{(p_2 - p_1)} = -\frac{p_1}{(p_2 - p_1)}\,\frac{\delta p_2}{p_2}. \tag{8}$$

An analysis of equations (7) and (8) shows that one and the same absolute error $\delta p_1 = \delta p_2$ exerts a varied influence on corresponding errors in the determination of the powder energy f.

The error $+\delta p_1$ at a lower density of loading Δ_1, increases the energy f; while the error $+\delta p_2$ at a higher density of loading decreases the powder energy f. At the same time, the effect of the magnitude δp_1 at a low Δ_1 is greater than the effect of δp_2 at a higher Δ_2, because in the first case at $\dfrac{\delta p}{p_2 - p_1}$ the multiplier is of the magnitude $\dfrac{p_2}{p_1} > 1$, while in the second case it is $\dfrac{p_1}{p_2} < 1$. Moreover, both errors of determination increase with a reduction of the difference between the loading densities Δ_1 and Δ_2, which entails a reduction of the denominator $p_2 - p_1$ and an increase of $\delta f/f$. Thus, in order to reduce the error in determining f, it is necessary to increase the difference $p_2 - p_1$, selecting whenever possible a greater difference between Δ_2 and Δ_1. Still, a large error in the values for pressure p_1 results at too low Δ (<0.10), by virtue of losses in heat transfer. Therefore in practice Δ_1 = 0.15 and Δ_2 = 0.25 are selected for determination of the energy of pyroxylin powders, while Δ_1 = 0.12 and Δ_2 = 0.20-0.22 are taken for nitroglycerin powders.

b. Errors in Determining α

By differentiating the expression (b), we obtain:

$$\delta\alpha_1 = \frac{\frac{1}{\Delta_1} - \frac{1}{\Delta_2}}{(p_2 - p_1)^2} p_2 \delta p_1 = -\frac{f}{p_2 - p_1} \frac{\delta p_1}{p_1}; \qquad (9)$$

$$\delta\alpha_2 = \frac{\frac{1}{\Delta_1} - \frac{1}{\Delta_2}}{(p_2 - p_1)^2} p_1 \delta p_2 = \frac{f}{p_2 - p_1} \frac{\delta p_2}{p_2}. \qquad (10)$$

Contrary to δf_1 and δf_2, the error $\delta\alpha_1 < 0$ and $\delta\alpha_2 > 0$. At given magnitudes of Δ_1, Δ_2, p_1 and p_2, and at $\delta p_1 = \delta p_2$, the error ($\delta\alpha_2 > \delta\alpha_1$) since $p_2 > p_1$.

It is evident from a comparison of expressions (7) and (9), as well as (8) and (10), that one and the same error δp_1, or δp_2, affects f and α in opposite ways.

Dividing (7) by (9) and considering the equality (a), we obtain:

$$\frac{\delta f_1}{f} = -\frac{p_2 - p_1}{\Delta_2 - \Delta_1}\,\frac{\Delta_2}{p_2}\,\frac{\Delta_1}{p_1}\,p_2\delta\alpha_1 = -\frac{p_2}{f}\,\delta\alpha_1 = -\frac{\delta\alpha_1}{\frac{1}{\Delta_2} - \alpha} \tag{11}$$

and

$$\frac{\delta f_2}{f} = -\frac{\delta\alpha_2}{\frac{1}{\Delta_1} - \alpha}. \tag{12}$$

It follows from a comparison of equations (11) and (12) that the error $\delta\alpha_2$, of the magnitude α, at a higher density of loading Δ_2 produces a smaller error in the magnitude f than does the error $\delta\alpha_1$ at a lower density of loading.

5. PRESSURE DURING THE INTERMEDIATE MOMENT. GENERAL FORMULA OF PYROSTATICS

The Nobel equations applies to the instant of attaining maximum pressure, when all the powder is burnt. For the intermediate moment, when all of the powder is not as yet burnt, but only a portion ψ of it is converted into gases, we use the physical state equation for $\omega\psi$ kg of gases:

$$p_\psi W_\psi = RT_1\omega\psi = f\omega\psi,$$

where the index ψ indicates that the given magnitude corresponds to the intermediate moment in which the portion of the charge ψ is burned and converted into gases.

W_ψ, the free volume of the bomb at the given moment, is equal to the volume W_0, of the bomb after the deduction of the volume of the still unburnt powder $\omega(1 - \psi)/\delta$ and of the covolume of gases of the burnt powder $\alpha\omega\psi$.

$$W_\psi = W_0 - \frac{\omega}{\delta}(1 - \psi) - \alpha\omega\psi.$$

In this way, the intermediate pressure for the moment in which the portion of the charge ψ will burn out, will be found on the basis of the formula

$$p_\psi = \frac{f\omega\psi}{W_\psi} = \frac{f\omega\psi}{W_0 - \frac{\omega}{\delta}(1 - \psi) - \alpha\omega\psi} . \qquad (13)$$

Combining the terms with ψ in the denominator, we write the general pyrostatics equation or the physical state equation for the intermediate moment in the second form:

$$p_\psi = \frac{f\omega\psi}{W_0 - \frac{\omega}{\delta} - \omega\left(\alpha - \frac{1}{\delta}\right)\psi} .$$

Dividing the denominator and the numerator by W_0, and replacing ω/W_0 by Δ, we obtain equation (4) in the following form:

$$p_\psi = \frac{f\Delta\psi}{1 - \frac{\Delta}{\delta} - \Delta\left(\alpha - \frac{1}{\delta}\right)\psi} = \frac{f\psi}{\frac{1}{\Delta} - \frac{1}{\delta} - \left(\alpha - \frac{1}{\delta}\right)\psi} . \qquad (14)$$

Inserting given expressions of ψ, we can calculate the corresponding expressions of p_ψ on the basis of this equation.

If we assume $\psi = 1$ in equation (14), then it converts to a general equation:

$$p_1 = \frac{f\Delta}{1 - \alpha\Delta} .$$

The general pyrostatics equation, characterizing the magnitude of the pressure in a combustion of powder, shows that, according to the degree of powder combustion completed, the free space W_ψ (in the denominator) increases to the value $\omega\psi/\delta$ as a result of liberation of the space from the combustion of powder, and decreases as a result of the addition of the molecular volume of formed gas (covolume) $\alpha\omega\psi$ (fig. 15).

Fig. 15 - Scheme of Variations in the Free Volume of the Bomb During a Combustion of Powder

1) beginning of combustion; 2) intermediate moment;
3) end of combustion.

Investigation shows that in the final count, the free volume decreases with the progress of combustion. Consequently, the pressure p_ψ does not increase proportionately to the burnt fraction of ψ, but faster.

Actually, at the beginning of the combustion, at $\psi = 0$ and a density of loading Δ, the free space in the chamber (or in the bomb) $W_\Delta = W_0 - \omega/\delta$. At the end of the combustion, at $\psi = 1$, the free space $W_1 = W_0 - \alpha\omega$.

Since for pyroxylin and nitroglycerin powders

$$\alpha > \frac{1}{\delta}\left(\alpha = 1.0 - 0.8, \quad \delta = 1.6 \text{ and } \frac{1}{\delta} = 0.625\right),$$

then

$$\alpha\omega > \frac{\psi}{\delta} \text{ and } W_0 - \alpha\omega < W_0 - \frac{\psi}{\delta};$$

$$W_\Delta > W_\psi > W_1,$$

i.e., the free space of the chamber, or of the bomb, is smaller at the end of the combustion than at the beginning of it.

6. THE INVERSE DEPENDENCE OF ψ ON p

The general formula of pyrostatics is of great importance for interior ballistics. Namely, establishing relations between the burnt fraction of the charge ψ and the pressure at that instant, it also permits solving the inverse problem: to determine, on the basis of the magnitude of pressure at a given moment, what portion of the charge ψ was completely burnt up to that moment. The latter data are of importance to the gas formation characteristic of the powder.

Actually, by selecting pressure magnitudes over given intervals of time, we can calculate the corresponding magnitudes of ψ on the basis of the curve which we obtained in the test with the bomb, of pressure as a function of time. Consequently, we are in a position to judge the variations of the burnt fraction of the charge relatively to time, and the rate of gas formation.

Solving equation (14) for ψ, we obtain

$$\psi = \frac{\frac{1}{\Delta} - \frac{1}{\delta}}{\frac{f}{p_\psi} + \alpha - \frac{1}{\delta}} = \frac{p_\psi\left(\frac{1}{\Delta} - \frac{1}{\delta}\right)}{f + p_\psi\left(\alpha - \frac{1}{\delta}\right)} \qquad (15)$$

Replacing f by $p_m\,(1 - \alpha\Delta)/\Delta$, and subtracting and adding $1/\Delta$ in the denominator, we can modify equation (15) to this form:

$$\psi = \frac{1}{1 + \dfrac{1 - \alpha\Delta}{1 - \dfrac{\Delta}{\delta}}\,\dfrac{p_m - p_\psi}{p_\psi}}, \qquad (16)$$

where p_m is the maximum gas pressure in the given experiment.

In this equation, the ratio $(1 - \alpha\Delta)/(1 - \Delta/\delta)$ is a value constant for a given experiment and characterizing the conditions of charging (we will designate it by ∂). p_m is also constant, with only p_ψ varying.

The magnitude $\partial = (1 - \alpha\Delta)/(1 - \Delta/\delta)$ represents the ratio of the free space of the bomb at the end of the combustion $W_1 = W_0 (1 - \alpha\Delta)$ to its free space at the beginning of the combustion $W_\Delta = W_0 (1 - \Delta/\delta)$. This value is always less than unity; at $\Delta = 0.25$, $\alpha = 1$, and $\delta = 1.6$, $\partial = 0.89$. At smaller Δ, the magnitude ∂ approaches unity.

7. CONSIDERATION OF THE INFLUENCE OF THE IGNITER

The general pyrostatics equation determines the pressure developed in a constant space by gases formed during the combustion of powder. In this connection, atmospheric pressure is disregarded, because of its smallness as compared with the pressure of powder gases.

In Nobel's experiments with black powders, black powder was also used for the igniter, and the weight of the igniter was included in the over-all weight of the charge for the purpose of calculating the density of loading.

Usually, during experiments in a bomb or discharges from guns, smokeless powder is ignited by means of a different type igniter (black powder, pyroxylin). Burning itself out first, the igniter produces a certain pressure, and ignites the powder through its heated gases and glowing particles. The powder begins to burn at a certain initial pressure p_B, developed by the gases of the igniter.

We shall use the designations: weight of igniter charge $-\omega_B$, igniter energy $- f_B$, covolume $- \alpha_B$, pressure of igniter gases prior to the beginning of powder combustion $= p_B^0$.

Calculation of the pressure p_B^0 is made on the basis of Nobel's equation, taking into consideration the space ω/δ occupied by the powder itself prior to its combustion:

$$p_B^0 = \frac{f_B\omega_B}{W_0 - \frac{\omega}{\delta} - \alpha_B\omega_B} \approx \frac{f_B\omega_B}{W_0 - \frac{\omega}{\delta}} = \frac{f_B\Delta_B}{1 - \frac{\Delta}{\delta}},$$

where $\Delta_B = \omega_B/W_0$. The magnitude for the covolume of igniter gases $\alpha_B\omega_B$ may be disregarded, in view of its smallness in comparison with the free space of the bomb $W_0 - \omega/\delta$.

For the intermediate moment in a combustion of the powder itself, the magnitude of pressure, with an allowance for the effect of igniter gases, is expressed in accordance with Dalton's law for the pressure of a gas mixture;

$$p_\psi' = \frac{f_B\omega_B + f\omega\psi}{W_0 - \frac{\omega}{\delta} - \left(\alpha - \frac{1}{\delta}\right)\omega\psi - \alpha_B\omega_B}.$$

Disregarding once more the magnitude $\alpha_B\omega_B$, as compared with the value for the free space $W_\psi = W_0 - \frac{\omega}{\delta} - \left(\alpha - \frac{1}{\delta}\right)\omega\psi$, we obtain:

$$p'_\psi = \frac{f_B\omega_B + f\omega\psi}{W_\psi} = \frac{f_B\omega_B}{W_\psi} + p_\psi$$

where p_ψ is the pressure of powder gases without allowance for the effect of the igniter, and is expressed by the general pyrostatics equation

$$p_\psi = \frac{f\omega\psi}{W_\psi}.$$

Since W_ψ diminishes, then $f_B\omega_B/W_\psi$ increases.

At the end of the combustion, the total p essure p'_m, with an allowance for the effects of the igniter, is expressed by the equation:

$$p'_m = \frac{f_B\omega_B + f\omega}{W_0 - \alpha\omega - \alpha_B\omega_B} \approx \frac{f_B\omega_B}{W_0 - \alpha\omega} + \frac{f\omega}{W_0 - \alpha\omega} = p'_B + p_m,$$

where

$$p'_B = \frac{f_B\omega_B}{W_0 - \alpha\omega} = \frac{f_B\Delta_B}{1 - \alpha\Delta} \quad \text{and} \quad p_m = \frac{f\omega}{W_0 - \alpha\omega} = \frac{f\Delta}{1 - \alpha\Delta}$$

(Nobel's equation without consideration of the igniter).

Since $1 - \alpha\Delta < 1 - \Delta/\delta$, then $p'_B > p^0_B$.

Under the existing conditions of functioning in a manometric bomb ($\Delta \le 0.25$; $\alpha \approx 1$; $\delta \approx 1.6$), [illegible] for smokeless powders is located in the range from 0.80 to 1. That is, the difference between

$p_B^{\cdot}$ and p_B' does not exceed 10%. Since, generally speaking, the pressure of the igniter is small (from 20 to 50, and not more than 100 kg/cm^2), then it may be assumed with a sufficient degree of accuracy that $p_B' = p_B^{\cdot}$ and, consequently, p_B may be regarded as a constant value.

Therefore, from here on we shall consider the following equality as applicable:

$$p_B \approx p_B' \approx \frac{f_B \omega_B}{W_0 - \frac{\omega}{\delta}}.$$

In view of this assumption, which will greatly simplify all further calculations, the Nobel equation and the general pyrostatics equation will be written in the following form:

$$p_m' = p_B + \frac{f\Delta}{1 - \alpha\Delta} = p_B + \frac{f\omega}{W_0 - \alpha\omega},$$

where

$$p_B = \frac{f_B \omega_B}{W_0 - \frac{\omega}{\delta}} = \frac{f_B \Delta_B}{1 - \frac{\Delta}{\delta}};$$

$$p_\psi' = p_B + \frac{f\Delta\psi}{1 - \frac{\Delta}{\delta} - \left(\alpha - \frac{1}{\delta}\right)\Delta\psi} = p_B + \frac{f\omega\psi}{W_0 - \frac{\omega}{\delta} - \left(\alpha - \frac{1}{\delta}\right)\omega\psi}.$$

The equations show that the over-all pressure of gases usually registered in a manometric bomb, is obtained as a sum of two pressures: the pressure of igniter gases p_B, and the pressure of powder gases p_ψ; or p_m, determinable on the basis of the initial generalized pyrostatics equation, or Nobel's equation without consideration of the influence of the igniter.

Determining ψ from the last equation, we obtain the magnitude ψ taking into consideration the influence of the igniter:

$$\psi = \frac{\frac{1}{\Delta} - \frac{1}{\delta}}{\frac{f}{p' - p_B} + \alpha - \frac{1}{\delta}} = \frac{1}{1 + \frac{1 - \alpha\Delta}{1 - \frac{\Delta}{\delta}} \frac{p'_m - p'}{p' - p'_B}}$$

The included pressures p'_m and p' constitute the actual pressure registered by the crusher, or by any other instrument.

Since the equation renders calculations of a series of expressions for ψ very awkward in plotting an experimental pressure curve registered by the instrument, we have compiled tables for the purpose of expediting the work involved. From the magnitude of the ratio $(p' - p_B)/(p'_m - p_B)$, it is simple and easy to find, by the aid of these tables, the corresponding expressions of ψ as a function of time t, and to make a ballistic analysis of the powder.

The magnitude of the denominator $p'_m - p_B$ is constant for a given experiment; p' is taken from the measurement of the pressure curve; also from it, we mentally calculate the pressure p_B of the igniter gases, constant for all points of measurement. Then we determine, by the aid of a slide rule,

$$\beta = \frac{p' - p_B}{p'_m - p_B}.$$

We make the conversion listed above.

$$\psi = \frac{p' - p_B}{p' - p_B + \partial (p'_m - p')} = \frac{p' - p_B}{p' - p_B + \partial [p'_m - p_B - (p' - p_B)]} =$$

$$= \frac{\dfrac{p' - p_B}{p'_m - p_B}}{\dfrac{p' - p_B}{p'_m - p_B}(1 - \partial) + \partial}.$$

At this time, the same ratio $\beta = (p' - p_B)/(p'_m - p_B)$ is introduced into the denominator and the numerator; and consequently ψ appears as a function of the constant magnitude ∂ and the variable β:

$$\psi = \frac{\beta}{\partial + (1 - \partial)\beta}.$$

The magnitude $\beta = (p' - p_B)/(p'_m - p_B)$ varies within the range from 0 to 1. The magnitude $\partial = (1 - a\Delta)/(1 - \Delta/\delta)$ which depends on three constants a, δ and Δ (when a approaches 1, δ approaches 1.6), usually varies from 0.86 to 1, depending on the fluctuations of Δ, within the limits of 0.25–0.

The tables are arranged for each expression of ∂, from 0.86 to 0.97 by variations of 0.01, at 0.01 variations of the ratio $(p' - p_B)/(p'_m - p_B)$ within the range from 0 to 1.

The arrangement of the table is analogous to tables of four-place logarithms.

The tables are in the supplement, which also includes instructions for their use.

Knowing the principle of Ψ variation relatively to time, it is also possible to find the experimental law of variation of the magnitude $\frac{d\Psi}{dt}$, i.e., the rate of gas formation. This value is one of the more important characteristics. Knowledge of it permits regulating the efflux of gases during a combustion of powder, and checking the law of gas pressure variation.

8. ON REDUCED LENGTHS

Among other things, the pressure in the bore of the gun appears as a function of the volume of initial air space, corresponding to the location of the projectile in the bore at a given instant. At the beginning of the powder combustion, this volume W is equal to the volume of the chamber W_0. Subsequently, it increases with the motion of the projectile to a volume equal to the volume of a cylinder having the cross section of the gun bore (including grooves) as its base, and the length of the travel l of the projectile as its height:

$$W = W_0 + s l .$$

Since, in practice, pressure is commonly expressed as a function of the travel accomplished by the projectile, rather than of the volume, it is more convenient to replace all volumes by corresponding lengths. However, in view of the fact that cross sections of the chamber are not identical at various points, and are larger than the cross section of the bore, the volumes of the chamber and of the bore are not proportional to actual lengths. Therefore, to facilitate a more convenient operation with additional equations obtained in pyrodynamics, "reduced lengths" are introduced to replace chamber volumes in equations by cylinder volumes of equal magnitude and having the cross section area of the gun bore as their basis. The length of such cylinders is called "the reduced length of the chamber." It is designated by ℓ_0, and determined by the expression:

$$\ell_0 = \frac{W_0}{s} \; .$$

Since the actual cross section of the chamber will be larger than s, the reduced length ℓ_0 will be greater than the actual length of chamber ℓ_{km}. (*)

The volume of the initial air space will now appear as:

$$W = s\ell_0 + s\ell = s(\ell_0 + \ell).$$

After deduction of the volume of the still incompletely burnt powder and the covolume of the burnt portion of the charge, the free volume of the initial air space will be expressed in this way:

$$W_0 + s\ell - \frac{\omega}{\delta}(1 - \psi) - \alpha\omega\psi = W_\psi + s\ell$$

It can be represented in the form of a sum

$$s\ell_\psi + s\ell = s\,(\ell_\psi + \ell),$$

(*) The introduction of the reduced length is a purely mathematical operation. It fails to consider the influence of the form of the chamber, and of its cross section, on the gas formation law, and consequently on the magnitude of gas pressure.

where

$$l_\psi = \frac{W_\psi}{s} = \frac{W_0 - \frac{\omega}{\delta}(1-\psi) - \alpha\omega\psi}{s} = l_0 \left[1 - \frac{\Delta}{\delta} - \Delta\left(\alpha - \frac{1}{\delta}\right)\psi\right]$$

is the reduced length of the free volume of the chamber at a given moment.

During the period of powder combustion, the magnitude l_ψ varies within the range from $l_\Delta = W_\Delta/s = (W_0 - \omega/\delta)/s = l_0(1 - \Delta/\delta)$ at the beginning of the combustion, to $l_1 = W_1/s = (W_0 - \alpha\omega)/s = l_0(1 - \alpha\Delta)$ at the end of the combustion ($\psi = 1$).

Meanwhile

$$l_\Delta > l_\psi > l_1.$$