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TRANSITION OF THE COMBUSTION OF CONDENSED
SYSTEMS, INTO AN EXPLOSION

A. F. Belyaev, et al

Foreign Technology Division
Wright-Patterson Air Force Base, Ohio

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	А а	A, a	Р р	Р р	R, r
Б б	Б б	B, b	С с	С с	S, s
В в	В в	V, v	Т т	Т т	T, t
Г г	Г г	G, g	У у	У у	U, u
Д д	Д д	D, d	Ф ф	Ф ф	F, f
Е е	Е е	Ye, ye; E, e*	Х х	Х х	Kh, kh
Ж ж	Ж ж	Zh, zh	Ц ц	Ц ц	Ts, ts
З з	З з	Z, z	Ч ч	Ч ч	Ch, ch
И и	И и	I, i	Ш ш	Ш ш	Sh, sh
Й й	Й й	Y, y	Щ щ	Щ щ	Shch, shch
К к	К к	K, k	Ъ ъ	Ъ ъ	"
Л л	Л л	L, l	Ы ы	Ы ы	Y, y
М м	М м	M, m	Ь ь	Ь ь	'
Н н	Н н	N, n	Э э	Э э	E, e
О о	О о	O, o	Ю ю	Ю ю	Yu, yu
П п	П п	P, p	Я я	Я я	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
 When written as ё in Russian, transliterate as yë or ë.
 The use of diacritical marks is preferred, but such marks
 may be omitted when expediency dictates.

GREEK ALPHABET

Alpha	Α α	•	Nu	Ν ν
Beta	Β β		Xi	Ξ ξ
Gamma	Γ γ		Omicron	Ο ο
Delta	Δ δ		Pi	Π π
Epsilon	Ε ε	•	Rho	Ρ ρ ϱ
Zeta	Ζ ζ		Sigma	Σ σ ς
Eta	Η η		Tau	Τ τ
Theta	Θ θ	•	Upsilon	Υ υ
Iota	Ι ι		Phi	Φ φ
Kappa	Κ κ	•	Chi	Χ χ
Lambda	Λ λ		Psi	Ψ ψ
Mu	Μ μ		Omega	Ω ω

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	\sin^{-1}
arc cos	\cos^{-1}
arc tg	\tan^{-1}
arc ctg	\cot^{-1}
arc sec	\sec^{-1}
arc cosec	\csc^{-1}
arc sh	\sinh^{-1}
arc ch	\cosh^{-1}
arc th	\tanh^{-1}
arc cth	\coth^{-1}
arc sch	sech^{-1}
arc csch	csch^{-1}
—	
rot	curl
lg	log

GRAPHICS DISCLAIMER

All figures, graphics, tables, equations, etc. merged into this translation were extracted from the best quality copy available.

ACRONYMS

IKhF (ИХФ)	-	Institute of Chemical Physics
ZhFR (ЖФР)	-	camera with driven sweep
ZhLV (ЖЛВ)	-	high-speed sweep slow-motion camera
SFR (СФР)	-	high-speed streak camera
AP (ПХА)	-	ammonium perchlorate
PS (ПС)	-	polystyrene
TG (ТГ)	-	trotyl-hexogen
PP (ПХК)	-	potassium perchlorate
ten (тэн)	-	PETN
octogen (октоген)	-	HMX
NG (НГЦ)	-	nitroglycerin
TNM (ТНМ)	-	tetramitromethane
NM (НМ)	-	nitromethane
PMMA (ПММА)	-	polymethyl metacrylate
DINA (ДИНА)	-	dinitroxydiethylnitramine
k-phase	-	condensed phase
g-phase	-	gas phase

Transition of the combustion of condensed systems into an explosion. Belyayev, A. F., Bobolev, V. K., Korotkov A. I., Sulimov A. A., Chuyko, S. V. M., "Science", 1973, 292 pp.

One of the main divisions of the combustion theory of condensed systems is the stability of laminar combustion. The development of this division of science is of great theoretical and practical interest.

The book is the first experiment of a systematic presentation of the physical views to the transition of the combustion of condensed systems into an explosion and corresponds to contemporary representations on this question. In the book the available published data are systematized and generalized.

The book is intended for scientists, engineers, post graduates and students who are engaged in combustion research and explosion.

There are 25 tables, 130 figures and 224 references.

Responsible editor
Doctor of Technical Sciences,
Professor P. F. Pokhil

PREFACE

Thoroughly investigated at present are the steady states of combustion and detonation of condensed systems whose research was initiated as long ago as at the end of the 19th century. Interest in the study of transient processes arose considerably later. The first works in this direction, carried out by Belyayev [1-5], Andreyev [6-8], and Patri [9], appeared at the end of the 1930's and beginning of the 1940's. Intense investigations of the emergence and development of an explosion were conducted in the last 15 years both in the USSR and abroad (USA, England). In spite of the achieved progress, the problem as a whole is far from its completion.

The emergence of an explosion under industrial conditions is an extremely dangerous phenomenon. Therefore, knowledge of the mechanism and conditions of the transition of combustion into an explosion has not only scientific but also a great national-economic value - first of all, for the development of problems connected with the safeguard of the explosion-proof nature of production.

The basis of this book is the experimental data obtained by the authors during operating period from 1959 to 1970 at the Institute of Chemical Physics of the Academy of Sciences of

the USSR. At the same time in the book the published data which are available at present on this question are systematized and generalized.

The transition of combustion into an explosion is a multi-stage process. The idea which was assumed as a basis of the investigations was to isolate and study each of the stages individually, and also the law governing the transition from one stage to another. In this case the primary attention was given to an explanation of the physical essence of the phenomenon. This approach was the most advisable, since in a number of cases (for example, with the excitation of detonation from an intense shock impulse) the separate stages are exceptionally little extended, and some of them can be absent. This approach completely justified itself and made it possible to obtain a sufficiently complete picture of the development of an explosion from a stable laminar combustion up to the emergence of detonation.

The book consists of an introduction and two sections. In the introduction the methods of the study of the rapidly flowing processes are examined. The instruments and devices intended for the study of the transition of combustion into explosion are described.

The first section is devoted to solid porous explosives whose combustion especially easily converts into an explosion. These explosives are widely utilized in practice with the production of powders, monolithic charges of explosives, and in the mining and building industry.

In Chapter I the general characteristics of porous systems is given. An account is given of the methods and basic results of the determination of porosity, gas permeability, the specific surface area of the pores, and distribution of the pores according to dimension.

Chapter II is devoted to slow smooth burning at a constant rate. A comparison is made of the obtained experimental results with the conclusions of the theory of the combustion of explosives and powders.

Chapter III gives results of the investigation of the initial stage of an explosion - the disturbance of stable laminar combustion. The basic positions of the stability theory of combustion are examined. The effect on the disturbance of the laminar combustion of the basic factors is investigated. The theory of limits of stability, which made it possible to create the basis for the quantitative description of the tendency of different explosives toward the disturbance of laminar combustion behavior is developed.

In Chapter IV data on the combustion stability of systems with free pores are given.

Examined in Chapter V are the basic stages of the development of explosion up to the emergence of detonation, in particular, the convective combustion, which appears as a result of destabilization.

The question concerning the propagation of the low-speed (800 to 3500 m/s) conditions of explosive conversion is examined. Results of the study of the transition of the combustion of explosives into detonation are given. Examined is the effect of different factors on the value of the predetermination section for uniform and mixture explosives. The mechanism of the emergence of detonation upon ignition is discussed. The results on the initiation of detonation in porous explosives by shock waves are represented.

The second section, which consists of two chapters, is devoted to questions of combustion stability of liquid explosives (ZnVV) [#BB].

In Chapter VI the theory of the limit of normal combustion basically of low-viscosity ZhVV is examined. The conditions of the transition of normal combustion to disturbed combustion and the effect of the properties of a liquid and conditions of combustion on combustion stability are analyzed. The phenomena characteristic for the combustion of ZhVV beyond the stability limit are examined.

Chapter VII is devoted to experimental data on the hydrodynamic combustion stability of homogeneous individual and mixture ZhVV and to the transition of the excited combustion into an explosion. In a separate paragraph results of the experimental study of laws governing the combustion of two-phase (liquid-solid) systems are presented.

It is possible to hope that this book will contribute to the development of investigations in this complex and interesting field of physics.

The authors express their gratitude to M. K. Sukoyan, I. A. Carpuchin, and A. V. Obmenin for their help in the preparation of the book.

INTRODUCTION

PROCEDURE FOR THE STUDY OF THE TRANSITION OF COMBUSTION INTO AN EXPLOSION

The transition of combustion into an explosion is a multistage unsteady process. In order to get an understanding of the very complex pattern of this phenomenon and to obtain comprehensive information, the use of complex methods of study is required.

In this case the problem consists not only of the correct determination of the most important parameters (velocity, pressure, temperature, etc.), but also the isolation of separate stages, since only this approach provides the obtaining of the comprehensive data. The latter was achieved by a change in the conditions of the experiment.

The methods used had to satisfy a wide circle of requirements. This becomes especially demonstrative if we keep in mind that the range of a change in the rate of propagation of reaction is 7 orders (from 10^{-1} with normal combustion to 10^6 cm/s in the final stage, if the process is developed before detonation), and the appropriate range of pressure change covers 8 orders (from 10^{-3} to 10^5 atm).

It is necessary to emphasize that the investigation of the emergence of explosion in the condensed systems as a result of

the destructive action of high pressures is connected with considerably greater difficulties than is the analogous investigation in the case of gas systems. These difficulties grow in the case of solid explosives, which unlike gases and liquid explosives are opaque, which to a great degree impedes the utilization of optical methods of study.

In the process of the execution of the work, the authors developed and applied new procedures and instruments.

Let us examine fundamental devices, methods and instruments for recording the most important characteristics of the process which are used in the study of the transition of combustion into explosion and of its separate stages.

An experiment shows that at low pressures and, in particular, at atmospheric pressure the combustion of the overwhelming majority of the explosives retains a uniform nature: normal laminar combustion at constant and low velocity occurs. Beginning from a certain elevated pressure, whose value depends on the density and properties of the explosives, there occurs a disturbance or interruption of the laminar combustion which is sharply accelerated and under specific conditions can turn into detonation.

Thus, an explosion appears if the explosives burn at pressures higher than a certain maximum.

§ 1. Devices of High Pressure

Bomb of "constant pressure" (BD) [BA]. The basic purpose of this bomb, which is made in several versions (up to 150, 350, 1000-5000 atm), is to study the laws governing the normal combustion of explosives and powders. However, it was utilized also

for the study of the transition of the combustion of porous explosives into an explosion. In foreign literature this device is known by the name of the "Crawford bomb". The term "bomb of constant pressure" is not strict, since the pressure somewhat grows, as a result of the combustion of the charge.

The bomb (Fig. 1) is a thick-walled steel casing 1 with a large internal volume (2-5 l and more). Its upper open part before the experiment was hermetically sealed by cover 2. Airtightness was achieved by the use of rubber joints. The observation of the process of the combustion and measurement of velocity was conducted mainly by the optical method. For this purpose

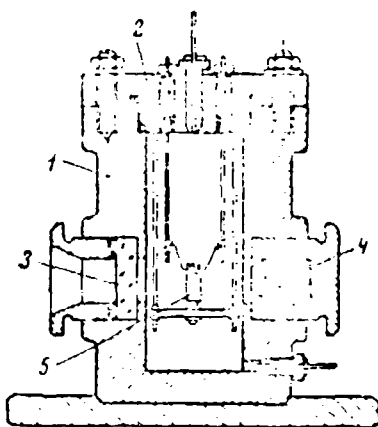


Figure 1. Bomb of "constant pressure"

the bomb has several transparent windows 3 of optical glass or plexiglass. For determining the rate of combustion electrical methods are also applied (§ 2). In the bomb which was used by the authors, the recording of pressure in the volume was realized by a specially developed sensitive piezoelectric quartz crystal sensor 4. The investigated specimen of explosives or powder 5 was fastened to a support connected with the cover of the bomb. The necessary pressure in the bomb was created by

compressed nitrogen from a cylinder or with the aid of a compressor. The magnitude of the pressure was determined according to the manometer connected with the internal volume of the bomb.

It is necessary to keep in mind that if special measures are not taken, then the pores of the investigated charge of the solid explosives prior to the beginning of combustion are filled with nitrogen, i.e., the pressure in the pores p_n^0 is equal to the pressure in the volume of the bomb p_0 . The pressure

differential Δp , which causes the penetration of products of combustion into the pores, is created in the process of combustion, and usually $\Delta p \ll p_0$. The destabilization of combustion in this case is realized by the jet mechanism (for greater detail, see section B, Chapter III).

For the study of the forced disturbance of the laminar combustion of porous explosives, when the inflow of gas into the pores occurs under the action of a definite strictly fixed pressure differential, created prior to the beginning of combustion, there was applied a specially assembled charge of explosives ("embedded charge") [10] whose diagram is shown in Fig. 2.



Figure 2.
Diagram of
"embedded
charge"

Pressed into the plexiglass shell 4 was a consecutively solid auxiliary substance 1, which performs the role of the combustible gas-impermeable partition, solid 2 and porous 3 investigated substances, and the lower end of the shell was glued.

The thus collected charge was placed into the bomb, which before the experiment was filled with nitrogen up to a pressure p_0 , whereupon ignition of the gas-impermeable partition was implemented. This diagram of the experiment eliminated preliminarily filling of the pores of the investigated porous specimen. Under these conditions the front of the combustion approached the porous charge when the initial pressure in the pores p_n^0 is equal to the atmospheric pressure (usually $p_n^0 \ll p_0$, $\Delta p = p_0 - p_n^0 \approx p_0$), and the penetration of combustion is realized as a result of the effect of pressure p_0 in the volume of the bomb. The diagram of the "embedded charge" models the combustion of the porous inclusion in the charge of the powder. Therefore, in a number of cases the combustion of the investigated porous charges was conducted directly in the model rocket chambers. Diverse variants of the rocket chambers were used.

Besides the continuous recording of pressure $p(t)$, the optical recording of the process of combustion was realized. For this purpose part of the used chambers contained transparent windows.

Manometer bomb. Pressure in the manometer bomb is created as a result of the combustion of the investigated substance placed into the closed volume of small magnitude. This instrument is frequently called the bomb of variable (rising) pressure. The manometer bomb makes it possible to determine the majority of the ballistic characteristics of powders and explosives (rate of combustion and its dependence on pressure, force of the powder, and quantity and composition of the gasses and is the basic instrument of laboratories of interior ballistics. The fundamental laws governing the normal combustion of the powders at high pressures (up to several thousands of atmospheres) were established with the aid of the manometer bomb.

At present different varieties of manometer bombs are widely applied for the stability analysis of the combustion of powders, solid rocket propellants and explosives. The important advantage of the manometer bomb is the fact that the pressure rises in the process of combustion of the investigated charge; therefore, easily the critical value p_c at which there is a disturbance of the stable combustion.

One of the varieties of the manometer bomb utilized at the present time is schematically represented on Fig. 3a. It is thick-walled cylinder, i.e., housing 5 of high-strength heat-treated steel. The testable substance in the form of pellets or powders in the form of charges 3, thoroughly armored along the lateral surface 4, except for the upper end, was placed into the channel of the bomb. The latter on both ends is hermetically sealed by covers 1 and 7 forced against the housing

of the bomb by adapter rings 2.

For the retention of pressure in the volume of bomb the connection of the housing of the latter with the covers is conducted with the aid of self-sealing copper rings 6. The covers are equipped with insulated hermetically self-sealing electric lead-ins 8 and 11, which maintain high pressures.

The electric lead-ins are made in the form of a cone turned by the base inside the bomb. The insulation of the electric lead-in from the housing of bomb was realized with the aid of plexi-glass conical rings. One of the covers (upper) has one lead-in for the feeding of electric current to the igniter 9. The latter is a paper holder with smoky powder or pyroxylin and nichrome spiral. The second cover (lower) is equipped with two insulated electric lead-ins 11, which were used for the measurement of the rate of propagation of the process.

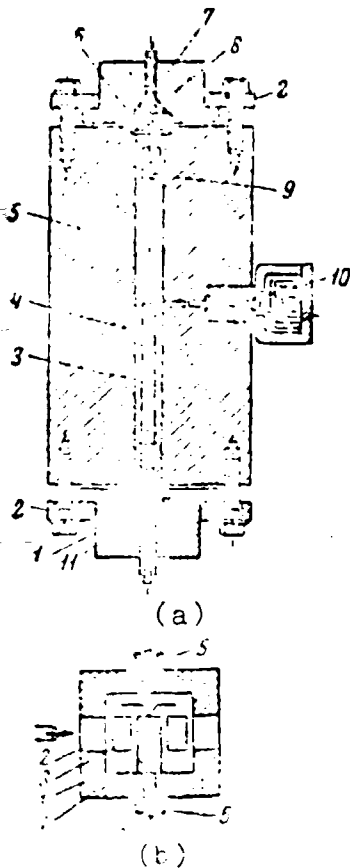


Figure 3. Manometer bombs with the piezoelectric sensor of pressure (a) and transparent windows (b).

For the recording of pressure change with time in the process of the combustion of the investigated charge developed low-inertia piezoelectric sensors 10 were specially applied (see § 3).

Figure 4 gives a typical oscillogram of recording $p(t)$ in the volume of the bomb of variable pressure when the interruption of laminar combustion is present. Thus far a stable laminar

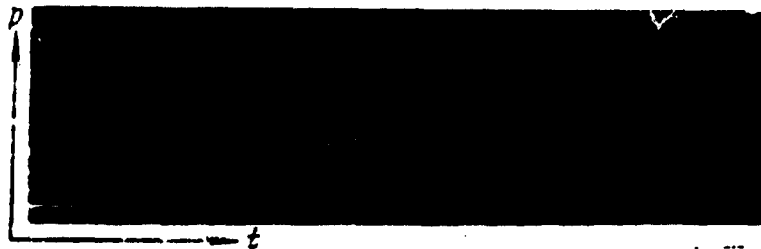


Figure 4. Recording of pressure $p(t)$ with the disturbance of normal combustion of the porous charge.

combustion was retained, and a smooth pressure buildup in the course of time was observed. The sharp growth in pressure (jump in the curve of $p(t)$) testified to the achievement of critical pressure - the disturbance of the laminar combustion and its break into the pores (initial peak in curve was caused by the combustion of the igniter).

One of the bombs (Fig. 3b) had in housing 1 two windows 2 of plexiglass for the optical observation through the light conductor 3, which made it possible to obtain additional information about the nature of the development of the process [11] in specimen 4. In this bomb the simultaneous recording of pressure in the volume of the bomb (by sensor 5) and in the pores of the burning charge (by sensor 6) was also conducted.

In the investigations a set of bombs with free space from 10 to 2000 cm^3 was used. The density of the charging (mass ratio of the combustible substance to the free space of the bomb) did not exceed 0.5 g/cm^3 , and the maximum pressure - 6000-8000 atm.

Bomb for research on the development of combustion in a single pore [12]. The investigation of the emergence and development of an explosion in the gas-permeable porous system is simplified if we utilize the ordered model - single pore. We

used, as a rule, the single pore (slit), formed by two plane-parallel plates of solid (nonporous) explosive. In part of the experiments one of the plates was replaced by a transparent plate of plexiglass, which facilitated the recording of the process of the propagation of combustion on the pore by optical methods.

The combustion of the slotted charges was conducted in the specially developed manometric bomb (Fig. 5) with large free space. The simultaneous optical recording of the process and the recording of pressure directly in the pore at the enclosed end was realized. The bomb contained a transparent window of plexiglass 6, two piezoelectric sensors, one of which 3 recorded the pressure $p_0(t)$ in the volume of the bomb, the other 1 -

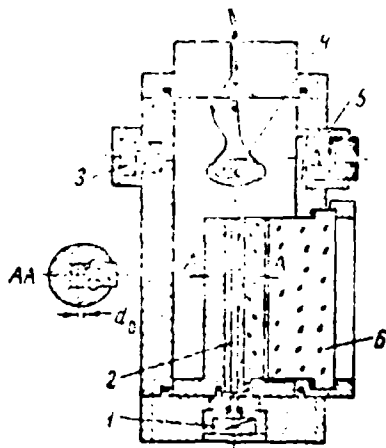


Figure 5. Bomb for research on the development of convective combustion in a single pore.

directly in the pore $p_n(t)$, and device 5 for the extinguishing of specimens by means of pressure relief. The ignition of the pore 2 was realized by the convection flow of hot gas, which is generated with the combustion of the igniter 4 (pyroxylin + ammonium perchlorate), which created the initial pressure in the bomb for a short time - 5 milliseconds. Thus, igniter created in essence the conditions of the filtration of gas products in the pore, which are characteristic for the diagram of the "embedded charge."

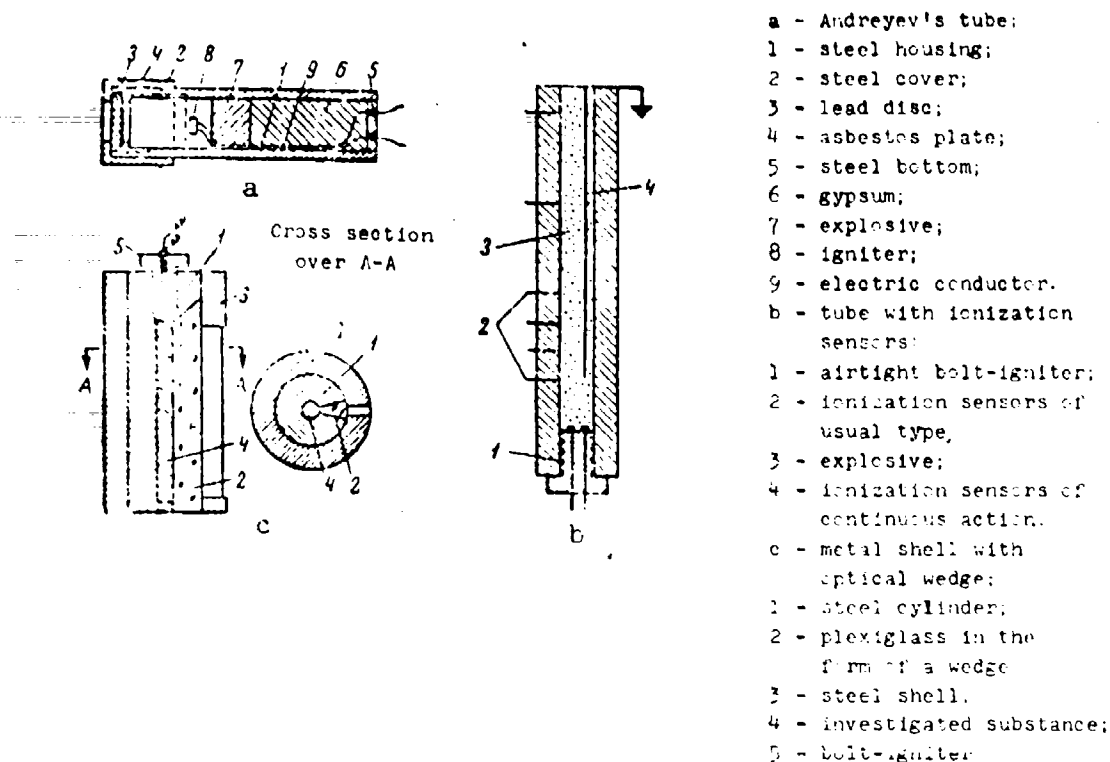
Let us now examine the devices for research on the transition of combustion into explosion and detonation. In the devices described above the density of the charging was substantially lower than the initial density of the explosive, which limited

the magnitude and rate dp/dt of the pressure buildup. With the limited length of the charge and the absence of a durable shell, the unsteady combustion emergent in these conditions did not convert into detonation. One of the first devices which was intended for the investigation of the emergence of detonation upon ignition was developed by Professor Andreyev [6, 7]. At present this device is widely known by the name of "Andreyev's tube."

Andreyev's tube (Fig. 6a). Usually used is a steel casing 40 mm in diameter with the thickness of the wall at 4-6 mm and height at 200 mm. The casing has a cover with an opening of large cross section enclosed with a metallic disc (usually of lead), which broke loose upon the achieving of a definite pressure. With low strength of the disc the combustion leads to its extraction without the disturbance of the completeness of the casing. With high strength, in spite of the extraction of the disc, the casing is broken into a larger or smaller number of pieces, which corresponds to that which is formed with the detonation of the charge caused by the percussion detonator. The deformation of the casing gives the concept about the nature of the explosion, and the minimum strength of the disc, beginning with which there occurs the destruction of the casing, serves as the measure of the tendency of the combustion of the explosive toward the transition into explosion and detonation.

The strength of the disc is determined by combustion in the tube of a coarse-grained smokeless powder. Such calibration determines the strength of the disc under conditions of the slowly increasing pressure. The real strength of the disc usually exceeds that which was measured, since the pressure buildup in the experiment is more rapid. The strength of the casing itself with the indicated dimensions was approximately 1000 atm. The combustion of the charge of explosive is conducted by a charge of

Figure 6. Devices used for the study of the transition of combustion into explosion and detonation:



pyrotechnic composition. For an increase in the density of charging, the casing can be filled with gypsum to a certain height.

The use of Andrejev's tube made it possible to obtain the first systematic data and, first of all, compare the different powder-like explosives with respect to the tendency of the transition of their combustion into an explosion.

In the opinion of Andrejev, the main disadvantage in his method is the fact that it gives only the final result of the experiment and furthermore only in a semiquantitative form (number and dimensions of the fragments) and does not characterize the development of the process in time. Furthermore, a

whole number of explosives (low-sensitivity powder-like explosives, molded and plastic explosives) does not convert into detonation under these conditions. Therefore, the subsequent improvement of Andreyev's tube included an increase in the length and strength of the tube and also the use of the ideal methods of recording, which made it possible to obtain reliable quantitative data.

Tests were conducted in thick-walled steel tubes wholly filled with explosives. Figure 6b depicts the tube which was used by Gipson and Mašek for the study of the transition of combustion into the detonation of the molded explosives [13]. The measurement of the rate of the process was conducted by the usual type of ionization sensors and by the ionization sensor of continuous action, which was assumed in parallel to the axis of the charge (description of the sensor, see § 2).

Tube with optical wedge [14]. We have developed a tube with an optical wedge of plexiglass, which makes it possible to conduct the continuous optical recording of the process of the transition of combustion into detonation. It is schematically depicted on Fig. 6c.

The tube consists of a thick-walled steel cylinder 1 with a wedge-shaped slot 2 in its middle part. Glued into the slit is plexiglass cut along its form. The point of the wedge was directed to the side of the channel, which made it possible to decrease the force acting on the wedge.

For an increase in the strength the tube with the plexiglass wedge was placed into the steel shell 3. The latter had a narrow slit located opposite the plexiglass wedge, through which optical observation of the process was conducted.

Placed into channel was the investigated substance 4 of necessary density. In the majority of cases it was pressed

directly into the shell by the portion method. The combustion of the investigated specimen of explosive was produced with the aid of the nichrome spiral, heated by electric current, through airtight bolt-igniter 5.

The described tube with the optical wedge made it possible to obtain qualitative continuous photographs of the transition of combustion into detonation in the explosive charges of different density (see § 27).

Research on transient processes was conducted also in transparent shells of plexiglass in the form of a cylinder and in the devices when the explosive (usually in the form of a thin layer) is pressed between two plates [15, 16] one of which is transparent (plexiglass). Unlike the devices examined above in the latter case the initiation of the explosion was realized in essence by the spark or the burning of a thin metallic wire placed in explosives with the aid of a capacitor discharge.

§ 2. Rate Measurement

Optical Method. This method of the determination of the rate of the luminous processes is at present basic and most widely accepted. Used for this purpose are the specially developed photorecordings, which give a continuous recording on film of the track of the front of the process with time, and the different movie cameras, which make it possible to produce frame-wise photographing. The principle of the device and description of the instruments are examined in detail in literature [17-19]. Therefore, let us recall only briefly the principle of determination of the rate of the process with the utilization of the optical method.

With the use of photorecording the determination of the rate of combustion or detonation entails the following. Photographing

is realized on film, which continuously moves perpendicular to the direction of propagation of the process. The image of the glowing reaction front is recorded on film in the form of an inclined line. By knowing the speed of movement of the film $v_{\text{пл}}$, it is possible by the angle ϕ of slope of front line to determine the rate of process D:

$$D = v_{\text{пл}} k' \operatorname{tg} \phi,$$

where k' is the ratio of the magnitude of the object (length of the charge) to the magnitude of the image on film, i.e., the degree of a decrease in the photographic system.

To study the processes of combustion (slow processes), low-speed photorecordings with drum scan with the rate of the motion of the film from several millimeters per second to several dozens of meters per second are used. Usually universal photorecordings with high acceleration are used. An example of this photorecording is the FR-11, developed and prepared at the Institute of Chemical Physics of the Academy of Sciences of the USSR (IKhF AN SSSR) [ИХФ АН СССР].

With the study of detonation processes high-speed photorecordings mainly of the mirror type are utilized. In this case the image of the process with the aid of a rotating mirror is constructed on stationary film. The use of the rotating mirror makes it possible to increase substantially the rate of photographing.

For these purposes at the IKhF of the AN SSSR were specially developed the high-speed (streak) cameras (SFR) [СФР], cameras with a driven sweep (ZhFR) [ХФР] and a high-speed sweep slow-motion camera (ZhLV) [ХЛВ] in which the mirror is made in the form of a polyhedron. The instruments ZhFR and ZhLV do not require synchronization of the process with rotation of the mirror.

With the study of transient processes, in a number of cases it is expedient to use simultaneously two photorecorders at different sweep speeds [11].

With the frame-wise photographing of the combustion or detonation of explosives with the aid of a different type of the movie cameras, the rate of the process is determined from the known frame frequency. The maximum frequency of photographing of cameras SKS-1M and SFR (in the version of slow motion) serially produced in the USSR comprises, respectively, $8 \cdot 10^3$ and $2.5 \cdot 10^6$ frames/s.

Method of ionization sensor. The essence of electrical method with the utilization of ionization sensors entails the ability of the products of combustion or detonation to conduct electrical current. Placed into the charge of explosive are two or more spark gaps, to which a definite voltage is fed. The explosives in the initial state possess very low conductivity, and electrical current does not pass through the spark gaps. In the detonation wave or in the flame the products are greatly ionized, and their resistance is low (for products of the explosion of typical explosives the resistance is approximately 10-12 Ω /mm), as a result of which with passage of the wave of combustion or detonation the spark gaps are consecutively closed, and in them appears the electrical current, which is also recorded on the oscillograph. According to the known distance between the sensors and the transit time of the process between them obtained from the experiment, the average speed is determined.

Method of the ionization sensor of continuous action. In works [20-22] the continuous method of the determination of the rate of the process was developed. The essence of this method entails the fact that into charge in parallel to its axis there is placed a reostat sensor whose resistance changes in proportion

to the motion of the front of ionization (front of the process).

The sensor is a copper rod 1.1 mm in diameter with the spiral which wound turn to turn made from conductor PFVKT 0.1 mm in diameter [20]. One end of the winding is soldered to a copper rod and the other together with the rod - to a coaxial cable. The sensor, together with the part of the cable, is placed into the investigated charge (mainly for this the molded charges or the charges of liquid explosives are applied). The free ends of the coaxial cable are connected with the cathode-ray oscillograph, which records a change in the resistance of the sensor with the passage of the process.

The determination of the rate of the process from the recording is conducted in the following way. The length of the sensor L corresponds to the initial beam deflection of the oscillograph b_0 . Then the sensitivity of measuring circuit $\beta = b_0/L$. The movement of the front of the investigated process with time $X(t) = \beta b(t)$ (where $b(t)$ is the recording of the investigated process). The rate of process D will be determined from the expression

$$D = \frac{dX(t)}{dt} = \beta \frac{db(t)}{dt}.$$

From the evaluation of the authors [20] this method makes it possible to determine the steady-state detonation velocity with a maximum error which does not exceed 2%.

To study the transition of combustion into detonation, the method analogous to that described above was applied by authors of works [21, 22].

Method of the determination of the rate of normal combustion (u) of solid specimens with the aid of the piezoelectric sensor of pressure [23]. In connection with combustion conditions in the manometer bomb a new method was proposed for the determination of the rate of normal combustion - from the "bends" of the curve of pressure $p(t)$. This method is the rapid method and makes it possible by one experiment to determine the values of the rate of combustion, which correspond to different pressures. The essence of method entails the following.

Since in the closed volume the rate of growth of pressure dp/dt is determined by the speed of the gas formation $u\rho S$ and by the force of the powder f ($dp/dt \sim u\rho S f$), then by composing the combined charge, which contains substances with different values of rate u and f (cross-sectional area $S = \text{const}$), it is possible to obtain on recording $p(t)$ the bends, which correspond to the combustion of each of the substances. As a rule, the combined charge is composed of small cylinders of the auxiliary substance with a large value of dp/dt whose combustion sharply raises the pressure in the bomb, and between them the investigated substance with the small value of dp/dt is placed. The form of the obtained recording is represented on Fig. 7. Thus, determined from recording $p(t)$ is simultaneously the time of the combustion of the small cylinder of the investigated explosive of known length and the mean pressure at which its combustion occurs. Each subsequent small cylinder of explosive burns at a pressure higher than the preceding pressure.

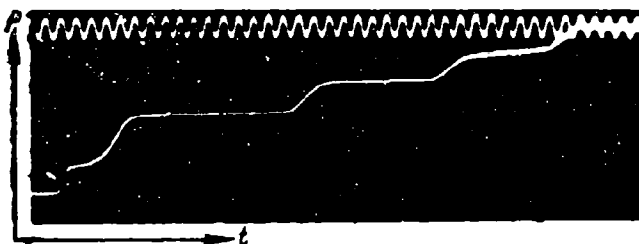


Figure 7. Curve $p(t)$ with combustion of the combined charge, which includes three (1, 2, 3) small cylinders of the investigated explosive (trotyl).

In other experiments was applied the charge of the investigated explosive, which contains the sections with a small and large diameter alternating along the length, which performed respectively the role of the main (basic) auxiliary (forcing pressure) element. By the method according to the "bends" of the curve $p(t)$ the dependences of $u(p)$ of a number of explosives and model mixtures up to pressures of 4000 atm were determined [23].

In connection with the conditions of combustion in the bomb of "constant pressure" the proposed method was modified. Applied was a highly sensitive piezoelectric sensor, which recorded a small pressure increase appearing in the volume of the bomb during the combustion of the charge and, therefore, the beginning and end of the combustion.

§ 3. Pressure Measurements

Piezoelectric method. The piezoelectric apparatus is based on the fact that the measured pressure p by means of the piezoelectric material is converted into the voltage U proportional in value. The obtained signal is amplified and then recorded with the aid of loop or cathode-ray oscillographs. The measured pressure, acting on the piezoelectric material, causes the appearance on its faces of an electrical charge $q=nF$. This charge at the input of the amplifier creates a voltage U , equal to

$$U = \frac{q}{c_M + c_R} = \frac{nF}{c_M + c_R} = \frac{npS}{c_M + c_R},$$

where n is the piezoelectric modulus; p - the measured pressures; S - the area of the piezoelectric material receiving the pressure; c_M - scale capacity (capacity at the input of the amplifier);

c_n - capacity of the piezoelectric material; F - force.

The development of the piezoelectric sensor intended for research on the transition of combustion into explosion and detonation is connected with great difficulties. The fact is that in this case it must possess the full gamut of the natural frequencies: from the lowest - for the recording of combustion, and up to the highest necessary for the study of sufficiently rapid processes close to detonation. Furthermore, this sensor must possess high mechanical strength and be hermetically sealed. The creation of the universal sensor, which satisfies the enumerated requirements, presents great difficulties. Nevertheless as a result of the work carried out at IKhF, there was developed a piston-type piezoelectric sensor, making it possible to record pressure of up to 12,000 atm with the rate of growth $dp/dt < 300$ atm/ μ s [10].

Its schematic sketch is represented on Fig. 6. The sensor consists of a steel heat-treated housing 6 screwed into the body of the bomb, piston 8, which receives the pressure of the gases, and covers with a piezoelectric packet.

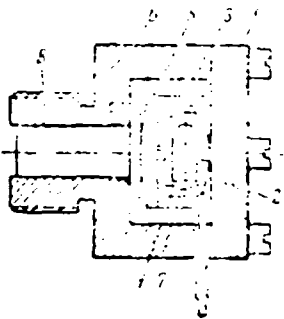


Figure 6. Diagram of the piezoelectric pressure sensor.

The piston and channel of the housing of sensor are thoroughly ground. The piezoelectric packet consists of a steel plate - base 4, limiting metal ring 3, two or four cylindrical piezoelectric elements 1, two hemispheric inserts 2, heat-treated steel membrane 5, and electrode 7 placed between the piezoelectric materials.

The second electrode is the housing of the sensor. It is necessary to keep in mind that the normal operation of the sensor is provided for when the parts of the piezoelectric packet are preliminarily

pressed by a sufficiently great force. Used as a piezoelectric material was a crystal quartz, which possesses high mechanical strength and stable piezoelectric modulus ($n=2.1 \cdot 10^{-11}$ C/kg).

It is known that the compressive strength of the piezocrystal under static conditions is approximately 1000 atm, and in dynamic - 2000-3000 atm. With transient processes the appearing pressures exceed the indicated value. Therefore, used was the principle of compensation for pressure, which was achieved by the use of a piston whose area was substantially (6-10 times) less than the area of the piezocrystals. In the majority of the used sensors the diameter of the piston was 3-4 mm, and the diameter of the piezoelectric quartz crystal plates was 10 mm. Thus, with the aid of this sensor it would be possible to measure principally the pressure of up to 15,000-20,000 atm. However, as it was noted in [24], at pressures greater than 12 thousand atmospheres, the piston sensor can distort results (understate the value of pressure) due to the considerable lateral deformation of the piston and its wedging in the channel of the housing of the sensor.

In the case when the sensor did not have a piston, and pressure affected the piezoelectric packet directly, it made it possible to record low pressures of $\sim 10^{-1}$ atm.

The electric signal which enters from the sensor was amplified. For this purpose Zverev designed a special electronic amplifier. This amplifier had a slow response, which made it possible to use the piezoelectric apparatus also in prolonged processes. At the same time it had a high overall passband ($\sim 350,000$ Hz) and was suitable for the recording of short-time high-frequency processes.

The transmission of the signal from the sensor to the amplifier was conducted with the aid of an antivibration cable.

Used for the recording of the signal from the sensor were the loop oscillographs MPO-2 and N-107 (with slow processes) and the apparatus PID-9, developed at IKhF AN SSSR by Sokolik and colleagues [25] (with quickflowing processes). The apparatus PID-9 on the basis of the cathode double oscillograph OK-24 was intended for the recording of the pressure change with time in a shock wave during the investigations of the action of an explosion.

With the measurement of pressures different in value at the input of the amplifier scale capacitors of different capacity were included. The calibration of sensors was conducted by the static-dynamic method. For this purpose the piezoelectric pickup was secured in the special device in which on a press by means of oil there was created a definite pressure measured by a specimen manometer. Then the pressure relief during a short ($\sim 10^{-3}$ s) time was realized, and the obtained deviation was recorded on an oscillograph.

Thus, although the calibration was conducted in the conditions of the removal of the load, this was not reflected in the results of the experiment, since it is known that piezocrystals equally operate both under compression and with discharging. All the sensors used had a linear amplitude characteristic. An error in the piezoelectric method of pressure measurement did not exceed 3%.

Besides the piezoelectric sensor, used for determining the pressure is also a strain gauge, the deficiencies in which are high sensitivity to a change in temperature, and the need for the routine (after several experiments) calibration of the sensor.

Let us examine the methods of pressure measurement in a

compression wave. The study of the structure of compression waves, which appear in explosives upon the transition of combustion into detonation, has great significance for the understanding of the mechanism of the phenomenon. The most reliable and simple method of the recording of parameters of compression waves is the electromagnetic method [26, 27], which makes it possible to investigate not only the shape of the wave, but also to calculate the absolute value of pressure, since by this method the velocity of front D and the velocity of motion of substance behind the front U are measured simultaneously. The calculation of pressure is realized according to formula $p = \rho_0 D U$ (ρ_0 - the initial density of the explosive).

The basic purpose of the method is the measurement of the rate of motion of the substance.

Electromagnetic method. The essence of the electromagnetic method consists in the following: with the movement of the conductor in a magnetic field, in it there is induced the emf of induction, which is connected with the rate of motion of the conductor, its length and magnetic field strength by the relation

$$\mathcal{E} = HLU \cdot 10^{-9},$$

where \mathcal{E} is the emf in V; H - magnetic field strength, Oe; U - rate of motion of the conductor, cm/s; L - length of the conductor, cm.

Hence it is possible to determine the rate of motion of the conductor U. The conductor (we will subsequently call it the sensor) is a strip of thin aluminum foil (usually with a thickness of 0.05-0.25 mm) and width of 10-15 mm in the form of the letter \square whose cross-beam I, is the working part of the sensor.

Sensor 2 is located in charge 1 perpendicular to its axis, and then together with the charge it is placed into a magneto-static field so that with motion the working plane of the sensor would intersect the lines of force of the magnetic field (Fig. 9).

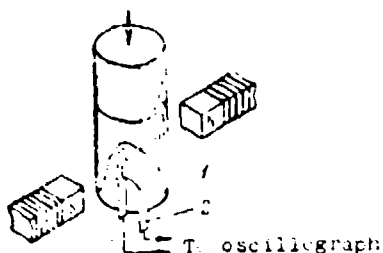


Figure 9. Diagram of the electromagnetic method of the measurement of the mass flow rate of the movement of a substance.

With the passage of the compression wave along the charge, the sensor is set into motion. The emf, induced on its ends, is recorded on the cathode-ray oscillograph. With constant H and L the value of the emf is a function of only the rate of motion of the sensor, which is equal to the mass flow rate of the substance in the wave.

The magnetic field is usually created by an electromagnet. The electromagnets, used at IKhF, have a magnetic field strength in the center of the clearance of 400-800 Oe with a uniformity of 1%. Used as a recorder was the double-beam cathode-ray oscillograph OK-17 with the frequency of transmission along both channels of 10 MHz and the rise time of the transient characteristic of 0.035 μ s. The time of the avalanche of the leading front of the pulse from the beginning of the rise to the maximum value is 0.07 μ s. The avalanche of front can grow with an increase in the thickness of the sensor and specific gravity of the material from which it is made.

For the measurement of the wave front velocity there are used either two sensors or one but of stepped form, which was

proposed by Dremynym and colleagues [27]. Thus, in one experiment the average wave velocity and the velocity of motion of the substance behind the front are simultaneously measured. The electromagnetic method was widely applied in the measurement of the detonation parameters and also for studying the formation of the detonation wave in experiments on percussion initiation. However, its utilization for the study of the mechanism of the formation of the shock wave in the process of the transition of combustion into detonation encounters great fundamental difficulties. The fact is that the indicated transition is usually observed if the charge of explosive involves a sufficiently durable metal shell. The electromagnetic method can be applied if the shell of the charge is made of nonmagnetic material, which frequently is incompatible with the conditions of strength.

Sensors of compression. For determining the propagation velocity of compression waves [13], sensors of compression were applied. The sensor consists of two wires separated by insulation. The principle of their action is based on the closing of the circuit of electrical current as a result of the destruction of the insulation under the influence of a compression wave. The sensors are calibrated by a definite pressure. The advantage of the sensors is the fact that they make it possible to record the passage of the compression waves in explosives independently of the material of the shell. However, they are unsuitable for recording the shape of the compression waves, since the sensors operate when the pressure exceeds a certain critical value (in [13] sensors with the threshold of operation of 800 and 2000 atm were used).

In conclusion one should emphasize that the systematic possibilities of the study of the wave pattern which appears upon transition of the combustion of solid explosives into

detonation are extremely limited and considerably lower than those which exist in the gas systems where for this purpose a highly efficient inertia-free Schlieren photograph is applied.

SOLID EXPLOSIVES

CHAPTER I

GENERAL CHARACTERISTIC OF POROUS SYSTEMS

The destabilization of the laminar combustion of porous explosive systems is caused by the penetration of the combustion into the pores as a result of the filtration of the combustion products [4-7]. In the analysis of conditions of the transition of combustion into explosion, we will utilize some results obtained in the filtration theory in the study of the flow of natural liquids and gases into porous systems and also the basic concepts and determinations formed here.

Understood by the porous medium is the body which contains pores - empty gaps. The flow of liquid (gas) is possible only in such a case when at least part of the pores is imparted to each other, and the system is gas-permeable. We will be restricted to the examination of the porous media, in connection with which the molecular structure of the filtering gas is not affected,¹ which occurs if the mean free path of molecule does not exceed the dimension of the pores. This condition is satisfied virtually for all systems which are of interest from the viewpoint of the

¹The emergence and development of an explosion is determined by the laws governing the filtration of mainly gaseous combustion products. The question concerning the role of the fusion will be examined specially.

possibility of the transition of their combustion into an explosion.

§ 4. Basic Parameters of the Porous Medium

The porous system is characterized by the following basic parameters: porosity, gas permeability, specific surface area, distribution of the pores according to dimension, and particle sizes.

Porosity m is a volumetric ratio of the pores V_n to the total volume of the specimen V_0 :

$$m = V_n / V_0 = 1 - \delta, \quad (1)$$

where $\delta = \rho / \rho_{\max}$ is the relative density; ρ - density of the specimen, g/cm^3 ; ρ_{\max} - maximally possible density of explosive (density of single crystal).

In the case of the mixtures value ρ_{\max} is determined by the calculation

$$f_{\max}^{\text{CM}} = \frac{1}{\sum_i \frac{x_i}{\rho_{i \max}}}$$

where x_i , $\rho_{i \max}$ - weight fractions and maximally possible density of the i th component.

Porosity is expressed in the fractions of one or in percentages. They distinguish the absolute (physical) porosity, which is defined from formula (1) and includes both the connected and closed pores. If the porosity is determined from the interdependent pore space, then it is called the open (effective)

porosity. Subsequently, without special stipulations understood by the term "porosity" will be absolute porosity.

The gas permeability k is that property of the porous medium by which the possibility of the flow of gas in the specimen is determined. The dimensionality of gas permeability is the square of the length. Frequently used as a unit of measure is the darcy: $1 \text{ darcy} = 9.87 \cdot 10^{-13} \text{ m}^2$.

The specific surface area of the specimen $S_{yA} \text{ cm}^2/\text{g}$ is defined as the surface of the pores per unit of mass of the solid substance.

Since the surface of the pores in the general case has an exceptionally complex form, the determination of the concept "dimension of the pore" d_n is connected with difficulties of a fundamental nature. Convenient from a geometric point of view is the definition according to which the dimension of the pore at any point of the pore space is a diameter of the greatest sphere which contains this point and remains a whole within the space of the pore [28]. The physical side of the question is more correctly reflected by the following definition: the dimension of the pore is the diameter of this tube, which is equivalent to this pore according to its hydraulic properties. This approach is utilized in the construction of various kinds of theoretical models of the porous medium. It is natural that the porous specimen is characterized by the defined distribution of pores according to the dimension. With the processing of the obtained results, standard distribution curves, known from mathematical statistics (of Gauss type), are used.

An important characteristic is also the particle sizes - especially for the porous systems in which the shape and dimension of the particles do not change in the production of specimen and its combustion.

The enumerated parameters are determined experimentally. The methods and results of their measurement in connection with the explosives will be presented below (in § 5).

At the same time, of considerable interest are the theoretical ways of evaluating the indicated magnitudes and the establishment of the dependences between them. Thus, in a number of cases it is necessary to evaluate the mean diameter of the pore, the particle sizes, the value of specific surface area in terms of the known values of the gas permeability and porosity. Such estimates can be obtained from examination of the simplified theoretical models of the porous medium.

Theoretical Models of the Porous Medium

A distinctive feature of the porous systems is the disorder of their structure. The solution to the Navier-Stokes equation for viscous fluid flow in the disordered systems is impossible. Therefore, in theoretical studies the real porous medium is replaced by the simplified ordered models with the equivalent hydraulic properties. The exact solution of the Navier-Stokes equation exists for the case of flow along a direct round tube. This fact was used in the design of models.

Wide acceptance was given to the model of an ideal ground, which consist of identical pores of a cylindrical shape whose axes are parallel to each other [29]. For this model the average hydraulic diameter of the pore $d'_p = 4S/\chi$ (where S is the cross-sectional area of the pore, - wetted perimeter) is determined in terms of the gas permeability and porosity in the following way:

$$d'_p = 43 \sqrt{k/m}. \quad (2)$$

The value β weakly depends on the form of the cross section of the pore, and its average value is taken as $\beta=1.37$ (for the section in the form of a circle $\beta=1.41$). Expression (2) makes it possible to evaluate the average hydraulic diameter of the pore, since in this model it is assumed that all the pores are identical. An ideal ground is an example of the capillary model of the porous medium.

More complex is the model proposed by Koseny and the model perfected by Karman in which the porous medium is the totality of channels of different cross sections but definite length. This model makes it possible to establish the connection between gas permeability, porosity and specific surface area of the pores S_{yA} :

$$k = \frac{n^3}{2S_{yA}^2 \cdot \mu_{\text{max}} (1 - n)^2} \quad (3)$$

The equation of Kozeny (3) is used for determining the specific surface area of the pores S_{yA} and particle sizes.

The single bond between the diameter of the pore and particle sizes occurs for the porous systems which consist of identical spherical particles with a diameter of r . In this case, as this follows from the theory of the stacking of the spheres [28, 29], the porosity does not depend on the diameter of the particles. A stable stacking with minimum porosity $m=0.259$ is rhomboidal. A stable stacking with maximum porosity is not yet found (the stable stacking of the spheres with porosity $m=0.875$ is described in literature). The average hydraulic diameter of the pore for the system of identical spherical particles is equal to [29]

$$d_n = \frac{m}{3(1-m)} r \quad (4)$$

For the multi-disperse systems, which consist of particles of arbitrary form, the hydraulic diameter of the pore can be calculated [30] from the formula

$$d'_h = \frac{2}{3} \frac{m}{1-m} r' \sqrt{\frac{0,205 \cdot s'}{V'^{2/3}}} \quad (5)$$

where V' is the volume of the particle; s' - area of the particle; r' - diameter of the sphere equivalent to this particle in volume.

A precise estimate of the actual form and size of the particles is extremely difficult. Nevertheless, the particles are characterized by a definite dimension (see § 5).

Numerous attempts at the theoretical calculation of gas permeability did not enjoy success. The obtained computed values always differed significantly from the experimental values. Also unsuccessful proved to be the attempts to establish the single universal dependence between the gas permeability and porosity. Therefore, gas permeability is determined only experimentally.

It is necessary to emphasize the following important fact. In the construction of theoretical models of the porous medium it was assumed that all the pores were opened for the course of the liquid (gas). Therefore, the porosity, which enters into expression (2)-(5), makes sense to be opened.

Some Equations of the Filtration of Gas in a Porous Medium.

Usually the motion in the pores is considered to be laminar. One should apply the Navier-Stokes equation to the process of

the laminar filtration of viscous fluid in the porous medium. As was noted, the direct integration of this equation, due to the complexity of the boundary conditions, is not possible. Leybenzon [29] derived the general equation which describes the unsteady laminar filtration of the compressible fluid in an undeformable ($k=\text{const}$, $m=\text{const}$) porous medium, after replacing the effect of viscosity with fictitious resisting forces.

In the case of gas it is recorded in the form

$$\nabla^2 P = \frac{n\mu}{nk} \frac{1}{p} \frac{\partial P}{\partial t}, \quad (6)$$

where $P=p^{n+1/n}$; n - polytropic exponent in equation $p^{1/n}=\text{const} \cdot \rho$; p , ρ , μ - pressure, density and viscosity of the gas respectively.

Equation (6) is a nonlinear second-order equation with partial derivatives of the parabolic type. The integration of (6) is facilitated for the case of one-dimensional motion under the following conditions:

1) if the filtration is isothermal ($n=1$), then (6) is written

$$\frac{\partial^2 p^2}{\partial z^2} = \frac{2n\mu}{k} \frac{\partial p}{\partial t} \quad (7)$$

[solution to (7) was given by Boussinesq];

2) if it is possible to assume the pressure of gas p to be constant ($p=p_0$) (for example, for the case when the filtration of the gas is realized under the action of a differential $\Delta p \ll p_0$). Then the solution to the approximate equation

$$\nabla^2 P = \frac{n\mu}{nk p_0} \frac{\partial P}{\partial t} \quad (8)$$

is the solution to the usual equation of thermal conductivity.

For the laminar motion the law of Darcy is valid, according to which the linear rate of filtration is proportional to the pressure gradient:

$$v = - \frac{k}{\mu} \frac{dp}{dx}. \quad (9)$$

The minus sign shows that the flow has a direction opposite to an increase in the gradient.

The law of Darcy is applicable if Reynolds number $Re = v d_p \rho / \mu$ (d_p the diameter of the pore or particle size), which determines the flow pattern of the gas in the pores, does not exceed critical value. According to different authors, the indicated value lies in the interval $Re = 1-75$. The law of Darcy is fulfilled in a wide region of filtration rates, and deviations from it occur extremely slowly and are observed only at high and low rates of flow. In the first case this is connected with the emergence of the turbulent flow and in the other case with the molecular effects. Based on the utilization of the law of Darcy are the methods of the determination of the gas permeability of porous specimens.

Such is briefly the general information about the porous medium, which we will subsequently use.

The obtaining of porous explosive systems. As was noted, the minimum porosity which can be reached in the case of identical spherical particle is 0.259. The real porosity of the bulk charges of the explosives, as a rule, is substantially higher than the theoretical and is equal to 0.4-0.7. For the purpose of a decrease in the porosity different methods of packing are used.

The method basic and widespread in practice of the packing of explosives is the method of dead-end pressing. This method, extremely simple in execution, makes it possible to prepare the specimens whose porosity and gas permeability can be changed over wide limits. The advantage of the method is the possibility of obtaining (with the observance of definite rules of pressing) specimens uniform in length and diameter with the necessary and well reproducible properties. Furthermore, as it will be shown below, a large part of the pore space proves to be that which was interconnected. For this very reason the porous specimens of explosives prepared by this method were the basic object in the study of the transition of combustion into explosion.

Usually used are press molds with rounded cross section. Recently there began to be used also press molds of rectangular cross section. The experience of pressing shows that the molding uniform in volume of the specimen is reached with the optimum relationship between the height and diameter of the specimen equal approximately to 0.5. Therefore, we obtained elongated charges by the connection of a considerable quantity of thus pressed cylindrical pellets whose number was decreased when using rectangular plates. With the pressing of explosives into a cylindrical shell there was applied the portion method, which entails the successive pressing (without overflow) of separate charges of the explosives. The height of each pressing in this case did not exceed half of the diameter.

The substance with pressing is found under condition close to hydrostatic stress. Under the action of the applied load there occurs the packing of the substance, which is determined by the processes of destruction (fragmentation) of the particles and plastic deformation. After the overflow the specimen is unloaded, which is accompanied by a small increase in the volume. The obtaining of charges with a different porosity is achieved by

a change in the compacting pressure p_{np} . The minimum maximum porosity which can be obtained by dead-end pressing depends on the individual properties of explosives and, first of all, on its strength characteristics, which is confirmed by the data given below:

Index	TNT	Picric acid	PETN	Cyclonite	Lead azide
Maximum porosity	0,02	0,025	0,025	0,035	0,15
Tensile strength σ_{np} , kg/cm ²	340	520	600	820	1550

Represented here are the values of minimum porosity of some explosives, obtained at the maximum operating pressure of pressing of 4000 atm, and the tensile strength determined in work [31]. The corrected values of the tensile strength are established in the study of the sensitivity of the explosive to the shock and characterize, in the opinion of the authors, the trans-crystalline (intrinsic) strength of the explosive as a material. In spite of the specificity of the conditions of the deformation, the obtained values of σ_{np} give the concepts about the strength of different explosives.

Thus, the less the tensile strength, the lower the minimum porosity and higher the compressibility of the explosive. In § 5 it will be shown that the strength properties of explosives exert a substantial influence also on the physical structure of the pore space.

The density of the pressing at fixed compacting pressure depends also on the dimensions of the particles of explosives, the presence of the cementing addition and the relationship

between the geometric dimensions of the specimen whose role is not examined here. That presented above was related to the case when the pressing was implemented at room temperature and without the use of a solvent. When using preheating and special solvents, it is possible to obtain the specimens virtually devoid of porosity.

For obtaining the charges of explosives and the mixture powders of high density, a casting method is also utilized. The structure of the porous charges, prepared according to casting technology, differs significantly from that which is obtained by the method of dead-end pressing. For the cast systems is characteristic the porosity in the form of bubbles and craters, the overwhelming majority of which is not connected with each other. The value of porosity in the cast charges depends on the conditions of cooling and polymerization, and the method of pouring and is 0.01-0.03. The possibilities for obtaining by the given method of charges with a different porosity, which is changed over wide limits, are very limited. With the aid of casting technology it is extremely difficult to obtain uniform porous specimens with definite, preassigned properties.

The pressed porous systems are deprived of the indicated deficiencies and open up considerably greater possibilities from the research point of view. With following presentation everywhere (without special stipulations) by the terms "porous explosives" and "porous medium" one understands as systems obtained by dead-end pressing.

§ 5. Methods and Results of Measurement of the Basic Parameters

Determination of porosity. In the measurement of absolute porosity in essence the method based on the measurements of

density is utilized. The calculation of porosity is conducted according to formula (1). The density of the specimen ρ is determined by the method of volumetric displacement. Used is a fluid (for example, mercury) which does not interact with the substance and does not penetrate the pores of the specimen. The preliminary coating of the specimen with a film of corresponding material makes it possible to expand the circle of the fluids used. Introduced here is a correction for the volume of the coating. The volume measurement of the specimens with low porosity can be conducted by means of hydrostatic suspension, without resorting to coating. The volume of the porous specimen of correct form is also determined from its geometric dimensions.

There is also a whole series of special methods of the determination of the absolute porosity, with the content of which it is possible to be acquainted in works [28, 29].

For the measurement of the open porosity the method of saturation or the method of the expansion of gas is applied.

The first of the indicated methods is based on the saturation of the porous specimen by the fluid. Utilized is either the fluid, which penetrates well into the pores (for example, kerosene), then the saturation of the specimen is realized in a vacuum, or mercury, which is forced into the evacuated specimen under high pressure. The amount of fluid which enters into the specimen characterizes the value of the interdependent pore space.

The method of the expansion of the gas is based on the direct measurement of the air volume in pores of the specimen. For this purpose the specimen is connected with the chamber of increased pressure whose volume is known. The pressure change in specimen-chamber system makes it possible to calculate, on the

basis of the law of Boyle-Mariotte, the volumes of the connected pores.

Represented below are results of the measurement of open porosity in specimens of TNT, tetryl, cyclonite (initial particle size $r=110-140 \mu$) and ammonium perchlorate (AP) [ПХА] ($r=10 \mu$), obtained by the saturation method.

Index	TNT			Tetryl	Cyclonite	Ammonium perchlorate		
Absolute porosity m	0,16	0,08	0,05	0,05	0,05	0,2	0,1	0,07
Open porosity m_0	0,16	0,06	0,027	0,035	0,05	0,2	0,03	0,05

The specimens of TNT, tetryl, and cyclonite were saturated by mercury,¹ and ammonium perchlorate - by kerosene.

As follows from these data, with porosity $m > 0.16-0.2$ the pores of all investigated explosives are completely interconnected. With a decrease in porosity m the volume of the connected pores is decreased, which is clearly exhibited for explosives which are characterized by low strength (TNT, tetryl). However, in the case of high-strength cyclonite even with low porosity close to maximum, the formations of closed (not connected) pores is not observed. Thus, the structure of the pore space depends on the strength properties of the explosives and, therefore, on the nature of the deformation of explosives with pressing.

¹The determination of open porosity and distribution of the pores according to dimension (see Fig. 10) was conducted by Mel'nikov and Volkov, utilizing the method of the forcing of mercury into the pores.

Determination of the Distribution of Pores According to Dimension

Usually the method of the forcing of mercury into the system of pores which partially has already been examined above is utilized. The distinction consists only of the fact that the volume of mercury in the pores is determined at different pressures. The porous specimen is placed into the chamber with a strictly defined volume and evacuated. Then the forcing of the mercury at a certain elevated pressure is realized, whereupon the volume of the mercury getting into the pores and, therefore, the volume of the pores of the given dimension V_n . The indicated operator is repeated, but already at a higher pressure, when pores of less dimension are filled with mercury, and is continued until the mercury fills all the pores. The dimension (diameter) of the pores d_n is calculated from the equation of the capillary drop. Thus, experimentally obtained is the dependence of the volume of the pores V_n on dimension of d_n , i.e., the integral distribution curve of the pores according to dimension $V_n(d_n)$. Used more frequently are differential curves $\alpha(d_n)$, where α is a part of the pore space which includes pores with a dimension of d_n to $d_n + \Delta d_n$.

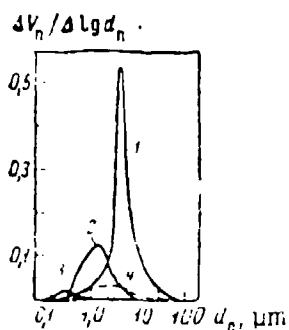


Figure 10. Differential curves of the distribution of pores according to the dimension obtained by the method of the pressing of the mercury (initial particle size) $r=110-140 \mu\text{m}$):

- 1-3 trotyl:
- 1 - $m=0.21$;
- 2 - 0.16 ;
- 3 - 0.05 ;
- 4 - cyclonite, $m=0.05$

Figure 10 depicts the differential curve distribution of the pores according to dimension, which are obtained by the

graphic differentiation of the experimental curves $V_{\Pi}(d_{\Pi})$ (plotted along the axis of the ordinates is the value of the derivative $\Delta V_{\Pi} / \Delta \lg d_{\Pi}$).

Data of Fig. 10 give a demonstrative concept about the value of the significant dimensions of the pores.

It is interesting to trace, first of all, a change in the dimension of the pores, which correspond to a maximum in the distribution curve in specimens of TNT of different porosity. Even with a comparatively high porosity ($m=0.21$) the corresponding dimension is a sufficiently low value ($\sim 4 \mu$), and with a porosity of $m=0.05$ it decreases by one order. The greatest (maximum) dimension of the pores decreases in this case from 50 to 1 μ .

The value of the pores in the specimen of cyclonite is noticeably higher than that in the case of TNT of the same porosity ($m=0.05$) and of the initial dispersity, which is in accordance with the data presented earlier.

In § 15 of Chapter III it will be shown that the high combustion stability of secondary explosives is connected with the formation on the surface of a continuous molten layer which stabilizes the combustion until its thickness becomes commensurable with the maximum size of the pores. The estimates carried out on the basis of this condition gave the value of the pores close to that which follows from the immediate determination of the distribution of pores according to dimension. It is interesting that the experiments on combustion and the estimate of the dimension of the pores were carried out earlier than the distribution curves of the pores according to dimension were obtained.

Measurement of Gas Permeability

The gas permeability, which determines the flow of gas along the pores and, therefore, the possibility of the destabilization of the laminar combustion depends not only on the porosity, but also on the dimension of the particles, nature of their packing and structure of the pore space. Therefore, there does not exist the universal theoretical dependence between the gas permeability and porosity, and its concrete form is established experimentally. The measurement of gas permeability is based on the utilization of the Darcy law. Experiments are conducted, as a rule, in conditions of the steady-state isothermal filtration of the gas. The procedures used differ only in terms of the structural formulation.

The determination of the gas permeability in specimens with small porosity ($m < 0.15$) was conducted [10] on an apparatus whose diagram is represented on Fig. 11a. The basic difficulty which appears in the measurement of gas permeability in this case entails the elimination of the possibility of the flow of gas over the lateral surface of the specimen, which was reached in the following way.

The substance investigated was filled into well ground conical mold 4 and pressed up to the necessary porosity. Before pressing the surface of the mold is coated with a thin layer of bitumen, applied from a solution in gasoline, which improved the cohesion between the specimen and the mold. The use of a conical mold eliminated the possibility of the displacement of the porous specimen 7 in the process of the experiment due to the effect of the pressure differential. The packing of mold in the apparatus was realized with the aid of rubber packings 6 and a nut 3. As the specially carried out checking showed, the accepted measures provided the air tightness of the assembly as a whole.

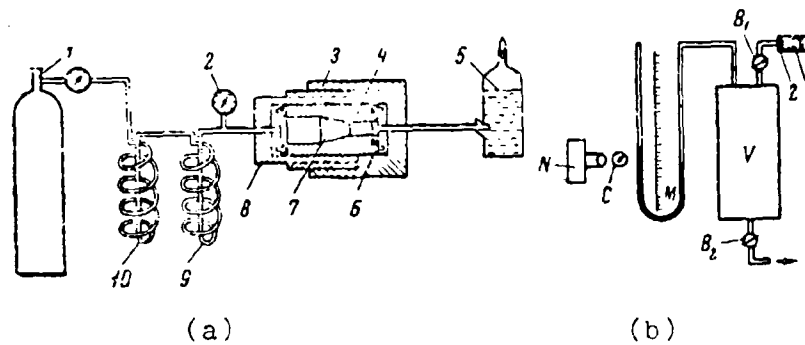


Figure 11. Diagram of installation for the measurement of gas permeability in specimens with low (a) and high (b) porosity.

Gas (mainly nitrogen) from cylinder 1 through the reducer and coils 9 and 10 approached the entrance of the porous specimen 7. In coil 10 the gas was purified of the water vapors by means of freezing out by dry ice. In coil 9 the dried gas was heated to room temperature at which the measurements were conducted. The pressure of the gas p_2 at the inlet was measured by a specimen manometer 2, and the pressure at the output p_1 was virtually equal to the atmospheric pressure. A pressure differential $\Delta p = p_2 - p_1$ on ends of the specimen maintained constant and did not exceed 10 atm. By means of a small-scale gas meter 5 was determined the volumetric flow rate of the gas passed through the specimen, the dissolution and absorption of which was eliminated by the preliminary saturation of water in the gas meter. The gas flow was measured after the establishment of the filtration conditions.

The calculation of gas permeability was conducted on the basis of the Darcy law (9), taking into account the compressibility of the gas. Presenting (9) in the form of

$$\frac{Q_{\text{exp}}}{S} = \frac{k}{\mu} \frac{p_2 - p_1}{L}$$

and writing down the filtration flow of gas, referred to the mean pressure $p_{cp} = (p_1 + p_2)/2$ with isothermal flow as $Q_{cp} = p_1 Q / p_{cp}$, we obtain the initial formula for the calculation of the gas permeability:

$$k = \frac{2p_{cp}QL}{S(p_2^2 - p_1^2)}, \quad (10)$$

where k is the gas permeability, Darcy; L - length of the specimen, cm; S - the middle cross-sectional area, cm^2 ; Q - the measured flow of gas (cm^3/s) at atmospheric pressure at the output $p_1 = 1 \text{ atm(abs)}$; μ - viscosity of the filtering gas, cp.

From (10) it follows directly that the flow rate of the gas which passed through the specimen Q with constant geometric dimensions of the specimen changes linearly with value $v_2^2 - v_1^2$.

On this apparatus there was conducted the determination of gas permeability in the specimens of explosives with a porosity of $m = 0.15 - 0.03$. The corresponding interval of the variation in the gas permeability was $10^{-2} - 10^{-6}$ Darcy.¹

Some of the obtained results [10] are represented on the graph of Fig. 12. Plotted along the axis of the ordinates is the logarithm of inverse gas permeability (expressed in Darcy) and along the axis of the abscissas - absolute porosity.

¹Gas permeability $k = 10^{-6}$ darcy is a very low value and is substantially less than the gas permeability of the overwhelming majority of the natural rocks and soils.

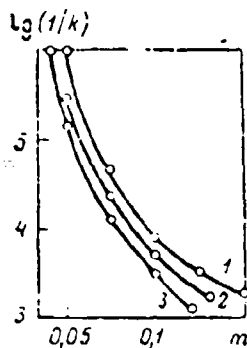


Figure 12. Dependence of the logarithm of reverse gas permeability on porosity (initial particle size $r=5-20 \mu\text{m}$): 1 - PETN; 2 - stoichiometric mixture of trotyl with ammonium perchlorate; 3 - trotyl.

The measurement of gas permeability in the specimens with high porosity ($m > 0.15$) was realized [32] on an apparatus whose diagram is shown on Fig. 11b. The investigated porous specimen 1 was placed on the backing 2 of the filter paper for ensuring the stability of the results of the measurements. Before the experiment there was produced the preliminary pumping out with a closed valve B_1 of volume V ($\approx 1.5 \text{ l}$) up to a certain pressure p_2 less than atmospheric p_1 at $\Delta p = p_1 - p_2 = 100-150 \text{ mm H}_2\text{O}$. Then the valve B_2 was closed, and B_1 was opened. The inleakage of air through the investigated charge of the explosive in volume V was begun. Simultaneously with the aid of a movie camera N a recording of the pressure change with time from readings of the manometer M and stopwatch C was made. In connection with experimental conditions, the utilization of the law of Darcy leads to the following expression for determining the gas permeability:

$$k = \mu \left(\frac{LV}{S} \right) \cdot \left(\frac{dp}{dt} \cdot \frac{1}{p \Delta p} \right). \quad (11)$$

With derivation of expression (11) the compressibility of the gas was not considered, which was justified since $\Delta p \ll p_1$. With the examination of results of the measurement the correction which considers the resistance of the backing 2 and other parts of the apparatus was introduced.

With the aid of the apparatuses described above the determination of the gas permeability of the specimens of a series of explosives in the wide interval of the variation in the porosity ($m=0.8-0.03$) was conducted, and in this case the range of the change in the gas permeability was 7-8 orders. As an example the graph of Fig. 13 shows the corresponding results for the PETN of different dispersity.

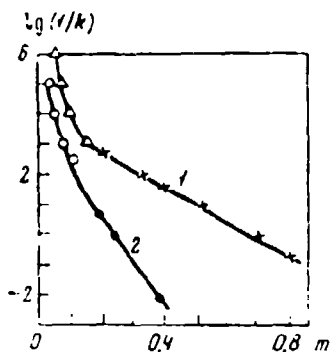


Figure 13. Dependence of the logarithm of reverse gas permeability on porosity for specimens of PETN pressed from particles 5 μm (1) and 500 μm (2) in dimension: \circ, Δ - data [10]; \circ, \times - data [32].

From an examination of data of Fig. 13, it follows that the nature of the dependence of the gas permeability of PETN on the porosity at the value of the latter of $m=0.1-0.2$ is substantially changed. If with $m>0.15$ the findings in coordinates $\lg(1/k) - m$ are satisfactorily placed on a straight line and are approximated by the dependence of the form $k=a'e^{b'm}$ (a', b' - constants, then at smaller values of porosity curves are noticeably steeper (a sharp drop in the gas permeability is observed). It is logical to connect this effect with a change in the structure of the pore space.

From the findings it is evident that the gas permeability substantially depends on the initial particle sizes of the explosives. This result is trivial in connection with specimens with high porosity. However, the fact that at very low values of porosity ($m=0.03-0.05$) the gas permeability of the specimens

pressed from large grains continues to remain noticeably higher deserves attention. Actually, it was possible to expect that the intense fragmentation of the substance in the process of pressing at high pressures (3000-4000 atm) leads to the disappearance of the dependence of the properties of the specimen on the initial particle size. An experiment shows that this does not occur. The specimen condensed to high density continues to "store" the history of its production.

Subsequently, it will be shown that this effect of the particle size in very compact specimens is exhibited both with combustion and with excitation and development of the explosion.

Having available the dependences of gas permeability on porosity for a series of explosives, we were able to compare the stability of their combustion with identical gas permeability and the close structure of the specimens. Only this comparison could determine the role of the physicochemical and thermochemical properties of explosives in the process of the destabilization of laminar combustion.

Measurement of the Specific Surface Area of the Pores and Particle Sizes

The determination of the specific surface area of the pores is based on the use of the equation of Kozeny and on the use of the experimentally obtained dependences of gas permeability on porosity. Besides this (basic) method, there is still a number of methods [28] of the determination of specific surface area (method of microphotography, the method based on the use of the phenomenon of the adsorption of vapor by a solid surface, etc.).

The magnitude of the specific surface area of the pores is an important characteristic of explosives whose knowledge

is necessary, first of all, in the examination of the question concerning the transition of combustion into detonation. There is special interest in the dependence of the specific surface area on porosity. Utilizing the equation of Kozeny (3) and experimental data on the measurement of gas permeability (see Fig. 13), we conducted the calculation of the specific surface area in specimens of PETN with different values of porosity and initial particle sizes of 5 and 500 μm (Table 1).¹

Table 1. Specific surface area and average particle size in the specimens of PETN with different porosity.

Index	Porosity, m							
	PETN	0,8	0,45	0,25	0,3	0,25	0,2	0,1
Specific surface area of pores $S_{ya} \cdot 10^{-3}, \text{cm}^2/\text{g}$	Fine	6,15	9,26	10,05	10,1	9,93	9,95	9,9
	Coarse	—	0,07	0,2	0,34	0,53	0,73	2,2
Average particle surface $r = \frac{6}{S_{ya} \rho_{max}} \mu\text{m}$	Fine	5,5	3,65	3,37	3,35	—	—	—
	Coarse	—	500	170	160	—	—	—

Note. Porosity of 0,8 and 0,45 corresponds to charges of bulk.

Results of the calculation of the specific surface area for a finely crystalline PETN are also represented on Fig. 14.

From the given data it follows that the dependence of the specific surface area of the pores on porosity for finely ground

¹In the equation of Kozeny one should substitute the value of the apparent porosity. Therefore, in conducting the calculation, it was considered that with the porosity $m > 0.2$ the pores are completely interconnected ($m = m_0$, and with $m = 0.1$ for a finely crystalline PETN $m_0 = 0.08$ was taken.

explosives is characterized by the presence of a maximum with $m \approx 0.3$.

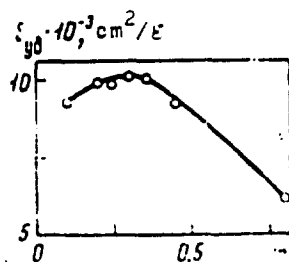


Figure 14. Specific surface area of the specimens of PETN of different porosity ($r \approx 5 \mu\text{m}$).

Table 1 also gives results of the calculation $S(m)$ for specimens pressed from large crystals (initial particle sizes $r=500 \mu$). From a comparison of the findings it follows that for specimens of the coarse-crystalline PETN the specific surface area of the pores monotonically and substantially (30 times) grows in proportion to a decrease in the porosity and in the whole investigated interval remains less than that for a finely crystalline PETN. An increase in the specific surface area is connected with the intense fragmentation of the large crystals, the degree of grinding of which increases with a decrease in m , but which, however, does not reach the level characteristic for the preliminarily thoroughly ground substance. In accordance with this there is no maximum on the curve $S(m)$.

In the case of finely crystalline PETN when the initial particles are already very small, the fragmentation and, therefore, an increase in the specific surface area is expressed more weakly. A further increase in the compacting pressure (density of explosives) does not lead to a decrease in the particle size but changes the structure of the pore space, and in particular, there appear closed cells, and the consolidation of the particles occurs due to an improvement in the contact between them, as a result of which the specific surface area decreases and a maximum on the curve $S(m)$ is observed.

The considerations about fragmentation presented above are fortified by an estimate of the average particle size in specimen, which is possible, since the specific surface area of the pores is known.

The connection between the average particle size and specific surface area can be obtained from simple geometric considerations and also by combining the expression of (2), (3) and (4):

$$r = \frac{6}{S_{\text{sp}} \rho_{\text{max}}} \quad (12)$$

Relation (12) is widely utilized for determining the average particle size, in particular, the polydisperse fractions of explosives (based on this principle is the laboratory instrument PSKh).

The values of the average particle size, determined according to formula (12), are represented in the last line of Table 1.

Table 2. Range of measurements of the dimension of particles and dimension of pores by different methods.

Method	Range of measurements	
	dimension of particles, μm	dimension of pores, μm
Optical microscope	0,25-250	0,25-250
Electron microscope	0,005-5	0,005-5
Screen analysis	40 and more	—
Liquid sedimentation	0,5-300	—
Gas sedimentation	1-200	—
Scattering of X-rays	0,005-0,05	0,005-0,05
Method of mercury - helium	—	0,005-10,0

It is necessary to note that the intense fragmentation of the large crystals is observed already at comparatively low

compacting pressures which do not exceed 200 atm. Thus, the effect of fragmentation virtually always occurs, and one must not fail to consider it, working with the pressed charges of the explosives.¹

The dimension and shape of the particles are retained unchanged if utilized are charges of bulk density, which in the process of the experiment do not undergo the effect of mechanical loads. Besides the method described above of the measurement of the average particle size in magnitude of specific surface area, for determining the initial particle size of the mono-disperse fractions of explosives the screen and microscope analysis is also used. Equigranular fractions² are obtained in essence by scattering with the aid of sieves.

The screen particle size is defined as arithmetic mean between dimensions of the cells of the sieves. Simply the boundary values of the dimension of cells of the sieves are more frequently indicated.

A microscope analysis results in the size determination of a large number of particles (not less than one hundred) from

¹Upon transition of the combustion into detonation, the explosive is subjected to the effect of compression waves, which can lead to the supplementary fragmentation of the substance, if such a possibility exists, i.e., when the maximum degree of grinding is not reached. The question concerning the fragmentation of crystals of the explosive under the dynamic (impact) conditions of loading was specially investigated in work [33]. The charges of the explosive of bulk density with the initial particle sizes ~1 mm were subjected to compression of a shock wave 1500-2000 atm in amplitude. The specimens were retained, whereupon the particle-size distribution was determined. It was established that the finite dimension of the particles, which corresponds to the maximum of distribution, is 10-20 μm .

²Fractions of the 100-140 and 320-400 μm type can be considered equigranular.

two mutually perpendicular directions and in the averaging of the obtained results. For the fraction which consists of particles of the extended form, the average microscope dimension, as a rule, is more than the average screen dimension.

For determining the granulometric composition of the powders, there are also applied sedimentation methods, which are based on the dependence of the rate of deposition (sedimentation) of uniform particles in the viscous medium on their dimensions. Usually used is the settling of solid particles under the action of gravitational or centrifugal forces.

Table 2 gives a summary of basic methods of the direct measurement of the dimension of the particles and also the dimension of the pores, and limits of the applicability of the method are shown (cited data are taken from work [34]).

The indirect method, based on the measurement of gas permeability, makes it possible to calculate, using (2), the dimension of the pores in the range of up to 0.1-1 μm depending on the resolution of the apparatus used.

CHAPTER II

STABLE COMBUSTION OF POROUS EXPLOSIVES

Under certain conditions the combustion of porous explosives is stable and uniform and is realized by parallel layers (in layers). In this case the magnitude of the mass rate of combustion is close to the same for continuous nonporous specimens.

The study on laws governing the slow laminar combustion of the porous systems is of considerable theoretical interest and gives additional material about the mechanism of the combustion of explosives. Actually, the density change leads to a change in conditions of heat propagation in the condensed phase, since the thermal conductivity and gas permeability of the explosives depend on density. There is a change also in the concentration of the substance in the solid phase, which has considerable importance for systems the leading reaction with the combustion of which is found in the condensed phase.

The study of the stable combustion of porous systems contributes also to a fuller understanding of the processes which determine the emergence of the filtration instability.

In the existing theories of normal combustion of the condensed systems, it is accepted that the heat transfer from the zone of reaction to the nonreacting substance is realized by thermal conductivity and radiation, but convection heat transfer

(penetration of gaseous products of combustion or fusion) is absent. In connection with the continuous systems, this position causes no doubts, and their combustion is normal. As regard to the porous systems, as it will be shown below, in a number of cases the penetration of products of combustion into the pores knowingly occurs, although the combustion is stable and uniform. It is natural that this combustion cannot be classed as being normal.

Unlike that of the solid system, the combustion of porous systems is characterized by a number of specific features. One should, first of all, consider the nonuniform nature of combustion caused by the geometric nonhomogeneity of the porous systems. The presence in the charge of pores leads to bending of the burning surface, and as a result there is a change in the conditions of the mass- and heat exchange in the zone of the chemical reaction and the structure of the products flowing from the surface of the combustion. Therefore, a great effect on the combustion is exerted by the physical state of the burning surface. The features of combustion are caused also by the dispersed nature of the porous medium, which includes solid explosives and the gas filling the pores.

The experimental study on the laws governing the smooth combustion of explosives with open gas-permeable porosity requires the observance of systematic precautions. The reliable data can be obtained if combustion is realized at a constant external pressure. This condition is strictly satisfied if combustion is conducted at an atmosphere. With combustion in the bomb of "constant pressure" even with a significant magnitude of free space (bombs, BD-150, BD1000) the pressure increases, which contributes to the penetration of the products of combustion into the pores. Furthermore, if special measures are not taken, the pores of the explosives prior to the beginning of the combustion are filled with gas (nitrogen), which is used for the creation of pressure in the bomb. Gas in the pores performs the role of a peculiar inert addition in explosives whose mass grows with an increase in the

pressure. Both these factors can distort the obtained results, and an objective account of their effect on combustion represents considerable difficulties. Let us examine, therefore, basically data obtained at constant - atmospheric pressure.

§ 6. Density Effect of Explosives on the Possibility of Combustion

Andreyev showed for the first time [35] that for the fusing explosives (tetryl, cyclonite) there is a maximum density lower than which the combustion extinguishes. At higher densities a uniform stable combustion is observed. Near the limit of extinction the combustion becomes nonuniform fluctuating. It was established that the density value on the lower limit decreases with an increase in the diameter of the charge and grinding of the particles of the explosives.

The density change differently affects the possibility of the combustion of the nitrocellulose, the nitroglycerin powder for which there is an upper density limit. The end of the combustion with a constant diameter of the charge is observed with increased density, while the combustion of the charges of less density is stable.

The extinction with combustion of porous charges can be explained if we utilize the general concepts about the critical diameter of combustion, the concept about which was introduced by Andreyev [36]. The critical diameter d_c characterizes the ability of explosives to burn and is defined as the minimum diameter of the charge at which the combustion of explosives is still possible. The impossibility of combustion with a diameter less than the critical is caused by the noncompensating heat dissipation from the thoroughly heated layer and combustion zone into the ambient medium. Therefore, all those factors (increase in external pressure, initial temperature) which decrease the relative heat losses and produce an increase in the rate of combustion lead to a

reduction in the value of the critical diameter. Of considerable importance also is the shell of the charge - the thermal conductivity of its material and the thickness of the walls.

Let us examine how the critical diameter depending on the density is changed. In works [37, 38] it was noted that an increase in the density of the fusing explosives (tetryl) raises the capability for combustion (d_{cr} decreases), and in the case of nitrocellulose the opposite picture is observed.

Thus, unlike the effect of pressure and initial temperature, the role of density on the value of the critical diameter of combustion proves to be different depending on the nature of the explosives. This shows one of the specific features of the combustion of porous systems. This fact is of interest and deserves attention. At the same time the results available in literature [37, 38] on this question are extremely scarce. Since the obtaining of charges with different porosity is conjugate with definite systematic difficulties, earlier experiments were conducted with the specimens either of the maximum density (prepared nitroglycerine and pyroxylin powder) or of bulk density or density close to it.

In order to trace the nature of the change in $d_{cr}(\rho)$ in a wide density range, we conducted additional experiments [39]. For a rough estimate of d_{cr} , the method of cones was applied. A refinement of the obtained values was conducted by the combustion of cylindrical charges. In order to decrease the lateral heat losses and exclude as far as possible the heating of the substance as a result of the propagation of thermal wave along a shell, the latter was prepared from materials with a low value of the coefficient of thermal conductivity (plexiglass, asbestos cloth). Used was a mold of rectangular cross section, which made it possible comparatively easily to obtain, after the appropriate treatment, the extended (30-50 mm) cylindrical and conical charges of high density. Then the charges were glued into the shell. The

system of ignition provided the uniform combustion of the investigated specimen over an entire surface of cross section.

The obtained results are represented on Fig. 15. Thus, the existence of the lower (for fusible explosives) and upper (for "infusible" explosives¹) limits of the extinction of combustion directly follows from the different nature of the dependence of the critical diameter on density. It will be shown below that in accordance with dependence $d'_{kp}(\delta)$ for the examined explosives the nature of the change with the density of the rate of combustion proves to be also substantially different.

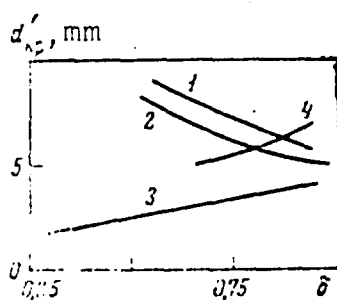


Figure 15. Dependence of the critical diameter of combustion on relative density ($p=1$ atm): 1 - cyclonite, $r=100-200 \mu$; 2 - tetryl, $r=100-200 \mu$; 3 - 10% poly-styrene + 90% AP, $r=15 \mu$; 4 - pyroxylin No. 1.

We will turn to the explanation of the causes which define the type of dependence $d'_{kp}(\delta)$. For this purpose let us examine how there is a change in heat losses in the process of the combustion of the charges with different density and, first of all, heat loss from the zone of reaction to the substance.

In the case of fusing explosives the correct way is outlined by Andreyev [38], who joined the increase in d'_{kp} at low densities with an increase in heat losses to the condensed phase as a result of the penetration of the fusion in the pores. In actuality, however, the situation is somewhat different, and the role of

¹"Infusible" explosives are understood as substances the burning surface of which is gas permeable. As follows from the experiment (see § 8), this condition is satisfied by pyroxylin [nitrocellulose], ammonium perchlorate and a mixture on its base.

fusion is not limited only to this. The optical observations of the burning surface of cyclonite showed that in charges with the low density close to bulk, the film of fusion in the process of combustion is continuously moved over the surface, which is accompanied by oscillations of the flame. The motion of the fusion is caused by the nonuniform increase in it by following gaseous products as a result of the nonuniformity of the burning surface and by foaming, which occurs as a result of expansion with the heating of the gas bubbles.

The drops of fusion moving along the surface and the separate formations, which contain the fused solid particles, under the action of forces of surface tension are enlarged, and the phenomenon of agglomeration occurs. The motion and agglomeration of the drops of fusion lead to an increase in the heat losses, to the constant destruction of the thoroughly heated layer of explosives prepared for combustion. Very interesting is the form of surface of the combustion of cyclonite after attenuation which occurs when limiting conditions (with $d=d_{lim}$) are reached. The end of burning can be easily obtained if we utilize, for example, conical charges. It turned out that the fusion with inclusions of the fused solid particles converges, as a rule, on the periphery, and the remaining part of the surface is devoid of the fusion. It causes no doubts that a sharp reduction in the burning surface as a result of the agglomeration of the separate drops of fusion was the reason for end of the burning.

With an increase in the density, the motion of the fusion and the oscillations of the flame cease, and the molten layer becomes solid. The heat losses originated by the movement of the molten film logically disappear, and, as a consequence of this, there is an increase in the capability for combustion, and the critical diameter decreases (Fig. 15). In this connection it should be noted that according to [40] for the fusing secondary explosives of low density, unlike liquid explosives, the rate of combustion with a decrease in the diameter is maintained constant up to

attenuation. The nonconformity with theory [41], which predicts a decrease in the rate of combustion in proportion to approach to the limit, the authors [40] correctly explain by heat losses due to the motion of fusion along the surface.

For the "nonfusible" explosives with "dry" burning surface, the basic reason for incidence d_{cr} with a decrease in the density is the limited penetration of the gaseous products in the pores. While not being in a state to ignite the explosive, the penetrating gases preheat it and produce a change in the thoroughly heated layer. The additional heat supply in the explosive from the gaseous phase, which rises with a decrease in the density, compensates for the lateral heat losses and makes possible stable combustion in the charges of a small diameter. The effect of the limited penetration of products into the pores is observed, as this will be clear from the following presentation (§ 3), not only at low (bulk) densities, which was assumed by Andreyev [38] in examining the reasons for the emergence of the fluctuating and nonuniform combustion, but also with the combustion of very compact charges.

In the explanation of increase d_{cr} with density, it is necessary to consider also [38] that with an increase in the density the thermal conductivity of the explosive, and, therefore, the heat withdrawal in the condensed phase increase.

§ 7. Laws Governing the Laminar Combustion of Porous Systems

For the condensed systems the most widespread were the approximate thermal theory of Zel'dovich-Belyayev combustion, a brief presentation to which we will be restricted. In this theory it is accepted that the reaction rate exponentially increases with the temperature, and the combustion occurs in one narrow zone in the gaseous phase. The basic heat release is concentrated in the narrow temperature range with a width of order of RT_p^2/E near the maximum temperature of combustion T_p . The heat transfer from the

zone of reaction to the nonreacting substance is realized by means of thermal conductivity.

Initially the theory was developed by Zel'dovich and Frank-Kamenetskiy in connection with the combustion of the gases [41, 42]. After the fundamental investigations of Belyayev, who showed that the combustion of volatile secondary explosives occurs in the gaseous phase similarly to the combustion of homogeneous gas systems, the theory was widespread without any supplements for the combustion of volatile explosives. The fullest and most successful comparison of theory with the experiment was conducted precisely in an example of volatile explosives [5].

According to this theory, expression for the mass rate of combustion takes the form

$$u_M = u_p \sim \sqrt{\frac{2\lambda}{g^2} \Phi_{\max} \frac{101^2}{L}}, \quad (13)$$

where λ is the coefficient of the thermal conductivity of the substance which flows into the reaction zone; E - activation energy; g - heat of reaction; Φ_{\max} - the rate of heat liberation per unit volume of the zone of reaction at the combustion temperature T_r .

In theory it is accepted that $\Phi_{\max} \sim \exp(-E/RT_r)$. For the reaction of the n -th order $\Phi_{\max} \sim C^n$ (C is the concentration of the reactant). Then for gas-phase reaction we obtain the following approximation:

$$u_M \sim p^{2n} \exp(-E/2RT_r).$$

Principally the theory is applied also to the case when the reaction is realized in one narrow zone of the condensed phase.

The study of the laws and mechanism of the stationary combustion of nonporous explosives and powders is the subject of many works. The basic results are quite fully presented in monographs [38, 44]. The contemporary concepts about the mechanism of combustion and the basic development trends of the combustion theory are contained also in review works [45-47].

Let us examine the basic laws governing the combustion of porous charges.

From the theory it follows that:

a) the independence of the mass rate of combustion of density for the case of volatile explosives ($u_M = \text{const}$), when the leading reaction occurs in the gaseous phase¹;

b) an increase in the mass rate of combustion with an increase in density if the reaction is realized in the narrow zone of the condensed phase. In this case $\Phi_{\text{max}} \sim \delta^n$. If one assumes that the density of the substance δ does not change in the wave of heating, then from (13) we have

$$u_M \sim \sqrt{\lambda \delta^n}.$$

In accordance with the data available in the literature, it is possible to consider approximately that the thermal conductivity of the explosives $\lambda \sim \delta^2$. Then

$$u_M \sim \delta^{1+n/2}. \quad (14)$$

The presence of heat losses with combustion causes (case a) or amplifies (case b) the incidence in the rate of combustion in proportion to a decrease in density.

¹An analogous form of the dependence ($u_M = \text{const}$) must be observed for the fusing secondary explosives, when the molten explosive preliminarily burns.

The account presented above is correct in the absence of convection heat transfer from the combustion zone into the non-reacting substance when there does not occur the penetration of products of combustion into pores. We will turn to the available experimental results.

In the experiment, as a rule, the linear burning rate is determined. Implied by the linear burning rate u is the apparent rate of movement of the entire combustion zone.

The combustion of the porous systems is usually characterized by the mass flow rate u_m , which is obtained by the multiplication of the linear rate by the density of the explosives: $u_m = u \rho$. The mass flow rate is equal to the mass of the substance, which burns per unit time per unit area of the cross section of the charge.

Let us designate by $\xi = u_m(\delta)/u_m(\delta')$ the ratio of the mass rate of combustion at the given density δ to mass flow rate at the highest density δ' which is utilized in the experiment. Value δ' is usually lower than the maximum density δ_{max} , since by the method of pressing it is difficult to obtain continuous specimens. Furthermore, at high density the combustion of a number of substances ceases, which is connected with the achievement of the upper limit on density.

In composite Table 3 data known to the authors on the dependence of the mass flow rate of laminar combustion on density are given (experiments were conducted at atmospheric pressure). Data for some substances are also represented on Fig. 16.

One should note first of all that strict constancy of the mass rate of combustion in the wide interval of the variation in density is not observed virtually for any of the investigated explosives.

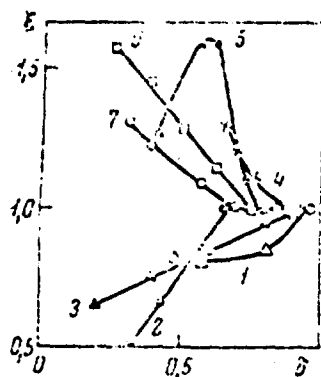


Figure 16. Dependence of value $k = u_M(\delta) / u_M(\delta')$ on relative density ($p=1$ atm): 1 - cyclonite; 2 - 25% Al + 75% Fe_2O_3 ; 3 - polyvinylnitrate; 4 - mercury fulminate; 5 - 2% Cu_2O + 98% AP; 6 - pyroxylin No. 1; 7 - 10% polystyrene + 90% AP.

In the form of dependence $u_M(\delta)$ the conditionally investigated substances can be divided into two groups.

1. For substances of the first group an increase in the mass rate of combustion with an increase of density ($\delta < 1$) is characteristic. It includes the secondary explosives (cyclonite, tetryl), nitroglycerin powder (finely ground), polyvinylnitrate, and thermite compositions. The distinctive feature of the substances of this group is the ability to be melted or liquified in the process of combustion.

Another feature of the majority of the substances of this group entails the fact that of vital importance with their combustion is the heat release in the condensed phase. The course of total-exothermic reaction in the k-phase and the existence of the liquid-viscous layer, which is made foamy by bubbles of gaseous decomposition products with the combustion of nitroglycerin powders, was established by Pokhil [50, 55]. The rate of combustion of the thermite composition of 25% Al + 75% Fe_2O_3 and especially the gas-free composition of 70% (25% Al + 75% Fe_2O_3) + 30% Al_2O_3 is determined by chemical reactions in the fusion [51, 53]. According to data [52], the leading reaction in the combustion of polyvinylnitrate also occurs in the liquid-phase - in the foam zone.

Consequently, the increase in the mass rate of combustion observed in the experiment with an increase in density corresponds to the predictions of the theory. However, the dependence $u_M(\delta)$

Table 3. Dependence of the mass rate of combustion μ , ($\text{g}/\text{cm}^2 \cdot \text{s}$) on the relative density for a number of substances ($p=1 \text{ atm}$)¹.

Substance	Initial dimension of particles μm	Flam- m- eter of charge, mm	Relative density $\delta = \rho/\rho_{\text{max}}$							Litera- ture	
			0,3	0,4	0,5	0,6	0,7	0,8	0,9		0,95-0,99
Cyclonite ($\rho_{\text{max}} = 1,80 \text{ g}/\text{cm}^3$)	5	10	—	—	0,038	0,038	0,04	0,072	0,015	0,048	(See ²)
Petryl ($\rho_{\text{max}} = 1,78 \text{ g}/\text{cm}^3$)	—	24	—	—	0,062	0,065	—	—	—	—	[35]
Pellivanitrate	—	8	0,13	0,137	0,145	0,155	0,162	0,172	1,82	—	[32]
25% Al + 75% Fe ₂ O ₃ ($\rho_{\text{max}} = 4,23 \text{ g}/\text{cm}^3$)	20	10	1,2	1,6	1,95	2,1	2,85	—	—	—	(See ²)
70% (25% Al + 75% Fe ₂ O ₃) + 30% Al ₂ O ₃ ($\rho_{\text{max}} = 4,0 \text{ g}/\text{cm}^3$)	—	—	0,28	0,31	0,4	0,55	—	—	—	—	[1]
Nitroglycerin powder "H" ($\rho_{\text{max}} = 1,60 \text{ g}/\text{cm}^3$)	400	10	—	0,07	0,075	0,08	0,095	0,09	0,092	0,095	(See ²)
The same	1500	10	—	—	—	0,22	0,14	0,09	Does not burn	—	
10% polystyrene + 90% AP ($\rho_{\text{max}} = 1,80 \text{ g}/\text{cm}^3$)	15	10	0,183	0,172	0,162	0,15	0,142	0,14	0,14	0,14	(See ²)
2% Cu ₂ O + 98% AP ($\rho_{\text{max}} = 1,975 \text{ g}/\text{cm}^3$)	15	10	—	0,11	0,132	0,145	0,12	0,09	Extin- guishes	0,15	(See ²)
Pyrexyl in No. 1 Mercury fulminate ($\rho_{\text{max}} = 4,31 \text{ g}/\text{cm}^3$)	~50	6	0,235	0,215	0,195	0,175	0,16	0,15	Explosion	6,90	[1]
							6,90	6,1	5,70	—	[5]

¹Part of the experimental data is taken from the curves.
²Data of the authors.

proves to be weaker than this which follows from theory (14), on the assumption that the leading stage of combustion is found in the condensed phase.

The reduction of $u_m^{(0)}$ with a decrease in density for a volatile explosive - cyclonite, the leading reaction in the combustion of which is found in the gaseous phase, is connected usually [44] with a decrease in the heat release per unit volume and the corresponding increase in the role of heat losses. It is assumed that this effect has common nature for volatile explosives.

As a whole, the derivations which follow from the dependence $u_m^{(0)}$ for substances of the first group agree with the existing concepts about the mechanism of their combustion and can be explained within the framework of one theory of combustion.

2. The mass rate of combustion of substances of the second group decreases with an increase in the density. This group includes the "infusible" with the combustion of the substance: pyroxylin, mercury fulminate, ammonium perchlorate (catalyzed) and a mixture of AP with a combustible addition.

It was noted above that the critical diameter of combustion for these substances (unlike the first group) is decreased in proportion to a decrease in the density. Thus, a definite parallelism is observed between the nature of the change with the density of the mass flow rate and the critical diameter of combustion for the defined representatives of these two groups of substances. The laws governing the combustion of substances of the second group are of considerable interest not only because they are not placed in the existing representations, but, first of all, because precisely with the combustion of the "infusible" systems one should expect the manifestation of specific features characteristic for porous systems. At the same time in literature there is very limited information on this question. Therefore, we undertook a more detailed study on the stable uniform combustion

of porous "infusible" systems.

§ 8. Combustion of "Infusible" Substances [39]

Selected as the "infusible" substances were pyroxylin, a mixture of ammonium perchlorate with a combustible addition (polystyrene), ammonium perchlorate, catalyzed 2% Cu_2O (particle sizes of the components $r \approx 15 \mu\text{m}$).

In literature direct indications about the possibility of the melting of pyroxylin are absent. As regards ammonium perchlorate, until recently it was considered that ammonium perchlorate sublimates with combustion. However, in recent works devoted to the study of the mechanism of the combustion of AP, it was reported that ammonium perchlorate is melted with combustion. According to [54], the melting point of AL is high ($T_m \approx 850 \text{ K}$), and the formed layer of fusion is very small and not continuous. The selected substances belong to the "infusible" category, since the experiments carried out by us showed that the burning surface of the porous charges of these substances is gas-permeable, and therefore the continuous molten layer is absent.

In experiment the following characteristics were determined: the dependence of the mass rate of combustion on density $u_m(\delta)$, the distribution of temperature in the condensed and gaseous phases $T(\delta)$ and also the pressure change in the pores of the burning charge $p_u(\delta)$. Thermocouples of tungsten-rhenium and copper-constantan 30 μm in thickness were used. The recording of pressure in the pores was taken near the enclosed bottom end of the charge by a sensitive liquid manometer (water, mercury) of the open type. All the experiments are carried out at atmospheric pressure.

Let us examine the obtained results. Experimental data on the dependence of the mass rate of combustion of the investigated substances on density are represented in Table 3 and, on Fig. 17. As was already mentioned, a characteristic feature of curve $u_m(\delta)$

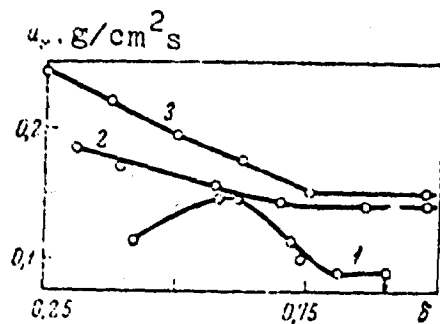


Figure 17. Dependence of the mass rate of combustion on relative density ($p=1$ atm): 1 - 2% Cu_2O +98% AP; 2 - 10% of polystyrene + 90% AP; 3 - pyroxylin No. 1.

lies in the fact that with a decrease in the density, beginning with a certain defined value, there occurs an increase in the mass rate of combustion. For the catalyzed AP on curve $u_m(\delta)$ the maximum of rate is observed. One should emphasize that in this density range the combustion is uniform and stable, and the values of the rates are reproduced well. An increase in the mass rate of combustion with a decrease in the density indicates the presence of convection heat transfer from the combustion zone into the non-reacting substance and the limited penetration of products of combustion into the existing pores. In connection with the combustion of mercury fulminate, for the first time Belyayev focused attention on this possibility [5, 49]. The findings testify to the fact that the penetration of products into the pores with stable burning is characteristic not only for the quick-burning mercury fulminate, but is a common property of the "infusible" explosives, including substances which burn at low (about mm/s) rates. The penetration of the products is observed under conditions of combustion at strictly constant low (atmospheric) pressure and, which is especially important, with the combustion of very dense systems. For perchlorate compositions and pyroxylin, an increase u_m is started with $\delta=0.7-0.8$, and for mercury fulminate - with $\delta=0.9$.

Before stating the subsequent results which give the direct confirmation of the validity of the penetration of products of combustion into the pores, let us indicate the fact which is indirect to the confirmation. If we decrease the density of the substance, then with $\delta < 0.65$ for mercury fulminate [5] and

$\delta < 0.12$ for pyroxylin [56] there occurs the destabilization of the combustion, which is characterized by a sharp (by an order of magnitude and more) increase in the rate of combustion. The combustion becomes nonuniform fluctuating. In the case of mixtures on the basis of AP the combustion at atmospheric pressure up to the minimum (bulk) density is stable. However, the destabilization of the combustion of a mixture of 10% PS + 90% AP appears, if we somewhat modify the experimental conditions: for example, conduct combustion in the long gas-bleeding tube when as a result of the gas friction against the walls of the tube on the burning surface a small ($\sim 10^{-3}$ atm) pressure differential appears. At present it is convincingly shown that the destabilization of combustion occurs as a result of the filtration of gaseous products into the pores (see Chapter IV).

Let us turn to results of the thermocouple measurements made with the stoichiometric mixture of ammonium perchlorate and polystyrene ($\rho = 0.65 \text{ g/cm}^3$). First of all, it was noted the noticeable deviation in the temperature profile in the condensed phase from the Michelson: the thickness of the thoroughly heated layer is increased 3-4 times.

Also measured were the temperature of the surface T_n [on the bend of the temperature curve $T(x)$] and the gradient of temperature in the gaseous phase near the surface $(dT/dx)_{T=T_n}$, which made it possible to evaluate the quantity of heat q liberated with combustion in the condensed phase.

Disregarding radiation as a result of smallness, from the equation of heat balance we have

$$q = c_p(T_n - T_0) - \frac{\lambda}{u_M} \left(\frac{dT}{dx} \right)_{T=T_n}, \quad (15)$$

where c_p is the heat capacity of the k phase; λ - coefficient of the thermal conductivity of products in the gaseous phase; T_0 - initial temperature.

By substituting in (15) values of $c_p = 0.35$ cal/g·deg, $\lambda = 1.6 \cdot 10^4$ cal/cm·s·deg and the experimentally measured values, $T_u = 600^\circ\text{C}$, $(dT/dx) = 3.1 \cdot 10^4$ deg/cm, we obtain $g = 175$ cal/g.

It is necessary to keep in mind that the heat in the k phase is composed of two components: together with the introduction of heat by the penetrating products heat release as a result of chemical reactions occurs [48]. A strict separation of the indicated components is very difficult, since they act simultaneously. Therefore, a rough estimation is feasible. According to the measurements carried out, the thermal effect of total-exothermic reactions in the condensed phase with combustion of the monolithic specimens, when there is no convection, is approximately 100 cal/g. This value is maximum, since with a decrease in the density of the reactant in accordance with (14) the heat release because of reactions in the k phase must be decreased. However, even if we accept this knowingly high value, we will find that by the products penetrating into the pores not less than 75 cal/g is introduced.

Interesting data were obtained in experiments on the pressure measurement in pores of the burning charge $p_n(t)$ (diagram of the experiment and results were shown on Fig. 18)¹. It was established that with the combustion of pyroxylin and mixtures with ammonium perchlorate as the base with the combustible addition in the pores the rarefaction of relatively external atmospheric pressure $\Delta p = p_n - p_0 < 0$. is recorded. In this case at the moment after ignition, the rarefaction increases, whereupon the saturation ($\Delta p = \Delta p_n$) begins. Despite the fact that the combustion is continued, the pressure in the pores does not change.

¹In this series the experiments were conducted with charges of large diameter ($d = 16$ and 30 mm), which made it possible to avoid the distorting effect of the additional free space which unavoidably appeared with the connection of the manometer.

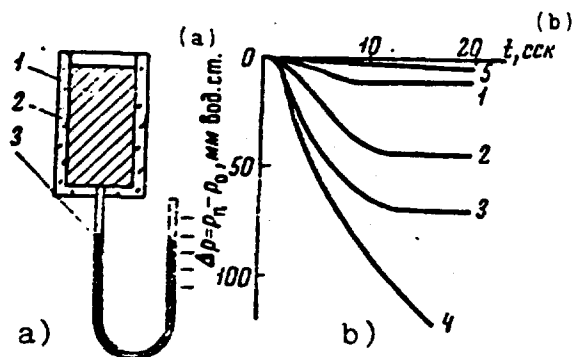


Figure 18. Diagram of experiment (a) and results (b) of pressure measurement in pores of charge $\Delta p_{\Pi}(t)$ with the combustion of the specimens of a mixture of 10% PS + 90% AP with different density ($p=1$ atm): a: 1 - charge; 2 - plexiglass shell; 3 - manometer; b: 1 - $\delta=0.35$; 2 - 0.5; 3 - 0.61; 4 - 0.8; 5 - 0.9. Key: (a) millimeters H_2O ; (b) s.

For purposes of the detailed investigation of this phenomenon, the density effect of the specimens and composition of the mixture of AP + polystyrene was studied.

It was found (see Fig. 18) that with an increase in the density (a decrease in size of the pores d_{Π}) the value of rarefaction Δp_{Π} is increased, reaches a maximum value and then sharply decreases.

Thus, for instance, for a mixture of 10% PS + 90% AP the deepest rarefaction $\Delta p_{\Pi} \approx 0.1$ atm is observed at sufficiently high density $\delta \approx 0.8$. It is interesting that at approximately this density there begins an increase in the mass rate of combustion with a decrease in the density (see Fig. 17). In the interval $\delta < 0.8$ the value of rarefaction Δp_{Π} is inversely proportional to the mean hydraulic diameter of the pore: $\Delta p_{\Pi} \sim 1/d_{\Pi}$, where value Δp_{Π} was determined from formula (2).

In charges with high density ($\delta=0.9-0.95$) the rarefaction is virtually not recorded. Thus, there is the optimum dimension of the pores at which the observed effect is exhibited especially greatly.

It was established that the magnitude of rarefaction depends not only on the dimension of the pores, but also on the composition of the mixture. The pattern close in nature to that described above was observed with the combustion of pyroxylin.

The emergence of rarefaction in the pores of the burning charge, at first glance, contradicted the fact of the penetration of the products of combustion into the pores of the charge. For the purpose of an explanation of the physical nature of the observed effect, several possible hypotheses were examined.

Let us note only two of them. Proving to be outwardly attractive was the stream hypothesis, according to which the suction of air which is contained in the pores was caused by the ejector action of the ebbing streams of the products formed with the combustion of single particles. However, according to this point of view, the value of rarefaction must not exceed 10^{-4} atm, which is several orders lower than the value observed in the experiment.

The second hypothesis, which, in our opinion, corresponds to actuality, entails the following. Flowing into the charge at a pressure close to p_0 , the hot products of combustion fill the pores and, in transferring the heat to the surrounding substance, are cooled, which regularly must be accompanied by a pressure drop in the semiclosed pore space. The condensation of the products also contributes to a decrease in the pressure in the pores. This hypothesis was confirmed by the direct experiments the essence of which consisted in the fact that injected into the porous specimen of inert substance (MgO) with a dead-end bottom was hot nitrogen with different temperature or products of combustion. In these experiments a rarefaction whose value increased with an increase in the temperature of the blown gas was observed. In accordance with this hypothesis, it was to be expected that the pressure drop in the pores will be greater, the higher the degree of cooling of the gas and concentration of products capable of condensation.

Specifically, from these positions the effect of the dimension of the pores and composition of the mixture observed in the experiment finds its explanation.

Thus, the entire totality of the presented data indicates the fact that with the combustion of the porous "infusible" substances there virtually always occurs the penetration of the products of combustion into pores, and the combustion of such systems is not normal¹. It is necessary to emphasize that the stable laminar combustion was examined when the penetration products did not cause the ignition of the internal surface of the pores.

Data presented in § 6-8 correspond to the combustion at strictly constant atmospheric pressure. The combustion of porous explosives at pressures exceeding atmospheric was investigated [37, 38, 82]. Combustion was conducted in the bomb of "constant pressure." Unfortunately, the findings were not analyzed from the viewpoint of the possible effect of the penetrating products, which is contributed by a pressure increase in the bomb with the combustion of the charge².

The effect of the nitrogen filling the pores of the charge was also not examined. Therefore, the interpretation of the available data is difficult.

§ 9. On the Dynamic Pressure Increase on the Burning Surface

The pressure on the surface of combustion of the condensed substances p' can exceed the pressure in the surrounding volume

¹Besides the thermal effect, the penetrating products they can exert a catalytic action.

²The penetration of gaseous products into pores of the charge does not occur if formed on burning surface is a continuous molten layer, which occurs, for example, with combustion of the secondary (fusible) explosives with low porosity.

p_0 if the heat release in full or in part occurs in the gaseous phase. The pressure increase appearing on the burning surface is usually called dynamic $\Delta p_x = p' - p_0$.

As is known, unlike detonation, combustion occurs with a lowering in the pressure and the expansion of reaction products. Combustion at a constant rate corresponds to the lower branch of the Hugoniot adiabatic curve. The rate of those products of combustion flowing from the surface increases in accordance with the nature of the heat release with respect to the height of the flame jet. Thus, between the sections which consist of the combustion zone there is a pressure differential Δp_x , whereupon the pressure is maximum on the burning surface.

Historically the question of the determination of Δp_x was given considerable attention [4-8, 38], which was conditioned by the following facts.

Previously it was proposed [4-8, 38] that the dynamic pressure increase is the basic reason for the destabilization of combustion. Although, as further investigations showed, this reason is not basic and universal (the real reasons are considerably more widespread and varied, see § 12), under certain conditions, for example, with combustion under constant external pressure one must not fail to consider Δp_x . Furthermore, the fact of the existence of Δp_x was attracted for the explanation of the dependence of the rate of the quick-burning explosives on pressure [58].

Let us determine the pressure differential appearing on the burning surface by utilizing the laws of the conservation of mass and momentum. For simplicity let us examine the case of the one-dimensional combustion of compact (nonporous) explosives. We will characterize the state of the gas directly near the surface by pressure p' , density ρ' , rate v' , temperature T' (v' - the rate of the gas separating from the surface, in the general case $v' \neq 0$; T' is temperature of surface). The gas in this section

contains products of gasification (vaporization) of the condensed phase. Let us designate the appropriate parameters for end products after the combustion zone by p_1 , ρ_1 , v_1 , and T_1 . We assume that with combustion the condensed particles are absent.

Pressure p_1 in the end products of reaction is determined by the boundary condition at infinity, and for subsonic flow it is equal to pressure p_0 in the surrounding volume ($p_1 = p_0$). A pressure differential, thus, can arise only because of compression near the surface of products of gasification.

Let us write the equation of mass and momentum conservation in the form

$$\begin{aligned} \rho u &= \rho' v' = \rho_1 v_1, \\ p' + \rho u v' &= p_1 + \rho u v_1, \end{aligned}$$

whence

$$\Delta p_x = p' - p_1 = (\rho u)^2 \left(\frac{1}{\rho_1} - \frac{1}{\rho'} \right). \quad (16)$$

If $\Delta p_x \ll p_1$, which is correct for the overwhelming majority of the explosives, then from (16) we will obtain

$$\Delta p_x = \frac{(\rho u)^2 R}{p_1} \left(\frac{T_1}{M_1} - \frac{T'}{M'} \right), \quad (16')$$

where M' and M_1 are molecular weights in the appropriate sections of the gas flow.

From (16') it follows that a noticeable pressure increase on the burning surface can be realized for the quick-burning explosives and with a considerable change in the value $(T_1/M_1) - (T'/M')$.

If the products of gasification and combustion contain the condensed particles, the weight fraction of which consists, respectively, of ϵ' and ϵ_1 , and their rate is equal to the gas rate, then the pressure differential, according to calculation [57], is

determined by the expression

$$\Delta p_x = (\rho_1)^2 R \frac{(1 - \epsilon_1) T_1 / M_1 - (1 - \epsilon') T' / M'}{p_1 - (1 - \epsilon_1) (\rho_1)^2 / \rho_1} \quad (17)$$

If with a decrease in the external pressure rate of combustion decreases more weakly than linearly, then the rate of the outflow of products $v_1 = u\rho_1/\rho_1$ increases. However, it cannot exceed the speed of sound $c = \sqrt{\gamma RT_1/M_1}$. This means that the pressure in the products cannot be lower than a certain minimum value:

$$p_{\min} = (1 - \epsilon_1) \rho_1 \sqrt{\gamma RT_1/M_1} \quad (18)$$

In such a manner, as soon as the speed of sound is reached, the pressure in the products $p_{\min} = p_1 > p_0$ is maintained constant independently of a further decrease in the external pressure¹. In this case the surface pressure of the charge is $p_{\min} + \Delta p_x$, where Δp_x is determined from expression (17). This fact limits the value of the minimum pressure at which the explosive burns [5] and is essential, first of all, with combustion in a vacuum.

For determining Δp_x in principle an account of the multistage nature of the process of combustion is not required. It suffices to be restricted to an examination of the transition from the initial state of the products of combustion (of surface) to the final state. In this case special importance is acquired by the correct determination of the temperature and composition of products of combustion in the indicated sections.

¹According to the estimation carried out in work [57] for mercury fulminate, the value $p_{\min} = 4-8$ mm Hg (not allowing for the effect of solid particles on the speed of sound). A considerably higher value $p_{\min} = 4$ atm is obtained for the most quick-burning explosive - lead styphnate.

Examined was the one-dimensional combustion, which is realized if the charge of the explosive is placed into a casing. In the absence of a casing the lateral expansion of the flowing products occurs, and the flow becomes nonuniform. In this case the pressure increase is lower than that with one-dimensional combustion. In the simplest case when burning surface is plane, and the zone of heat release forms a cone with an apex angle ϕ , the pressure differential can be determined from expression (17), where instead of $(\rho u)^2$ it is necessary to substitute $(\rho u \sin \frac{\phi}{2})^2$.

In general the problem of the determination of the pressure differential in an oblique wave front with energy release is examined in [86].

Let us turn to the presentation of results of the experimental measurement of excess pressure on the burning surface. Investigated were mainly the initiating and quick-burning explosives, since for secondary explosives and powders Δp_x is so small that it virtually cannot be recorded. It follows from the very beginning to note that the available experimental data are very scarce and obtained, as a rule, by the method based on the measurement of the reaction F, which the burning charge exerts on the elastic support. It was assumed that the pressure differential, determined from expression $\Delta p = F/S$ (S - cross-sectional area of the charge) is a dynamic pressure increase. By the indicated method Belyayev conducted the determination of Δp_x for some quick-burning explosives at atmospheric pressure [5].

The experiments were conducted with specimens 4 mm in diameter, the lateral surface of which was armored with collodion. Attention is drawn to the fact that the measured values of Δp_x are very low (Table 4).

Table 4. Mass rate of combustion w_m and value of dynamic pressure increase Δp_m for some initiating and quick-burning explosives ($p=1$ atm).

Substance	$w_m, \text{g/cm}^2 \cdot \text{s}$	$\Delta p_m, \text{mm Hg}$	Literature
Trinitroazidobenzene $\text{C}_6(\text{NO}_2)_3(\text{N}_3)_3$	1.1	4	[5]
Tricycloacetone peroxide $\text{C}_3\text{O}_6(\text{CH}_3)_6$	1.15	4	[5]
Potassium picrate $\text{C}_6\text{H}_3(\text{NO}_2)_3\text{OK}$	2.74	-	[5]
	1.3	5	[5]
	(in a casing)		
Mercury fulminate $\text{Hg}(\text{ONC})_2$	5.9	13	[5]
		10-15 ¹	[39]
Lead styphnate $\text{C}_8\text{H}_8(\text{NO}_2)_8\text{O}_2\text{Pb} \cdot \text{H}_2\text{O}$	100	85-90 ²	[38]

¹ shell is less than 40 mm long.

² In a casing of more than 40 mm long.

The greatest interest is in data obtained for the mercury fulminate, the mechanism of the combustion of which is investigated sufficiently thoroughly [5, 49]. It was established that the combustion of mercury fulminate occurs in two stages. The rate of combustion is determined by the low-temperature (800-1000°K) stage which adjoins the burning surface. The glow in this zone is virtually absent. At this stage not more than 20-35% of the parent substance is decomposed, remaining part is dispersed and burns up to the end products in the second high-temperature (glowing) zone, which is located at a considerable distance from the surface. The dark zone and the largest dispersed particles in the form of separate glowing tracks are visible in the photograph of Fig. 19 [93]. With a decrease in the pressure the width of the dark zone increases and at 40-50 mm Hg the bright glowing flame disappears. The dependence of rate of combustion on pressure (with $p < 1$ atm) is approximated by the linear function of

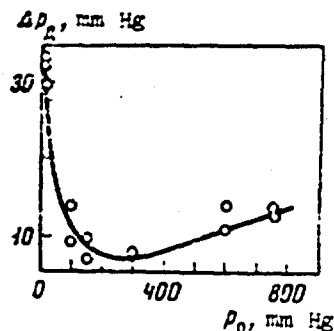


Figure 19. Photograph of the combustion of mercury fulminate ($p=1$ atm).

the form $u = A + Bp$. An analysis of the gaseous combustion products for a low-temperature stage gives the average value of the molecular weight of products $M \approx 120$. For the high-temperature stage the tentative thermodynamic calculation (not allowing for dissociation), according to the usually recommended equation of reaction $Hg(O\dot{N}C)_2 \rightarrow Hg + 2CO + N_2$, gives $T_1 \approx 3500^\circ K$, $M_1 \approx 70$, and $T_1/M_1 \approx 50$.

At pressure p_0 less than atmospheric, for mercury fulminate is experimentally the dependence Δp_x on the external pressure p_0 (Fig. 20), which takes a unique form is determined [5]. This nature of the curve (with a minimum) follows from expression (16) with the substitution in it of the dependence $u(p)$ in the form of $u = A + Bp$.

Figure 20. Dependence of dynamic pressure increase Δp_x on the burning surface of mercury fulminate on the value of the external pressure p_0 .



However, the computed values of Δp_x lie noticeably below experimentally measured (calculation was conducted taking into account only the low-temperature stage, which is correct for combustion in a vacuum).

An interesting result was obtained [39] with combustion at atmospheric pressure of specimens of mercury fulminate pressed up to high density ($\delta=0.97$) into thin-walled tubes of different length $L_{\tau p}$ (Fig. 21). The height of the specimen is maintained

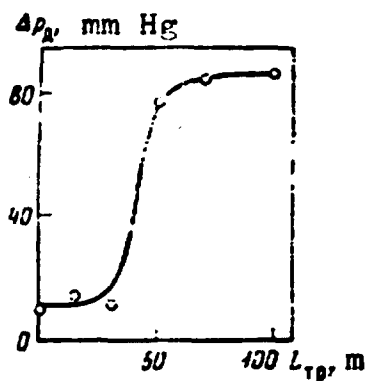


Figure 21. Dependence of dynamic pressure Δp_d on the length of the gas-bleeding tube for mercury fulminate ($p=1$ atm).

constant (5 mm). Used as a measurer of reaction force was a highly sensitive piezoelectric gauge. As follows from Fig. 21, with the length of the tube $L_{tp} > 40$ mm essential increase in Δp_d from the value of 10-15 mm Hg (which coincides with data [5] up to 85-90 mm Hg is observed¹.

It is logical to assume that the obtained result is conditioned by the stepwise nature of the process of combustion so that with $L_{tp} > 40$ mm in the tube there is placed the high-temperature stage, in which the afterburning of the dispersed particles occurs, and the basic heat of reaction is separated. In this case the excess surface pressure is determined by the total effect of both stages (entire combustion zone) with the predominant effect of the last stage². Confirmation of this point of view is the satisfactory accord of the experimental (≈ 90 mm Hg) and theoretical (≈ 130 mm Hg) values of Δp_d especially if one considers that with the calculation was utilized the high value $T_1/M_1 \approx 50$, which corresponds to the products of full combustion.

Let us note one characteristic feature inherent in the quick-burning explosives [5]. At the initial moment of the combustion

¹ This fact cannot be explained by the frictional effect of the products against walls of the tube.

² In the short ($L_{tp} < 40$ mm) tube the appearing differential is determined by the low-temperature stage of combustion.

of mercury fulminate on notation $\Delta p_{\pi}(t)$ a considerable jump of pressure is observed, and on an optical oscillogram the increased rate in combustion on section in several (up to 2-4) millimeters is recorded, whereupon the combustion is spread at constant velocity¹.

This feature is exhibited both with the ignition by a spiral and through a layer of slowly burning substance. The noted effect, which can be explained within the framework of the nonstationary theory of combustion [43], is connected with the creation in the quick-burning explosives with ignition of a sufficiently thick thoroughly heated layer and with its accelerated burnout. Quick-burning explosives are thus a good model for the study of the nonstationary processes of combustion.

In conclusion it should be noted that the results presented here referred to the combustion of very dense explosives.

¹An increase in the rate of combustion in the initial stage was noted also for other quick-burning substances (styphnate and lead picrate [38]).

CHAPTER III

DISTURBANCE OF THE STABLE COMBUSTION OF THE GAS-PERMEABLE POROUS SYSTEMS

The stable stationary combustion of explosives under certain conditions is disturbed, which is expressed in a considerable (dozens and hundreds of times) increase in the mass rate of combustion. Examined in this chapter is the complex of questions connected with the explanation of the mechanism of acceleration and the establishment of laws and critical conditions of the destabilization of combustion - the initial stage of the emergence of explosion.

§ 10. Basic Positions of the Stability Theory

The stability of the stationary steady-state condition of combustion of the condensed systems was theoretically investigated by Belyayev and Andreyev [4, 5, 8]. The theory is based on the examination of the equilibrium between the gas inflow and the gas vent with combustion. It was shown that the destabilization of combustion is the consequence of simple laws of gas dynamics.

Actually, the dynamic pressure increase, which appears with ignition on the charge's surface (§ 9), must lead to a certain

increase in rate of combustion, since with an increase in pressure the rate of combustion, as a rule, increases, which causes a further rise in pressure, etc. The problem, thus, was reduced to the determination of conditions under which the equilibrium establishment in the indicated process proves to be impossible, i.e., the combustion becomes unstable, and a continuous increase in the rate of combustion and surface pressure occurs. It was assumed that this path of the emergence of the instability in principle was feasible, if the solid (nonporous) charge of explosives burns.

From conditions of the equality of gas inflow and gas vent, and under the assumption of the linear dependence $u_1(p)$ Belyayev, for the first time in an example of mercury fulminate, calculated the critical rate of combustion, which corresponds to the stability limit [4].

The stability theory obtained its further development in Andreyev's work [8]. An examination was conducted for the case of the end combustion of a cylindrical charge, taking into account the dependence of the rate of combustion on pressure in the form of $u_{11} = A' + Bp^V (< 1)$. Utilized was the expression for gas vent, valid for the critical (sonic) discharge of products of combustion¹, which is established when the pressure at the surface exceeds approximately 2 times the external pressure. It was shown that the combustion is stable if with the equality of the gas inflow and gas vent the gas inflow increases with pressure more rapidly than does the gas discharge, i.e., the derivative of

¹Earlier it was noted that the indicated conditions of discharge can be realized with the combustion of explosives in a vacuum or for the very quick-burning explosives of the type of the lead styphnate.

the mass rate of combustion in terms of pressure du_m/dp does not exceed a certain limit. The value of this limit is equal to the discharge coefficient:

$$A = \sqrt{\frac{\gamma}{RT} \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}}}$$

(T - temperature of the gases, °K; $\gamma = c_p/c_v$; R - gas constant). Value A is 7-7.6 g/cm²·s·atm.

It was found that for all the studied secondary explosives the value du_m/dp is 50-200 times lower than the gas-dynamic limit. For the initiating explosives, which in the state pressed to the high relative density are capable of stable combustion, the value du_m/dp is also lower than the extreme value, although it approaches to it. One should emphasize that the initiating and quick-burning explosives (for example, mercury fulminate, lead styphnate), for which first of all destabilization as a result of the high rate of their combustion was to be expected, are characterized by a weakening of the dependence $u_m(p)$ at increased pressures [38].

Thus, one of the basic results of the theoretical examination carried out was the substantiation of the capability for stable combustion of the overwhelming majority the explosives investigated at present. In this case it was assumed that the surface of the gas inflow (combustion) is equal to the area of the gas vent (end of the burning charge), which is fulfilled if the solid nonporous substance burns. At the same time in the experiment there was observed the emergence of instability not only with the combustion of the initiating but also secondary (slowly burning) explosives, which naturally required explanation. It was assumed [4, 6] that the basic reason is an increase in the burning surface, which can occur by different means. For destabilization the burning surface must increase by not less than B/A times.

In the case of porous systems the surface grows as a result of the penetration of combustion into pores of the charge. As the investigations carried out showed [10-12, 59-70], precisely this mechanism of acceleration is most widely accepted and characteristic for solid explosives.

Specifically, obtained by this method in recent years were the especially interesting and virtually important results, to presentation of which was devoted basically this chapter.

Andreyev attached much importance to another possible mechanism of an increase in the burning surface, which is realized, if the combustion of the explosives occurs with intense dispersion, the result of which is the formation in products of combustion of the suspended matter of particles with the developed surface [38, 72]. Dispersion can have not only a chemical nature (gas-forming reaction in the condensed phase), but also a physical nature - particles of the explosives can be formed as a result of the splitting of crystals under the effect of thermal shock, as a result of the liberation of vapors of highly volatile impurities, etc. This mechanism of an increase in the gas inflow is extremely interesting, especially in connection with solid explosives. Unfortunately, with respect to this question, in literature there are very limited and partial data (see § 19).

In the case of liquid explosives the basic mechanism of the acceleration of combustion is based on the theory of self-agitation advanced by Landau [73]. According to this theory, the front of the combustion is unstable to infinitesimal disturbances when small distortions of the front of combustion spontaneously increase.

Belyayev focused attention also to the fact that with the combustion of liquid explosives nonhomogeneous in their structure the mechanism of acceleration based on the penetration

of combustion to the volume on the existing nonhomogeneities (bubbles) becomes important [4]. From these positions Belyayev explained the emergence of the explosion in the burning methyl nitrate at low pressure when there began the boiling of liquid, which is accompanied by the formation of bubbles, and the absence of explosion at higher pressures when the boiling was suppressed [2].

Such are briefly the basic positions of the stability theory of the combustion of condensed systems which with following presentation will be examined in more detail.

In conclusion it is necessary to note that in the case of gas systems the acceleration of combustion is also conditioned by an increase in the burning surface. According to the fundamental investigations of Snchelkin [75], the basic reason for the acceleration of flame is the agitation of the unburned gas, which moves ahead of the front of the flame, which causes bending and fragmentation of the front of combustion. Motion of the non-reacting mixture is realized as a result of the expansion of the products of combustion. The acceleration of combustion is observed when the Reynolds number, referred to the flow of unburned gas, exceeds the critical value, i.e., when the emergence of turbulence is unavoidable. With the ignition of the gas in the tube the agitation of the gas begins on walls of the tube and is spread to the axis. A convincing confirmation of the presented point of view is the sharp acceleration of combustion in rough tubes (in comparison with smooth), which increase the turbulence level of the flow. In accordance with Zeldovich's concepts [76], the acceleration of the combustion of the gaseous mixtures is also the result of the bending (extension) of the flame front. In the center section of the tube the flame moves faster than it does near the walls.

With the ignition of the gaseous mixture in tubes of large diameter, just as in the case of liquids, self-agitation becomes important.

In connection with solids the penetration of combustion into the pores (volume) of explosives is the basic mechanism of the destabilization of the combustion of porous systems¹.

The first experimental stability analyses of the combustion of condensed systems were carried out by Andreyev [6, 7] and Belyayev [5].

In works [6, 7] it was shown that the emergence of an explosion with the ignition of porous secondary explosives in a closed volume (see Fig. 6a) occurs if in the process of combustion sufficiently high pressure is reached. In accordance with the data [5] the combustion of the initiating explosives (mercury fulminate) at a density of $\delta < 0.65$ becomes unstable already at atmospheric pressure.

Undoubtedly, these few observations, which had in essence a qualitative nature, did not make it possible to create a single and physically substantiated quantitative picture of the phenomenon and answer some virtually important questions connected with the provision of an explosion-proof nature of processes of production and exploitation of explosives and powders. Therefore, further studies of the destabilization of the combustion of porous systems [10-12, 59-70] were conducted according to the following basic directions: 1) research on the mechanism of the penetration of combustion into pores in connection with the typical conditions of combustion; 2) determination of the critical conditions of destabilization for different classes of explosives and powders; 3) investigation of the effect on the combustion stability of parameters of the charge (gas permeability, porosity, geometric dimensions), and also of the physicochemical and thermochemical

¹With the following presentation the terms "penetration of combustion into the pores," "destabilization of the combustion of gas-permeable porous systems," and "emergence of filtration instability" are used as equivalent in their meaning.

properties of explosives; 4) the establishment of the quantitative laws determining the loss of stability.

In this section the basic, mainly experimental, results which concern the emergence of the filtration instability in porous gas-permeable systems will be presented. Another important side of the considered question - the development of instability - is the subject of special chapters.

§ 11. Formulation of the Problem

The destabilization of combustion is a complex nonstationary phenomenon which includes gas-dynamic, thermophysical and physico-mechanical processes. The processes of the filtration of products of combustion into the pores and the combustion of explosives are defined. In a number of cases when the specimen at the stage of stable combustion is subjected to the effect of mechanical loads, it is necessary to consider the deformation of the specimen.

Thus, in general the theoretical examination of the problem is reduced to the joint solution of the equation of the unsteady nonisothermic filtration of gas into the deformed porous medium and of the equations which describe the heat transfer and combustion explosives. If in this case we keep in mind that it is necessary to consider also the concrete mechanism of the combustion of explosives, then it is not difficult to present those enormous difficulties with which we encounter in theoretical studies of the question. It is no wonder that at present there is no solution of the problem in general. The tendency to the simplified theoretical examination is therefore natural (§ 13, 14). Let us discuss the basic simplifying assumptions which are made.

1. Usually one disregards the deformation of the charge, i.e., assumes that the initial values of gas permeability, porosity and dimension of the pores in the process of stable combustion

are retained invariable. This assumption is justified for the overwhelming majority of the crystal explosives of increased density.

2. Examined separately are: a) the filtration of gases into the pores and b) the problem of the combustion of porous explosives, assuming that the gas-dynamic pattern of flow is known.

3. With a description of conditions of the ignition of walls of the pore [70] the theory of combustion of Zeldovich [43], developed in connection with volatile explosives, which does not consider exothermal reaction in the condensed phase, is put to use.

Let us define concretely the concept "destabilization of combustion."

The necessary condition of the disturbance of the stable laminar combustion of gas-permeable systems is the lead by gas products of the front of the laminar combustion. In other words, for the realization of gas permeation, it is necessary that the average speed V_p of the gases flowing in relative to the wall of the pore exceed the linear speed of the laminar combustion of the charge $u: V_p > u$.

The indicated condition is necessary and does not mean in any way a loss of stability. Above in an example of the combustion of "infusible" explosives it was shown (§ 8) that although the limited penetration of products to the pores occurred, i.e., the necessary condition was fulfilled, the combustion retained a stable nature.

The sufficient condition of destabilization is expressed in the fact that the hot gaseous products, which lead the front

of laminar combustion, cause the combustion of the porous substance, which is spread at a velocity which exceeds the rate of the laminar combustion.

The fulfillment of the necessary condition is connected with the examination of the problem of the filtration of gases into the pores, while the fulfillment of the sufficient condition is connected with the solution of the problem of the thermal effect of gases on the substance and the possible conditions of combustion. From this viewpoint the separate examination of each of the indicated problems is justified.

From that which was presented above, it is clear that it is clear that it is expedient to speak about destabilization only in connection with the concrete conditions of the combustions by which the laws governing the processes of filtration of the products and heat transfer are determined.

§ 12. Mechanism of the Penetration of Gases

Before we examine the flow of gas over the pores, it is necessary to answer the question, what is cause - moving force of penetration, which forces the products of combustion to flow into pores?

The cause of the penetration of the products determines the mechanism of the destabilization of combustion as a whole.

The basic cause is the forced mechanism of penetration in which the inflow of gas is caused by a pressure difference. With the forced inflow the surface pressure of the burning charge p' exceeds the pressure in the pores p_n : $\Delta p = p' - p_n > 0$ or $\Delta p = p - p_n > 0$ (if we disregard the dynamic increase in Δp_n in comparison with the external pressure p). The differential value depends on the

combustion conditions. Let us designate by a symbol with index "0" the initial value of pressure, and without "0" - the instantaneous value.

Let us examine the following characteristic cases which correspond to the standard conditions of combustion:

1. Combustion according to the scheme of the "embedded charge" (see Fig. 2) (external pressure is maintained constant $p=p_0=\text{const}$, the initial pressure in the pores $p_n^0=1 \text{ atm}$, $p_0 \gg p_n^0$).
2. Combustion with the rising external pressure in a manometer bomb (see Fig. 3) [$p(t) \neq \text{const}$; $dp/dt > 0$; $p_n^0=1 \text{ atm}$].
3. Combustion at constant external pressure ($p=p_0=\text{const}$, $p_0=p_n^0$).

Case (1) and (2) are of greatest interest, since they correspond to the practical conditions, and in this case it is possible to trace the emergence of the instability in specimens with a different porosity changing over wide limits [$m > (0.03-0.05)$]. A pressure differential appears in these cases naturally, since $p > p_n$.

The scheme of the "embedded charge" models the combustion of the porous inclusion in the powder charge in the process of a rocket thrust-chamber firing. The advantage of the scheme is the determinacy of the initial and boundary conditions, which was used in the theoretical examination of the gas inflow. The use of this scheme makes it possible to investigate the combustion stability under the influence of strictly defined pressure differentials, which is easily reached by changing the external

Conditions of the rising pressure are realized in practice with the accidental igniting of explosives in industrial

apparatuses, with the ignition of various kinds of disruptive detonators, etc. The advantages of the method of rising pressure are its high productivity and the simplicity of experimental formulation. The results obtained by the given method and from the scheme of the "embedded charge" prove to be similar. Therefore, the method of the manometer bomb was widely applied for the experimental study of destabilization.

With combustion under constant pressure (case 3) the differential is created in the process of the combustion itself and by no means in trivial form. Prior the ignition of the charge the pressure of the gas in the pores is equal to the external pressure ($p_n^0 = p_0$), which is maintained constant with combustion ($p_0 = \text{const}$)¹. In this case the reason for penetration into the pores of the first portions of the gas is actually the dynamic pressure increase Δp_d which appears on the charge's surface at the moment of ignition and, which through Andreyev's figurative expression, "performs the role of a unique trigger mechanism."

At the same time the investigations carried out recently made it possible to expand substantially our concepts about the mechanism of gas permeation under these conditions. As it was noted, the surface of the burning porous specimen in the general is not plane. Flowing from the surface in this case is a system of streams, the source of which consists of separate burning grains of explosives. As a result of bending of the burning surface, there are formed the streams directed at an angle to each other, and their "cumulative" interaction becomes possible [10, 61]. As a result of the collision of streams, new streams, part of which is directed into the pores of explosives, appear (Fig. 22). At the place of the collision of the streams a local

¹The condition of constancy of the external pressure is strictly fulfilled with combustion at an atmosphere.

pressure increase, which does not exceed Δp_A in value, is observed. However, an important fact is that with the stream interaction the pores are penetrated by gas with a temperature higher than that directly near the surface, since the inflow occurs from the combustion zone located at a greater distance from the surface.

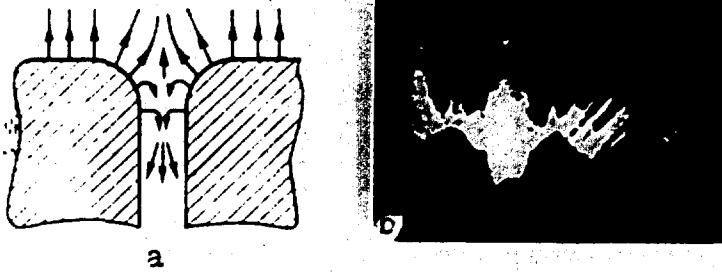


Figure 22. Diagram (a) and photograph (b) of the interaction of streams at the inlet at the right time.

As it was shown in § 8, the hot products penetrating into pores are cooled and the pressure of the gas in pores contained prior to combustion is decreased more intensely, the higher the degree of cooling (T/T_0) (T - temperature of the stream which flows into the pores). Thus, unlike the first and second case, with the combustion of the "infusible" substances under constant pressure the pressure differential appears in essence as a result of a drop in the internal pressure in the pores. In this case its value can exceed by several orders the dynamic pressure increase (see Fig. 18). The generating differential is self-sustained and regulates the flow of gas during the entire combustion period of the charge.

Consequently, in the third case the gas permeation is forced; however, a pressure differential is created specifically. A vital importance in the considered mechanism of the gas penetration is acquired by the stream interaction and nonisothermal flow pattern. Therefore, it is expedient to name this mechanism

of gas permeation stream (spontaneous) and consider it as a variety of the total, forced mechanism of penetration.

The authenticity of the stream mechanism is confirmed by the following experimental results. It was established that the factors facilitating the emergence of instability with combustion under constant external pressure are: a) the artificial formation of an indentation at the inlet into the pore [10] and an increase in the angle of the colliding streams [61]; b) an increase in the temperature of the penetrating gases. Only by action of the stream mechanism is it possible to explain the fact established in work [61] of the destabilization of combustion under conditions of the falling external pressure.

The spontaneous penetration of combustion will be examined in detail in § 16. Let us note only that since the stream mechanism is not in a state to ensure the high pressure differentials, the field of its action is limited. This mechanism is important under conditions when the specimens with low density burn at a constant external pressure ($p_0 = \text{const}$) and when $p_n^0 = p_0$.

A. FORCED PENETRATION OF COMBUSTION INTO THE PORES

As was noted, the emergence of filtration instability is completely determined by the flow pattern of the products of combustion over the pores. Let us examine, therefore, some problems of the filtration of gas in connection with the concrete standard conditions of combustion, which will make it possible to establish not only the pattern of the flow, but in a number of cases conduct quantitative estimates. The question concerning the role of the fusion, which is formed with the combustion of the fusing explosives, will be discussed in § 15.

§ 13. Filtration of Gas

Let us examine the filtration of gas in connection with the conditions of the scheme of the "embedded charge" [10].

In general it is necessary to examine the unsteady and nonisothermal filtration of gas into the porous medium, which is extremely difficult, since the flow is described by the nonlinear equation (6).

Let us make the following simplifying assumption. We will consider that the filtration is isothermal and one-dimensional (in the direction of the x axis). Let us disregard also the initial pressure in the pores.

A powerful assumption is the assumption about the isothermal nature of the process. At the same time it is physically justified for the two limiting cases of the combustion: 1) when the effective means of the heat emission of the gas $L_{oxn} \ll L$ (L - length of the charge), i.e., when the gas is cooled in the narrow surface layer, 2) with $L_{oxn} > L$, when the temperature of the filtering gas virtually does not change. The disregard of the initial pressure in the pores p_n^0 is substantiated for the most interesting case of the combustion of charges with low porosity, the destabilization of which is observed at high external pressures p_0 (in dozens-hundreds of atmospheres) and, therefore, $p_0 \gg p_n^0$. The problem is stated in the following way (Fig. 23). The interface ($x=0$) is assigned: gas ($x < 0$) with viscosity μ at a constant pressure p_0 - the nondeformable porous medium ($x > 0$) with defined values of gas permeability k , porosity m and initial pressure in

¹The disturbance of the combustion stability of charges with a low density close to bulk occurs, as a rule, under the influence of small pressure differentials $\Delta p \ll p_0$. The flow of gas in this case is described by the equation of thermal conductivity (8).

the pores $p_n^0 = 0$. Examined is the unsteady (with $t > 0$) viscous motion of the gas in the nondeformable porous medium, which is described by the equation of Boussinesq (7).

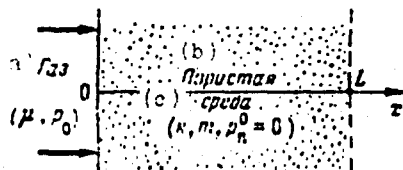


Figure 23. On the calculation of the filtration of gas with the combustion of the "embedded charge."
Key: (a) gas; (b) Porous; (c) medium.

Filtration into an Unrestricted Porous Medium

Taking into account the assumptions made, we have

$$\frac{\partial p}{\partial t} = C^2 \frac{\partial^2 p^2}{\partial x^2}, \quad (19)$$

$$p(x, 0) = 0, \quad (19a)$$

$$p(0, t) = p_0. \quad (19b)$$

In this setting the problem of this type was solved by Barenblatt [77], who obtained the analytical expressions for the coordinate of the leading edge of the gas $X(t)$ and for the distribution of pressure $p(x, t) = p_0 \phi(\xi)$, where $\xi = \frac{x}{C \sqrt{p_0 t}}$ is the parameter of self-similarity. Function $\phi(\xi)$ for the approximate computations can be written in the form $\phi(\xi) = 1 - \xi/\xi'$, where ξ' is the constant equal under the given initial (19a) and boundary (19b) conditions $\xi' = 2.29$.

Thus, approximately

$$p(x, t) = p_0 \left(1 - \frac{x}{\xi' C \sqrt{p_0 t}} \right), \quad (20')$$

i.e., it is possible to consider that the pressure drops according to the rectilinear law.

The depth of penetration of the gas, which is determined by the coordinate of leading edge, takes the form

$$X(t) = \xi \sqrt{\frac{k p_0 t}{2 m \mu}} = 1,62 \sqrt{\frac{k p_0 t}{m \mu}}, \quad (20)$$

and the rate of motion of the front

$$U_r(t) = 0,81 \sqrt{\frac{k p_0}{m \mu t}}. \quad (21)$$

We will use (20) in order to obtain in clear form the expression of the necessary condition of the destabilization of the combustion, which is fulfilled when during time of the burnup of the thoroughly heated layer $\tau = \kappa / u^2$ the gas penetrates at the depth which exceeds the thickness of the thoroughly heated layer κ / u

$$X(\tau) > \kappa / u, \quad (22)$$

where κ is the thermal diffusivity of the explosive; u is the rate of laminar combustion.

From (20) and (22) we find that the necessary condition is satisfied if

$$\frac{k p_0}{\kappa u^2} > 0,38. \quad (23)$$

The substitution into (23) of the characteristic values $p_0 = 50$ atm, $\mu = 3 \cdot 10^{-4}$ n, $\kappa = 10^{-3}$ cm²/s, $k = 10^{-6}$ darcy $\approx 10^{-14}$ cm², and $m = 0.05$ convinces us of the fact that the necessary condition of

destabilization is knowingly satisfied for specimens with very low values of gas permeability. We will subsequently return to this important derivation, which for the "infusible" explosives will agree with the experiment.

Filtration into a Limited Porous Medium

In this case it is necessary to place an additional condition on the gas-impermeable (with $x=L$) boundary

$$\left. \frac{\partial p}{\partial x} \right|_{x=L} = 0, \quad (19c)$$

and rewrite the initial condition in the form

$$p(x, t') = 0, \quad (19d)$$

where t' is the time of the reaching of the gas-impermeable boundary by the leading edge of the gas.

For the solution to this problem, let us present pressure $p(x, t)$ in the form of the trinomial:

$$p(x, t) = \bar{a} + \bar{b}x + \bar{c}x^2, \quad (24')$$

where \bar{a} , \bar{b} , \bar{c} are the functions of time which determined by satisfying $p(x, t)$ in the form of (24') the integral equation of the unsteady filtration:

$$\int_0^L \frac{\partial p}{\partial x} dx = C^2 \int_0^L \frac{\partial^2 p}{\partial x^2} dx,$$

and also the initial (19d) and boundary (19b) and (19c) conditions.

By omitting the calculations, let us write the final result of the solution:

$$\bar{p}(x, t) = p_0 - \frac{p_0}{L^2} \exp\left[-\frac{3k p_0}{m \mu L^2} (t - t')\right] \cdot (2Lx - x^2). \quad (24)$$

When $t < t'$ the pressure distribution is described (20') according to [77], and when $t > t'$ - by expression (24) (Fig. 24).

A change in pressure on the gas-impermeable boundary ($x=L$):

$$p(L, t) = p_0 \left\{ 1 - \exp\left[-\frac{3k p_0}{m \mu L^2} (t - t')\right] \right\}. \quad (25)$$

Thus, as soon as the leading edge of the gas reaches the gas-impermeable boundary, the pressure on it rises in accordance with (25), the pressure gradient is $\partial p / \partial x$, and therefore the rate of the inflow of gas in the specimen is decreased. From (25) it is evident that the more the gas permeability k and the less the length of the specimen, the faster the pressure in the pores of the specimen up to the external pressure is equalized.

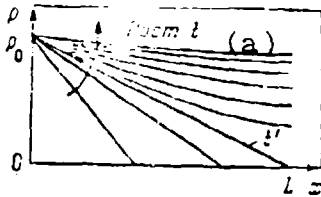


Figure 24. Pressure distribution with time and along the length with the inflow of gas into the porous charge with a blind bottom.

Key: (a) increase in t .

The time $t_{p, \eta}$ during which the relative pressure in the enclosed end $p_0 / (p_0 - p)$ rises "e" times will be called the characteristic equalizing (relaxation) time. From (25) we have

$$t_{p, \eta} = t - t' = \frac{m \mu L^2}{3k p_0}. \quad (26)$$

Thus, the presence of the enclosed end stabilizes the flow and can raise the combustion stability if the pressure balance occurs earlier than the combustion in the pores.

For the checking of the validity of the calculation carried out, we have run the special tests in which determined was the time of the reaching by the leading edge of the gas of the enclosed end of the charge with its stable combustion. Charges from a mixture of 10% polystyrene +90% AL, the burning surface of which is gas permeable, were ignited in a special bomb by an igniter, which created a pressure of $p_0 < p_c$ for a short time (5 ms), and this pressure in the process of combustion was maintained constant. Used were two piezoelectric pickups, one of which recorded the pressure in the volume of the bomb, and the other - in pores of the burning charge in the enclosed end. The time t' was determined according to the beginning of operation of the sensors. Represented below are values t' in s, obtained at a pressure of $p_0 = 25$ atm for specimens with a porosity of $m=0.15$ and gas permeability of $k=10^{-3}$ darcy.

Length of charge, cm	Calculation by equation (20)	Experiment
1	0.07	0.05
2	0.28	0.26

The observed satisfactory accord $t'_{\text{расч}}$ and $t'_{\text{эксп}}$ indicates the legitimacy of the assumptions made during the calculation.

The account presented above corresponded to conditions when the external pressure p_0 , which is suddenly being raised above the porous charge, was not changed in the course of time.

Filtration under conditions of combustion under the rising pressure. In the setting analogous to the problem of filtration into the unlimited medium, but with boundary conditions of the type of $p(0, t) = p_0 t^\alpha$, ($\alpha > 1$), this problem is solved in [77]. Let us examine the simpler case when filtration is realized into a bounded medium, and the pressure in the pores manages to be adjusted slightly for a change in external pressure. The last

requirement is fulfilled if the characteristic time of the pressure balance in pores t_{np} is substantially less than the relaxation time of the external pressure:

when $t_{p,n} < t_{p,b}$, where $t_{p,b} = \frac{p}{dp/dt}$.

In this case it is possible to consider the filtration to be quasi-stationary and utilize [61] for the calculation of the rate of the gas flowing in the expression

$$V_r = \frac{L}{p} \frac{dp}{dt} \frac{T_r}{T_0}, \quad (27)$$

where T_r is the temperature of the filtering gas; T_0 - the initial temperature of the porous substance; dp/dt - the speed of the change in external pressure. Formula (27) is obtained from the equation of the conservation of mass and is valid with $dp/dt < 3 \text{ kp}^2/\text{msL}^2$.

Let us estimate the limits of fulfillment of the last inequality. Assuming that $k=10^{-3}$ darcy, $m = 0,15(d_{11} = \sqrt{\frac{32k}{m}} \approx 0,5 \mu$, $p=50$ atm, and $L=5$ cm, we obtain the maximum rate of the change in external pressure $dp/dt < 50$ atm/s. Thus, the assumption about the quasi-stationary nature of filtration is fulfilled in the sufficiently wide interval of the variation in parameters. The quasi-stationary approach is substantiated with the inflow of gas into the not too narrow and blind pores.

After the examination of conditions of the inflow of gas into the pores, let us turn to the question concerning the after-effects of the penetration of the products.

§ 14. Conditions of the Ignition of Walls of the Pore

At present it is experimentally established that the most typical result of the thermal effect of the hot gases in flowing is the ignition of the surface of the pore [10, 12]. Theoretical studies of conditions of the ignition is conducted by Margolin and Chuyko [70].

Following the data [70], let us examine the simplified problem of the heating of walls of a pore of constant cross section with a hydraulic diameter of d_n by the flow of gas which flows in at a rate V_r relative to the walls of the pore and having the initial temperature T_r , heat capacity c_r , coefficient of thermal conductivity λ_r , and density ρ_r . In the coordinate system connected with the burning surface of the charge, the gas flows into the pore at the speed $(V_r - u)$, where u is the linear burning rate of the explosive. The gas flowing in gradually cools, giving up its heat to the wall, and its temperature falls from T_r down to the temperature of the wall T_0 . In the first approximation, let us assume that the temperature of the gas changes not smoothly but by a jump: on a certain segment L_{ox} from the inlet it is equal to T_r , and then $- T_0$. Let us accept also that the temperature of the wall on segment L_{ox} is constant and equal to T . Let us write the equation of the heat balance:

$$(V_r - u) c_r \rho_r (T_r - T) \frac{dV_r^2}{4} = \frac{Nu \lambda_r}{d_n} (T_r - T) L_{ox} c_w, \quad (28)$$

where Nu is the Nusselt number of the gas flowing in at the right time.

From (28) let us find the distance L_{ox} at which the gas gives up the heat:

$$L_{oxn} = \frac{(V_r - u) d_n^2}{4Nu\alpha_r}; \quad x_r = \frac{\lambda_r}{\rho_r c_r} \quad (29)$$

Values of V_r and Nu are measured or calculated (§ 13) on the basis of the conditions of the gas inflow. According to [113], for the laminar flow with $\frac{x}{d_n} \frac{1}{Re Pr} \gg 0,1$ the Nusselt number can be considered as constant (here x is the distance from the inlet into the pore; Re and Pr are Reynolds and Prandtl numbers) and equal to $Nu=3.66$. From (29) it follows that at small diameters of the pore the depth at which the hot gas flowing into the pore cools is very small¹. Thus, when $V_r=1$ m/s and at a pressure equal atmospheric, the value L_{oxn} has following values:

$$L_{oxn}(d_n = 1 \text{ cm}) \approx 30 \text{ cm}; \quad L_{oxn}(d_n = 10 \text{ }\mu\text{m}) \approx 30 \text{ }\mu\text{m}; \\ L_{oxn}(d_n = 10 \text{ }\mu\text{m}) \approx 0,3 \text{ }\mu\text{m}.$$

The wall of the pore is heated for the period of time τ_0 equal to

$$\tau_0 = L_{oxn} u. \quad (30)$$

For determining the time τ_1 of the reaching on the surface of temperature T' , let us formulate the equation of heat balance on the wall of the pore:

$$\frac{Nu \lambda_r}{d_n} L_{oxn} d_n (T_r - T') \tau_1 = (T' - T_0) \rho_r c_r L_{oxn} d_n \sqrt{\alpha_r \tau_1} \quad (31)$$

($\alpha=0$ for the slit; $\alpha=1$ for a pore of round cross-section). Subscript "r" refers to the solid phase. Here it is assumed that

¹The depth of cooling can substantially increase, if with combustion heat release in the condensed phase occurs.

the depth of the thoroughly heated layer $l = \sqrt{\kappa_T \tau}$ is constant on L_{oxn} .

From (31) we find that

$$\tau_1 = \frac{q_{\text{u}}^2}{\kappa_T} \left(\frac{\beta}{\lambda u - \sigma_{\text{u}}'} \right)^2; \quad \beta = \frac{\lambda_T}{\lambda_T} \frac{T' - T_0}{T' - T'}. \quad (32)$$

The time τ_2 of the formation of the thermal layer $l_0 = \kappa_T / u$, which corresponds to conditions of stationary combustion, is equal to

$$\tau_2 = l_0^2 u = \kappa_T u^2. \quad (33)$$

Combining the equality (30) with $l_0 = \sqrt{\kappa_T \tau_0}$, it is possible to obtain the following relation:

$$F = I_{\text{oxn}} l_0. \quad (34)$$

According to the theory developed by Zel'dovich [43] (not allowing for the reaction in the condensed phase), the combustion of the powder includes: 1) the creation in the condensed phase of a sufficiently deep thoroughly heated layer; 2) the heating to the temperature of the surface T' by which the intense gasification of powder begins; 3) the combustion of products of gasification. Zeldovich showed that the heat required for the combustion of products of gasification is considerably less than the heat going for the heating of the powder.

Thus, in accordance with theory [43] for the ignition of the pore, it is necessary that the relations be fulfilled:

$$l_0^2 \tau_1 > 1, \quad (35)$$

$$l_0^2 \tau_2 > 1. \quad (36)$$

From a comparison of (35) and (36) it is evident that (35) is equivalent to the following:

$$L_0 = L_{ox} / l_0 > 1 \text{ or } \tau_0 / \tau_s > 1, \quad (35')$$

i.e., the requirement of a sufficient thickness of the thermal layer (35) coincides with the condition of the fact that the effective means of the heat emission of the gases L_{ox} exceeds the thickness of the thermal layer l_0 .

By substituting relations (30), (32) and (33) into (35) and (35'), we obtain the conditions of ignition in the form

$$L_0 = \left(\frac{V_r^2}{V_0^2} = \frac{L_{ox}}{L_0} = \frac{(V_r - u) m_0^2}{4 Nu_0 z_1 z_T} \right) > 1, \quad (37)$$

$$V_0 = \frac{(V_r - u) Nu_0 (z_1 z_T)^{1/2} (T_r - T_0)^{1/2}}{m} \left(1 - \frac{z_1^2}{Nu_0} \right)^{1/2} > 1. \quad (38)$$

The ignition point T' depends on the chemical kinetics, the thermophysical characteristics of the substance, its initial temperature and heat-transfer conditions. From (37) and (38) it is evident how the fundamental characteristics of the combustion of the gas flowing in and the explosives affect the conditions of ignition. Specifically, it is evident that ignition is possible only when $V_r - u > 0$.

From the examination carried out there are interesting qualitative results, the physical content of which corresponds to experimental observations, which principally can be obtained independently - from general considerations. The findings become obvious if we present them graphically (Fig. 25). In the coordinates, pressure of gas p and dimension of the pore d_p , the conditions of ignition (37) and (38) are depicted, respectively, by lines 1 and 2. Above 1 and 2 inequalities (37) and (38)

are fulfilled. Then the coordinate plane is divided into the following characteristic regions, each of which corresponds to the defined conditions of thermal effect.

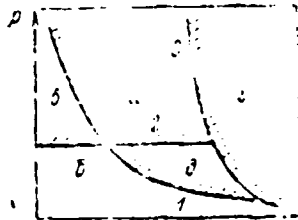


Figure 25. Dependence of pressure p of the ignition of the wall of the pore by the inflowing gas on the diameter of the pore d_p .

At low pressures and not too wide pores (region 6) stable laminar combustion occurs; although the gas permeation occurs, the explosive is not ignited, since both inequalities (37) and (38) are not fulfilled simultaneously. Region 6 covers the case of the stable combustion at the stage preceding destabilization.

With an increase in pressure there appears the ignition of pores average in dimension (region 2), which is characteristic for destabilization by the thermal condition. In this case both inequalities are fulfilled.

In region 6 (high pressures - narrow pores) there occurs forced combustion (pyrolysis of the explosive) when the condition (37) of the formation of the sufficiently thick thoroughly heated layer is not satisfied.

In region 4 inequality (38) is not fulfilled: the prolonged heating of the explosives is realized. It is possible to assume that this region corresponds to the thermal explosion (flash) of the layer of explosive heated to considerable depth.

Finally, region 5 (to the right of curve 3) corresponds to

the turbulent combustion of the gaseous intermediate products, which can under certain conditions fill the wide pores of the burning charge. Obtained are the conditions by which the combustion being spread over the intermediate products capable of igniting the wall of the pore [70].

In conclusion it should be noted that the strict quantitative calculation of conditions of the ignition of the walls of the pore is very difficult.

§ 15. Experimental Study of the Disturbance of Stable Combustion

An experimental study is conducted basically with the utilization of the method of the rising pressure. The combustion of the investigated porous specimens was realized in the manometer bombs (see Fig. 3) with the continuous recording of pressure in the volume by piezoelectric quartz crystal [10, 11] or tensometric [64] pressure sensors. Besides the recording of pressure in the volume of the bomb, the optical recording of the process through the transparent windows of the bomb was used [10, 63]. In separate experiments the recording of pressure in pores of the burning charge was also taken.

The lateral surface and the lower end of the charge were armored. The ignition of the upper end was realized by a wire heated by current or an igniter, which created a small pressure increase, so that a further increase in the volume of the bomb occurred because of the combustion of the porous charge to be investigated. One should emphasize that reliable data can be obtained in such a case when the igniter does not exert a disturbing action. Specifically, the pressure created by them must be substantially lower than the critical pressure. The igniter must provide a stable and simultaneous ignition of the charge over the entire surface with minimum delay. Used as the igniter were

finely divided black powder, pyroxylin, and also a mixture of pyroxylin with ammonium perchlorate.

Figure 26 shows the standard recording of pressure in the volume of the bomb $p(t)$ and the optical recording with the disturbance of the stable laminar combustion of the porous charge. Thus far the stable combustion was retained, a smooth pressure buildup was observed, and in this case the rate of combustion of the charge is close to that determined under conditions of the Crawford bomb. The sharp growth in pressure and velocity (bend in the recording) indicated the achievement of critical conditions, the disturbance of stable combustion by parallel layers and the break of combustion into the pores. The destabilization of combustion can be characterized by critical values of pressure in the volume, rate of combustion or gas permeability. Usually used as the fundamental characteristic is the critical stall pressure of stable combustion p_c , which is preferable for conditions of the rising pressure and scheme of the "embedded charge." Actually, with forced penetration the pressure precisely determines the rate of the gas flow [see (21)] and, therefore, the final effect of the inflow. The completeness of combustion and the distribution of the temperature in the gas phase are also functions of pressure. The critical pressure is determined directly from the oscillogram $p(t)$. The utilization of an optical recording, which makes it possible to measure the critical rate of combustion, is not always possible, in particular, in the manometer bombs of high pressure.

The disturbance of the stable combustion of the fusing secondary explosives, as a rule, is accompanied by a sharp break on recording $p(t)$, according to which the stall pressure was determined. With prolonged stable combustion, and also for a number of the infusible explosives the emergence of instability occurs in the form of a smooth increase in pressure and rate of

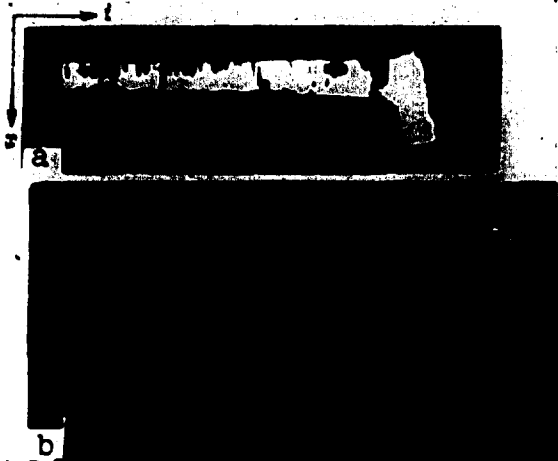


Figure 26. Optical oscillogram (a) and the recording of pressure $p(t)$ (b) with the disturbance of the stable combustion of the porous charge in the manometer bomb.

combustion, and the sharp break on recordings $p(t)$ is absent. The determination of critical pressure from these oscillograms was conducted by reconstructing them for the convenience of processing in semilogarithmic coordinates ($\lg p-t$) or comparing them with recordings of the stable combustion of the solid (standard) charge.

The method simple in execution of the manometer bomb with the continuous recording of pressure $p(t)$ made it possible to investigate and compare the combustion stability of different classes of explosives and powders.

Effect of Porosity and Gas Permeability

Research on the destabilization of the combustion of charges of explosives with high porosity ($m > 0.15$) was conducted in works [11, 32, 62-69]. In the investigations of Belyayev with colleagues [10, 60] the primary attention was given to the radiation of the emergence of instability in specimens with low values of porosity ($m = 0.15 - 0.03$) and gas permeability ($k = 10^{-3} - 10^{-6}$ darcy), which was conditioned by the following facts. With porosity $m < 0.15$ it is possible to disregard the deformation of charges at the stage

of laminar combustion, since their stability is disturbed at pressures considerably less than those with which the specimens were pressed. Furthermore, the obtained results correspond to the destabilization of the combustion of the unrestricted charges when there is no effect of the enclosed lower end. Finally, as it will be clear from the following presentation, at low values of porosity, especially in relief, the effect on the stability of physicochemical properties of the explosives is exhibited.

Let us examine the results obtained in the works of Belyayev with colleagues [10, 60]. Used were porous specimens whose diameters are 5 and 10 mm and lengths, 40-70 mm. The initial particle size comprised basically 5-20 μm . The density of the charging was constant and equal to 50 kg/m^3 , and the speed of the pressure change with laminar combustion $dp/dt=0.1-10 \text{ atm/ms}$.

It was shown that the combustion stability of the investigated specimens does not depend on the length of the section of the laminar combustion and is unambiguously determined by the value of the critical stall pressure. Therefore, the experimental data are represented in the form of dependences of the critical stall pressure on the basic parameters of the charge.

The dependences of critical pressure on porosity for the secondary explosives and mixture compositions (with the stoichiometric relationship of components) are given, respectively, in Figs. 27 and 28. Points on the curves represent average values of 3-4 measurements. In the region of pressures lower than the curve, the combustion is stable, and above the curve - unstable.

Let us note the basic results which follow from the findings:

1. The destabilization of the combustion of the secondary explosives - trotyl, DINA, picric acid, and PETN, in the whole

investigated interval of porosity, occurs at pressures substantially greater than in the case of pyroxylin and mixture compositions on the basis of potassium and ammonium perchlorates.

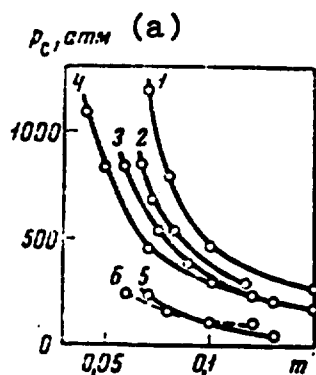


Figure 27

Figure 27. Dependence of critical stall pressure on porosity for secondary explosives ($d_3=10$ mm, $r=5-20$ μ m). 1 - trotyl; 2 - picric acid; 3 - DINA; 4 - PETN; 5 - cyclonite; 6 - pyroxylin No. 1. Key: (a) atm.

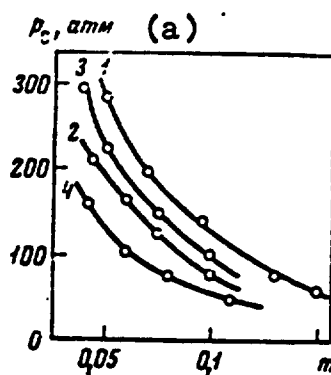


Figure 28

Figure 28. Dependence of critical stall pressure on porosity for mixture explosives ($d_3=10$ mm, $r=5-20$ μ m). 1 - bitumen+ $KClO_4$; 2 - polystyrene+ $KClO_4$; 3 - trotyl+ NH_4ClO_4 ; 4 - bitumen+ NH_4ClO_4 . Key: (a) atm.

2. Burning of the compositions on the basis of ammonium perchlorate (AP) [ПХА) in the interval of pressures of 100-200 atm is stable if the porosity of the specimens does not exceed 0.05.

3. Values of critical pressure for the investigated mixture compositions with different combustibles (polystyrene, bitumen, trotyl) with identical porosity proves to be close. This result indicates that the possibility of the destabilization of this type of systems is determined basically by the properties of the oxidizer.

4. With a decrease in porosity the critical pressure rises, and in this case connection $p_c(m)$ is satisfactorily described by the hyperbolic dependence of the form:

$$P_c(m - b) = a, \quad (39)$$

where a, b are constants the value of which are represented below:

	a	b
Trotyl	24	0.05
Picnic acid	15	0.05
PETN	20	0.025
Mixture compositions	3-7	0.025

The value of the constant a is determined by the physico-chemical properties of the substance and by experimental conditions. The constant b approximately characterizes the value of the enclosed (gas-impermeable) porosity. This follows from a comparison of the given data with the dependence of gas permeability on porosity (see Fig. 12): in the interval of the variation in porosity $m=0.03-0.5$, the gas permeability of the specimens is extremely small and consists of the value of the order of 10^{-6} darcy. According to (39), with the porosity $m < b$ the stable combustion to high pressures must be maintained, which was confirmed by the direct experiment. The stable combustion of the specimens of PETN and mixture compositions with a porosity of $m=0.02-0.03$ was observed up to the maximum (in our experiments) pressure of 3000-4000 atm [23]. An insignificant increase in the porosity up to value of 0.05 leads, as can be seen from Fig. 28, to instability. Thus, the transition from stable combustion to unstable burning in this interval of the variation in porosity occurs exceptionally sharply.

We will turn to an explanation of the effect of gas permeability, since, namely, the gas permeability determines the

possibility of the filtration of the products of combustion into the pores. The corresponding data are represented on Fig. 29; the measurement of the dependence of gas permeability on porosity was conducted according to the procedure described in § 5.

One should, first of all, note that the distinction in the combustion stability of the investigated explosives is especially distinctly exhibited at low values of the gas permeability ($k \sim 10^{-5}$ darcy). With an increase in the gas permeability (porosity) and, consequently, also the dimension of the pores, the distinction in values of critical pressure is smoothed over. This fact indicates that the role of the physicochemical properties explosives as a factor which affects destabilization is important, first of all, with the small dimension of the pores.

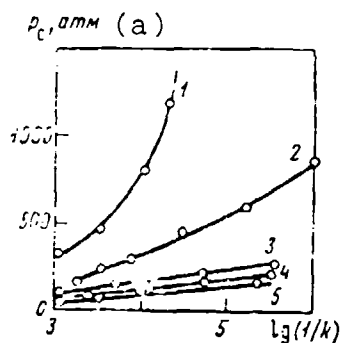


Figure 29. Dependence of critical stall pressure on the logarithm of reverse gas permeability ($d_3=10$ mm, $r=5-20$ μ m). 1 - trotyl; 2 - PETN; 3 - bitumen+ $KClO_4$; 4 - trotyl+ NH_4ClO_4 ; 5 - bitumen+ NH_4ClO_4 .
Key: (a) atm.

The combustion stability of mixture explosives with small gas permeability $k=10^{-5}$ darcy is disturbed at the low pressures $p_c=100-200$ atm, which qualitatively agrees with results of the calculation carried out above (page 74). In the case of the secondary explosives this accord is absent. It is remarkable that the combustion stability of powerful explosives, PETN, is significantly higher than that of mixture explosives. Essentially different proves to be also the nature of the dependence of stall pressure on gas permeability.

For mixture explosives it is comparatively weak and takes the form

$$k \exp(p_c F) = G, \quad (40)$$

where constants G and F weakly depend on the nature of the combustible.

The secondary explosives detect, as a rule, a more powerful and more complex dependence of stall pressure on gas permeability. The established features in the behavior of the investigated systems are conditioned by the distinctions in the mechanism of their combustion and, first of all, in the physical state of the combustion surface.

The data presented are acquired on systems pressed from particles of identical dimension ($r=5-20 \mu$).

Let us examine the effect of the initial particle sizes of explosives (PETN) on the possibility of the disturbance of laminar combustion. The dependence of the critical stall pressure on porosity and gas permeability for specimens of PETN with the different initial particle sizes are represented on Figs. 30 and 31 (with the construction of dependence $p_c(\lg l/k)$ data of Fig. 13 were utilized). From the given data it follows that an increase in particle sizes with constant porosity or gas permeability of the charge leads to a considerable reduction in the critical stall pressure. This result indicates the fact that not only does the porosity but also the gas permeability determine unambiguously the stability of the laminar combustion. Together with the gas permeability a considerable effect on the disturbance of laminar combustion is exerted by the distribution of pores according to dimension (more correctly - the presence in the distribution of large pores).

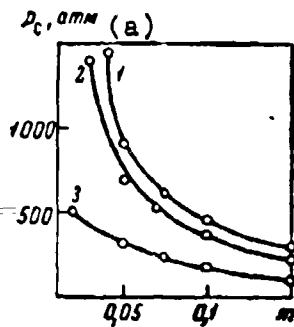


Figure 30

Figure 30. Dependence of critical stall pressure on porosity for PETN with different initial particle sizes ($d_3=5$ mm). 1 - $r=5-10$; 2 - 120; 3 - 500 μm .

Key: (a) atm.

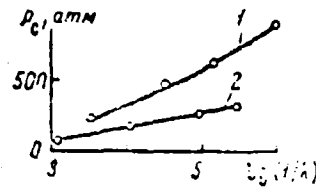


Figure 31

Figure 31. Dependence of critical stall pressure on the logarithm of the reverse gas permeability of PETN ($d_3=10$ mm). 1 - $r=5-10$; 2 - 500 μm .

Stability Rows

The investigations carried out, made under identical conditions, make it possible to conduct the classification of different explosives according to the degree of their stability. Compared was the combustion stability of specimens with the gas permeability equal to 10^{-5} darcy when the initial particle sizes, geometric dimensions of the charge and conditions of combustion were identical. The findings are integrated below for values of gas permeability $k=10^{-5}$ darcy, the initial particle size $r=5-20$ μm , the length of the charge $L=40-70$ mm, the diameter of the charge $d_3=10$ mm, and the density of the charging 0.05 g/cm^3 . Given below are values of critical stall pressures in atmospheres:

Secondary fusing substances		Infusible substances	
trotyl	2000	pyroxylin	200
picric acid	800	compositions on the basis of AP	100-175
PETN	550		
cyclonite	250		

Initiating substances

mercury fulminate	100
lead azide +2%	
paraffin	see ¹

¹Detonates at any pressure.

(For crystal explosives and ammonium perchlorate with a particle size of 5-20 μm the porosity of specimens $m=0.06-0.07$ corresponds to a gas permeability $k=10^{-5}$ darcy).

The greatest stability is possessed by the secondary explosives, and the least stability - the initiating explosives. In this case a change in properties of the substances in the stability rows obeys the completely defined law: the capability for melting decreases, and the role of reactions in the condensed phase increases.

The main feature of the majority of the secondary explosives is their ability to be fused during combustion without noticeable decomposition in the condensed phase. Research on the burning surface of the extinguished porous specimens, and also the simultaneous recording of pressure in the volume and pores of the burning charge showed that high combustion stability of very dense secondary explosives (trotyl, picric acid, DINA, PETN) was caused by the existence on the burning surface of continuous molten layer [10, 59, 60]¹. With stable combustion, when the

¹Irrespective of the authors, the position about the stabilizing effect of the molten layer with the combustion of the porous fusing explosives was advanced by Taylor [82].

pressure is lower than the critical, the molten layer performs the role of a gas-impermeable partition, which eliminates the filtration of gas products into the pores: the pressure in the pores is virtually retained equal to atmospheric up to burnout, i.e., up to the approach of the front of combustion to the sensor located on the end of the charge. The disturbance of the continuity of the fusion occurs at a pressure close to the critical. Under these conditions the penetrating gases are intensely cooled as a result of heat removal for melting and vaporization of the substance, which also contributes to the flame stabilization.

In the first approximation, it is possible to assume that the combustion of the fusing explosives is stable as long as the molten layer remains continuous. The condition of continuity of the molten layer means that its thickness x is not less than the maximum size of the pores, i.e.,

$$x \geq d_{p \max}. \quad (41)$$

Hence there ensues a number of interesting consequences. First of all, it appears that the computed values of the thickness of the molten layer correspond to the experimentally established series of stability of the secondary explosives.

Values of the thickness of the molten layer were calculated from the formula

$$x = \frac{\lambda}{\rho c} \ln \frac{T_x - T_0}{T_{\text{ms}} - T_0}. \quad (42)$$

where ρc is the mass rate of combustion; λ - thermal conductivity of fusion; c - heat capacity; T_x - critical temperature; T_{ms} - melting point; T_0 - initial temperature.

Utilizing the values available in literature [78-80] of the quantities which enter into expression (42), we find that at

a pressure of 100 atm the thickness of the molten layer for trotyl, picric acid, PETN, and cyclonite is equal, respectively, to 50, 35, 13 and 5 μm , and at a pressure of 300 atm - 18, 12, 3 and 2 μm . The fact that the indicated explosives in the stability row are located in the same sequence once more confirms the validity of the developed representations.

Furthermore, the relation (41) makes it possible to estimate the maximum size of the pores. Thus, for instance, for trotyl with a porosity of $m=0.15$ the critical stall pressure is equal to $p=300$ atm. At this pressure the thickness of the molten layer, and, consequently, the maximum size of the pores, is $d=18$ μm . From the distribution of the pores according to dimension (see Fig. 10), it follows that the directly measured value in specimens of trotyl of the same porosity proves to be close and equal to 10 μm .

In the line of decreasing stability to the right of the secondary fusing explosives there are located the substances with the combustion of which the molten layer is not formed (pyroxylin, mercury fulminate), or it is not continuous (mixture on the basis of ammonium and potassium perchlorates). In the process of combustion the ammonium perchlorate and potassium perchlorate are melted at high temperature with decomposition. At atmospheric pressure the melting point of ammonium perchlorate is $T_{\text{пл}} \approx 850^\circ\text{K}$ [54]. The corresponding value for potassium perchlorate $T_{\text{пл}} \approx 883^\circ\text{K}$ [81].

The emergence of instability is furthered also by the course of exothermal reactions in the condensed gas, which play an important role in the combustion of pyroxylin [50], compositions on the basis of AP [48] and mercury fulminate [5]. The gaseous decomposition products forming in the k-phase cause the dispersion of substance, lead to a constant destruction of the surface

layer and make the shaping of the continuous molten layer impossible, even if a liquid film is formed. On the other hand, the heat liberation in the k-phase increases the path of heat emission of the products of combustion penetrating into the pores and facilitates the combustion of the internal surface of the pores.

With the disturbance of the laminar combustion there is great significance in the temperature of the penetrating products, which depends on the combustion temperature of the explosives and the distribution of temperature near the surface. Andreyev [37] correctly considered the high combustion temperature as a reason for the increased tendency toward the emergence of the explosion. The experiments carried out showed that an increase in the combustion temperature, which was achieved by the introduction of a combustible to the pure ammonium perchlorate, caused a decrease in the stall pressure.

However, a decisive importance for blowout is exerted by the nature of the distribution of temperature in the gas [10], since, first of all, the gaseous products which adjoin the surface penetrate. It was established that the precisely narrow temperature zone which is characteristic for systems on the basis of AP [81, 161] is mainly responsible for the low stability of their combustion. Together with other factors noted above, this leads to the fact that the compositions on the basis of AP in their stability virtually do not differ from mercury fulminate. The high value of the temperature gradient near the surface provides combustion of the porous substance with gas of high temperature and makes combustion in the narrow pore possible.

It is necessary to emphasize the following fact. With the destabilization of the combustion of the "infusible" substances by the forced mechanism, the value of the mass flow rate of laminar combustion does not play a significant role (unlike the disturbance by the spontaneous mechanism, see § 12, 16). Thus,

for instance, with close stability the mass rate of combustion of mercury fulminate by one order of magnitude exceeds the appropriate value for perchlorate compositions.

From that presented above it is not difficult to see that the combustion stability is connected in the closest way with the mechanism of combustion and depends on the complex of physico-chemical properties.

Let us determine the critical dimension (diameter) of the pore d_{kp} at which the penetration of combustion into it is observed. For this we utilize the condition of flame stabilization by the molten layer: $d_{\text{kp}} = x$. If $d_{\text{kp}} > x$, then the combustion penetrates into the pore, and with $d_{\text{kp}} < x$ the penetration is absent. For PETN, for example, critical stall pressure is equal to 300 atm with the porosity of the charge $m = 0.1$. At this pressure the value of the molten layer, and, consequently, the critical dimension of the pore, is $d_{\text{kp}} = 3 \mu^1$.

With an increase in pressure and rate of combustion, the critical dimension of the pores decreases. Taking into account that for the fusing explosives $d_{\text{kp}} = x \sim 1/u$, and $u \sim p$, we obtain

$$d_{\text{kp}} \sim 1/u \sim 1/p,$$

¹We compare the obtained value d_{kp} with the average hydraulic diameter of the pore. We will describe the investigated porous medium by the model of an ideal ground. In accordance with (2), for PETN at critical values of the porosity $m = 0.1$ and gas permeability $k = 1.5 \cdot 10^{-4}$ darcy, we have $d_{\text{п}}' = 0.2 \mu\text{m}$, which by one order of magnitude is less than d_{kp} . The obtained distinction is connected with the fact that the disturbance of laminar combustion begins into the largest (and not into average in dimension) pores of the charge: $d_{\text{kp}} = d_{\text{пmax}}$.

whence

$$ud_{np} = \text{const} \quad \text{or} \quad pd_{np} = \text{const}.$$

These relations for the fusing explosives are approximately fulfilled.

With the combustion of the porous systems, which do not form a continuous molten layer, the relation $pd_{np} = \text{const}$ also occurs; however, the value of the constant in this case is substantially lower. This means that the penetration of combustion into pores identical in dimension of "infusible" explosives occurs at lower pressure. If for PETN the combustion penetrates into pores with a dimension of 3 μm at a pressure of 300 atm, then into pores close in dimension of mixture systems - at $p < 100$ atm.

As was already mentioned, in Andreyev's works with colleagues [64-69] the combustion stability of the low-compact charges of the explosives was studied. The following substances were investigated: trotyl, xylyl, picric acid, trinitrobenzene, hexanitrodiphenol, tetryl, octogen [HMX], PETN, and mercury fulminate. A high-compact ($\delta = 0.95-0.97$) charge was used as the standard. The experimental data are represented in the form of curves of $p(t)$: pressure in the volume - time. The basic parameter was the critical density. It was established that at a relative density of $\delta = 0.7$ ($r = 50-100 \mu\text{m}$) the combustion stability of all the investigated explosives is disturbed at a pressure which does not exceed 50 atm. The pressure which was created by the igniter, which ignites the charge, was 50 or 100 atm, i.e., it was close to or exceeded the critical value. Therefore, these data are interesting from the viewpoint of combustion beyond the stability limit. Those results which correspond to the combustion of very dense charges and which give the representation about the relative combustion stability of different explosives will agree as a whole with those which were presented above.

Effect of the retarder. In work [63] the combustion stability of mixtures of cyclonite with paraffin was studied. Cyclonite with particle sizes of 200 μm was used. The findings are represented on Fig. 32. From them it follows that the introduction of 10% paraffin does not affect the value of the critical stall pressure. Experiments rich in the retarder content were not conducted. In the opinion of the authors, the basic effect of the introduction of the retarder lies in the fact that it significantly changes the nature of the development of the process after the disturbance of the laminar combustion and eliminates explosions which occur in pure explosives.

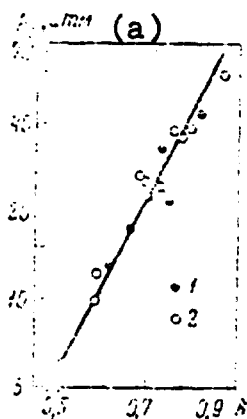


Figure 32. Disturbance of the stable combustion of mixtures of cyclonite ($r=200 \mu\text{m}$) with paraffin. 1 - pure cyclonite; 2 - cyclonite+10% paraffin. Key: (a) atm.

Role of the Geometric Dimensions of the Charge

The effect of the diameter d_3 and length L of the charge was studied [10]. Charges with a blind (gas-impermeable) bottom were investigated.

Experimentally it was shown that under conditions of the manometer bomb the combustion stability of the samples usually applied in work [10] with gas permeability $k < 10^{-3}$ darcy

virtually does not depend on the length of the section of the laminar combustion preceding the emergence of the convective combustion, and it is determined by the magnitude of the stall pressure (in this case at the moment of the achievement of the critical pressure the remaining length of the charge was, as a rule, more than 15-20 mm).

The obtained result indicates that at sufficient length the presence on the lower end of the charge of the gas-impermeable boundary does not affect the process of the filtration of products and the interruption of the laminar combustion.

Thus, the data [10, 60] correspond to the case of the disturbance of the laminar combustion of the unlimited porous charges. It is necessary to emphasize that under these conditions the critical stall pressures, determined by the method of the manometer bomb and from the scheme of the "embedded charge", virtually coincide.

At the same time the compression of the filtering gas at the lower end of the charge, which leads to a pressure equalizing in the pores and a decrease in the rate of filtration, can stabilize the combustion. Stabilization occurs if products which penetrated to the entire length of the charge are not in a state to ignite the internal surface of the pores.

Theoretical analysis shows (§ 13) that the less the length of the charge, and the more its gas permeability, the more noticeable the effect is exerted by the gas-impermeable boundary. For the purpose of research on the stabilizing correction of the enclosed end, experiments by the scheme of the "embedded" charge were carried out (see Fig. 2) in which the low-density charges ($m > 0.2$, $k > 10^{-3}$ darcy) of different length were ignited.

Experiments were conducted with the mixture system (on the basis of APO at constant pressure p_0 , the value of which exceeded the critical pressure p_c determined for a long charge. The findings in schematic form are represented in Fig. 33 (plotted along the axis of the abscissas is the value of the length of the charge L and along the axis of the ordinates - delta-function Δ' : with $\Delta' = 0$ the combustion is stable, and

with $\Delta'=1$ the combustion is unstable). It is evident that there is a threshold value of the length of the charge (L'), lower than which the combustion was stable, laminar and was realized with the mass flow rate close to the same for a solid specimen. With an increase in the length of the charge ($L>L'$) a convective combustion mode appeared. An analogous effect was observed in work [64].

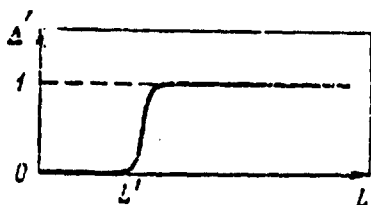


Figure 33. Effect of the length of the charge on the disturbance of stable combustion.

The transition from stable combustion to unstable was observed in the narrow interval of the variation in the length of the charge. In the transient region the convective combustion initiated at low speed was usually retarded and was changed by laminar combustion (Fig. 34 depicts the combined recording of pressure $p(t)$ obtained of one experiment and the optical recording when the scanning speeds of the recorders were equal).



Figure 34. Recording of pressure $p(t)$ and optical oscillogram with the combustion of the "embedded charge."

Thus, the existence with $p_0 > p_c$ of the threshold value of the length of the charge L' is connected with very rapid pressure

equalization in the pores. Thus, for instance, in accordance with (26) for the charge with $m=0.3$, $k=10^{-2}$ darcy, length $L=0.3$ cm at a pressure of $p_0=50$ atm, the characteristic time of the pressure balance in the pores is extremely little and consists of $t_{p.n}=0.5 \cdot 10^{-3}$ s, which is substantially below the usually observed ignition delay.

The investigation of the effect of the diameter of the charge (Fig. 35) was conducted in the manometer bomb on an example of PETN. The constancy of the density of loading with the combustion of the specimens were achieved by the use of a set of manometer bombs with a different free volume. Figure 35 shows that an increase in the diameter of the charge in the interval of $d_3=3-10$ mm reduces the combustion stability, and with a further increase in the diameter its effect is insignificant. In the investigation of other explosives an analogous effect of the diameter of the charge was observed.

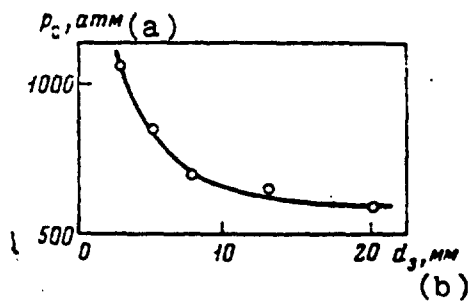


Figure 35. Effect of the diameter of the charge on the disturbance of stable combustion.

Key: (a) atm; (b) mm.

It is appropriate to compare the dependence $p_c(d_3)$ with data on the effect of the initial particle sizes (see Figs. 30, 31). A reduction in the combustion stability with an increase in the diameter of the charge and initial particle size with identical gas permeability of specimens indicates that the laminar combustion is disturbed not simultaneously on the whole front, but in separate centers - the largest pores into which, first of all, the penetration of combustion begins¹. With an

¹That stated above is confirmed also by the form of the optical recording of convective combustion (see Fig. 34), which is characterized by the uneven "ragged" front, which is caused by the penetration of combustion on separate pores in the center section of the charge with the subsequent yield of combustion to the lateral charge surface.

increase in the diameter of the charge and initial particle size there is an increase in the number of large pores and, consequently, the number of centers of the penetration of combustion, which is also the reason for a reduction in the stability of the laminar combustion. From these data there follows the important role of the distribution of pores according to dimension. For this very reason the gas permeability, which is the integral parameter of the porous medium, does not determine unambiguously the possibility of the destabilization of the laminar combustion. The need for an account of the distribution of the pores according to dimension in macroscopically uniform porous systems is a specific feature of the investigated phenomenon.

Effect of Conditions of Test Work [10]

The possibility of the disturbance of laminar combustion depends on conditions of the experiment, which determine the original reasons which cause the filtration of products of combustion into the pores (see § 12). A comparison of the combustion stability of identical porous specimens, carried out in conditions of the manometer bomb and bomb of "constant pressure" (with the filling of pores with nitrogen), showed that in the latter case the laminar combustion is disturbed at pressures 5-15 times greater; in this case the nature of the emergent convective combustion is substantially distinguished (see § 23). Let us examine the combustion of the porous charges under these conditions.

It was shown that the increased combustion stability under conditions of the bomb of "constant pressure" was conditioned by the filling of pores in the process of the creation of pressure by inert cold gas. Special tests were run when pumped into the manometer bomb preliminarily was nitrogen, which filled the pores of the explosive, whereupon the charge was ignited by the wire heated by current. The obtained results for one concrete example

(PETN, $m=0.24$; $r=20 \mu\text{m}$) are represented in Fig. 36 (plotted along the axis of the abscissas is the initial pressure in the pores p_n^0). From the given data it follows that with an increase in the pressure in the pores, the stability of laminar combustion substantially rises. With the combustion of this charge in the manometer bomb ($p_n^0=1 \text{ atm}$) the critical stall pressure is $p=100 \text{ atm}$, and under conditions of the bomb of "constant pressure" (with the filling of the pores with nitrogen) the value $p_c=700 \text{ atm}$.

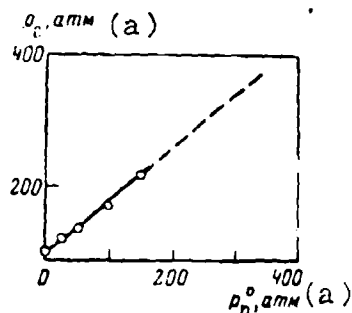


Figure 36. Dependence of critical pressure on the initial pressure of nitrogen in the pores.
Key: (a) atm.

Thus, under conditions of the manometer bomb or the scheme of the "embedded charge", the critical stall pressure of laminar combustion (or, which is the same, the critical dimension of the pores) proves to be considerably lower than that in the bomb of "constant pressure". The reason for the indicated distinction is connected with the fact that under these conditions the mechanism of the penetration of products into the pores substantially changes (see § 12).

B. SPONTANEOUS PENETRATION OF COMBUSTION INTO THE PORES

The disturbance of the laminar combustion by spontaneous (stream) mechanism occurs when there is no forced gas permeation and there are a non-univariate nature and a transiency of the structure of the combustion zone and gas flows in the immediate proximity of the surface.

If the flow of the gases above the combustion surface is one-dimensional and with removal from the surface the temperature

and gas velocity increase, then from the Hugoniot adiabatic curve it follows that the pressure with removal from the surface will be gradually decreased. Thus, a local pressure increase can be only with nonstationary and nonuniform combustion. The existence of the spontaneous gas permeation was established in the following experiments.

The combustion under falling pressure was studied. It is clear that under conditions of combustion under the constant and all the more falling pressure, the forced gas permeation does not occur. In this case the penetration, if it occurs, must occur according to the mechanism of spontaneous penetration.

Were prepared the charges which had a clearance modelling the blind pore with a height of 40 and width of ~ 0.1 mm between the plate of the secondary explosives of cyclonite and the plate of fiberglass. Also used were charges with the additional volume $V_{\text{доп}}$ connected to the "pore" [61]. The combustion was produced in a bomb 2 l in volume, the pressure in which was created by nitrogen. The control valve made it possible to obtain the necessary rate of the change in pressure in the bomb during the combustion of the charge, including $dp/dt=0$ and $dp/dt<0$. The course of the change in pressures in the bomb was recorded with a piezoelectric pickup and recorded on an oscillograph. Simultaneously through the plate of fiberglass high-speed filming was produced. It was established that with the combustion of the described charge without the supplementary volume with a completely enclosed valve, the propagation of combustion into the "pore" occurs when the pressure at the moment of ignition of the charge exceeds 25 atm. With an increase in p the penetration into the pore is substantially facilitated. Table 5 gives some characteristic results obtained with $p=45$ atm.

Here V_0 is the intrinsic volume of the pore; u_p - the average rate of propagation of combustion on the pore; V_r - rate of the

velocity of the forced inflow of gases into the pore, not allowing for spontaneous inflow, calculated from the formula:

$$v_r = \frac{V_0 + V_{доп}}{S} \frac{dp}{dt} \frac{1}{p} \frac{T_r}{T_0}$$

where S is the cross-sectional area of the inlet of the pore.

Table 5. Combustion of slotted charge.

dp/dt, atm/s	25	9	70	40	0	-5	-15	-5	-15	-18	-15
U_1 , cm/s	125	80	55	35	0	-4,5	-74	-135	-510	-900	-490
$V_0/(V_0 + V_{доп})$	5,5	1	1	1	1	1	5,5	30	40	55	30
u_0 , cm/s:	33	210	190	160	120	88	30	60	1,2	1,2	1,2
Result	Combustion penetrates into the pore						Combustion does not penetrate into the pore				

From the data of Table 5 it is clear that the combustion penetrates into the pore not only with $dp/dt > 0$, but also at a truly constant and even falling pressure. Under conditions of falling pressure an increase in the supplementary volume in contrast to the effect with the rising pressure leads to the difficulty of the penetration of combustion into the pore. With a certain value of $V_{доп}$ at the given rate of pressure decay the combustion into the pore was not at all spread. This paradoxical effect of the supplementary volume (destabilization of combustion under conditions of the rising pressure and stabilization under conditions of the falling pressure) is explained by the fact that with $dp/dt < 0$ the cold gas escapes from the pore outside and impedes the penetration of gases into it from without, and with $dp/dt \gg 0$ the forced gas permeation of combustion into the pore occurs. Indicating this is data according to which the value p_c - the critical pressure of the disturbance of normal combustion - best of all correlates not with dp/dt or

$V_0/(V_0+V_{доп})$, but with the rate of flow of gases V_r , which considers both the value $V_0/(V_0+V_{доп})$ and dp/dt . Under conditions of the falling pressure the normal combustion can occur at pressures which considerably exceed the critical pressure determined in normal conditions. So, we observed the normal combustion of the charge described above with $V_0/(V_0+V_{доп})=300$ with $p_0=65$ atm and $dp/dt=12$ atm/s. The experiments on the combustion of the charge with the pore under the falling pressure showed that the disturbance of normal combustion can occur also in the absence of forced penetration. Under these conditions the gas permeation is caused by the structure of the zone near combustion surface and occurs spontaneously. With combustion under the falling and truly constant pressure, the spontaneous penetration is the sole cause capable of leading to the disturbance of normal combustion. The heat transfer because of the spontaneous flowing in of the gases must be considered also with the combustion under a weakly rising pressure.

Let us still give several facts which confirm the existence of the spontaneous penetration of the gases. With the combustion of the charge of explosive in the air (i.e., at a truly constant pressure), the gases of combustion flow back only into the half-space above the charge's surface. The divergent gas stream. If one moves the wall or the second burning charge toward the burning charge, then there appears the interaction of the gas stream with the wall or with the gas stream from the second charge, and the gases begin to flow into the clearance between the wall and the charge (between the two charges, see Fig. 22). In this case it is possible to obtain not only the flowing in of the gases, but also the penetration of combustion in the clearance. It is doubtful that the gas permeation appearing here occurs as a result of the collision of gas streams with wall or between the streams themselves. From the theory of the streams it is known that with the collision of the two streams, directed

at an angle to each other, formed again are two streams the gas in which moves to the opposite sides in the direction of the bisector of the angle of convergence.

Belyayev and his colleagues [10] established that the rounding of the edge of the charge turned to the clearance facilitates the propagation of combustion into the clearance. The explanation on the basis of the stream mechanism was given to this result. The experiments showed that by changing the angle of the surface slope of the charge for the wall within close margins, it is possible to obtain quiescent combustion of the charge or intense propagation of combustion into the clearance. An analogous effect is observed at increased pressures: a decrease in the slope angle from 60° to 10° led to an increase in p_c by 20-40%. These experiments made it possible to draw the conclusion that among the mechanisms of spontaneous gas permeation, one of the basic is the stream mechanism. By the action of the stream mechanism it is possible to explain the results obtained in work [109], where it was established that with the combustion of the charge in air there is a certain dimension of the clearance with which the combustion most easily penetrates into the clearance between the wall and the charge.

It is necessary to emphasize that especially favorable possibilities for spontaneous penetration are created with the combustion of the powder-like charges of the explosive: due to the irregularity of the front of combustion there are always colliding streams of hot gases, and the conditions for an ejection from the surface of the particles of the explosives are facilitated.

§ 16. Criterion for Penetration

The criterion for the spontaneous destabilization of stable combustion must include conditions of the penetration of gaseous

products of combustion into pores of the charge and its effect on the process of combustion. It must be expressed as the relationships of the dimensionless parameters, which describe the combustion of the porous charge. The diameter of the pore d_{Π}' can form the dimensionless parameter in the form of the ratio to another value with the dimensionality of the length, which characterizes the process of combustion. Such values are the widths of the characteristic combustion zones l (there can be several such zones l_1) and the significant dimension of the grains of the substance r^1 . Furthermore, entering into the criterion will be dimensionless numbers, which characterize the flow of gas and heat exchange (Nusselt, Prandtl, Lewis-Lykov numbers):

$$d_{\Pi}' l = F(l; l/r; Pr; Nu; Lu; T, T'; T_r, T_0; \lambda_g/\lambda_r). \quad (43)$$

Here λ_r and λ_g are the coefficients of thermal conductivity of the condensed and gas phases; T_0 , T_r , T' - temperatures (initial, of the combustion and the surface of the k-phase with combustion).

In the case of the narrow zones or weak effect of the parameter l/r for this substance we have:

$$d_{\Pi}' l = \text{const} = An \text{ with } l/r \rightarrow 0. \quad (43')$$

Actually the condition $l/r \rightarrow 0$ is not always satisfied. In the case of small sizes of particles making up the charge, especially with $r \sim l$ substantially facilitated is the ignition of walls of the pores analogous to how the presence of the roughness of the optimum dimensions contributes to the ignition of the surface of the powder grain [70, 175]. As a result the combustion stability of the charges from finely divided particles under conditions when $d_{\Pi}'/l > An$ and $r \sim l$, proves to be decreased.

If for the group of substances the criterion weakly depends on the dimensionless numbers in the brackets of formula (43),

then also in this case it will take form (43'). An analysis of the experimental data shows that usually the most important parameter of those which were given in formula (43) is the ratio d_n'/l , since the ranges of the change in the remaining complexes is considerably more narrow. In connection with this, in the first approximation the criterion of the disturbance of normal combustion assumes the form of (43'). From the combustion theory it is known that the width of the heating zone of the condensed and smoke-gas phases l_r and l_T is $l \sim \lambda/\rho u c$. The width of the zone of chemical reaction in the condensed and smoke-gas phases is proportional to the width of heating zone, and only the width of the zone of burning out can differ somewhat from this value. Taking into account the observations made, we define concretely the condition (43'):

$$\rho u d_n' (c/\lambda) \geq \text{const} = An, \quad (44)$$

where c/λ can belong either to the condensed or gas phase.

Condition (44) means that if the value of the product of the mass rate of combustion ρu by the hydraulic diameter of the pores d_n' is less than a certain constant, then the normal burning is stable, but if the indicated product exceeds the critical value ϕ' , the combustion penetrates into the pores of the charge. Since the ratio of heat capacity c to the coefficient of thermal conductivity λ of the explosive changes within relatively narrow limits, criterion (44) is approximately reduced to the condition

$$\rho u d_n' = \phi' > \psi' = (\rho u)' d_n'. \quad (44')$$

An analysis showed [90] that both the requirement of the formation of the thoroughly heated layer of the k-phase in the wall of the pore and the condition of its ignition or pyrolysis are determined by the same set of dimensionless parameters which

enter into the criterial expression (43). With the derivation of condition (44') it is assumed that the distinction in the chemical kinetics of the substances is completely considered by the rate of combustion ρu and temperatures T_r and T' . This assumption is justified, since Zeldovich showed that the ignition process, which to the greatest degree is affected by the chemical kinetics, can be described approximately by values ρu and T' [43]. Furthermore, it is considered that the process does not depend significantly on the parameter ρ_r/ρ_T .

The stability criterion of the combustion of porous charges was obtained for the first time in work [89]. Later [60] it was suggested to consider in criterion (43) l to be the width of the layer of fusion for fusible and the width of the zone of heating of the gas for infusible substances and take the stability condition of combustion in the form of $pd \leq \text{const}$ or $p(1-\delta) < \text{const}$. Examined in work [11] were conditions of the disturbance of the completeness of the layer of fusion on the surface of the substances fusing with combustion. Found for the critical rate of combustion u' is the expression of the form

$$u' = \frac{12\delta x (\rho - \rho') u_1}{(1 - \delta) r_p}$$

where ρ and ρ' are densities of the parent substance and fusion; x - thickness of the layer of fusion; u_1 - rate of combustion at 1 atm; δ - relative charge density. At low densities u' usually corresponds to very low pressures.

Analysis of experimental data. The processing of experimental data in the form of condition (44') made it possible to show [62, 90] that the theory in the first approximation correctly reflects the laws governing the phenomenon, and value ϕ' can be considered as a sufficiently representative characteristic of the stability of the combustion of porous charges. At the same

Table 6. Critical parameters of normal combustion of homogeneous systems.

Substance	$\phi' \cdot 10^2$, g/cm ³ s	d_p , μm		h	
		10 atm	100 atm	10 atm	100 atm
Trotyl	13,2	1400	178	1	1
Picric acid	12,81	940	136	1,5	1,3
Nitrocellulose	9,8	330	100	4,25	1,8
PETN	11,1	540	55	2,6	3,3
Powder "N"*	4,35	120	40	11,7	4,5
Powder "NE"*	7,0	—	—	—	—
Tetryl	7,1	235	48	6,0	3,7
Cyclonite	6,9	163	21	8,6	8,7
Octogen	6,5	140	24	10	7,5
AL	3,7	110	20	12,7	8,9
Mercury fulminate	11,4	11,5	4,3	12	41
Ammatol 80/20	14,4	—	—	—	—

*Translator's note: These designations are transliterations from the Russian.

Note. The dimension of the pores was calculated from formulas (2), (4) and (5). Data of Tables 6, 7, and 8 are acquired in the bomb of "constant pressure" (with the filling of the pores with nitrogen).

time the introduction of the critical value ϕ' creates the basis for the subsequent refinement of the role of different factors which did not enter directly into the condition (43'). Table 6 gives the average values of the critical quantity ϕ' for a number of individual substances and homogeneous mixtures. The secondary explosives, initiating explosives, and two ballistic powders are entered here. The table is compiled according to published results of the experiments. As a whole it covers experimental data on charges on a relative density of 0.25 to 0.7 with relatively large sizes of the particles making up the charge from

50 to 730 μm (including the polydisperse charges [62]). Critical values of rates of combustion lie within limits of 0.33 to 8 $\text{g}/\text{cm}^2\cdot\text{s}$ and pressure from units to 750 atm.¹

On the basis of experimental data, calculated were values of dimensions of pores d'_n , the excess of which under these conditions (pressures of 10 and 100 atm) will cause the disturbance of normal combustion. This characteristic makes it possible to evaluate the relative tendency of different substances toward the spontaneous disturbance of normal combustion. Having available substances in series in decreasing values of d'_n at this pressure (in Table 6 at 10 and 100 atm), we find that (not allowing for the amatol) trotyl and picric acid burn most stably, and least - mercury fulminate. As quantitative characteristic it is possible to use value h of ratio d'_{n1}/d'_{n2} , where d'_{n2} refers to this substance, and d'_{n1} - to trotyl at normal temperature and the same pressure. Value $1/h$ can be called the trotyl stability factor of the combustion of the porous charge from the viewpoint of the critical dimension of the pores:

$$h(p) = \frac{d'_{n1}}{d'_{n2}} = \frac{\lambda_{n1}(p, d)_{1}}{\lambda_{n2}(p, d)_{2}} \approx \frac{(\lambda_{n1})_1}{(\lambda_{n2})_1}$$

It is necessary to keep in mind that in connection with the nonlinear nature of the dependence of the rate of combustion on pressure for some explosives the row according to the stability level of combustion, obtained at one pressure, cannot coincide with a row at another pressure, which is evident from the data given in Table 6.

¹In addition to the data collected in work [90], let us say that for mercury fulminate with $\delta=0.89$ and $r=50 \mu\text{m}$ the following is found: $p_c=70 \text{ atm}$, $(\rho u)'=26.2 \text{ g}/\text{cm}^2\cdot\text{s}$, i.e., $\phi'=11.4 \text{ mg}/\text{cm}\cdot\text{s}$.

Table 6 is refined in comparison with that which is given in [90].

Thus, with the comparison of the relative combustion stability of explosives, the indication of a pressure range is a necessary and sometimes also decisive fact.

The value of the critical quantity ϕ' , as can be seen from Table 6, differs somewhat from one substance to the next and lies within limits of 13.2 to 4.35 mg/cm·s. The average value for nitroesters is 10.5 ± 0.7 , and for nitro-compounds, 7.5 ± 1 mg/cm·s. Without diminishing the values of the observed distinctions, one should recognize that as a whole the value ϕ' lies in relatively narrow limits. It is doubtful that the observed distinction reflects the effect of the factors not considered under condition (44'), including the defined facts of the experiments. However, the value of the construction of a row with respect to the relative combustion stability consists of the possibility of a comparison and an account of the different effects. So, with the comparison of values ϕ' for the powder-like charges and charges with an artificial slotted pore, which has a very smooth surface, in the latter case ϕ' proves to be 1.5-2 times higher. At the same time charges from finely divided PETN ($r \sim 20 \mu\text{m}$) had ϕ' less than the average for coarsely-dispersed particles by 2 times [90]. The indicated facts will agree with the aforementioned expected effect of fine particles with $r \sim 1$.

By substituting into condition (44') the average value of $\phi' = 8$ mg/cm·s and standard value $(\lambda/c)_T = 1.5 \cdot 10^{-3}$ g/cm·s, we obtain the value of the constant $An = (c/\lambda)_T \phi' \approx 6$. Calculation of the constant according to the condition of the ignition of the wall of the pore in the form of (35) with $V_T = (\rho u)/\rho_T$ gives the value of approximately 1.5-2. Thus, the theoretical value will reasonably agree with the experiment. Let us note that the value of the constant on the order of 2 corresponds to the smallest value ϕ' observed in the experiment. In other words, the theory gives the lowest maximum estimation, whereas in the experiments usually the combustion is more stable.

In work [171] the question concerning the possible connection between An and the combustion temperature of the substances is discussed. It is noted that trotyl, in which the highest value of ϕ' among the secondary explosives is observed, has a low combustion temperature. By an increase in the combustion temperature with pressure, in work [171] the behavior of the potassium picrate in which with $\rho=0.85 \text{ g/cm}^3$ there are two ranges of the accelerated combustion is explained: at 7-20 atm, where $\phi'=13.6 \text{ mg/cm}\cdot\text{s}$, and above 60 atm, where $\phi'=7.7 \text{ mg/cm}\cdot\text{s}$. Analogously ϕ' at elevated pressures in pyroxylin proves to be 2 times higher than that at atmospheric pressure. As it was noted above, also, in works [62, 90], the effect of parameters T_r/T_0 , T_r/T' and ρ_r/ρ_r with the construction of condition (44') was not considered. However, it is not difficult to see that the experimental observations will agree with the expected effect of pressure through the completeness of combustion on the possibility of the disturbance of the normal mode.

Let us make the additional observation. If we consider that in (44) c and λ refer to the gas phase, then relation (44) is the analog of the Péclet number (ρu - rate of combustion). After substituting into (44) $(\lambda/c)=2\cdot 10^{-4} \text{ g/cm}\cdot\text{s}$, we will obtain the critical value of the Péclet number $Pe'=(\rho u d)' \cdot (c/\lambda)_r=40-45$. In general the combustion stability is affected by the condensed and gas phase. If we consider, as this was done above, that for the group of substances $\lambda_r/\lambda_r=\text{const}$, then it is possible to substitute λ_r and λ_r into condition (44).

Let us turn to the examination of data on heterogeneous systems. The estimation of critical conditions developed above was constructed for homogeneous systems. In the case of heterogeneous and especially polydisperse mixtures there appear the supplementary characteristic parameters not considered in condition (44'). Investigated in work [62] were the standard

heterogeneous systems, which consist of the mixture of combustible (saccharose, urotropin) and oxidizers: AP and potassium perchlorate (PP). [ПХН]. The latter, unlike AP, is not able to independent combustion. The selected substances essentially differ from each other in physicochemical characteristics, in particular, in terms of the fact that the AP and urotropin are not melted with combustion, whereas PP and saccharose, as a rule, are melted in the surface layer of the condensed phase of the burning mixture. Results of experiments are given in Table 7.

Table 7. Limits of normal combustion of mixtures of fuels and oxidizers.

Components	Composition, % by weight	δ	$r, \mu\text{m}$	ρ, atm	$\dot{m}, \text{g/cm}^2 \cdot \text{s}$	$\dot{m}, \text{mg/cm}^2 \cdot \text{s}$
AP (100-160 μm) - saccharose (100-160 μm)	100:0	0,537	67	20	0,735	3,58
	90:10	0,58	62,5	13	0,68	3,31
	80:20	0,58	62,5	8	0,627	3,00
	70:30	0,568	66	7	0,671	3,13
AP (110-160 μm) - urotropin	85:15	0,683	69,5	7	0,732	3,22
	75:25	0,631	57,5	6	0,655	3,18
	65:35	0,687	47	9	0,705	3,33
PP (160-250 μm) - saccharose (160-250 μm)	90:10	0,535	119	14	0,76	3,6
	80:20	0,555	110	7	0,825	3,95
	70:30	0,540	116	6	0,775	3,65
	60:40	0,537	105	6,5	0,88	4,20
PP (63-100 μm) - urotropin	75:25	0,558	62	9	1,1	5,1
	65:35	0,63	57	10	1,83	10,05
	55:45	0,654	55	12	1,87	10,4
	45:55	0,60	45	16	2,15	9,6

Note. Particle size of urotropin is $\sim 100 \mu\text{m}$.

Results of the investigation of the mixture of AP and cyclonite are given in Table 8. Both components of this mixture are capable of independent combustion and have differing values of the critical quantity.

An analysis of the effect of the composition of the mixture on the stability of its combustion (see Tables 7 and 8) made it

Table 8. Limits of normal combustion of the mixtures of AP with cyclonite.

Composition of AP-cyclonite, % by weight	δ	d, μM	p_c , atm	ϕ' , $\text{g}/\text{cm}^2 \cdot \text{s}$	ϕ' , $\text{mg}/\text{cm}^2 \cdot \text{s}$
100:20	0,535	119	12	0,315	3,71
75:25	0,543	115	3,5	0,350	4,05
50:50	0,544	115	2,8	0,553	6,65
25:75	0,542	107	5	0,607	7,25
0:100	0,564	106	12	0,65	7,75

Note. Particle sizes of both components is equal to 160-250 μm .

possible to establish that the addition to ammonium perchlorate both by the fusible saccharose and the infusible urotropin (up to 30-35 % by weight) leads to a very weak change in the critical value of quantity ϕ' characteristic for pure AP. Analogously it can be concluded that both the composition and properties of the fuel weakly affect ϕ' of mixtures with potassium perchlorate as a base. Data of Table 7 show that the mixtures of PP with saccharose and urotropin have $\phi' \approx 9-10 \text{ mg}/\text{cm} \cdot \text{s}$, close to the same for the standard secondary explosives [90]. The critical value ϕ' of the mixture of AP with saccharose has a tendency toward an increase with an increase in the content of the combustible, and for the mixture with urotropin it passes through the maximum and further is somewhat decreased.

A change in the particle sizes of the components did not affect values of ϕ' . Thus, experiments with the mixture of AP and saccharose of the composition 80:20 with reduced particle sizes ($r=50-63 \mu\text{m}$, $\delta=0.557$, $d'_n=30 \mu\text{m}$) led to $\phi'=3.96 \text{ mg}/\text{cm} \cdot \text{s}$, $p_c=23 \text{ atm}$, $u_p'=1.28 \text{ g}/\text{cm}^2 \cdot \text{s}$), which coincides with the value of ϕ' for a mixture with particle sizes of 100-160 μm .

The study of the combustion of the mixture of AP and cyclonite (see Table 8) was conducted over a wide range of relationships

of components. It was found that the critical value of ϕ' is not the additive function of the composition but is determined by that component the volumetric content of which is more in the mixture.

It is important that with a composition change, for example, the mixture of AP-saccharose, there occurs, in particular, a very powerful change in the calculated temperature of the combustion products (for the mixture of the composition 80:20 in comparison with 100:0, 2 times). Nevertheless, this did not affect the value ϕ' .

In work [90] it was shown that critical value ϕ' of such low-melting substances as trotyl and picric acid does not substantially differ from ϕ' of the infusible nitrocellulose (13 and 10 mg/cm's respectively). From Table 7 and 8 it follows that the ability of the combustible to melt is not the decisive factor which determines the combustion stability and the possibility of its penetration in the large pores of the charge, i.e., under conditions when on burning surface the continuous molten layer is absent.

In Andreyev's works [68, 172] it was indicated that the addition to ammonium perchlorate of a small quantity of finely dispersed aluminum facilitates the transition of the combustion of the mixture with the rising pressure into an explosion. The experiments showed that the critical value ϕ' (for conditions of combustion at a constant pressure) of the mixture of AP and aluminum ($r \sim 25 \mu\text{m}$) is not below and even exceeds the value ϕ' for pure AP. Thus, the introduction of aluminum raises the combustion stability of the considered mixture in comparison with pure AP in conditions of the test work under a constant pressure. At the same time in the conducting of the experiments with this mixture, in conditions of combustion under a rising pressure, the

introduction of aluminum facilitated the transition of combustion beyond the stability limit into an explosion. Similar data are found in work [171] in the investigation of the effect of the dispersity of aluminum. Here it was established that for the mixture of large AP with 5% Al ($r \sim 14 \mu\text{m}$) $An' = 20$, and the mixture of fine AP with powder ($r \sim 1 \mu\text{m}$) had $An' = 1.6$. For the mixture of large AP with 10% carbon black $An' = 2.5$, and for the mixture with coke ($r = 150-250 \mu\text{m}$) $An' = 34$. Thus, some heterogeneous systems, which include components incapable of independent combustion, require a fuller account of the factors which affect the process of combustion than in the form of condition (44). As regards the mixtures of oxidizers with organic fuels and also mixtures of substances capable of independent combustion, the stability of their combustion is described by condition (44) in a sufficient measure. It should be noted that as the experiments on mixtures of AP with aluminum powder show, the same factor can simultaneously increase the critical value of quantity ϕ' and contribute to the intensification of the convective combustion of the charge beyond the stability limit.

Deviation from the criterion is observed also with the combustion of powder-like charges from fine particles ($r \sim 15 \mu\text{m}$). In accordance with data of Lobanov for substances of 10% polystyrene + 90% AP, 2% Cu_2O + 98% AP, pure AP and PETN, value ϕ' is 0.45, 0.4, 1.5 and 3 $\text{mg}/\text{cm}\cdot\text{s}$, respectively.

An analysis showed [62] that best results are obtained when using the value of the diameter of the pores according to results of the experimental determination of the gas permeability of the charges. The conclusion was made about the determining role in the process of the spontaneous disturbance of normal combustible of porous systems of pores with a medium size, which in the charge are the greatest number.

In the conclusion of this section it is possible to recommend for new systems refining the value of the number An' or ϕ' at least at one point, since condition (44) is satisfied for one system more precisely than for the entire totality of the substances.

CHAPTER IV

COMBUSTION OF SYSTEMS WITH UNCONNECTED PORES

In this section we examine the combustion of systems, which contain closed pores which are not connected with each other; where the system as a whole is gas-impermeable. The shape of the pores can be diverse: from individual pores or pores distributed over the volume in the form of spheres to extended cylindrical and plane pores (cracks).

The causes of the formation of the pores are exceptionally diverse in their nature. Let us note only some of them.

Unconnected pores form in powders and explosives during manufacture (bubble technological porosity, craters), and also in the process of exploitation: during storage or combustion (cracks, porosity). A significant effect on the formation of pores is exerted by the physico-mechanical properties of the system. According to American researchers [124], especially inclined toward the formation of those types of pores are mixed powders, which are a heterogeneous mixture, containing in its composition components with highly diverse properties: elastic combustible-binder, crystalline oxidizer (ammonium perchlorate) and metallic additives. During the combustion of a charge of the channel type firmly fastened to the engine housing, as a result of the effect of the

powder gases elongation of the powder occurs, which leads to the disruption of the adhesive bonds between the fuel and the oxidizer. Around the filler particles separations (hollows) form. The separation of the binder from the oxidizer is the basic physical process, which determines the pore formation process [124]. The indicated process occurs not only under the effect of mechanical, but also under thermal stresses. Since the coefficient of linear expansion of the powder mixture ($\sim 10^{-4}$ 1/deg) exceeds the corresponding values for steel by an order of magnitude, during cooling in the charge-steel housing system temperature tensile stresses arise. The coefficients of linear expansion of the components of the powder itself are also quite different, the result of which is the formation at low temperatures of "frozen" porosity [160]. The stress concentration at the sites of the separations and the disruption of the binder under specific conditions leads to the joining of the pores and crack formation.

Pores and cracks can also form during the ignition of the charge as a result of the effect of great pressure and temperature gradients.

It is natural that the penetration of combustion into unconnected pores is a considerably lesser danger, than in the case of gas-permeable systems. At the same time the presence in a specimen of pores causes deformation of the combustion front, an increase in the burning surface, and consequently, a pressure rise in the engine.

It is known that steady pressure in an engine is defined by the formula of the Bori [Translator's Note. Name Bori not found]:

$$P_c = \left(\frac{b_0 S_0}{A E} \right)^{1/(1-\sigma)}, \quad (45)$$

where S_0 is the burning surface; A is the exhaust coefficient; σ is the cross-sectional area of the nozzle; ρ is the density of

powder b and v are constants in the burning rate law $u=bp^v$.

From (45) it is not difficult to see that a change in the burning surface can lead to an essential increase in the pressure in the engine (especially at high values of v), which exceeds the maximum allowed value. Consequently, the engine can be destroyed as a result of activation due to the presence of pores of the limited (supplementary) burning surface ΔS .

If $v < 1$, then after an increase in the burning surface from S_0 to $S=S_0+\Delta S$ gas-dynamic equilibrium will again be stabilized at the pressure

$$p = p_0 (S/S_0)^{1/(1-v)}. \quad (45')$$

Since $p=p_0+\Delta p$, $S=S_0+\Delta S$, then from (45'), utilizing the expansion of value $(S/S_0)^{1/(1-v)}$ into a series and being limited by the first two terms, we obtain the expression

$$\frac{\Delta p}{p_0} = \frac{1}{1-v} \frac{\Delta S}{S_0},$$

which makes it possible with sufficient accuracy for practical purpose to calculate the relative increase in pressure.

If the surface of the pores is defined, then in calculating $\Delta p/p_0$ we usually employ simple geometric considerations and assume that the rate of combustion in a pore does not differ from the combustion outside it. When necessary it is possible to take into account the increase in the gas inflow from the pore surface, connected (the increase) with the emergence in the pore of excess pressure (see § 22). This approach to determining $\Delta p/p_0$ is legitimate in the case, when the possibility of the growth (increase in the initial depth) of pores in the process of combustion is excluded. The problem of pore growth during combustion is examined in § 22.

Thus, to ensure the normal operation of an engine the reduction in superscript v in the burning rate law and also the improvement in the physico-mechanical properties of the powder and the correct design of the engine, which makes it possible to exclude pore formation, at all stages of the "life" of the charge have great significance.

§ 17. Critical Conditions of the Penetration of Combustion into a Single Pore

Above in (§ 15) we evaluated the critical dimensions of a pore into which the penetration of combustion is possible, utilizing for this purpose the data on the disruption of the stability of the combustion of gas-permeable porous systems. However, the combustion of closed pores is characterized by a number of specific features which must be considered in examining the critical conditions of penetration. The compression of the gas in the closed (dead) end of the pore stabilizes the flow of the products and impedes the penetration of combustion. On the other hand, favorable conditions are created for the inflow of gas by a spontaneous mechanism, since the periodic destruction of recesses, which generate combustion products in a pore, characteristic for compressed systems is absent.

The authors carried out direct experiments. Plane slotted charges (Fig. 37) were employed whose combustion was carried out in a bomb manometer. The pressure in the volume of the bomb $p(t)$ was recorded and photographing of the penetration process was also carried out. The critical pressure p_c was determined, at which combustion penetrated into a pore with a width of d_0 . The experiments were mainly conducted with charges of the 37a type (the pore was formed by explosive plates and plexiglass)¹.

¹It was shown that the value of p_c does not change during the combustion of pores of the 37b type (the pore was formed by two explosive plates).

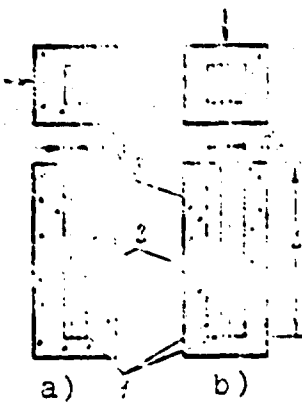


Figure 37. Diagrams of slotted charges being employed a) is a blind pore, formed by a plate of continuous explosive and plexiglass, b) is a blind pore, formed by two plates of continuous explosives: 1 - explosives; 2 - pore; 3 - shell of plexiglass. d_0 - the width; L - the depth of the pore; the arrow indicates the direction of photographing.

The results of the experiments for nitroglycerin powder, a mixed powder of two brands and cyclonite are represented in Fig. 38. It is evident that the most stable is the combustion of the powerful explosive - cyclonite and the least - mixed powders (nitroglycerin powder

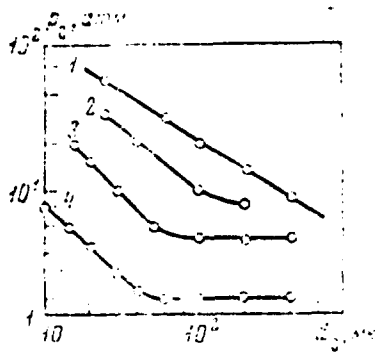


Figure 38. Dependence of critical pressure on pore width. 1 - cyclonite; 2 - nitroglycerin powder; 3 - mixed composition which is slow-burning; 4 - mixed composition which burns rapidly. [$P_c = \text{atm}$; $d_0 = \mu$].

occupies an intermediate position). The combustion stability of mixed powders decreases with an increase in the combustion rate, which directly follows from a comparison of the data for slowly burning 3 and rapidly burning 4 compositions. Thus, in comparing the combustion stability of explosives or of powders of one class in a narrow range of variation in the pressure the rate of combustion has vital importance.

As a whole the findings will agree with those which were presented in § 16 both in a numerical regard and from the viewpoint of comparative stability.

The low combustion stability of mixed powders in comparison with nitroglycerine powders is due to the differences in the temperature profile in the gaseous phase. It was noted [81, 83,

163], that the distance from burning surface to the high-temperature gaseous zone h_m for mixed powders is an order less than for nitroglycerine powders (when $p_0 \approx 40$ atm. the values of h_m are respectively 2 and 0.1-0.2 mm). The pressures also significantly differ at which completeness of combustion is attained (respectively 10-20 and 40-50 atm.). All this leads to the fact that the temperature of the gas, which is flowing into the pores of a mixed powder, even at low pressures, is higher than in the case of nitroglycerin powder. This was confirmed by direct measurements of the temperature in the pores [12, 59]. The indicated difference is also exhibited in the nature of the ignition of the pores after penetration (§ 22).

For mixed powders two sections are observed on the curve $p_c(d_0)$: strong dependence in the region of small gaps and attenuation with the large d_0 .

From the conditions of ignition examined in § 14 [see (38)] it follows that it is possible to expect a dependence of the type

$$p_c^{1+2\nu} d_0^2 = \text{const.} \quad (46)$$

A comparison of the calculations with the experiment shows that at low values of d_0 satisfactory agreement is observed: the slope of the curves corresponds that which is expected from theory and is equal to $-2/(1+2\nu)$. For the investigated powders (with $\nu=0.5$) the relation of the critical pressure and dimensions of a pore is hyperbolic [12] $p_c \cdot d_0 = \text{const.}$ It is interesting that in the case of cyclonite ($\nu=1$) in accordance with (46) dependence $p_c(d_0)$ is weaker than for the powders. The absence of the agreement of the calculations with the experiments at high values of d_0 (section of weak dependence $p_c(d_0)$) is connected, apparently, with the need for taking into account the dependence of Nusselt number on the velocity of the gas flowing in ($Nu \sim Re_x^{0.5}$).

Also studied was the effect of the surface roughness of the pore. Experiments were conducted with cyclonite plates to which different degrees of roughness had been imparted. It was shown that in accordance with the calculations the presence of roughness reduces stability: with an average gap width $d_0 = 40 \mu$ and dimensions of roughness of $\sim 10 \mu$ the critical pressure is reduced from 35 to 20 atm. Variation in the roughness dimensions had a weak effect on the magnitude of critical pressure. The effect of pore roughness reduces to the fact that the projections are heated faster, and to a higher temperature, than a smooth surface, and are centers of ignition.

§ 18. Combustion of Systems with Bubble Porosity

Belyayev in his work [59] studied the combustion of powder specimens, which contained pores in the form of bubbles (spheres) 0.1-0.5 mm in diameter uniformly distributed over the volume. Specimens with different porosity were obtained by varying the manufacturing technology. The combustion of cylindrical charges with diameters of 10 mm and with heights of $H = 15-20$ mm, jacketed on the lateral surfaces, was carried out in a HP [БД - High Pressure] instrument. From burn-up time t and the height of the specimen H the linear burning rate $u = H/t$ was computed. The mass rate of combustion was calculated as the product of the linear velocity and density. In this case $u_M = up$ is the quantity of substance, which burns in a unit of time from a unit area of the cross section of the specimen (neglecting the relief of surface).

The results of the measurements are represented in Fig. 39; along the abscissa axis is plotted the density ρ and the porosity m of the specimen, along the ordinate axis - the linear u and mass u_M combustion rate. Experiments are carried out at pressures from atmospheric to 42 atm.

As follows from the findings, at a pressure equal to atmospheric, the mass combustion rate does not depend on density. At elevated pressures in proportion to the increase in porosity both the linear and the mass combustion rate increases, and more sharply, the higher is the pressure.

The processing of the findings in coordinates $\lg u - \lg p$ (Fig. 39b) showed that the presence in a charge of closed pores leads to a variation in the combustion law $u = bp^v$. The conventional combustion rate b when $p = 1$ atm(abs) does not in practice depend on porosity, but exponent v increases with an increase in porosity.

The photographic observations of the combustion of individual closed pores, made by Chuyko, showed that in accordance with the data of Fig. 39 at low pressures the internal surface of pores is ignited with great lag in time, and the distortion of the combustion front is insignificant. Combustion seemingly does not sense the presence of pores. In proportion to the increase in pressure the lag in ignition is decreased and surface distortion increases (Fig. 40).

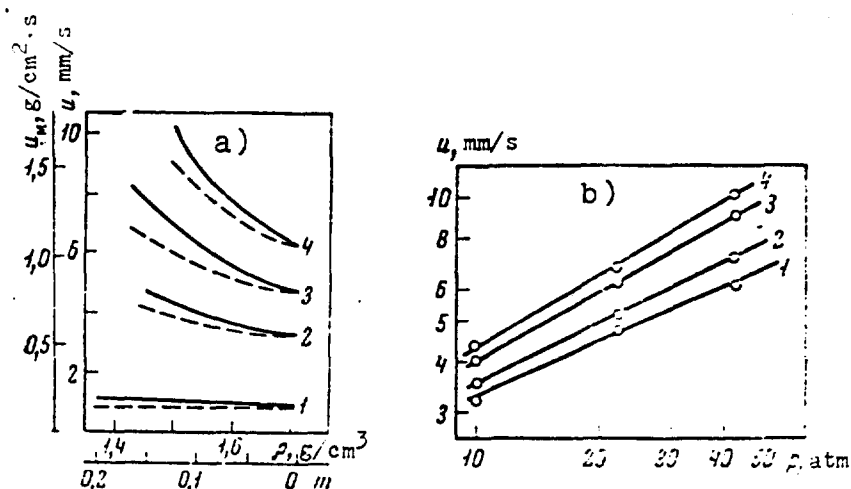
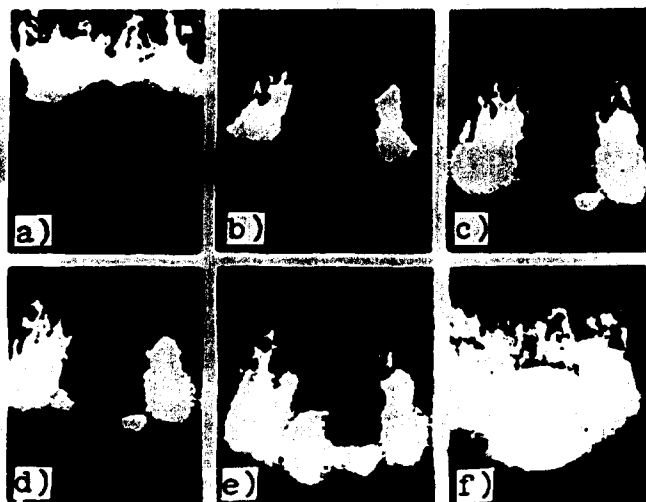


Figure 39. The effect of closed (bubble) porosity and pressure on linear u and mass u_M combustion rate. a) 1 - 1 atm.; 2 - 10 atm.; 3 - 22 atm.; 4 - 42 atm.; the unbroken curves are u ; the broken curves are u_M . b) 1 - $m=0$, $v=0.45$; 2 - $m=0.05$, $v=0.51$; 3 - $m=0.10$, $v=0.57$; 4 - $m=0.125$, $v=0.6$.

Figure 40. Motion-picture frames of the ignition of a spherical pore (d=4 mm, p=50 atm.).



Pressure equalization in a spherical pore upon the approach to it of the combustion front occurs extremely rapidly and, consequently, the supply of heat, introduced by the

combustion products, is insignificant. The fact, that the pore is nevertheless ignited, indicates the significant role of the heat supply from the combustion zone.

A decrease in the lag in the ignition of a pore with an increase in pressure makes it possible to explain the increase in the effect of porosity at high pressures established in the experiment (see Fig. 39).

A somewhat different explanation [59] for the findings (see Fig. 39) can be given, if we examine a simplified setup of the combustion of a porous charge (Fig. 41) and assume that all the heat is liberated in the narrow zone of the gaseous phase and is transmitted to the condensed phase by thermal conductivity.

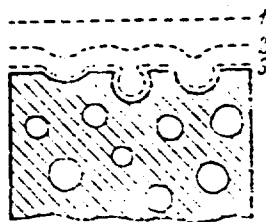


Figure 41. Diagram of the combustion of a system with closed porosity at various pressures. The broken line indicates the position of the reaction zone relative to the surface at various pressures $p_1 < p_2 < p_3$.

For the case of a driving reaction in the gaseous phase the quantity of burning substance per unit of surface of the flame front at a given pressure is a specific quantity. During a steady combustion mode a quantity of intermediate products goes from the condensed phase into the gaseous phase, which the flame at a given surface can "process" regardless of what the density of the original substance is. The "self regulation" of the supply of a necessary quantity of intermediate products is accomplished by varying the distance from the reaction zone of the gaseous products to the surface of the substance and by a corresponding variation in heat flux.

At low pressures the reaction zone is located far from the charge surface; the combustion front in the gaseous phase is undistorted and plane (position 1 in Fig. 41); thus the mass combustion rate is determined only by pressure, and not the density of the original substance. The linear burning rate is inversely proportional to the density; it is obvious that in order to ensure the necessary influx of intermediate products, the flame must be brought somewhat closer to the surface of the porous specimen as compared with a nonporous one. This is one limiting case.

In another limiting case (at rather high pressures) the distance from the reaction zone in the gaseous phase to the charge surface becomes much less than the dimensions of the pores; the surface of the flame completely repeats the relief of the charge surface (position 3 in Fig. 41). The mass combustion rate of a porous charge (since it is calculated for the cross section of the specimen) is as many times higher than mass combustion rate of a nonporous charge, as the surface of porous charge is greater than the cross section. The latter relation with an idealized arrangement of pores of identical diameter at the points of a cubic lattice is equal to $1 + \sqrt{36\pi} \text{mm}^2$. Comparison with the experiment (see Fig. 39) shows that this limiting case at maximum (42 atm.) pressure is still not realized.

Between these limiting cases lies the range of intermediate pressures, in which with an increase in pressure the flame front (position 2 in Fig. 41), approaching the surface of the condensed phase, varies from a plane front to a maximally distorted front. The position of the boundaries of this region depends on the dimensions of the pores; more precisely on the relationship of the dimensions of the pores and the distance from the surface to the reaction zone in the gaseous phase. In this range of pressures during the combustion of a system with closed pores on the usual "chemical" increase in combustion rate with pressure (due to the increase in the reaction rate in the flame) a "geometric" increase (due to the increase in the curvature of the flame in proportion to the increase in pressure) is superimposed, which also leads to an increase in the exponent in the combustion law $u=bp^v$.

In the general case the dependence of the mass combustion rate on pressure during the combustion of a system with closed pores should take the form, schematically shown in Fig. 42. For clarity

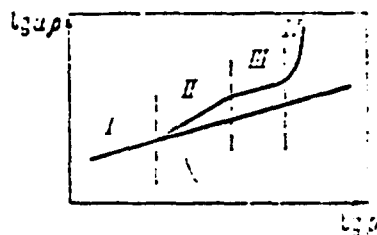


Figure 42. Schematic representation of the dependence of combustion rate on pressure for a system with closed porosity. The upper curve corresponds to $m > 0$, the lower to $m = 0$.

the dependence for a continuous system is taken to be identical in the entire range of pressure variation $u=bp^v$, $v = \text{const}$. The position of the boundaries between the regions depends on the physicochemical properties, the mechanical characteristics of the system and the dimensions of the pores.

Regions I, II, III correspond to positions 1, 2, 3 in Fig. 41. In region III the ignition of the pores occurs so rapidly, that the combustion rate of the specimen is determined only by the burnup of the partitions between the pores. Therefore, the value of v for a porous and continuous specimen is identical. The

separation of the pores by gas-impermeable partitions impedes the penetration of combustion into the volume of the specimen. However, the noted stabilization of the process is accomplished up to a specific pressure.

At high external pressures mechanical destruction of the partitions occurs, the pores are connected and combustion penetrates into the volume, which is accompanied by a sharp increase in the combustion rate of the charge (region IV).

In this connection it is necessary to note that the effect of the destruction of the partitions upon the approach of the combustion front to a pore is observed even at comparatively low pressures (~40 atm.). However, the thickness of the destroyed arch in this case is small and depending on the physicommechanical properties of the system, it is approximately 0.1-0.2 of the diameter of a pore.

We examined the case of the combustion of a system with closed pores of technological origin. The combustion of deformed specimens reduces to this case. As was noted, during the tensioning of mixed powders as a result of the breakdown of the adhesive bonds proceeds separation of the fuel-binder from the ammonium perchlorate crystals. Separation begins first of all on the large crystals. Thus, in the tensioned specimens closed pores are formed which lead to an increase in combustion rate. According to [124], in contemporary powders it was possible to avoid localization of damages: the separation of the binder from the oxidizer has a uniform nature, which one can see well from the photograph in Fig. 43. The connection between porosity and the greater of the main normal deformations ϵ takes the form:

$$m = \epsilon(1 - 2\mu') - \mu'\epsilon^2(1 - \epsilon)$$

(μ'^1 - Poisson's ratio).

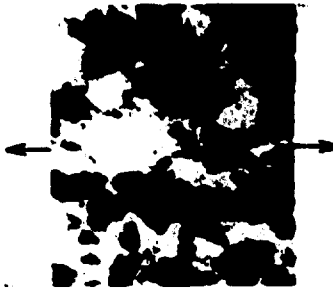


Figure 43. Formation of pores during tensioning of a mixed powder. Deformation $\epsilon=50\%$; the arrow shows the direction of the tensioning; the dark regions indicate the formation of hollows around the oxidizer particles, which are white in color.

In Sorkin's book [94] the following expression is given for the dependence of combustion rate on deformation:

$$u_{\epsilon} = u_0(1 + \xi\epsilon^n), \quad (47)$$

where ξ and n are the numerical coefficients, which depend on propellant composition.

Consequently, the combustion rate of a powder in the general case depends not only on pressure, initial temperature, the rate of gas flow, but also on deformation, which is considered when carrying out intraballistic calculation of an engine with the charge, solidly fastened with the housing.

What has been presented above corresponded to the conditions, when combustion was not the direct cause for the formation of pores (cracks) and the role of combustion reduced only to the "development" of already existing structural defects.

§ 19. Concerning Thermal Shock During Combustion

During the combustion of continuous brittle systems and primarily of crystalline explosives crack formation can occur in the process of combustion under the effect of thermal shock - the thermal stresses, which appear in the heated layer of the explosive [38]. The magnitude of stress is increased with an increase in the temperature gradient and, consequently, of combustion rate.

The splitting of the single crystals of the initiating explosives during combustion was experimentally observed by Bowden with coll. [88]. Whittaker and Barham [96] detected an analogous effect for single crystals of ammonium perchlorate, which ignited and burnt at a pressure of 42 atm.

This question was theoretically investigated in work [174] the authors of which connect the sharp increase in the combustion rate ($v > 1$) of the specimens of ammonium perchlorate at pressures of $p > 350$ atm. observed in experiment [95] with crack formation¹. The calculation carried out in [174] showed that in the whole pressure range (350-1600 atm.) the splitting of ammonium perchlorate is determined by thermal stresses, and not by shear stresses as was assumed earlier.

The splitting of explosive crystals under the effect of temperature differentials, but in the absence of combustion, was experimentally studied by Andreev and Gorbunov [97]. Crystalline particles of explosives were dumped into water with different temperatures. The temperature differential ΔT which led to crack formation was determined. It was established that large explosive crystals were very sensitive to thermal shock; sudden heating from the surface produces splitting of a crystal at a small temperature differential. For PETN [TSHA] and cyclonite crack formation was already observed at $\Delta T = 15-20^\circ\text{C}$, for those less sensitive - picric acid and trotyl - at $40-50^\circ\text{C}$.

During combustion considerably higher temperature differentials are realized. At the same time reliable data are absent in literature, which attest to the splitting of powders and

¹However, according to Glazkova's data [158], the form of curve $u(p)$ for ammonium perchlorate in the pressure range 350-1000 atm. strongly depends on the nature of the shell and the presence of a catalyst, which indicates the important role of chemical factors. Thus, for instance, with the introduction of 5% $\text{K}_2\text{Cr}_2\text{O}_7$ curve $u(p)$ takes the normal form ($v=0.6$). Thus the explanation, advanced in [174], is not unconditionally all-inclusive.

polycrystalline explosive specimens in the process of combustion. Research on the combustion of specimens of secondary and initiating (mercury fulminate) explosives compressed to the maximum possible density showed [23, 38, 80] that the dependence of combustion rate at high pressures up to 1000-4000 atm. (where the effect was to be expected¹) does not undergo anomalous changes. This result indicates that the mechanism of crack formation during the combustion of polycrystalline explosive specimens, apparently, differs from that for single crystals, and that combustion has a significant effect. It is possible that during the combustion of secondary explosives the formation and the development of cracks is impeded by the fusion process. It is also possible to assume that the thermal shock will be exhibited under especially favorable conditions to it, for example during the blowing of a high-temperature gas flow around a burning specimen which increases the intensity of heating of the solid phase. In any case the available indirect data are grounds for this assumption.

In conclusion it should be noted that the data existing in literature do not make it possible to formulate the mechanism and the laws governing crack formation in the combustion process. Thus, a vast field for theoretical and experimental investigations of this indisputably interesting phenomenon is preserved.

¹Thermal stresses increase with an increase in combustion rate as a result of an increase in the temperature gradient.

CHAPTER V

THE DEVELOPMENT OF EXPLOSION

§ 20. General Pattern

Chapter III presented the results of the investigation of the initial stage of the development of explosion - the stage of the disruption of stable laminar combustion.

The present chapter will examine the data, which concern the explanation of the mechanism and the laws governing the propagation of the process after the loss of stability in order to answer the basic question, how explosion develops and detonation arises. The concept, "explosion" is treated in the broad sense and includes the totality of various modes (stages), preceding the appearance of detonation.

The first investigations, which showed the fundamental possibility of the transition of the combustion of solid explosives into detonation, were made about 30 years ago by Andreev [6, 7], Belyayev [1-5], Patri [9]. It was already established then that if for initiating explosives (of the mercury fulminate type) of low density the indicated transition occurs very easily - during ignition in the atmosphere, then in the case of homogeneous explosives it can be obtained, when an explosive is ignited and burns under conditions of high pressure, in a strong closed shell. The simple method used by Andreev for the study of the transition

of combustion into detonation (see Fig. 6a), which bears his name, is also broadly employed in one or another variant at the present time.

The development of explosion in connection with the conditions of mechanical effects (upon the striking of a striker against an anvil) was studied in great detail by Bowden with his coll. [15]. The experiments were conducted with the thin layers of explosive, included between flat surfaces, pressed together by high pressure. These works revealed the general external pattern of the development of an explosion from the focus of the reaction and the complex stage nature of the propagation of the process was established: combustion-accelerated combustion-detonation at a slow rate (1000-2500 m/s)-normal detonation.

The appearance of normal detonation was observed, as a rule, upon the egress of the process from the pressed layer into the unpressed explosive. Although the general pattern of the development of an explosion was also established, a detailed investigation of the individual stages was not carried out due to their small three-dimensional extent.

Bowden's works obtained their subsequent development in the investigations of Bobolev with his coll. [16, 126, 127].

The transition of combustion into the detonation of pressed [14, 142-144, 165] and cast [13, 121, 125, 131] explosives, contained in strong closed shells has been studied in the works of recent years. These investigations introduced considerable clarity into the understanding of the physical essence of transition phenomena and made it possible to ascertain the basic laws governing predetonation development.

On the basis of the existing concepts the transition of the combustion of solid explosives into detonation can be represented by

the general simplified diagram (Fig. 44), which includes the following stages: I - stable laminar combustion; II - convective combustion; III - low-speed (800-3500 m/s) mode of explosive conversion¹; IV - steady-state, normal detonation. Each of the stages is distinguished by

the mechanism of the transfer of heat and the excitation of the reaction. The basic form of heat transfer in laminar combustion is molecular thermal conductivity, in convective combustion - forced convection. The low-speed mode is excited by compression

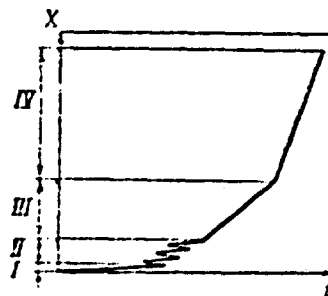


Figure 44. General diagram of the transition of the combustion of a solid explosive into detonation.

waves, detonation - by a shock wave. In the general case the development of the process is accelerated. The final result of accelerated development is the formation of a shock wave which initiates the detonation of the explosive, if its amplitude exceeds the critical value, and the system is detonatable (the diameter of the charge exceeds the critical detonation). The existence and the three-dimensional extent of the individual stages depend on the structure of the charge, physicochemical (individual) properties of the explosive, and the conditions under which the experiment is carried out. Thus, for instance, convective combustion can directly change over into detonation, by-passing stage III. The development of the process can end with the establishment of a low-speed mode with a constant velocity, and the appearance of detonation is absent.

¹The rate of propagation of the low-speed mode is considerably slower than the rate of normal high-speed detonation. At the time unified conventional terminology for this process is lacking. The following names are employed: detonation at low rate (for powdered explosives), wave combustion, low-speed mode. We will mainly employ the term the "low-speed mode of explosive conversion" (NSR), since in charges of high density the rate of propagation of the process is usually considerably slower than the speed of sound in the original explosive.

For the purpose of simplifying the following presentation of the material it is expedient to examine convective combustion, low-speed wave modes, impact initiation of detonation separately. This is all the more necessary, since each of the indicated processes is of independent interest. At the same time, until recently our knowledge about them has been extremely fragmentary and limited. Separate research on the individual stages has made it possible to recently obtain new results which fill in, although incompletely, the existing gap. An increase in the three-dimensional extent of each of the stages is attained by the appropriate formulation of the experiment, in which the transition from one stage to another is impeded. It is possible to set up the experiment in such a way that the process develops stably, at considerable distances in the mode only of convective combustion or of low-speed explosive conversion. This systematic procedure significantly simplifies investigation and creates the basis for a detailed analysis of the individual stage.

The difficulties in presenting material on the transition of the combustion of solid explosives into detonation are due to the fact that often the available data are obtained under diverse conditions which are difficult to compare and with different systems. Thus in order to determine the role of the physical structure of the charge, the chemical nature of the explosive, we attempted to present the basic characteristic results (peculiarities), and, first of all those of them that were obtained in the unified formulation of the experiment.

A. CONVECTIVE COMBUSTION

After the disruption of stable combustion the mode of convective combustion arises in which the internal surface of the pores will be ignited by the gaseous combustion products penetrating into the pores, at velocities, exceeding the rate of laminar combustion by tens and hundreds of times. Before setting forth

the basic results of the research on the convective combustion of porous systems, let us examine the existing concepts on the mechanism of the ignition of solid explosives and powders.

§ 21. The Basic Concepts on the Mechanism of Ignition

Until recently little attention was given to the ignition of powders and explosives. In the last decade the interest in this problem has sharply increased in connection with the creation of solid-propellant rocket engines. A considerable quantity of works has been published, dedicated to experimental and theoretical studies of the process of the ignition mainly of powders of different types. In spite of this, many of the aspects of the ignition mechanism continue to remain unclear. The questions concerning this aspect where ignition occurs, as to what kind of role is played by the processes in the condensed and gaseous phases are broadly discussed in literature.

The mechanism of ignition depends considerably on the physicochemical properties of the investigated system, intensity of the heat supply and the state of the ambient medium.

At present the gas-phase [43, 102, 104] and solid-phase [98-100] theories of ignition have received broad acceptance.

The gas-phase theory. The simplest approach to the formulation of the gas-phase theory is Zeldovich's approach [43], which is based on the mechanism of the combustion of volatile explosives [5], which have a clearly expressed gasification point, equal to the boiling point. It is assumed in this theory, that on account of the energy of the heat source heating of the substance to the gasification point occurs. From this time on, the substance is gasified, and the basic reaction, which leads to ignition, takes place in the gaseous phase at a certain distance from the surface.

A necessary condition for ignition is the creation in the condensed phase of a thoroughly heated layer whose depth should be such as to ensure the necessary critical temperature gradient near the surface [Zeldovich's theory has already been briefly examined in deriving the conditions of the ignition of pore walls (§ 14)]. Not considered in it are the heat release in the condensed phase, and also the hydrodynamic pattern in the ambient medium. However, the theory examines the question of the transition from ignition to stable combustion. Zeldovich's concepts were subsequently developed in work [102]. At the present time attempts are being made to perfect this model (in connection with mixed powders) taking into account, for example, the processes of the diffusion of the oxidizer and the propellant.

Serving as the basis for the creation of gas-phase theories are experiments with powders with high heat fluxes. Having an effect on increasing the role of the gas-phase processes with an increase in the intensity of heat supply are the intensification of the effect of the oxygen concentration in the ambient medium and the pressures for lag and ignition energy [104].

The solid-phase theory. There are several variations of the theories developed in the works of Zeldovich [98], Hicks [99], and Merzhanov with his coll. [100]. Solid-phase theory proceeds from the driving role of the reaction in the condensed phase. It describes very well the low-temperature modes of the thermal effect in which the substance during the course of a considerable length of time after the application of heat flux behaves like an inert substance, and at a certain temperature a reaction begins to be exhibited in the condensed phase, and the surface temperature T_{\square} sharply increases. The temperature at which the salient point of curve of $T_{\square}(t)$ occurs, is identified with the ignition point. Attesting to the insignificant effect of the gas-phase processes in low-temperature ignition are the experiments, according to which under these conditions ignition delay weakly depends on

pressure and oxygen concentration.

The question of the transition from ignition to steady-state combustion is not examined in solid-phase theory.

In the works of Merzhanov with his coll. [100, 101] the apparatus of solid-phase theory is employed for determining the effective kinetic parameters of heat release (E , k_0 , Q) from the experimental data on low-temperature ignition. In work [100] the criterion of ignition is proposed, according to which the ignition of the condensed substance begins, when the rates of heat arrival from the external source and the chemical reaction become equal to:

$$q(t_s) = Qk_0 \int_0^{\infty} \{ \exp[-E/RT(x, t_s)] - \exp(-E/RT_0) \} dx, \quad (48)$$

where x is the distance from the surface; q is the heat flux from the external source; T_0 is the initial temperature; E is the activation energy; R is the universal gas constant; k_0 is the pre-exponents; Q is the thermal effect of the reaction (per unit volume); t_s is the lag time of ignition.

The study of the ignition of pyroxylin and the composition of ammonium perchlorate (90%) + polyethylene (10%) showed [101] that at an intensity of convective heat flux of $q=1-10 \text{ cal/cm}^2 \cdot \text{s}$ good agreement of the calculated [employing criterion (48)] and the experimentally measured lags of ignition is observed. This attests to the applicability of the theory and criterion (48) to the description of ignition under these conditions.

Thus, the low-temperature modes of the thermal effect are described by the solid-phase theory of ignition; the high-temperature modes - by the gas-phase theory, although there is no sharp boundary with respect to intensities. At the present time

a tendency is noted toward the creation of a general theory which would consider the exothermic transformations both in the condensed and in the gaseous phase. The difficulties in creating such a theory are due to the absence of a complete physical pattern of ignition, especially at high intensities.

Usually the simplest modes of heat supply are accomplished in the experimental study of ignition.

The results of the investigation of ignition under the effect of convective heat fluxes are of interest from the viewpoint of the transition of the combustion of porous systems into explosion. Let us examine some of them.

The ignition of mixed powders under the effect of convection currents with rather high intensity ($10-100 \text{ cal/cm}^2 \cdot \text{s}$) has been investigated [105]. A shock tube with an outflow of gas through an adjustable nozzle was used. The gas velocity above the investigated specimen of propellant was varied within the range $50-100 \text{ m/s}$. Ignition delay t_3 was defined as the time between the moment of the application of the heat flux and the appearance of luminescence, recorded by a photomultiplier. The dependence

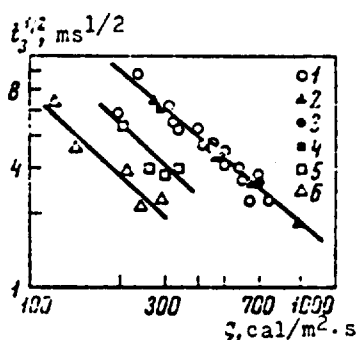


Figure 45. Dependence of the lag time of the ignition of mixed propellant on the magnitude of heat flux [105]. 1 - air, 17.5 atm.; 2 - air, 25 atm.; 3 - N_2 , 17.5 atm.; 4 - N_2 , 25 atm.; 5 - O_2 - 10 atm.; 6 - O_2 , 17.5 atm.

of t_3 on the average value of heat flux \bar{q} for a propellant based on ammonium perchlorate is represented in Fig. 45 (the propellant was ignited at a pressure of air and nitrogen of 17.5; 25 atm. and of oxygen of 10; 17.5 atm.). It has been established, that in pure oxygen t_3 decreases more noticeably, the higher is the pressure. The dependence of $t_3(q)$ was different for different propellants. The

conducted experiments showed that the physical properties of the propellant (the form of binder, the nature of the adhesion between the binder and the oxidizer, the dispersity of the ammonium perchlorate) have considerable importance. The ignition lag was 5-45 ms when $q=10-100 \text{ cal/cm}^2 \cdot \text{s}$.

The ignition of mixed powders, model compositions and pyroxylin by convection currents of lesser intensity is described [101].

There is little information about the ignition of explosives in literature. It is possible to note only two works.

The ignition energy of several explosives at a strictly fixed time of the effect of the ignition source, equal to 3 ms was determined [164]. The experiments were carried out under conditions of the effect of explosive specimen of heated gas (mainly helium). The findings which are given below, give an idea about the relative capacity of the explosives towards ignition.

Explosives	Trotyl	Tetryl	Cylo-nite	PTEN	Lead azide	Lead styphate
Ignition energy, cal/cm^2 ,	>0.38	0.33	0.33	0.25	0.087	0.046

Andreev and Rogozhnikov proposed [112] a method for determining the ignitability of explosives, based on ascertaining the igniter charge, necessary for exciting the stable combustion of a specific explosive charge in a bomb manometer. A mixture of pyroxylin No. 1 and ammonium nitrate (50:50), which yield gaseous products combustion was employed as the igniter. The ignitability of a number of explosives was determined by the indicated method. In the order of reduction in ignitability they are arranged in the following manner: potassium picrate, tetryl, 62% dynamite, xylyl, ammonium perchlorate, trotyl, trinitrobenzene and ammonite. This method is a simple, convenient rapid method and, apparently, makes it possible to carry out a comparative

evaluation of the ignitability of various explosives. However, as the authors themselves correctly note the theoretical treatment of the obtained results runs into difficulties which are caused by the complex nature of the temperature effect, connected with the inconstancy of the pressure and the temperature of the igniter gases.

§ 22. Development of Combustion in Single Pore

The penetration of combustion into a pore includes: 1) the ignition of the entrance section of a pore, exposed to the effect of hot combustion products, 2) the propagation of the combustion front along the length of the pore from the arising focus of ignition. The first aspect of the problem in principle can be solved on the basis of the existing concepts, discussed in the preceding section. With respect to the question of the propagation of the combustion front along the powder surface (explosive), at the present time a strict mathematical model of the process and a rather complete physical understanding of the phenomenon is absent. This question is not solved for the practically important case - the ignition of the channel of a powder charge in the process of rocket engine operation. Certain approaches to the solution of this question are contained in work [106]. In this work the rate of propagation of the combustion front is identified with the rate of the displacement of the leading front of the zone in which the critical conditions of ignition are attained. It is assumed that the ignition of a surface element occurs instantly upon the attainment of a certain critical temperature of the surface or upon the accumulation of a critical amount of heat taking in calculating for a unit surface area of the thoroughly heated layer. The question of the effect of the ignition mechanism is not examined in this approach. The mathematical analysis of the phenomenon is carried out employing a number of simplifying assumptions. The results of the analysis

are not compared with the experiment.

The authors, taking into account the complex nature of the phenomenon, gave their primary attention to solving the problem experimentally.

The study of the appearance and the development of convective combustion in disordered porous systems is hindered in view of the fact that as will be shown below, the convective combustion front is not plane. Thus, the optical methods, which record luminescence on the lateral charge surface, in the case of opaque (solid) explosives do not give a sufficiently complete and objective picture of the development of the process. It seemed that the basic laws, concerning the propagation of convective combustion in porous systems, can be obtained, if we utilize a simplified ordered model - a single pore. With the aid of this model it has become possible to experimentally investigate all the consecutive stages of the appearance and development of convective combustion.

Let us examine a single pore (crack), into which on the one hand the igniting products are supplied. After ignition of the end of the pore the boundary, which separates the ignited and the unignited part of the surface, is propagated along the length of the pore in the form of a combustion front. The problem reduces to the determination of the propagation rate of the combustion front along the surface (ignition rate) and its dependence on various parameters: the properties of the system, the geometric dimensions of the pore (width, length, shape of pore), pressure, conditions on the opposite end of the pore (open, closed end).

Ignition of a Pore

Procedure of the experiment. The slotted charges employed are shown in Fig. 37. We mainly investigated a plane blind pore,

formed by two plane-parallel plates of continuous (nonporous) substance with smooth surfaces. In studying the ignition process one of the plates was replaced by a transparent plate made from plexiglass (Fig. 37a), which facilitated the recording of the process of combustion propagation by optical methods, since in this case the entire internal surface of the pore was visible. The ignition of the pore was accomplished on the upper end. The geometric dimensions of the pore were determined by the length (depth) L and by the distance d_0 between the plates of the substance which characterizes the magnitude of the equivalent diameter of the pore d_n (for a plane pore $d_n = 2d_0$).

The combustion of the slotted charges was carried out in a specially developed bomb manometer (see Fig. 5) the design of which is described in detail on page xx. The pore was ignited by a convection current of hot gas, which was generated during the combustion of the igniter. Simultaneous optical recording of the process was accomplished (with a high-speed movie camera or a photorecorder), which made it possible to measure the lag t_g and the rate u_g of the ignition of the pore, and also to record the pressure directly in the pore $p_n(t)$ at the closed end of the charge.

A part of the experiments was carried out in the atmosphere and in a "constant pressure" bomb (Crawford bomb), when the initial pressure in the pore was equal to the pressure in the volume. In this set of experiments the ignition not only of a blind, but also of an open pore was studied. The ignition of the pore was accomplished from a nichrome spiral, heated to incandescence by a current. Besides the optical recording of the process of combustion propagation along the pore, measurement of the temperature in the pore employing thin (30μ) tungsten-rhenium thermocouples was carried out. Temperature measurement was conducted by the procedure, developed by Zenin [163].

In all experiments the initial width of the pore d_0 exceeded the critical width d_{sp} , which ensured the penetration of combustion into the pore.

Serving as the basic subject of the investigation was mixed and ballistite type powder.

General pattern of pore ignition. The mode of ignition which is propagated in the form of sequential displacement of the combustion over the surface is typical (Fig. 46)¹. The use of optical methods made it possible to establish the detailed pattern and the characteristic features of the flow of the products in the zone, adjacent to the ignition front. The flow pattern becomes especially graphic upon the introduction into the powder of metal particles. It has been established that in front of the ignition

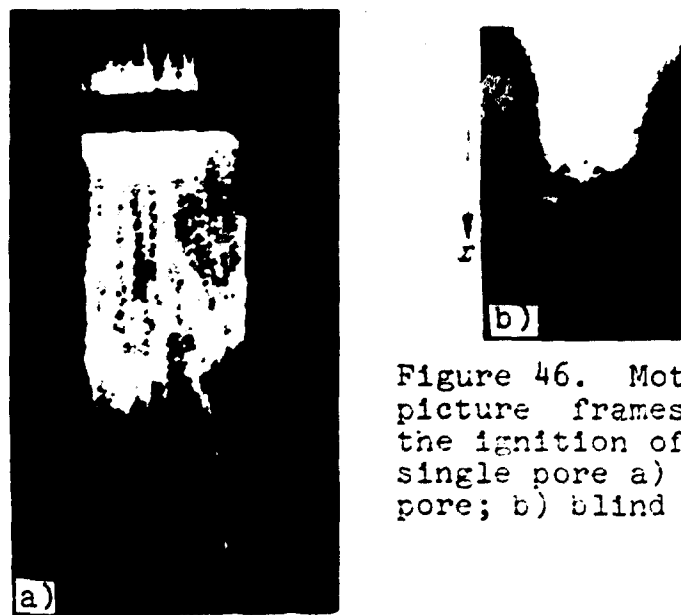


Figure 46. Motion picture frames of the ignition of a single pore a) open pore; b) blind pore.

¹Under specific conditions, when in the composition of the products, which move along the pore, condensed particles are contained, focal ignition can be observed: the condensed particles, falling on the surface, produce ignition in separate centers in front of the primary front. According to the experiment, the minimal size of the condensed particles, which produces focal ignition, is 50-100 μ .

front the combustion products which heat the surface of a pore, being cooled in this case move at a high rate. The outstripping of the ignition front by the combustion products always occurs. The ignition front separates the products moving along the pore from the flow of products, going out of the pore.

In a pore with an open end the products are mainly moving translationally (in the direction of propagation, see Fig. 46a). In this case in the initial stage the ignition rate sharply increases along the length of the pore: ignition has an avalanche-type character (Fig. 47), since the ignition front is propagated along the thoroughly pre-heated substance; however, with sufficient length of the pore rate saturation is observed.

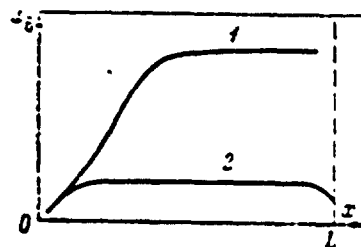


Figure 47. Variation in ignition rate along the length of an open (1) and blind (2) pore.

In a closed-ended pore the motion of the products in front of the ignition front is more complex: the appearance of circulation currents is observed (see Fig. 46b), when the products also move in the direction, opposite the propagation of the ignition front. Circulation currents play an important role in the heat transfer in the ignition process of a blind pore and are formed as a result of the fact that the ignition front is not plane: its separate sections, as a rule, move at different rates. The combustion products from the sectors of the front projecting forward are also the source of circulating streams. A detailed investigation of the structure of an ignition front, supplemented by temperature measurement, showed that in the case of mixed powder the following characteristic zones are distinguished (Fig. 48): the flame zone 1, the weakly glowing zone 2, mixing zone 3, the condensation zone 4. The ignition front corresponds to the boundary of zones 1 and 2. The circulation of products arise in zone 4. The gases of

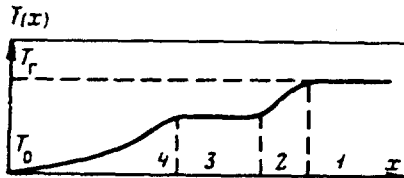


Figure 48. Temperature distribution $T(x)$ in the channel of an open pore during ignition (mixed powder, $p=1$ atm., $d_0=4$ mm).

it consist of the products of the pyrolysis of powder and are capable of combustion in air. In a blind gap the extent of the temperature zones virtually does not change in proportion to propagation. The remarkable characteristic of a blind pore consists in the fact that its ignition rate is practically constant for a considerable section along the length of the pore (see Fig. 47). This experimental fact was established in work [109]. A decrease in the rate is observed at the closed end of the pore.

With an increase in external pressure the three-dimensional extent of the zones is decreased, simultaneously with this the temperature of the combustion products increases. The gas temperature in a pore of a mixed powder attains the value of the maximum combustion temperature even at comparatively low pressures (10-20 atm.), and, in rather narrow pores ($d_0 \geq 0.1$ mm). This result agrees with the data known from literature according to which the maximum combustion temperature of the compounds based on ammonium perchlorate is attained at a distance from the surface h_M of the order of several tenths of a millimeter.

The short distance h_M from the surface to the high-temperature gas zone significantly facilitates not only the disruption of stable combustion (see § 15), but also the development of convective combustion along the pores. This explains the fact, that combustion in the case of a mixed powder penetrates into identical pores at pressures less than in the case of substances, which have large h_M as, for example, nitroglycerin powder, and at high rates. It is known [81, 83, 163], that value h_M for a mixed powder is an order less than for nitroglycerin powder.

The temperature measurements carried out in a pore of nitroglycerin powder with a pore width $d_0 < 2h_m$ showed (Fig. 49) that at a pressure of $p_0 = 30$ atm. the temperature at the initial moment after penetration is rather low $\sim 1000^\circ\text{K}$ and increases in proportion to the combustion of the pore. The combustion of the powder in the pore in the initial stage is flameless and up to a value of $d_0 \approx 2h_m$ occurs at a rate, less than the rate of normal combustion [84].

Under specific conditions combustion in a pore is unstable, which is expressed in the repeated ignition of a pore with subsequent extinguishment. Anomalous combustion in a pore is observed at low pressures, close to atmospheric.



Figure 49. Recording of temperature $T(t)$ (1) and pressure $\Delta p(t)$ (2) in the volume of a bomb during the penetration of combustion into an open pore (nitroglycerin powder, $p = 30$ atm., $d_0 = 100 \mu$).

Figure 50 shows motion-picture frames of anomalous combustion. In frame 1 the ignition front is spread over the entire length of the pore. The combustion of the substance occurs over a course of 10^{-3} s, after which extinguishment ensues during a very short time $t < 2 \cdot 10^{-3}$ s. At the moment of extinguishment a noticeable increase in the luminescence intensity is observed. The substance did not burn 0.004 s, and then ignition began at isolated points (frames 2, 3), and spread over the entire pore.

The repeated (after extinguishment) ignition of a pore occurs either as a result of sequential propagation of the front or as was noted, as a result of the development of combustion from



Figure 50. Motion-picture frames of the anomalous combustion of the substance in a pore.

individual points. The latter case is characteristic for a mixed powder and attests to the significant role of the processes, which take place after extinguishment in the condensed phase.

The anomalous combustion of a pore can be explained on the basis of the concepts, developed by Zel'dovich [107] in connection with the combustion of a powder in a semiclosed volume, since an ignited pore represents an expenditure nozzle (more precisely a combination of an expenditure and thermal nozzle) with very small free space. Zel'dovich showed that under conditions of critical discharge, when the relaxation time of the chamber is considerably less than the relaxation time of the thoroughly heated layer, i.e., at low pressures, the combustion of the powder in a chamber with a small free space is unstable and anomalous.

Another possible cause of anomalous combustion is the impossibility of the stable combustion of the substance in a narrow pore, when an active (driving) combustion zone is absent.

The effect of various factors on the ignition rate of a blind pore. We will subsequently examine only a blind pore, the average ignition rate of which is held invariable along the length of the pore.

It was established in work [109] that the dimensionless rate of combustion propagation $\chi = u_g/u$ into the gap between the wall and the burning powder charge increases in propagation to the decrease down to a specific value of gap width, then it passes through the maximum and sharply falls off to unity ($u_g = u$). The

experiments carried out by us showed that with an increase in external pressure the maximum of the curve $\chi(d_0)$ is displaced into the region of lesser dimensions of the pores, and the propagation rate χ simultaneously increases (Fig. 51). The section of curve



Figure 51. Schematic representation of the dependence of dimensionless ignition rate on the width of a blind pore at different pressures. 1 - p_1 ; 2 - p_2 , $p_1 > p_2$

$\chi(d_0)$ to the right of the maximum was mainly experimentally investigated. As one would expect, the ignition rate u_B depending on the conditions varies within exceptionally broad limits from tens of millimeters per second to hundreds of meters per second.

It is more convenient to trace the effect of different factors on ignition rate for the case when the penetration of combustion does not lead to the appearance in it of considerable (in magnitude) excess pressure. This case is realized, if the combustion of slotted charges of the a or b type (Fig. 37) (but at greater values of d_0) is realized in a Crawford bomb. Under these conditions the penetration of combustion occurs according to a spontaneous mechanism.

Experiments in a Crawford bomb. The effect of pressures in a bomb p_0 and of gap width d_0 on the magnitude of the average combustion propagation rate along a blind gap was studied. The results obtained for a mixed powder are shown in Fig. 52. It is evident that with an increase in pressure and a decrease in the width of a pore the ignition rate of the pore increases.

The processing of the results gives the dependence:

$$\chi d_0 p_0^{-0.6} = 0.26 \text{ cm} \cdot \text{atm}^{-0.6}.$$

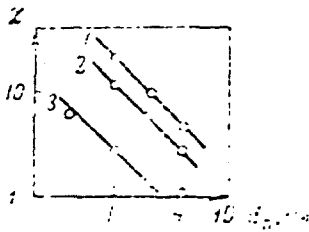


Figure 52. The dependence of ignition rate on pore width.
1 - $p_0=30$; 2 - 10; 3 - 1 atm.

A dependence of a similar type can be theoretically obtained.

In contrast to the initial pressure, a variation in the initial temperature of the powder from $+20^\circ$ to -70°C practically does not affect the ignition rate of a pore.

A set of experiments was carried out in which the composition of the powder was varied. It has been established that the physicochemical properties of an organic propellant in a mixed system based on ammonium perchlorate have a definite effect on the ignition rate of a pore surface. Polystyrene, polymethyl methacrylate, bitumen, polyester were employed as the propellant. The metallic fuel - aluminum - has a peculiar effect. Aluminum with an average-mass size of $\sim 15 \mu$ was employed which was introduced instead of an oxidizer into a system of 15% bitumen + 85% ammonium perchlorate. The findings are presented below ($p_0=50$ atm., crack $d_0=0.1$ mm, $L=30$ mm).

Al, %	0	5	10	20
Ignition rate, m/s	1	1.33	0.97	0.58
Dimensionless ignition rate	59	74	64	41

Upon the introduction of aluminum the ignition rate increases up to 5-10%, and with the larger aluminum content a retarding effect is exerted. An analogous effect was obtained earlier by Andreev and Rogozhnikov [68], who carried out experiments with binary mixtures of AP + Al in a powder-like state.

In another series the role of the geometric dimensions of a pore was studied. A comparative testing of charges of type a and of type b (see Fig. 37), and also of charges with a different crack depth L showed that the ignition rate of cracks, having an identical value L/d_0 , is different¹. In the case of the transition from type a charges to type b charges and with an increase in crack depth the ignition rate increases.

Ignition rate depends significantly on pore shape. If instead of a usually accepted plane pore (crack) we employ a cylindrical pore with the same equivalent hydraulic diameter, then in the latter case value u_g turns out to be considerably lower. At the present time there is no sufficient clarity in the question concerning the cause of the observed difference. It is possible to assume that in a cylindrical channel the development of circulation currents of combustion products is impeded.

Ignition rate noticeably increases in pores with uneven rough walls. The penetration of combustion in this case is intensified because of an increase in the heat-transfer coefficient in the projection region and their accelerated heating and ignition.

Experiments in a bomb manometer. If experiments are carried out with narrow and rather deep cracks, then their ignition occurs at such high rates, that a considerable excess pressure appears in them [59, 110]. In this case the experiments were conducted with the use of a bomb (see Fig. 5), which made it possible to record the pressure in a crack. The pore was enclosed in a strong shell, made of plexiglass and steel. It was established that the excess pressure within the pore has an enormous effect on the ignition process, since the ignition rate and the pressure

¹In the case of cracks of type b in calculating L/d_0 a width value equal to half of the actual value was utilized, i.e., the "linear" nature of the crack was considered.

in the pore mutually determine each other. The nature discussed above of the effect of different factors on the ignition rate of cracks is also retained in this case with only one difference, that the general pattern becomes rougher. The appearance of excess pressure in a narrow pore leads, in particular, to a peculiar paradox: with a decrease in crack width (down to $d_0 = d_{\text{kp}}$) the ignition rate and the maximum excess pressure in the pore (p_n^M) continuously increase in it, but with an insignificant decrease in d_0 combustion does not penetrate into the crack, i.e., the section of the curve $\chi(d_0)$ to the left of the maximum becomes so narrow, that it cannot be detected (see Fig. 51).

The concepts of the absolute values of the ignition rate of a crack of a mixed powder give the results, presented below ($p_0 = 50$ atm., $L = \text{const}$). The rate of the normal combustion of a powder when $p_0 = 50$ atm. is approximately 10 mm/s.

d_0 , mm	0.6	0.4	0.2
u_B , m/s	55	100	300
p_n^M , atm.	300	700	1800

Thus, the ignition rate of a crack can exceed the rate of normal combustion by 3-4 orders and attain values of hundreds of meters per second. This result deserves attention in connection with the fact that such high rates of convective combustion are observed for undetonatable systems, such as mixed powders [160].

The experiments, carried out with mixed powders at different external pressures p_0 , showed that with an increase in pressure the ignition rate is increased, and ignition lag t_3 sharply falls off:

p_0 , atm.	10	50	100
t_3 , ms	20-40	5	2.0
u_3 , m/s	0.2	70	100
p_n^M , atm.	10	300	400

The ignition of a crack in a bomb manometer corresponds to the conditions of intense heat supply, where the gas-phase processes play a significant role. The fact of the reduction of ignition delay with an increase in pressure, and also the estimate of the magnitude of heat flux convinces us of this. For the entry part of the crack the heat flux, calculated from expression $q = \alpha(T - T_{CT})$ (α is the heat-transfer coefficient, which was calculated on the basis of the Nusselt criterional function [113]; T is the temperature of the filtering gases, which was taken to be equal to the combustion temperature of the igniter; T_{CT} is the mean wall temperature), constituted when $p_0 = 50$ atm., $d_0 = 0.1$ mm the value $q \approx 200$ cal/cm²·s. The ignition delay of the mixed powder experimentally measured for these conditions turned out to be equal to 5 ms.

The question logically arises, as to what is the maximum possible ignition rate of a narrow pore of constant cross section under conditions of a high pressure differential. It follows from general considerations that the ignition rate cannot exceed the velocity of the gas moving along a pore, i.e., the speed of sound in the products (1000-1200 m/s)¹. The maximum ignition rate of a pore in our experiments was approximately 600-700 m/s.

¹What has been said is correct for the case when a shock wave does not arise in a pore and the friction of the gas against the pore walls is not considered.

Consequences of the Penetration of
Combustion into a Crack [12, 59, 110]

Determining excess pressure in an undeformed crack. It is not difficult to show that the ignition of a pore at a rate, which considerably exceeds the rate of normal combustion of a substance, should lead to the appearance of excess pressure in the pore $\Delta p = p_n - p_0 \neq 0$, which we confirmed experimentally¹. The pressure in the pore is a function of the following basic parameters:

$$p_n = f(u, u', d, h_n, L, d, z, x; L), \quad (49)$$

where u' is the rate of pore combustion; L, d are the depth and the width of the pore; z is the coefficient, which considers the resistance to the products flowing back; x is a coordinate, calculated from the entrance part of the pore.

The first two parameters in expression (49) are connected with the process of ignition and combustion, three others - with the geometric dimensions of the pore and the state of its surface.

An experimental study of the increase in pressure in a crack was carried out in a bomb manometer (see Fig. 5). The crack was formed by two thin (2-3 mm) plates of powder and was enclosed in a strong shell of plexiglass and steel, which practically eliminated crack deformation during combustion.

Figure 53 depicts a diagrammatic representation (Fig. 53a) and oscillograms (Fig. 53b, c) of the recording of pressure in a crack at the closed bottom end (lower curve 1) and in the

¹It is necessary to note that Serebryakov [111] on the basis of an analysis of extinguished specimens of Kisnemskiy powder after a gun shot assumed the possibility of the appearance of excess pressure in narrow channels.

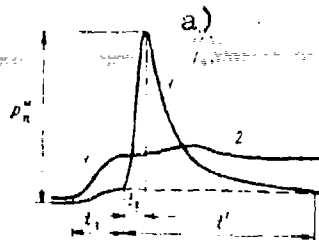


Figure 53. Diagrammatic representation (a) and oscillograms (b, c) of pressure during the penetration of combustion into the pore. 1 - recording of pressure in a pore at the closed bottom end; 2 - recording of pressure in the volume: t_3 - lag time of ignition; t_B - time of pore ignition; t' - time of the existence of excess pressure in a pore.

volume of the bomb (upper curve 2). The pressure increases from bottom to top, the time - from left to the right. The recording of the pressure in a pore $p_n(t)$ was done as follows. Within a time of the order of 10^{-3} - 10^{-4} s after the beginning of a pressure increase in the volume of the bomb a pressure balance begins in a pore as a result of the penetration into it of combustion products. The salient point of curve $p_n(t)$ after time t_3 attests to the beginning of the ignition of the pore.

For a period of time t_B the pressure in the pore increases, attains the maximum value p_n^M , after which a pressure decay occurs, caused by the burn-up of the pore and by the mechanical destruction of the crack walls. The time of the existence of increased $\Delta p \neq 0$ pressure in a pore is $t' \approx 10^{-4}$ - 10^{-2} s. The simultaneous optical recording of the process and the recording of the pressure in a pore showed that in narrow cracks the values t_3 and t_B correspond approximately to the lag time and the crack ignition time. It was established that all those factors which lead to an increase in the ignition rate, contribute to a pressure rise in a crack.

The increase in pressure in a crack was studied depending on parameter L/d_0 , which represents the ratio of the combustion surface to the flow passage cross-sectional area (Pobedonostsev's parameter).

Some of the results, obtained for a mixed powder, are represented in Fig. 54. As can be seen from the curve, in proportion to the increase in L/d_0 (the decrease in d_0 when $L=\text{const}$), beginning with a certain critical value $(L/d_0)_{\text{кр}}$, progressive increase in the pressure in the pore is observed. In this case a simple geometric similarity is absent: in the pores of identical geometry ($L/d_0=\text{const}$) the pressure increases with an increase in the depth, which is connected with the difference in the ignition rate of geometrically similar pores.

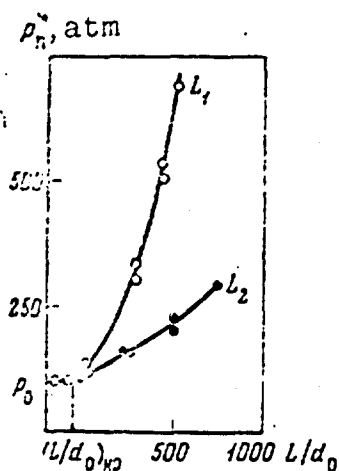


Figure 54. Dependence of excess pressure in cracks of different depth on the parameter (L/d_0) , $L_1 > L_2$.

The experimental data in a broad range of variation are satisfactorily described by an analytical dependence of the type¹:

$$\Delta p_{\text{ex}} = 1.1 p_0 [L/d_0 (L/d_0)_{\text{кр}}]^n - p_0 \quad (50)$$

where $(L/d_0)_{\text{кр}}$ - the value at which $\Delta p_{\text{ex}} = 0.1 p_0$; n - a constant whose value depends on crack depth; for cracks with a depth of several centimeters value n is close to unity.

¹Formula (50) is valid both at subsonic and sonic (critical) discharge of the combustion products.

Dependence (50) automatically considers the nature of crack ignition, and also - the nonsteady-state effects of powder combustion in a crack.

Value Δp_m with values L/d_0 less than $(L/d_0)_{np}$, can be calculated, by employing expression (51) which is obtained from the equations of conservation of mass and momentum for an incompressible liquid not allowing for wall friction¹:

$$\Delta p_m = c \frac{u_0^2}{p_0} \left(\frac{L}{d_0} \right)^2, \quad (51)$$

where $c = \rho_n^2 RT/M$ (ρ_n - the density of the powder, M , T - the molecular weight and the temperature of the combustion products); u_0 - the rate of normal burning.

With small pressure increases $\Delta p_m \ll p_0$, the combustion rate u_0 in expression (51) depends only on pressure p_0 in the chamber volume.

By substituting in (51) the typical values going into it, we obtain:

$$\left(\frac{L}{d_0} \right)_{np} = 20 p_0 u_0. \quad (52)$$

When $(L/d_0) > (L/d_0)_{np}$ calculation according to (51) gives understated values of Δp_m in comparison with the experiment. This indicates the need for carrying out calculation which would consider the dependence of combustion rate on pressure and gas flow rate², and also the nature of the propagation of combustion along a crack.

¹The checking of formula (51) during the combustion of an inserted cylindrical charge in a rocket engine was first carried out by O. I. Leypunskiy [92].

²This type of calculation was carried out in work [117].

In contrast to mixed powders the excess pressure in a crack of nitroglycerin powder at low pressures in a bomb is so small, that it is not impossible to record it, although the penetration of combustion into the crack occurs. However, considerable in magnitude excess pressure in a crack appears, if the combustion of a slotted charge is carried out at elevated pressures. This result can be explained, if we consider the differences in the mechanism of the combustion of powders of the mixed and ballistite types.

Concerning crack combustion [12, 59]. It is known that with the presence of a gas flow, which blows a powder, the rate of its combustion increases. This effect is frequently called erosive combustion. An increase in combustion rate is usually connected with the turbulization of the surface layer of the gas, which leads to an increase in the heat flow into the condensed phase of the powder.

As a result of the existence of excess pressure and the erosive effect the gas inflow from the burning surfaces of a crack increases. From the oscillogram of Fig. 53c one can easily see that the noticeable increase in the pressure in the volume of the chamber corresponds to the beginning of a pressure increase in the crack, apparently, as the formation of the erosive peak occurs in curve 2. From the magnitude of the erosive peak the average (for the time of the effect of excess pressure) combustion rate of a powder in a crack was determined. Thus, it was possible to connect the change of the gas inflow in the crack with the excess pressure pulse - $\int_0^t \Delta p dt$.

A characteristic of the erosive burn-up of a crack is the presence of high rates of gas flow (up to sonic) and of high pressures. At high pressures the erosive effect is significant, since, as the specially carried out experiments showed,

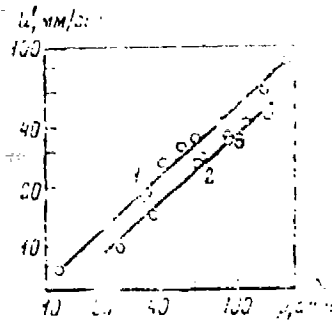


Figure 55. The dependence of the erosive rate of combustion on pressure at sonic flow of the products. 1 - nitroglycerin powder; 2 - mixed powder. [MM/СЕК = mm/s; atm = atm.]

intensification of the dependence of the erosive rate of combustion u' on pressure occurs. Thus, for instance, in a sonic flow when the gas velocity is equal to the speed of sound in the products, dependence $u'(p)$ (Fig. 55) takes the form

$$u' \sim p^{0.8} \quad (53)$$

independent of the value of superscript v in the normal combustion rate law $u=bp^v$. For powders usually value v is substantially less than 0.8. A dependence of type (53) was simultaneously established by Pokhil with his coll. (cited for [59]). It can be obtained theoretically on the bases of the relationship between Nusselt and Reynolds numbers, which describes heat transfer in a turbulent gas flow [113].

With a considerable pressure increase ($\Delta p \gg p_0$) mechanical destruction of the crack walls was observed in the exit part. The zone of destruction had, as a rule, a bell-shaped form.

The burn-up of the ejected powder particles led to a sharp increase in the pressure in the volume of the bomb.

The above presented results were obtained under conditions when the crack deformation was virtually absent, and crack growth was eliminated. Let us recall that a slotted charge, formed by thin layers of powder, was placed in a strong shell. Let us look at, what occurs during the combustion with a crack of limited dimensions, which is located in a powder mass, when the possibility of crack penetration exists.

Crack Growth

As was noted, the penetration of combustion into narrow pores (cracks) occurs at a high rate, result of which is the appearance in it of excess pressure. The experiments carried out showed the fundamental possibility of the fact that a local pressure increase in a burning crack is capable under specific conditions of causing its growth (increase in depth). These results [12, 59] served as basis for the setting up of special theoretical and experimental studies [110, 114, 117].

The behavior of cracks in the depth of the powder was studied when there is a possibility of expansion (deformation)¹ and crack penetration. To solve the problem it is necessary to consider the combustion process in the crack and the capacity of the powder as a material to resist crack growth. The dimensions of cracks, the penetration of combustion into which causes their growth (unstable cracks) were determined. In the case of stable cracks development is absent.

The question concerning the mechanical stability of burning cracks in a powder was theoretically studied by Leypunskiy and Kirsanova [114]. The basic results, obtained in work [114] are given below. They examined (Fig. 56) a plane infinite crack in the direction of the z axis, situated in plane xy perpendicular to the burning surface in a semi-infinite space of powder and being under conditions of all-sided hydrostatic compression by pressure p_0 . It was assumed that the ignition of the crack surfaces and the discharge of the combustion exhaust products occur instantaneously in the steady-state mode. It was also assumed, that the pressure increase in the crack is small in

¹It is natural that crack deformation is accompanied by a decrease in excess pressure as compared with the case of combustion in an undeformed crack of identical depth.

comparison with the chamber pressure p_0 ; therefore the rate of powder combustion in the crack was considered constant $u(p)=u(p_0)$.

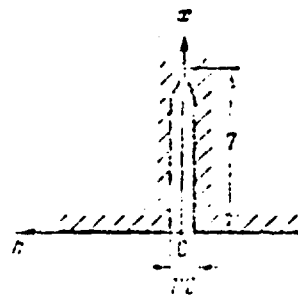


Figure 56. Diagram for the calculation of the mechanical stability of a burning crack.

Initially the magnitude and the pressure distribution in a plane burning channel were determined, and then the equilibrium of the crack which expands the obtained excess pressure was examined. The problem was solved in a static formulation, i.e., it was considered that the excess pressure does not change in the course of time. The mathematical theory of equilibrium cracks, created by Barenblatt [115] was utilized. According to this theory, the outline of the crack remains stationary, while the loads acting on the crack are small and are balanced by molecular cohesion forces, which act in the small end region of the crack, the region where the edges of the crack so closely approach each other, that the molecular forces of interaction are very great. With an increase in load the cohesive forces increase (due to deformation) to its maximum value. This type of crack can be called maximum, equilibrium; the total characteristic of the maximum value of the cohesive forces was proposed by Barenblatt

in the form of magnitude $K: K = \int_0^a \frac{g(x)}{x^2} dx$, where $g(x)$ - the distribution of the maximum value of the cohesive forces in the end region of the crack a , and it is called the cohesion modulus. A further increase in the load leads to crack growth.

The distribution of excess pressure in a plane crack with a length l and with a width $2a$ was determined from the conditions of conservation of mass flux and momentum:

$$\Delta p(x) = p(x) - p_0 = \Delta p_M (2x \cdot l - x^2 \cdot l^2), \quad (54)$$

$$\Delta p_M = \frac{\gamma - 1}{\gamma} q \frac{t^2 u^2 l^2}{p_0 d^2},$$

where Δp_M - the pressure at the bottom ($x=l$) end of the crack (γ - the adiabatic index, q - the heating capacity of the powder).

The condition of crack equilibrium with a crack length $(-l, l)^1$, burst by symmetrical pressure $\Delta p(x)$, takes the form [115]:

$$\frac{K}{1 - 2l} > \int_0^l \frac{p(x) - p_0}{1 - x^2/l^2} dx. \quad (55)$$

The modulus of cohesion K is determined experimentally under the corresponding conditions. Integration of (55) makes it possible to find the halfwidth d of a stable crack with a length l :

$$d > \sqrt{\frac{\gamma - 1}{\gamma} q \frac{t^2 u^2}{p_0 K} \sqrt{2} \left(2 - \frac{\pi}{4}\right) \cdot l^2}. \quad (56)$$

The equality in expression (56) defines the maximum dimensions of a stable crack. The substitution of (56) into equality (54) makes it possible to calculate the pressure in a maximum stable crack, which reduces when $x=l_{np}$ to the expression

$$\Delta p_M = \frac{K}{\sqrt{2} l_{np} \left(2 - \frac{\pi}{4}\right)}. \quad (57)$$

It is not necessary to consider that the pressure within the crack causes its deformation (expansion):

$$d = d_0 + \Sigma, \quad (58)$$

where d_0 - the initial halfwidth of the crack, and Σ is the

¹It was shown [114] that the nature of the examination does not change, if the supplementary interaction of region $x \geq 0$ with region $z < 0$ is introduced.

displacement of the edges of the crack, caused by the bursting pressure $\Delta p(x)$ (54).

The calculation of the displacement of the edges of a plane crack, which is located in a powder with modulus of elasticity ϵ and Poisson ratio μ , was performed on the basis of the classical methods of the theory of elasticity [116] and reduced when $|x| \leq l$ to an expression of the form

$$\Sigma = \frac{\Delta p_0 l}{\epsilon} (1 - \mu^2). \quad (59)$$

From (57) and (59) it follows that the opening of maximum stable crack is

$$\Sigma = \frac{K}{\epsilon} \frac{(1 - \mu^2)}{\sqrt{2} \left(2 - \frac{\pi}{4}\right)} \sqrt{l_{\text{III}}}. \quad (60)$$

The final result of work [114] was the determination with (56), (58), (60) of the boundary of the region of the stable dimensions of plane cracks:

$$d_0 = l_{\text{III}} \left\{ \sqrt{\frac{\gamma - 1}{\gamma} q \frac{\epsilon \mu^2}{\rho_0 K} \sqrt{2} \left(2 - \frac{\pi}{4}\right)} - \frac{K(1 - \mu^2) \sqrt{l_{\text{III}}}}{\epsilon \sqrt{2} \left(2 - \frac{\pi}{4}\right)} \right\}. \quad (61)$$

which is represented graphically in the form of curve 1 in Fig. 57. To the left of curve 1 is located the region of stable cracks, to the right - unstable (growing) cracks. The greater the value of the modulus of cohesion, the broader the region of stability. It is interesting that the short cracks turn out to be stable with a rather small initial width ($d_0 \rightarrow 0$), such that with which the penetration of combustion is still possible. The cohesive

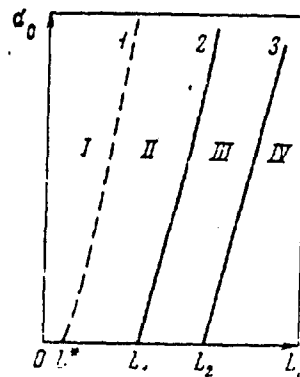


Figure 57. The stability regions of a burning crack. I-IV - stability regions; 1-3 - stability boundaries.

forces compensate for the expansion of cracks of small length. The dimensions of stable cracks of zero width ($d_0=0$) is determined from (61):

$$l = \left[\frac{K}{\sqrt{2} \left(2 - \frac{\pi}{4}\right)} \sqrt[3]{\frac{\gamma}{\gamma-1} \frac{p_0}{q} \left(\frac{1-l^2}{\rho u^2}\right)^2} \right]^2. \quad (62)$$

Such are the basic results of the calculation of the mechanical stability of a burning crack [114], on the basis of which the cause of crack growth is the excess pressure, which arises upon the penetration of combustion into it.

Before moving on to the results of the experimental study of the stability of cracks [110], it is necessary to note the following fact. The calculation of a pressure increase in a deformed crack Δp_M is of independent interest, for example from the viewpoint of evaluating the increase in the gas inflow from the burning surface, since in the general case the combustion rate in a crack exceeds the corresponding value outside it.

As will be clear from what follows, it is necessary to know the value of Δp_M in cracks whose depth exceeds the maximum depth, which corresponds to the boundary of mechanical stability (curve 1, Fig. 57). At the same time the direct experimental determination of Δp_M in a closed crack, situated in the depth of a powder, presents considerable difficulties.

On the basis of the approach proposed in work [114] we carried out the calculation of Δp_M in a deformed pore [110], which differed from that which was presented above in terms of the fact that instead of expression $\Delta p_M(l/d)$ of form (54), valid for small Δp_M , the experimental dependence (50) was the basis of the calculation. This made it possible to determine excess pressure Δp_M over a wide range of its variation $0.1p_0 < \Delta p_M < p_0$ up to the appearance of sonic discharge. Furthermore, expression (50) considers

the process of ignition, the dependence of combustion rate on pressure and gas velocity in the crack, and also the unsteady-state effects; therefore it is not necessary to introduce the special assumptions, which concern the conditions of ignition and the nature of the powder combustion in the crack. Finally, the calculation carried out is not connected with the examination of the mechanical stability of the cracks, and therefore the obtained results can be applied for growing cracks.

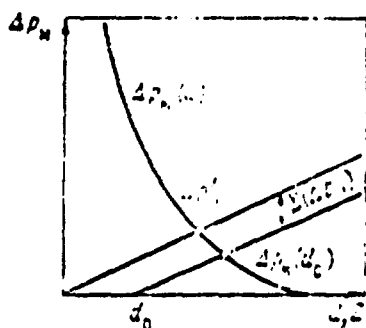


Figure 58. Determination of the value of excess pressure in a deformed crack by the graphic method.

The system of equation (50), (58), (59) was examined whose solution was accomplished by the graphic (Fig. 58) and analytical methods.

It was shown that for each powder there is a maximum possible value of the magnitude of pressure increase $\Delta p'_M \geq \Delta p_M(d_0, z_0)$ (see Fig 3). The magnitude of $\Delta p'_M$ is a function of the physico-chemical, physicommechanical characteristics of a powder and is realized in cracks with a width of $d_0=0$ at any initial z_0 .

Simultaneously solving equations (50) and (59) when $n=1$ and $d=\Sigma$, we obtain:

$$\Delta p'_M = \frac{p_0}{2} \left[\sqrt{1 + \frac{4.6\epsilon}{p_0(1-\mu^2) \left(\frac{l}{d}\right)_{\text{кр}}}} - 1 \right] \quad (63)$$

($\Delta p'_M$, p_0 , ϵ are expressed in kilograms per 1 cm²).

Taking (52) into account the following empirical exponential formula was selected for describing dependence (63):

$$\Delta p'_M = 6,5 \cdot 10^{-2} \frac{(u_0 \epsilon)^{1,5}}{P_0^2}, \quad (64)$$

valid when $1.7p_0^2 < u_0 \epsilon < 30p_0^2$, where $u_0 = u(p_0)$ is expressed in millimeters per 1 s. From (64) it follows that when $p_0 = \text{const}$ the excess pressure is determined only by the combustion rate and by the modulus of elasticity whose effect on the magnitude of $\Delta p'_M$ is identical.

When $d_0 \neq 0$ the connection between $\Delta p'_M$ and the initial dimensions of a plane pore in the first approximation, is described by the relationship

$$\Delta p'_M = \Delta p'_M \left[1 - \frac{d_0}{l_i} \left(\frac{l}{d} \right)_{cr} \right]. \quad (65)$$

Let us return to the question of crack growth. The experimental study showed [110] that disruption of mechanical stability does not lead to catastrophic crack growth. There is a number of features, specific for the process of burning crack growth which makes examination [114] insufficient. One should first of all consider the time factor. The time of the effect of elevated pressure in a burning crack due to the combustion is extremely small and is as was noted, hundredths of a second. In connection with this the rate at which a crack begins to grow acquires great significance.

It was established that the loss of stability by a burning crack has completely different consequences depending on the magnitude of the excess pressure developed in it. The following three characteristic cases are realized:

1. The increase in crack depth during the time of the effect of bursting pressure is negligibly small. Cracks, unstable in a mechanical sense (located in the region to the right of curve 1 in Fig. 57), practically retain their stability. This case occurs when

$$\frac{K}{\left(2 - \frac{\pi}{4}\right) \sqrt{2l_0}} < \Delta p_m < \frac{K'}{\left(2 - \frac{\pi}{4}\right) \sqrt{2l_0}} \quad (66)$$

2. The increase in crack depth during the time of the effect of excess pressure is finite. The stopping of growth is caused by the finite time of the existence of excess pressure at an insufficiently high growth rate as compared with combustion rate. Let us call this growth limited. It is realized when

$$\frac{K'}{\left(2 - \frac{\pi}{4}\right) \sqrt{2l_0}} < \Delta p_m < \frac{K''}{\left(2 - \frac{\pi}{4}\right) \sqrt{2l_0}} \quad (67)$$

where $K'' > K' > K$.

3. The increase in crack depth due to growth compensates for the increase in crack width due to combustion in such a way that the pressure increase always remains sufficient for the continuation of growth. This case is observed, when

$$\Delta p_m > \frac{K''}{\left(2 - \frac{\pi}{4}\right) \sqrt{2l_0}} \quad (68)$$

It is especially necessary to note that the difference in values K' , K'' from K is caused by the need for the taking into account the growth rate and is not connected with the dependence of the modulus of cohesion on time. The boundaries of practical stability and of self-sustaining growth cannot be obtained purely by calculation, without experiment, since the calculation of growth rate with the contemporary development of theory is not possible.

Substitution in expressions (66)-(68) of the value of maximum pressure from formula (65) makes it possible to connect crack stability during combustion with their initial dimensions.

The obtained results are represented schematically in Fig. 57. Plane L_0 , d_0 is broken down by curves 1, 2, 3 into four regions

[110]: I - the region of absolute (mechanical) stability [114],
II - the region of practical stability, III - the region of
limited growth, IV - the region of self-sustaining growth.

Values L' , L_1 , L_2 are determined by values K , K' , K'' and
by the maximum value of pressure increase $\Delta p_M'$:

$$L' \approx 1/3 \left(\frac{K}{\Delta p_M'} \right)^2; \quad L_1 \approx 1/3 \left(\frac{K'}{\Delta p_M'} \right)^2; \quad L_2 \approx 1/3 \left(\frac{K''}{\Delta p_M'} \right)^2.$$

The expansion of the stability region in comparison with the
mechanical calculation is mainly caused by the low growth rate
of cracks in a powder in conjunction with the brevity of the
existence of excess pressure in the burning crack.

It is necessary to note that consideration of the possibility
of stopping crack (self-stabilization) growth, which arises,
when growth rate does not greatly exceed combustion rate, is also
contained in work [114].

The experiments carried out made it possible to reveal the
role of combustion in crack development. It has been established
that in the initial stage combustion contributes to crack growth
since the penetration of combustion in the pores, which are
generated in the end part of a crack, occurs at a high rate. In
the final stage combustion can have a stabilizing effect which
is connected with the burnout of the crack top - stress
concentrator.

The data presented in § 22 correspond to the case when the
charge contained one pore.

§ 23. Propagation of Convective Combustion in Porous Explosives

Let us move on to an examination of convective combustion in
disordered systems when in the charge before combustion there is

set of pores connected with each other. Let us attempt to answer the question, how combustion develops after disruption of stability. It necessary from the very beginning to emphasize that this question has not been investigated too thoroughly. The concepts existing at the present time are based on the experimental results, obtained in works [10, 12, 32, 56, 63, 65-59, 120].

Experiments are conducted with explosives which were poured or pressed in batches into plexiglass and steel shells. The charges were usually ignited from the upper open end of the charge in such a way that a convective mode arose. Photographing was carried out from the lateral surface of the charge.

The characteristic features of convective combustion. Typical photoscannings of convective combustion, obtained under different conditions of carrying out experimentation, are shown in Fig. 59. The nonuniformity of the displacement of the ignition front, especially clearly expressed under conditions of an "immured charge" setup (Fig. 59a) attracts attention. In this case the scale of nonuniformity is rather great and can attain several diameters of the charge. During combustion in a Crawford bomb (in the absence of "immurement") (Fig. 59b, c) the nonuniformity is characterized by a smaller scale, in a number of cases the recording takes a step-like form (Fig. 59b): the combustion rate first increases sharply, then decreases. The flame luminescence usually has a banded structure. It is logical to connect [10, 32] the nonuniform nature of the recorded luminescence with the fact that ignition of the internal surface of the pores by penetrating gas jets of combustion products occurs not continuous in a front line, but at different rates. The pores, situated in the center section of the charge are ignited first, then the combustion front at individual points reaches the lateral surface propagates from them in all directions (on the photographic recording this is recorded in the form of peculiar



Figure 59. Typical photographs of the convective combustion of porous charges; a) 10% polystyrene +90% AP ("immured charge"); b) 10% polystyrene +90% Al; c) tetryl; b, c) combustion in a Crawford bomb.

"tongues", Fig. 59a). This nature of the development of the process is confirmed by the results of high-speed motion-picture filming. It was noted in § 15 that stable combustion is not disrupted simultaneously over the entire front, but at individual centers, which are the largest pores of the charge. This fact, and also the nature of the optical recordings of convective combustion give the basis to assert that the large pores will be ignited, into which the combustion products especially easily penetrate, which are also the best prepared for ignition. A pressure increase in it (large pore), which also leads to the penetration of combustion into the smaller pores¹ promotes the subsequent propagation of combustion along a large pore. Thus, the distribution of pores by dimensions (the heterogeneity existing in the explosives), and also the possibility of interaction between pores have great importance in the propagation of convective combustion. These

In this type of system of development it is not necessary that a pore be maximum in dimension and rather deep.

concepts are additionally confirmed by the following experimental results. Experiments were carried out [32], in which a thin paper served as the bottom of the charge. During convective combustion the paper is burnt nonuniformly at individual joints, while during stable combustion the burning was uniform. Furthermore, extinguishment was accomplished by means of dropping the pressure of the specimens, burning in a convective mode, which showed the existence of a system of branched channels with traces of combustion in them [63].

Consequently, the entire aggregate of cited data attests to the fact that the convective combustion front is not one-dimensional and is bent.

A characteristic feature of the convective combustion mode is also that penetration into the pores is accompanied by intense dispersion (ejection) of substance in the form of both of individual grains and small whole pieces which are carried away by the gaseous products flowing away from the charge surface.

The ejection of the substance whose remains can be frequently detected on the bottom of the bomb after the experiment, is recorded well on the frames of the high-speed motion-picture film. At the moment of ejection weakening of luminous intensity is usually observed. Subsequent ignition occurs from sections of the surface, not subject to ejection [63].

Dispersion is the consequence of the presence in the pores of excess pressure and especially pronounced during the combustion of pressed charges which are characterized by low mechanical strength

This effect leads to a number of interesting consequences. First of all the combustion zone is expanded: the particles

ejected from the charge surface burn in a layer of considerable thickness.

Furthermore, the dispersion of the substance limits the increase in pressure in the pores and is one of the stabilizing factors, which make possible combustion at high rates without its transition to explosion. In this respect the experiments of Chuyko [63] and Kondrikov [56] are very significant whose essence consists in increasing cohesion between the particles of the substance and thereby impeding particle escape. In these experiments a sharp increase in rate was observed in the case when the charge consisted not of freely poured, but of particles cemented to each other.

However, the stabilizing effect of dispersion is exhibited when there is no possibility of the burning up of ejected particles, for example with a small length of the charge shell. The fact is that the ejection of the substance leads to the formation of reactive suspended matter which burns to the final products with sufficient length of the gas-outlet tube. The accelerated combustion of suspended matter is accompanied by a rapid pressure buildup above the charge surface, which causes intensive penetration of gases at high temperature into the pores, the result of which is a further increase in the combustion surface and combustion rate¹.

Thus, the convective combustion of powder shavings, placed in long tubes, occurred initially at a low and almost constant velocity; in proportion to the submersion of combustion from the

¹Pressure during the combustion of suspended matter can increase so rapidly and intensively, that detonation of the remaining part of the explosive charge arises. Andreev examined [72] the explosion of suspended matter formed during combustion as one of the basic ways for the transition of combustion into detonation. The possibility of this mechanism for poured charges was experimentally shown by the authors (see § 27).

upper section of the tube the rate of the process increased by hundreds of times [56].

On the basis of what was discussed above the model of convective combustion can be represented by the following simplified diagram. The leading front of the gaseous combustion products as well as the ignition front moving at a slower rate, are uneven and greatly distorted. The combustion zone has a considerable extent and contains a large quantity of explosive volumes whose dimension decreases both as a result of combustion from the surface and the destruction of individual small porous pieces of explosives by the excess pressure in the pores. The development combustion surface makes it possible to understand the existence of high propagation rates. The presence of a gas flow, which blows the explosive particles out, leads as a result of erosion to an increase in their combustion rate, which in conjunction with high pressure contributes to the intense combustion of the suspended matter. The examined model is similar to the model of the large-scale turbulent combustion of gas systems. Therefore in developing the theory of convective combustion it is expedient to employ the approaches which put together in the theory of turbulent combustion.

Convective combustion modes. Depending on the conditions of the experiment and first of all on the relationship between the gas inflow and the gas outflow different propagation modes are observed. As a rule, the process has an unsteady-state nature: the rate of convective combustion increases or decreases along the length of the charge. However, if combustion is carried out in the atmosphere or in a Crawford bomb (with the filling of the pores with an inert gas), then the convective combustion of porous charges with a blind bottom occurs at practically a constant rate along the length of the charge (see Fig. 59c), complete analogy with the ignition of a blind single pore is observed. This mode,

which it is expedient to call quasi-steady-state, has been investigated most minutely.

Quasi-steady-state mode of convective combustion. Let us examine the basic laws governing the propagation of a quasi-steady-state mode. The effect on the rate of convective combustion of density, explosive particle dimension, charge diameter and pressure was studied in [32]. Homogeneous explosives (PETN, cyclonite, tetryl) were pressed into plexiglass tubes 5 mm in diameter (height 35 mm) with a blind bottom and were burnt in a BD-1000 bomb at pressures of up to 1000 atm.

The dependence of combustion rate on pressure for specimens of PETN with different dispersity and density is represented in Fig. 60. In the region of low pressures stable laminar combustion is observed whose rate barely depends on density and increase linearly with pressure. Upon attaining critical pressure a sharp increase in rate occurs and a convective mode arises, a characteristic feature of which is the strong dependence of combustion rate on pressure $u_g = bp^{v'}$, where $v' > 1$. A certain weakening of dependence $u_g(p)$ at high pressures is connected with the effect of the dilution of the explosive powder with gas (nitrogen), which fulfills the role of an inert additive, which reduces the temperature of the combustion

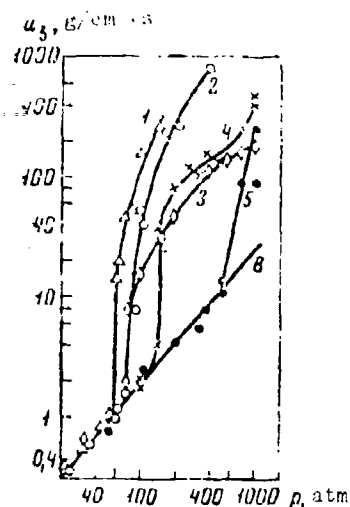


Figure 60. The dependence of PETN combustion rate with various dispersity and density on pressure size (μ) and density (g/cm^3): 1 - 200 μ and 1.08 g/cm^3 ; 2 - 200 and 1.17; 3 - 20 and 0.5; 4 - 20 and 0.71; 5 - 20 μ and 1.17 g/cm^3 .

products penetrating into pores. The mass of nitrogen increases with a decrease in the explosive density and with an increase in pressure.

It is interesting that the dependence of convective combustion rate on density (at constant pressure) (Fig. 61) takes the form,

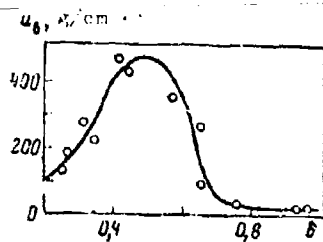


Figure 61. Dependence of the mass flow rate of convective combustion on relative density at a pressure of 1000 atm. (FETN, $r=20 \mu$).

similar to that which is observed during the ignition of a single pore (see Fig. 51). In proportion to the increase in density (decrease in pore diameter) the convective combustion rate increases, and then falls off. The rate of convective combustion is maximum at a certain optimum density whose value is close to that at which the maximum specific surface area of the pores is observed (see Fig. 14).

In contrast to normal the convective combustion rate is significantly affected [32, 56] by the diameter of the charge (Fig. 62). An increase in combustion rate with an increase in diameter, especially pronounced at low densities, is not connected with variation in the lateral heat losses.

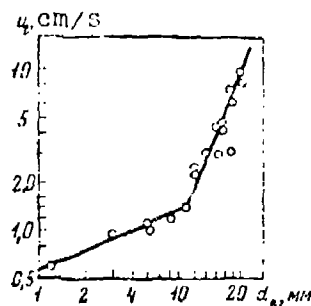


Figure 62. Dependence of convective combustion rate on charge diameter (cyclonite, $r=130 \mu$, $\rho=1.15 \text{ g/cm}^3$, $p=40 \text{ atm.}$).

During a quasi-steady-state combustion mode equilibrium is established between the gas inflow and the gas outflow, which with a limited length of the charge is stable. On the basis of the available experimental results and taking into account the data, obtained in § 16, let us attempt to establish the law of variation in the quasi-steady-state convective combustion rate. For large pores under conditions when a jet mechanism of penetration of combustion into the charge pores occurs, the following evaluational variants are possible.

1. Let us assume that combustion rate u_B beyond the stability limit exceeds the normal rate u_0 as a result of increase ΔS in combustion surface S_0 due to the ignition of pores at a certain depth, i.e., $N = u_B/u_0 = 1 + \Delta S/S_0$. After appropriate substitutions and the introduction of the variable $n = \phi/\phi'$ ($\phi = \rho u a$), which shows, how far from the limit combustion goes (see § 16), we obtain, that $N \sim n(1 + a_1 n)$. With large n , i.e., far from the limit, the ratio of the convective combustion rate to the normal combustion rate at the same pressure increases as n^2 .

2. Let us employ the result of [162], where for the rate of movement of the ignition front u_B which moves behind the flow of hot gas, which is flowing into a pore at rate v , an expression of the following type is obtained

$$\frac{v}{u_B} = 1 + \frac{4N a_1 z_1 z_T}{a^2 r_n^3} \quad (69)$$

Assuming rate v to be equal to the rate of the combustion product stream, flowing into a pore, we obtain: $N \sim n^2/(pn^2 + a_2)$, where a_2 - a constant, which depends on the charge characteristics. When $pn^2 \ll a_2$ we obtain $N \sim n^2$, and when $pn^2 \gg a_2$ $N \sim 1/p$, i.e., the rate of the ignition front falls off with an increase in pressure.

Figure 63 gives the processing of the experimental data [32,

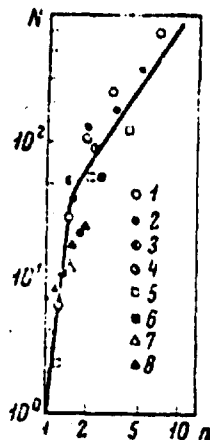


Figure 63. Generalized dependence of the quasi-steady-state convective combustion rate of powdered charges. 1, 3, 4 - PETN [32]; 2 - cyclonite; 5-8 - octogen [HMJ] [176]; average particle size (μ) and density (g/cm^3): 1 - 200 μ and 1.17 g/cm^3 ; 2 - 200 and 1.08; 3 - 200 and 1.07; 4 - 20 and 1.17; 5 - 400 1.2; 6 - 110 and 1.05; 7 - 70 and 1.07; 8 - 60 μ and 1.08 g/cm^3 .

82] on the combustion of powdered charges of several explosives. In spite of the great variance in the data, connected with the poor reproducibility of the convective combustion rates, a specific correlation, close to that which is expected, exists. Extremely interesting would be the obtaining of results in the parametric domain, where $N \propto 1/p$. Here it is possible to indicate Margolin's experiments with mercury fulminate in which a drop in the mechanical effect of the convective combustion of charges with a significant (300-500 atm.) increase in pressure was observed. It is possible that a certain role in this phenomenon (along with the dilution of the pores by nitrogen) could be played by the drop in the convective combustion propagation rate. This is all the more probable since at the indicated pressures N attained values of the order of hundreds, whereas in experiments with other substances it usually did not exceed ten.

The question touched on here has been worked out quite poorly. In refining it is necessary to consider the real pattern of convective combustion when the propagation of the combustion front does not move in a continuous front, but due to the individual streams which penetrate into the depth of the charge.

Let us examine the nature of convective combustion propagation during the combustion of a charge under conditions of increasing pressure and of an "immured charge" setup. Under these conditions

the development of convective combustion is usually unsteady-state. At a pressure, close to critical, convective combustion which began at a low rate can be retarded and pass over to laminar combustion (see Fig. 34). The damping of the process is connected with the contraction of the gaseous products, which outstripped the ignition front, at the closed bottom end.

Far from critical conditions and when using long charges the convective combustion rate increases in proportion to propagation, and the process is accelerated. The accelerated convective combustion mode is characterized by deep pulsations (see Fig. 59a), which attests to intense distortion of the ignition front.

In the development of convective combustion the determinant role is played by the pores, existing in the charge. The pores along which convective combustion is propagated, can also be formed in the combustion process, which is observed, for example, if an explosive charge burns in a closed deformed shell [120]. This effect has great significance first of all in the combustion of very dense (cast and pressed) charges. The formation of pores occurs as a result of the expansion of the internal duct of the shell due to the bursting effect of elevated pressure in it. The general pattern of pore formation was obtained in experiments in which part of the explosive, pressed to high density $\delta=0.98$ directly into a shell, was replaced by an inert substance. Analysis of the state of the inert substance (after combustion) showed that the gas permeation occurred along the gap between the charge and the shell, and also along the system of cracks, which formed on the lateral charge surface.

The existence of this effect was additionally confirmed by the following experiments. Charges with a diameter of $d_3=10$ mm made from a mixture of ammonium perchlorate with polystyrene ($\delta=0.98$) were burnt and recording of pressure $p(t)$ was carried out in the combustion process. In part of the experiments the

mixture was pressed into a thin-walled ($\Delta=5$ mm) steel shell, in another part of the experiments an inserted charge, armored over the entire surface, except the upper end and not directly touching the thick-walled ($\Delta=20$ mm) shell was used. In the latter case the charge during combustion was found under conditions of volumetric compression. The density of charging was maintained constant. It was established that during combustion of a charge, pressed directly into a thin-walled shell, recording of $p(t)$ experienced on abrupt salient point, attesting to the acceleration of process at a pressure of $p \approx 1$ kbar¹. The combustion of the inserted charge which was not in contact with the shell, to the end was laminar; in this case the pressure in the shell exceeded 4000 atm.

Thus, the possibility of the propagation of convective combustion along the pores, which form as a result of the separation of the charge from the shell, it is necessary to consider in analyzing the development of explosion.

With accelerated unsteady-state propagation of convective combustion in a porous charge a continuous pressure increase in the combustion zone occurs which leads to a further increase in the rate of the process. From the considerations, discussed above (pg. 154), it follows that a boundless increase in velocity is not possible and stabilization of the process at a convective combustion rate, close to the speed of sound in the products should be observed. However, during the ignition of a porous explosive charge of sufficient length at the closed end this limiting case of the propagation of convective combustion is practically not realized. The fact is that in proportion to the increase in the rate of the process the intensity of the compression waves

¹Calculation with the application of the formulas of elasticity theory shows that at pressure $p=1$ kbar the expansion of the internal channel of the steel shell ($d_3=10$ mm, $\Delta=5$ mm) is ≈ 10 μ .

increases, which move in front of the ignition front, and at certain threshold wave of compression rate becomes capable of initiating a chemical reaction. Replacement of the mechanism of reaction excitation occurs, and the convective combustion mode converts to the low-speed wave mode. The value of the threshold rate is determined in experiments in which the explosive charge is completely separated by a plate from the inert material (steel, plexiglass) [122, 125]. The plate eliminates the penetration of the gaseous combustion products and, therefore, cuts off convective combustion; however, it does not prevent the passage of compression waves. This systematic procedure makes it possible to separate convective combustion from the low-speed wave mode. It was experimentally established that for powerful compacted explosives (PETN, cyclonite) the value of the threshold rate (maximum value of the convective combustion rate) is 700-800 m/s [120, 127], i.e., it is considerably lower than that at which one would expect stabilization of the convective mode.

Figure 64 depicts a typical photograph of the process, which arises during the ignition of PETN with a density of $\rho=1.45 \text{ g/cm}^3$ in a closed plexiglass shell. It is evident that practically immediately after ignition the convective combustion mode arises with a characteristic "torn" front¹ whose rate increases in proportion to propagation, and attains a value of tens and hundreds of meters per second, which is accompanied by a decrease in the pulsations at the luminescent front. The further increase in the rate to 900-1000 m/s is characterized, as a rule, by a variation in the slope on the photographic recording, which is connected with the appearance of the low-speed mode. Actually, in the case of placing a steel plate in this zone, which separates the explosive charge, the process passed through the plate with

¹The laminar combustion stage is slightly extended, since the pressure in the closed volume rapidly increases and it attains the critical cutoff value.



Figure 64. Development of explosion during ignition (PETN, $\rho = 1.45 \text{ g/cm}^3$, $r = 500 \mu$, $d_3 = 5 \text{ mm}$).

certain decrease in rate, which was then increased to the previous value (Fig. 65), in this case the integrity of plate was retained.



Figure 65. Photograph of the propagation of the process with the separation of the charge by an inert barrier, situated in the zone of the low-speed mode (PETN, $\rho = 1.45 \text{ g/cm}^3$, $r = 500 \mu$, $d_3 = 5 \text{ mm}$).

B. LOW-SPEED WAVE PROCESS OF EXPLOSIVE CONVERSION

In accordance with the general system of development of an explosion (Fig. 44) convective combustion converts to the low-speed process of explosive conversion [HCP] (NSR), which in the majority of cases precedes the emergence of normal detonation. Figure 66 depicts the photograph of the transition of combustion to detonation for the case when the development of explosion passes through the basic stages: convective combustion - low-speed process - detonation.



Figure 66. Photograph of the transition of combustion of PETN into detonation ($\rho=1.55 \text{ g/cm}^3$).

The velocity of the low-speed process is substantially lower (2-10 times) than the rate of normal detonation. At present the wave nature of the low-speed process has been proven: the chemical reaction is initiated by the compression wave moving along the explosive charge [120, 125-127]. Low-speed conditions appear both during the ignition of explosives in a shell and under the influence on the explosives of a weak shock wave.

The propagation of the low-speed process in powder charges of explosives was observed for the first time by Apin and

Bobolev [132].¹ Considerably later the possibility was shown of the propagation of NSR in high density (cast and pressed) charges of explosives [13, 120, 122, 125-129, 131, 159].

The existence of low-speed conditions has been established now for a wide circle of homogeneous, mixture and initiating explosives. As a rule, the low-speed process develops in systems which are capable of normal detonation.

Until recently it was considered that the low-speed process is an unstable process which must die out or convert to normal detonation. An important result of the investigations carried out in recent years lies in the fact that the conditions were determined at which the propagation of NSR occurs stably, at a constant velocity along the length of the charge up to a considerable distance (on the order of 40-50 diameters of the charge).

The isolation of the stability region made it possible to conduct a systematic and detailed study of the propagation of low-speed conditions. Initially this type of investigation was carried out with powder-like, and then also with high density charges of explosives.

§ 24. Laws Governing the Stable Propagation of a Low-Speed Process

While following the general nature of the presentation of material, let us examine initially the laws governing the stable propagation of a low-speed process. To powder-like charges we

¹Low-velocity conditions in powder-like explosives are usually called detonation at low speed.

will apply the term "detonation at low speed" ("low-speed detonation"), for high density charges - "low-speed process" (see pg. 110).

The Propagation of Detonation at Low Speed in Powder-Like Explosives [122, 134-136]

Mainly homogeneous explosives (trotyl, tetryl, PETN, cyclonite) have been investigated in great detail. The coarse-crystalline powders of explosives were placed into thin-walled shells made of cellophane or plexiglass. The initiation of detonation at low speed was realized by a weak shock wave, appearing during the explosion of a special active charge. It was established [135] that if a stable process appears, then its velocity does not depend on the power of initiation. Steadiness of the propagation of the process was also investigated by changing the length of the charge: the maximum length, at which a stable small detonation velocity was spread, was 500 mm.

The stable propagation of detonation at low speed was observed at specific values of size of explosive particles and diameter of charge. The dependence of the rate of the process on the diameter of charge for the powders of tetryl and PETN of different disperisty is presented in Fig. 67.

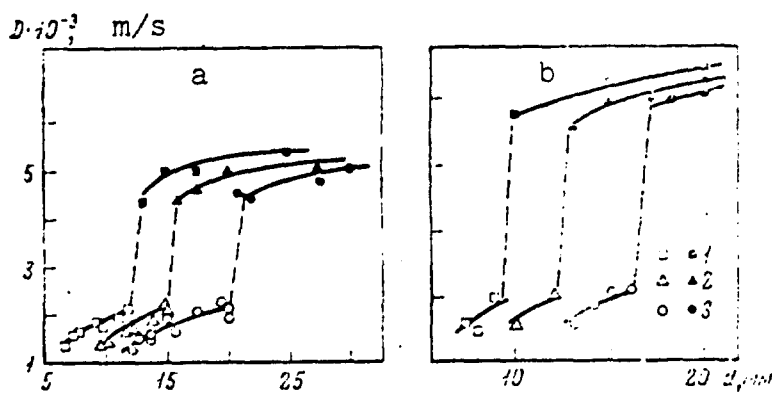


Figure 67. Dependence of the rate of low-speed (light figures) and high-speed (dark figures) detonation on the diameter of charge [135]. a) tetryl, $\rho=0.92$ g/cm³; 1 - $r=0.5$; 2 - 0.8; 3 - 1.3 mm. b) PETN, $\rho=0.95$ g/cm³; 1 - $r=1.3$; 2 - 2.0, 3 - 4.2 mm.

The stability region of propagation is limited above and below by values of the diameters of the charge, the extent of which is approximately proportional to the initial particle sizes of the explosive.

Outside the region of stable propagation with small diameters the process dies out, with larger diameters it converts to a normal high-speed detonation. In this case the maximum speed of low-speed detonation (2000-2300 m/s) does not depend on the dispersity of the substance and is virtually identical for different explosives.

As can be seen from Fig. 67, the rate of stable low-speed detonation increases with an increase in the diameter of charge and decrease in the size of particles.

The "aquarium" method [135] and the electromagnetic method [122, 136] were used to measure the pressures in the wave of a low-speed detonation, the findings are given in Table 9.

Table 9. Pressure in a wave of low-speed detonation.

Explosives (density 0.92-1.0 g/cm ³)	Diameter of charge mm	Size of particles, mm	Rate of low-speed detonation, km/s	Pressure, kbar	
				"aquarium" method [135]	electromagnetic method [122, 136]
Tetryl	20	0.5	2,12	14,8	—
	28	0,4-0,8	1,07	—	7,5
Tetryl	20	1,3	2,14	14,5	—
	20	1,0-1,6	2,0	—	13,4
Cyclonite	20	2,0	1,98	10,4	—

Pressure in the wave of the normal detonation of the investigated powder-like charges is approximately 50 kbar.

From the data in Table 9 it follows that the pressures during low-speed detonation conditions comprises 7.5-15 kbars and is considerably lower than the pressures attained during normal detonation in the same diameters of a charge. Another feature of the considered process lies in the fact that during the propagation of low-speed detonation only an insignificant part of the total energy is given off: in accordance with results of [135, 136] the heat release does not exceed 30-35% of energy during normal detonation.

In works [134, 135] the results are explained, on the strength of the model of "explosive" combustion [167], according to which the chemical reaction flows in the form of the surface combustion of separate grains of explosives. One of the basic reasons in favor of the applicability of the indicated model entails the fact that the lower and upper values of the diameters of the charge, which limit the region of stable propagation of low-speed detonation, are proportional to the initial particle size.

Density effect of charge. At it was noted, the data available in the literature on low-speed conditions were acquired on systems either of bulk or high density. Investigations at intermediate densities were not conducted.

In the tests made by the authors the possibility was shown of the stable propagation of the low-speed process at intermediate charge densities, which made it possible to determine in the example of PETN the nature of the dependence of the velocity of the process on density. The stable propagation of low-speed conditions was observed, if PETN with the initial particle sizes $r=1.0-1.25$ mm was enclosed in a low-strength shell made of plexiglass. Charge density varies from 0.95 to 1.68-1.70 g/cm³.

At a density $\rho > 1.70 \text{ g/cm}^3$ under these conditions the process died out. The resulting data are given in Fig. 68. It is evident that the velocity of the process in charges of $1.45\text{-}1.70 \text{ g/cm}^3$ density in practice does not depend on the value of the latter [120]. At lesser densities the velocity rises with a decrease in density (approximately $W \sim 1/\rho$).

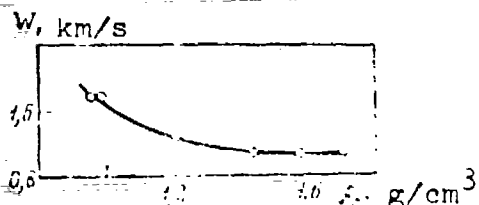


Figure 68. Dependence of the velocity of low-speed conditions on density (PETN, $r=1.0\text{-}1.25 \text{ mm}$, $d_3=5 \text{ mm}$, plexiglass shell).

Thus with the appropriate selection of test conditions it is possible to obtain the stable propagation of a low-speed process in charges with different density.

There is a great deal of interest in the study of the propagation of the low-speed process in high density charges of explosives. The fact is that unlike low-density explosives during the propagation of a low-speed process in a high density charge a substantial change in the specific volume of substance at the front of the compression wave does not occur, and the phenomenon is not distorted by the complex picture which appears with the collapse of pores. It seemed that the low-speed conditions in high density and low-density systems have a common nature. All this determined the approach to the problem [166], which was based on the attempt to explain the basic laws and to understand the nature of low-speed conditions on a simple model, which is a high density charge of explosives. This approach seems advisable first of all because at present there is no theory and physically substantiated mechanism of a low-speed process.

Propagation of a Low-Speed Process in High Density Explosives

A study was made of the stable propagation of NSR in charges of homogeneous explosives of high density [127-129, 131, 166]. In work [127] it was noted that the velocity of NSR in the layer of PETN ($\delta=0.95$), pressed between flat surfaces made from plexiglass, was approximately 1000 m/s. Propagation in cast trotyl, enclosed in a steel tube (wall thickness 10-15 mm), occurred at a constant velocity of 1800-2200 m/s [131]. The observed values of the velocity of NSR were below or close to the speed of sound in the initial explosives and changed within narrow limits. Investigations [127, 131] were conducted under conditions when the parameters of the shell were invariable. At the same time it is necessary to emphasize that the stable propagation of the low-speed process in high density secondary explosives is observed only if the explosive is surrounded by a sufficiently durable shell, which testifies to its important role in the propagation of NSR.

Systematic studies for an explanation of the influence of the shell on the velocity of the low-speed process were carried out in works [128, 129, 166].

If an example of PETN the dependence of the velocity of the stable low-speed mode W on wall thickness Δ (strength) of a steel shell was studied in detail by the optical method. PETN with particle sizes of 500 μm was pressed by the batch method directly into a shell made of steel 45 to density $\rho=1.73 \text{ g/cm}^3$ (relative density 0.975). The inner diameter of the shell was equal to 5 mm, the length of charge 150-250 mm. The wall thickness of the shell changed after every 0.5 mm. These simply formulated experiments made it possible not only to explain the role of the shell, but also to obtain a series of fundamentally

new results concerning the laws governing the propagation of NSR.

The initiation of the low-speed process was realized in essence by ignition in the enclosed end of the charge through a pin-igniter, and also by a weak shock wave with a known amplitude, appearing during the detonation of a special charge. It was shown that the velocity of the process does not depend on the method of initiation. With the aid of triggered photorecording measurement was made of the velocity of the process on the section of a steady-state process through radial openings in the shell (0.8 mm in diameter), arranged at a distance of 20 mm from each other. Photographing the process was conducted in natural light.

Besides velocity measurement of the low-speed process, the dynamic strength was determined for the shells used under conditions of loading, close to those that occur during the emergence of the low-speed process. For this purpose in a separate set of tests using the piezoelectric method the direct measurement was made of maximum pressure p' which appears in the channel of the shell at the moment of its destruction. The recording of pressure was made near the point of ignition, close to which (at a distance of 10-15 mm) the destruction of the shell took place. The piezoelectric gauge and registering apparatus used made it possible to record pressure to 12 kbar with a speed of build-up $dp/dt < 0.3$ kbar/ μ s.

Let us examine the results obtained. It was shown that the low-speed process in PETN is established at a distance of 20-30 mm from the point of ignition and is propagated stably at a rate which is constant in length to the remaining (about 30-40 d_3)

part of the charge.¹ Figure 69 shows characteristic optical photographs. On the curve of Fig. 70 the dependence of the velocity of the process on the wall thickness of a steel shell is presented [100]. These results correspond to the section of a steady-state process. Each point on the curve $W(\Delta)$ is the average value of 3-5 tests.

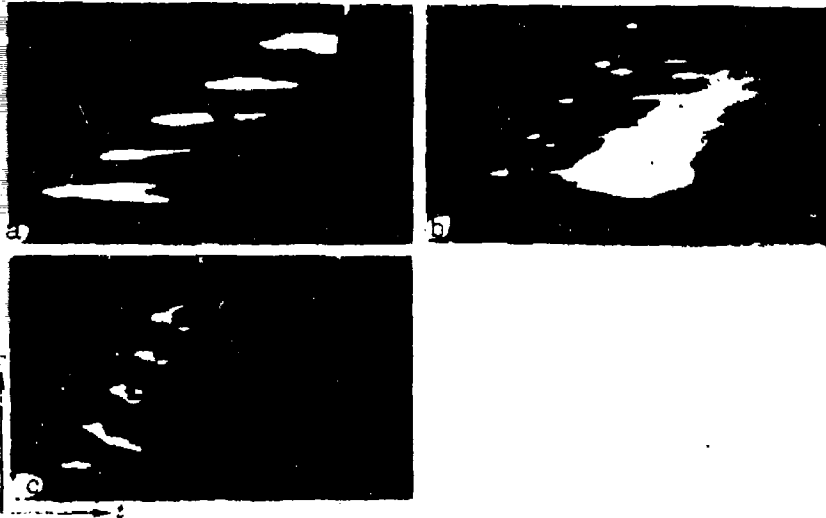


Figure 69. Photograph of the propagation of a low-speed process at different velocity (PETN, $r=500 \mu\text{m}$, $\rho=1.75 \text{ g/cm}^3$, $d_3=5 \text{ mm}$, steel shell). a) $W=1500 \text{ m/s}$; $\Delta=1.5 \text{ mm}$; b) $W=2400 \text{ m/s}$; $\Delta=4.0 \text{ mm}$; $W=3300 \text{ m/s}$; $\Delta=12.5 \text{ mm}$.

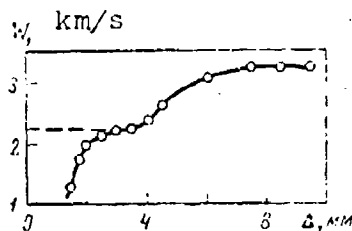


Figure 70. Dependence of the velocity of a low-speed process (W) on the wall thickness of a steel shell (PETN, $r=500 \mu\text{m}$, $\rho=1.73 \text{ g/cm}^3$, $d_3=5 \text{ mm}$).

¹Shells with a wall thickness $\Delta < 6 \text{ mm}$ were destroyed in the process of the test, thicker walled shells retained their completeness.

As it follows from the findings, the velocity of NSR varies continuously from 1300-to 3300 m/s. With an increase in the wall thickness of the shell from 1.3 to 2 mm the velocity increases from 1300 to 2000 m/s, then with $\Delta=2-4$ mm a section of slowing down of an increase in velocity is observed. In shells with $\Delta>4$ mm the velocity of the process again increases and reaches (with $\Delta\approx 8$ mm) the extreme value of 3300 m/s. A further increase in the outside diameter of the shell to 40 mm ($\Delta=17.5$ mm) did not lead to a change in the velocity of the process.

Consequently, the use of shells made of the same material (steel 45), but with a different wall thickness, makes it possible to change over wide limits the velocity of the low-speed process in charges of high density. In this respect solid explosives differ from liquid explosives, in which the velocity of propagation of detonation at low speed is changed discretely. For example for nitroglycerin, according to the published data [122], it is 1000 and 2000 m/s depending on the speed of sound in the shell.

Another important result entails the fact that the velocity of the low-speed process can be both lower and greater than the speed of sound in the initial explosives.¹ In Fig. 70 the dotted lines correspond to the value of the longitudinal velocity of sound in PETN with the given density and particle sizes ($C_L=2250$ m/s), which was measured by the ultrasonic technique.² In this connection it is appropriate to recall that previously subsonic [125] or transonic [131] propagation was considered characteristic,

¹Naturally the subsonic process cannot be classed as detonation.

²The cited value is the longitudinal velocity of sound in an unbounded medium. The speed of sound was determined with the aid of a UDM-1M instrument.

typical for the low-speed process in high density explosives. Taking into account the results obtained it is possible to explain also the reason for the nonconformity in values of the velocity of the process which was observed in the test of different authors who investigated the same explosives. During the analysis of Fig. 70 it is necessary to emphasize that the weakening of dependence $W(\Delta)$ is observed at the velocity of NSR close to the speed of sound C_7 .

The results of the measurement of pressure p' , which is withstood until destruction by the investigated steel shell with a different wall thickness, are shown in Fig. 71. Measurements are carried out for shells with a wall thickness of 0.7-2.7 mm for which the interval of change in p' comprised 4-10 kbar. The experimental data are described satisfactorily by the dependence of the exponential form $p' = p_0 \Delta^{0.7}$. The broken segment of curve $p'(\Delta)$ Fig. 71 corresponds to the extrapolation of the findings. The extreme point on the extrapolation curve is obtained from tests on impact initiation and answers to the blast pressure, at which the low-speed process at maximum speed (3300 m/s) is still excited. An insignificant increase in the intensity of shock wave led to detonation.

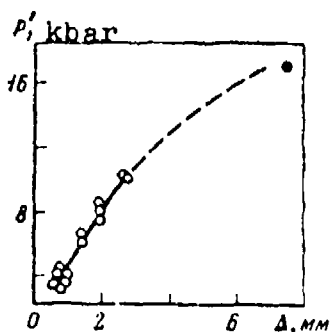


Figure 71. The dependence of the dynamic pressure p' , which destroys a shell, on the thickness of the wall (material of shell is steel 45, $d_3=5$ mm).

On the basis of the data of Figs. 70 and 71 the dependence of the velocity of the low-speed process on pressure in the shell $W(p')$ is obtained (Fig. 72).

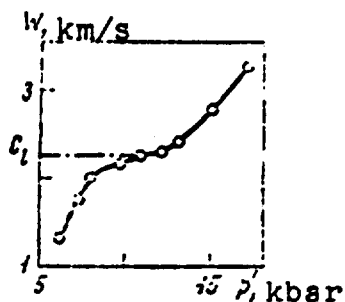


Figure 72. Dependence of the velocity of the low-speed process W on pressure in the shell p' (PETN, $r=5000 \mu\text{m}$, $\rho=1.73 \text{ g/cm}^3$, $d_3=5 \text{ mm}$).

On the curve $W(p')$ three sections are distinguished: 1) subsonic ($W < C_1$) with strong dependence $W(p')$, 2) transonic ($W \sim C_1$), for which the velocity of the process depends weakly on p' , 3) supersonic ($W > C_1$), where $W(p')$ again is amplified.

On the whole the findings testify to the fact that the velocity of the low-speed process is determined by the pressure which is realized in the shell, and in the final analysis - by the amplitude of the compression wave being spread in the explosive. The dominant role of the shell of the charge entails maintaining at a specific level the pressure in the wave. The fact that the determining effect on the velocity of the process is exerted mainly by the strength of the shell, i.e., the resistance caused by cohesive forces, is confirmed also by the following tests. The enclosing of a thin-walled ($\Delta=1.3 \text{ mm}$) shell by a massive water shell, but one without strength, does not change the rate of the process. When using a massive, but low-strength lead shell the process in PETN was not spread.

Furthermore, tests were run in shells of less durable (than steel) materials. In thick-walled shells of plexiglass, duraluminum, and brass the extreme value of the velocity of the process turned out to be equal correspondingly to 1100, 1200 and 2600 m/s, which is found in accordance with the value of the yield point of these materials.

Dependence $W(p')$ (see Fig. 72) gives the specific concept about the effect of the amplitude of compression wave on the

velocity of the process, since there is a basis for assuming that the amplitude of compression wave in explosives does not exceed p' . In favor of this assumption is the following fact. In a shell with $\Delta=1.3$ mm ($W=1300$ m/s) (see Fig. 72) pressure $p'=6$ kbar turns out to be close (somewhat exceeds) to that which was obtained in work [127], when the amplitude of compression wave, measured directly by another (electromagnetic) method, was 5 kbar with $W=1200$ m/s.

Unfortunately, at present the direct measurements of pressure in the compression wave of a low-speed process at different velocities of its propagation are absent.

As it was noted, during stable propagation the velocity of a low-speed process does not change at considerable lengths of charge, from which it follows that the amplitude of the compression wave, which guides the process is maintained constant. This support can occur, if a mobile equilibrium is established between the gas inflow due to the chemical reaction and the gas vent as a result of the strain (expansion) of the shell.

In the described tests the emergence of detonation was absent, which finds its natural explanation if we compare values p' (see Fig. 72) with the critical pressure p_{kp} of the initiation of detonation by a shock wave. Value p_{kp} was measured in tests on the transmission of detonation through an inert (copper) barrier (see § 29). The minimum amplitude of the shock wave which entered in the explosives and which initiated detonation was determined. It turned out that for the investigated charges of PETN ($\delta=0.975$) in a steel shell the critical pressure comprised 17 kbar.¹ But if the pressure in the initiating wave

¹The rate of normal high-speed detonation of PETN under these conditions is 8500 m/s.

was somewhat less than p_{HP} , which was achieved by an insignificant increase in the thickness of the barrier, then a low-speed process developed, the rate of which corresponded to the thickness of the walls of the shell. In a shell with $\Delta \approx 8$ mm it was possible to excite a low-speed process at a maximum velocity of 3300 m/s, when into the explosive a shock wave with a pressure of approximately 17 kbar entered. This value of pressure is presented on the curve in Fig. 71.

From a comparison of p' and p_{HP} follows the conclusion [128] that during the propagation of a low-speed process the pressure in the shell is lower than critical pressure of the initiation of detonation, i.e.,

$$p' < p_{HP}$$

Thus if conditions are created at which the pressure in the compression wave is maintained constant and less than the critical pressure of the initiation of detonation, then the propagation of the low-speed process is stable.

We have presented the basic results of the study of the low-speed process which were obtained in one explosive (PETN) and in a single setting up of the experiment [128, 129, 166].

We will now turn to the data available in the literature. The low-speed process of explosive conversion, which converts to detonation, was observed [13, 125] during the ignition of cast explosives (pentolite and DINA) in durable steel tubes. In the less sensitive cast trotyl the process under the same conditions was spread stably [125].

A detailed study of the stable propagation of the low-speed process in the cast trotyl was conducted by Babaytsev, Kondrikov,

and Tyshevich [131, 159]. It was shown that in durable steel tubes the propagation at a speed constant along the length (1800-2000 m/s) occurs for a considerable distance up to 50 cm. Pressure in the compression wave measured by the "aquarium" method comprised 5-8 kbar.

Table 10 gives the values of the maximum velocity of the low-speed process for different explosives of high density, which are compared with the longitudinal velocity of sound in explosives. Data known from the literature were used.

As it follows from Table 10, the most widely accepted and typical values of the maximum velocity of the process, obtained for different explosives and under different conditions, approaches the longitudinal velocity of sound in the initial explosives and is 2000-2500 m/s.

§ 25. The Nature of the Low-Speed Process in High Density Explosives

It was noted above that the low-speed process has a wave nature. Let us pause in greater detail on the experimental data for the substantiation of this position. First of all it was necessary to determine the role of the compression waves, which were being spread along the explosive charge and along the shell of the charge.

For the purpose of clearing up the effect of wave perturbations in the shell a special test was run in which the steel shell was cut completely in a plane, vertical to the axis, and separated by foam rubber (with a thickness of 5 mm), which extinguished the compression waves moving along the shell. It was shown that in this shell the low-speed process in PETN ($\rho=1.73 \text{ g/cm}^3$) is spread stably for the entire length of the

Table 10. The value of the maximum velocity of low-speed process in high density explosives (ρ - density, g/cm³; d_3 - diameter, mm; L - length, mm; Δ - thickness of wall, mm).

Explosive	Parameters of cylindrical shell	Longitudinal velocity of sound in explosives, m/s	Nature of process	Maximum velocity of low-speed process, m/s	Literature
PETN pressed	Plexiglass $\Delta=45$	2250	Stable	1100	[120]
$\rho=1.73$	Brass $\Delta=20$		The same	2600	[128]
$d_3=5$	Steel 45, $\Delta=2-4$		" "	2000-2400	[129]
L=200	Steel 45, $\Delta=8$		" "	3300	[129]
Cyclonite pressed	Steel 30KhGSA, $\Delta=8$		Converts to detonation	3300	[129]
$\rho=1.75$	Steel 30KhGSA	2500	The same	2400	[120]
$d_3=5$					
L=200					
DINA cast	Steel, $\Delta=9.5$	-	" "	2000-2300	[13]
$d_3=12.7$					
L=300					
Pentolite cast (50/50)	Steel, $\Delta=9.5$	2430	" "	2100-2500	[125]
$d_3=12.7$					
L=300					
Trotyl cast	Steel, $\Delta=5-13$	2300	Stable	2200	[131]
$d_3=9-15$					
L=500					

Note. Low-speed conditions in trotyl were excited by a weak shock wave, in all the remaining tests - by the wave which appears during ignition. The longitudinal velocity of sound in PETN, cyclonite, and trotyl was measured by the ultrasonic technique.

charge. The stability of propagation of NSR was not disturbed, if the explosive charge across the lateral surface was separated from the shell by a layer of foam rubber. Consequently, unlike liquid explosives, during the propagation of low-speed processes in solid explosives the determinant is the compression wave in the initial substance; the disturbances which move along the shell, do not play a significant role. This conclusion is strengthened also by the following data. The propagation of a low-speed process is observed in substances which do not have a shell: for example, in the crystals of the initiating explosives (lead azide and silver azide) [223] or in the charges of the secondary explosives (cast trotyl) [27]. The low-speed process which develops in cast trotyl under the influence of the shock wave is unstable (it dies out or converts to detonation [27]).

In the light of what was said there is a great deal of interest in the results of the study of the profile of compression waves in explosives during low-speed propagation. The data available on this question are very scarce.

Profile of compression wave. Gipson and Macek determined the rate of movement of a pressure front (with the aid of sensors of compression) and of the front of a chemical reaction (ionization sensors) [13]. The sensors were placed in one plane at different distances along the length of cast charges of DINA and pentolite. It was shown that the reaction appears behind the compression wave with considerable delay. The results of one of such tests, in which the sensors were arranged in the zone of the propagation of the low-speed process, are shown in Fig. 73. In this test the transition to detonation was not observed. It is evident that the distance between the compression wave 1, recorded by the sensors of compression with a threshold of operation of 0.6 kbar, and the reaction front 2, is approximately 40 mm. It is interesting that the distance between fronts

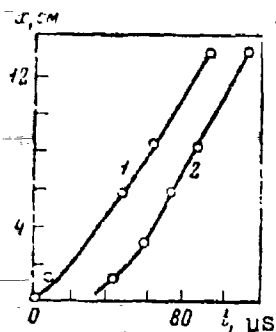


Figure 73. Propagation of the pressure front (1) and of the burning front (2) during a low-speed process (cast DINA, $d_3=12.7$ mm).

in proportion to the propagation of the process with a velocity of 1400 m/s virtually is not changed, i.e., the zone of reaction and the isolated points of the pressure front are spread along the charge at approximately an identical rate. When stronger sensors (2 kbar) of compression were used they showed a lesser distance between fronts. The pressure front is reproduced better than the reaction front.

In works [120, 127] as the indicator, which makes it possible to fix the passage of compression waves, a sensitive initiating explosive was used - lead azide, a thin layer of which divided the charge of PETN of high density across the entire section. It was established that the explosion of the lead azide occurred in front of the glowing reaction front at a distance of 5-10 mm at the process rate $W \approx 1000$ m/s.

The full profile of compression wave at one point along the length of the charge was measured by the electromagnetic method in work [127]. A typical recording during steady conditions of propagation at a rate of 1200 m/s is given in Fig. 74. From it it follows that the pressure gradually increases to the maximum value. The measured value of wave amplitude turned out to be equal to 5 kbar, which will agree with the results of determining p' .

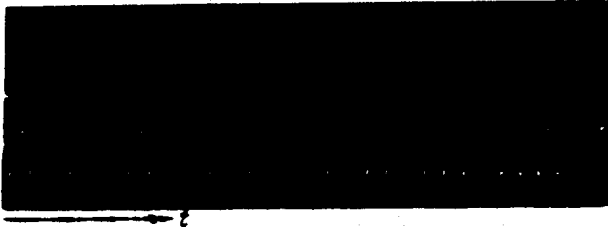


Figure 74. Oscillogram of the recording of mass flow rate $U(t)$ during the propagation of a stable process at a rate of 1200 m/s (time between markers 2 μ s).

Thus the entire totality of the given data indicates that during the propagation of a low-speed process in high density explosives at subsonic velocity the wave is not shock and is characterized by an expanded profile with a smooth pressure buildup. The existence of the compression waves, which do not have a pressure jump on the front, have long been established in tests for studying the propagation of explosive waves in soils [133].

At higher rates of the process (transonic or supersonic) measurements of full profile were not made. This position is connected with the fact that stable operations at these rates are observed in the durable metal shells, the presence of which extremely impedes the determination of the profile of the wave in explosives. However, the supersonic nature of the process indicates that the process in this case is spread by the shock wave. Such are the basic experimental results.

At present there is no final theory of low speed processes.¹ Therefore we first of all approached the creation of a consistent hypothesis, making it possible to explain, at least formally, the basic experimental results obtained on high density explosives.

¹Attempts at the theoretical examination of low-speed detonations were undertaken by a number of authors. Of greatest interest is Kuznetsov's work [119], which also contains a critical analysis of early works on this question.

On the basis of an analysis of existing data a hypothesis was proposed and substantiated [166] which entails the fact that the rate of a low-speed process is equal to the rate of movement along the explosive of a compression wave, in this case the self-sustaining complex of compression wave - zone of chemical reaction can be stable. It seemed that the results of studying the low-speed process can be explained, if we utilize data on the propagation of compression waves in solid (explosive and inert) substances.

For the purpose of the substantiation of the hypothesis advanced the laws governing the propagation of a low-speed process and weak (with an amplitude of 1-20 kbar) compression waves in solids were compared.

Let us examine what occurs if to the surface of a solid plane body at the initial moment we apply a constant pressure [130].

We will accept that for the considered solid (explosive) the stress (pressure p) - specific volume (v) diagram for states behind the wave front takes the form presented in Fig. 75. The

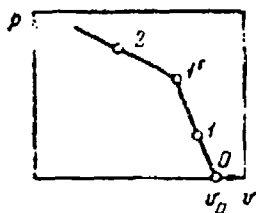


Figure 75. Stress (pressure) - volume diagram for a solid.

states which correspond to line $0-1'$ are described by Hooke's law and correspond to low pressures and strains.

With larger dynamic loads, when the pressure exceeds a specific value (yield point p_{TEK}), the solid converts to a flowing state similar to a liquid. The flowing state of the solid is characterized not by the full absence of tangential stresses, as in a

liquid, but by the absence of an increase in the tangential stresses with an increase in the shearing strains, Line $1'-2$ with less slope corresponds to the flowing state of the solid. Propagation

velocity of compression wave in the case of an elastic body (section 0 1') is equal to the longitudinal velocity of sound in the unbounded medium C_2 . Upon transition to a flowing state (section 1' 2) the propagation of the wave occurs at the volume velocity:

$$C_0 = \sqrt{(\partial p / \partial \rho)_s} = \sqrt{-V^2 (\partial p / \partial V)_s}$$

Depending on the relationship between wave amplitude and dynamic yield point the following versions are possible (Fig. 76). If $p < p_{\text{TEK}}$, throughout the body one elastic wave of compression with a velocity of C_2 (state 1 on the diagram p, v) will run (Fig 76a); if the applied pressure $p > p_{\text{TEK}}$, then in the body state 2 on diagram p, v is reached. However, in this case throughout the body two waves are spread: elastic with an amplitude of p_{TEK} and a state behind front 1', and following it - a plastic wave with a state behind front 2 (Fig. 76b). Since $C_0 < C_2$ the plastic wave does not overtake the elastic. In the case of a powerful shock wave (with $p \gg p_{\text{TEK}}$) its velocity $D > C_2$ and the splitting of the wave does not occur.

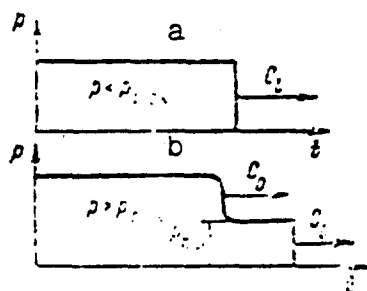


Figure 76. Two cases of the propagation of a compression wave in a solid a) one elastic wave; b) system of elastic and plastic waves. [MEK = flowing]

Such is the general picture which one should expect during the propagation of compression waves of different intensity. Quantitative laws can be obtained only experimentally. The pressure range in a compression wave, which is of interest for the considered question, comprises 1-20 kbar. However, paradoxically, but precisely in this interval of pressures the

dynamic compressibility of solids was investigated little experimentally, and in the literature on this question there are very limited data. The compressibility of high density trotyl was studied [27, 156]. It was shown that a wave with amplitude $p > 10-20$ kbar has an impact profile, and the impact adiabatic curve of trotyl is described by the conventional dependence of a linear form. At lesser pressures a deviation from linear dependence was observed [27], the shock wave with $p < 7-10$ kbar was split up into elastic and plastic [27, 156], the movement of the plastic wave occurred at subsonic speed. However, a systematic and detailed study of compressibility of explosives at low pressures was not made. Therefore supplementary tests were run on the study of the propagation of compression waves with an amplitude of 1-20 kbar [166].

They studied high density trotyl ($\rho = 1.60 \text{ g/cm}^3$), the compressibility of which was close to PETN, and also the inert organic substance plexiglass. The electromagnetic method was used which makes it possible to record the full profile of the compression wave. Magnetic field strength in the center of the gap of the electromagnet 200 mm wide was 450 Oe with a uniformity of 1%. Two L-shaped sensors made from aluminum foil with a thickness of 0.07 mm were utilized. They were placed perpendicular to the axis of the investigated sample, which had a diameter of 50-60 mm. Samples without a shell were used. Signals from the sensors were recorded on a double-beam cathode ray OK-17 oscillograph. The wave velocity (D) and mass flow rate of the substance (U) were measured.

A method was worked out for the creation in the investigated substance of a plane shock wave of low intensity. For the creation of pressures of 1-10 kbar a concussion wave was utilized which originated from the detonation of a spherical charge of TG 5' 50. More powerful waves were created by the detonation of a

cylindrical charge from a mixture of trotyl with common salt which contacted with the investigated substance. Waves of different intensity were obtained by changing the distance from the sample to the spherical charge or by changing the percentage of salt in the mixture.

Processing of data was done in the coordinates wave velocity (D) - pressure in the wave (p), since the velocity of motion and the profile of the wave are determined by its intensity.

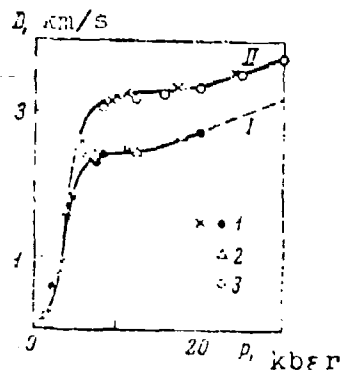


Figure 77. Dependence of the propagation velocity of a compression wave on pressure amplitude. I - pressed trotyl, $\rho=1.60 \text{ g/cm}^3$; II - plexiglass, $\rho=1.18 \text{ g/cm}^3$. 1 - data from [166]; 2 - [27]; 3 - [173].

The results obtained are shown in Fig. 77, and the characteristic oscillograms $U(t)$ - in Fig. 78. For a comparison in Fig. 77 the available data of other authors are also plotted [27, 173], These correspond to pressures $p > 7 \text{ kbar}$ and agree satisfactorily with the findings.

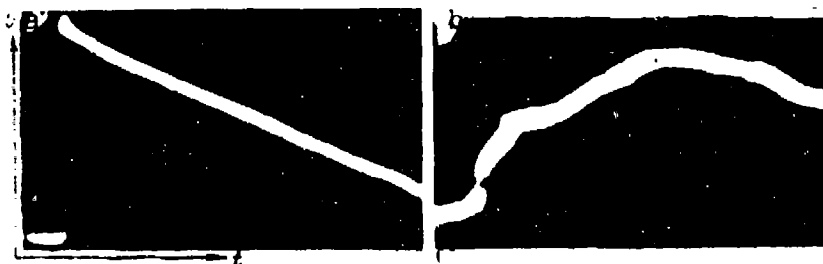


Figure 78. Oscillograms of recordings of mass flow rate in pressed trotyl. a) shock wave ($p=10 \text{ kbar}$); b) system of elastic and plastic waves ($p=5 \text{ kbar}$).

Figure 77 shows that the shape of the curve $D(p)$ for both investigated substances is identical, and the curve $D(p)$ consists of three characteristic sections.

In Fig. 77 the subsonic branch of the curve corresponds to the propagation of the plastic wave, the velocity of which, as follows from the findings, depends strongly on wave amplitude. It was established that the splitting of the shock wave with the formation of elastic and plastic waves for trotyl and plexiglass occurs at a close pressure (~ 7 kbar). The elastic wave is propagated at a velocity equal to the longitudinal velocity of sound (for trotyl $C_L=2300$ m/s, for plexiglass $C_L=2800$ m/s), its amplitude is not a constant value and depends on total pressure in the wave.¹ Pressure buildup in the plastic wave is realized in a time of 1-10 μ s depending on amplitude.

The interval of pressures from 7 to 15 kbar corresponds to the section of weak dependence ("plateau") on the curve $D(p)$, in this case the wave is propagated at a velocity close to the longitudinal velocity of sound, and it has an impact profile. A change in the amplitude of the shock wave in this range in practice does not affect wave velocity.

At a pressure $p > 15$ kbar a strengthening of the dependence $D(p)$ is observed and the impact adiabatic curve of the substance is described by a conventional linear dependence.

As it was noted, the compressibility of trotyl and plexiglass is described by curves of a similar form. It is possible that this form of curve $D(p)$ or $D(u)$ is typical for solid organic substances.

¹The corresponding data for an elastic wave are not shown in Fig. 77.

Let us compare the data presented with the results of a study of a low-speed process. For this purpose let us compare the data in Fig. 72 and Fig. 77. It is evident that the form of curves $W(p')$ and $D(p)$ is identical. On the whole also the pressures at which characteristic fractures are observed in the curve $W(p')$ will agree.

The established qualitative agreement in the laws governing the propagation of a low-speed process and weak compression waves confirms the validity of the expressed hypothesis and gives supplementary proof that the dominant role during the propagation of a low-speed process in solid explosives is played by the wave which moves along the explosive charge, and not along the shell of the charge. The results obtained can serve subsequently as a basis for the quantitative calculation of the velocity of the low-speed process, for conducting of which a knowledge of the compressibility of explosives and of the parameters of the compression wave is necessary. Specifically it was possible to obtain for PETN the satisfactory accord of experimental and calculated value of the maximum velocity of a low-speed process, which turned out to be equal correspondingly to 3300 and 3100 m/s. During the calculation the impact adiabatic curve of PETN was utilized and it was assumed in accordance with the developed representations that the maximum velocity of the process observed in the experiment coincides with the velocity of propagation of the shock wave, the amplitude of which is equal to the critical pressure of initiation of normal detonation ($p_{HP} = 17$ kbar).

What was said above makes it possible to explain the existence of subsonic low-speed processes which are caused by movement along an explosive of a plastic wave which does not have a pressure jump at the front, which will agree with the direct measurement of the profile of a wave in this case [127] (see

Fig. 74). The explanation of this fact from the viewpoint of the wave nature of low-speed processes previously caused the greatest difficulties.¹ It becomes clear why the different authors who experimented under different conditions and with different explosives (trotyl, pentolite, PETN, cyclonite) observed the most typical value of the velocity of the process (2000-2500 m/s) approaching the longitudinal velocity of sound (see Table 10). This value is most probable, since it corresponds to the section of "plateau" on the curve $W(p')$.

Finally it was to be expected that an increase in the velocity of the process can be reached, if we utilize explosives with a high value of p_{kp} and maintain a high pressure in the wave (for example by the utilization of shells made from highly durable materials). For the purpose of checking this assumption tests were carried out with PETN-agate ($\rho=1.76 \text{ g/cm}^3$), for which p_{kp} is substantially higher than for pressed, when the shell of the charge was made out of durable steel 30KhGSA. In this case the velocity of low-speed processes increased and was 3500 m/s.

The unstable propagation of NSR at a high velocity can also be observed under the influence on the explosives of a fabricated shock wave of considerable intensity which provides at a certain length of the charge the "forced" propagation of the process. Thus in the work of Dremin and Koldunov [27], who conducted experiments with charges of cast trotyl with a diameter of $d_3=60 \text{ mm}$ (without the shell), it was noted that under the influence of a shock wave of critical intensity ($p_{kp}=35 \text{ kbar}$) a process developed (in our terminology - "low-speed process")

¹One should also consider that the plastic wave moves over a substance, the structure of which can differ from the initial as a result of the effect of an elastic compression wave.

whose velocity at a length of $1-2 d_3$ was constant and was equal to 3600 m/s, whereupon detonation emerged. It is interesting that the velocity of propagation of a process measured by the optical method coincided with the velocity of the shock wave, determined with the aid of electromagnetic sensors placed on the axis of the charge. This fact indicates directly that the velocity of a low-speed process is equal to the velocity of propagation of shock wave on the explosive charge. Under the same conditions, but under the influence of the shock wave of subcritical intensity, the process died out.

Let us recall that the stable low-speed mode in high density charges of secondary explosives was observed only in the presence of a shell. In connection with this it is necessary to emphasize that the pressure in the compression wave of a stable process depends not only on strength of the shell, but also on the nature of heat release directly behind the wave.

At present the stability and steadiness of the self-sustaining complex, which includes the compression wave and a wide zone of the chemical reaction, has not been investigated either theoretically or experimentally: in many respects the mechanism of support of the compression wave is not clear. At the same time these questions have great significance for the construction of the theory of low-speed processes.

What was presented above was related to high density explosives. It is possible that the results obtained here can turn out to be useful during the explanation of the laws governing the propagation of low-speed "detonation" in powder-like explosives. In this respect there is interest in the work of Bolkhovitinov, et al. [154], in which it was shown that the shock compression of powder-like trotyl in an unsteady detonation

wave bears a complex stepped nature, and two waves are observed. In the opinion of the authors, initially the coverage of the pores occurs, whereupon - the further compression of the homogeneous substance.

Taking into account these data the process of low-speed "detonation" in powder can be presented in a simplified manner in the following form: behind the first wave front the substance is compressed to a density close to maximum, and it is moved at a velocity equal to the mass flow rate of the substance, and then over the moving high density substance a second wave is propagated, behind the front of which the chemical reaction develops. The expressed considerations make it possible to explain an increase in the velocity of NSR with a decrease in density (Fig. 68) and to evaluate the value of the expected difference (ΔW) in the velocities of propagation of the NSR in high density and low-density charges, which in the first approximation can be accepted equal to mass flow rate of the substance (U_1) behind the first wave front. According to [150] for PETN ($\rho \approx 1.0 \text{ g/cm}^3$) at $p_1 = 5 \text{ kbar}^1$ value $U_1 \approx 500 \text{ m/s}$, which does not differ strongly from the value $\Delta W \approx 700 \text{ m/s}$ observed in experiment. The real picture of development of the process during the propagation of low-speed "detonation" in powder undoubtedly is considerably more complex. First of all the emergence and the development of the reaction is facilitated, in consequence of which the stable low-speed modes in powders are spread in the absence of a durable shell.

The course of the chemical reaction during the propagation

¹In accordance with [139] the powder of urotropine is thickened to the maximum density by a shock wave with pressure $p_1 \approx 5 \text{ kbar}$.

low-speed processes in high density systems. Now conventional point of view according to which the chemical reaction under the influence of a weak shock wave on explosives appears in separate local foci - "hot" points. The estimation of the temperature of the shock compression of an explosive in a wave with pressure ~ 30 kbar shows that the volumetric heating of the substance is negligible and does not exceed several dozen degrees. The available data indicate that during the propagation of low-speed processes in high density systems the foci of the reaction are mainly the pores (heterogeneities) which exist in the charge. The number of these data includes the following.

The presence in the charge of low-magnitude porosity (\sim several percentages) exerts a substantial influence on the possibility of the propagation of NSR. This effect is exhibited especially sharply in charges which are surrounded by a low-strength shell. Thus, for instance, in a shell made of plexiglass a low-speed process is observed in PETN if charge density $\rho < 1.70$ g/cm³ ($m > 4\%$), at a higher density the process is not spread. In the charges of PETN with a density of 1.73-1.76 g/cm³ the propagation of NSR is possible only when using a durable steel shell.

The nature of the propagation of NSR depends also on the initial particle sizes of the explosive and, therefore, on the size of the pores. It was established that with a decrease in the initial size of particles of PETN from 500 to 20 μ m the rate of NSR is lowered from 2250 to 2000 m/s (a charge was used with a diameter of 5 mm, and density of 1.73 g/cm³ in a steel shell with wall thickness of 3.5 mm). In [159] it was noted that a process, stable in coarse-crystalline cast trotyl, died out if finely crystalline trotyl was used.

Let us estimate, using the theory of a focal thermal

explosion [123], the size of the focus and compare it with the size of the pores which exist in the charge.

The critical dimension of the focus is determined by the expression

$$r_{кр} \approx 3,48T_{кр} \sqrt{\frac{\lambda R}{zQE}} \exp(E/2RT_{кр}) \left[\ln \frac{E}{RT_{кр}^2} (T_{кр} - T_0) \right]^{0,3}. \quad (70)$$

The value of critical temperature we find from the expression, which joins $T_{кр}$ with critical induction period:

$$\tau_{инд} \approx \frac{2c\rho RT_{кр}^2}{QEz} \exp(E/RT_{кр}). \quad (71)$$

In expressions (70) and (71) E - activation energy; z - pre-exponent; Q - thermal effect of reaction; T_0 the initial temperature of substance; c - heat capacity; ρ - density; λ - the coefficient of thermal conductivity.

The delay in the initiation of reaction $\tau_{инд}$ was determined in the tests in which photographing was done against a background of a bright screen of the process of the exit of the low-speed process on the boundary of the division explosives - plexiglass. Value $\tau_{инд}$ was determined as the time between the exit of the compression wave from the explosive (this moment coincides with the beginning of movement of the interface) and the approach of the glowing zone of the reaction.

For PETN at a rate $W=1100$ m/s value $\tau_{инд}$ was 10^{-5} s.

Accepting for PETN $E=39500$ cal/mole, $z=10^{16}$ s $^{-1}$, $Q=10^3$ cal/cm 3 , $c=0.3$ cal/g·deg, $\rho=1.7$ g/cm 3 , $\lambda=2.4 \cdot 10^{-4}$ cal/cm·s·deg,

from (70) and (71) we obtain $T_{kp} = 400^\circ\text{C}$, critical dimension of focus $r_{kp} = 2 \cdot 10^{-4}$ cm.

Let us compare the calculation value of r_{kp} with the size of the pores which exist in the charge. Direct data for PETN are absent in the literature. However, in accordance with the results of the measurement of the distribution of pores according to size (see Fig. 10) the high density ($\delta=0.95$) pressed samples of trotyl and cyclonite contain pores on the order of 10^{-4} cm in size.

At the same time the heterogeneities, on which the reaction is excited, can be formed also in initially solid explosives in the process of the propagation of low-speed processes. Thus the authors of [127] connect the change in the transparency of the layer of cast PETN in front of the glowing front of an NSR noted by them with deformation and destruction of the substance.

In work [127] a point of view is advanced, according to which the formation of foci occurs during the strength destruction of solid explosives in the compression wave analogous with that as it takes place under mechanical influences and, in particular, during shock.

At present there is no clarity in the question concerning how a focus originates and just what is the specific physical mechanism of its formation. The most probable mechanism of heating is friction, caused by a difference in the rate of movement of the substance which fills the pore (heterogeneity) from the average speed of movement of the explosive behind the front of the compression wave.

The propagation of the reaction from foci in high density systems, just as in powders, is realized, apparently, in the

form of surface explosive combustion [167]. Specific confirmation of this are the tests in which the effect of the surface condition of particles of explosives on the speed of the process and the limits of its propagation was studied. The coating of particles of PETN ($r=500 \mu\text{m}$) with a thin (several microns) layer of paraffin led to essential deceleration of NSR up to the full stopping of the process, in spite of the fact that charges with the increased (to 5%) porosity were used.

We have presented the basic results concerning the stable propagation of low-speed processes.

C. TRANSITION OF COMBUSTION TO DETONATION

§ 26. Transition of a Low-Speed Process in High Density Explosives to Detonation

The stable propagation of a low-speed process is observed at specific values of density, size of particles of the explosives, diameter of the charge and strength of shell. A change in one of these parameters, for example a decrease in the density of the explosive, an increase in the diameter of the charge or strength of shell leads to the fact that the process becomes unstable and can convert to detonation. A necessary and sufficient condition of the emergence of detonation is the formation in the charge, the diameter of which exceeds critical, of a shock wave of critical intensity $p_{\text{кр}}$.

The basic relationship which determines transition to detonation is the relationship between pressure in the shell p' and the critical pressure of initiation of detonation.

In the preceding paragraph it was shown that the low-speed process was stable, if the pressure in the shell is less than critical, i.e.,

$$p' < p_{кр}$$

It was to be expected that the transition of a low-speed process to detonation will appear if the inequality¹

$$p' > p_{кр}$$

is fulfilled.

In this case the development of a wave of critical intensity becomes possible. In accordance with the last inequality the transition to detonation is promoted by all those factors which cause an increase of p' and lowering of $p_{кр}$. We will now turn to the available experimental results.

High density pressed explosives. In work [120] they studied the transition of NSR to detonation in PETN of different density. Change in the charge density creates the possibility for a change over wide limits in the magnitude of the critical pressure of initiation of detonation (see § 29).

The tests were conducted in plexiglass or steel (with optical wedge, see Fig. 6c) shells, which made it possible to conduct the continuous optical recording of the development of the process which develops after ignition of the charge. A typical photograph of the transition of NSR to detonation is presented in Fig. 79. From it it is evident that in pressed PETN the transition of a low-speed process to detonation bears an abrupt nature. In these tests the average speed of NSR at the stage preceding detonation was determined.

¹Indication that with the fulfillment of this inequality detonation originates is contained in work [125].



Figure 79. Photograph of the transition of a low-speed process to detonation (PETN, $\rho=1.45 \text{ g/cm}^3$, $r=500 \text{ }\mu\text{m}$, $d_3=5 \text{ mm}$).

Also the critical pressure of the initiation of detonation was measured for the investigated charges of PETN which were surrounded by a shell (Table 11).

Table 11. Results of the study of the transition of a low-speed process to detonation.

Parameter	Shell of plexi-glass	Steel shells with optical wedge		
Relative density of PETN	0.82	0.9	0.96	0.975
Diameter of charge, mm	10	5	5	10
Average velocity of low-speed process before the emergence of detonation m/s	1100	1500	2200	3300
Critical pressure of initiation of detonation, kbar	5	8	11	17
Pressure which destroys the shell p' , kbar	6	15-17		

Note. A steel shell with optical wedge based on its dynamic strength is equivalent to a steel shell with a wall thickness $\Delta \approx 8 \text{ mm}$.

From the given data it follows that the low-speed process converts to detonation when $p' \geq p_{kp}$ in this case the speed of the process before the emergence of detonation increases with an increase in p_{kp} .

Thus the emergence of detonation makes impossible the achievement of high velocities of low-speed propagation in charges with a lowered density.

Near the limiting conditions (with p'_{HP}) the development of instability is promoted by an increase in the length or diameter of the charge. Thus, for instance, in a plexiglass shell the low-speed process in PETN with a density of ($\delta=0.82$) did not convert to detonation at a length of charge of 150 mm, in this case the speed of NSR increased weakly along the length (from 800 to 1000-1100 m/s.) However, transition was observed when the length of the charge was increased to 300 mm (see Fig. 79). A similar pattern was observed with an increase in the diameter of the charge.

Upon transition to detonation the slope and amplitude of the compression wave continuously increase. On the strength of the concepts developed in § 25, it was possible to assume that the speed of NSR at the stage preceding the emergence of detonation must change in accordance with the established dependence $W(p')$ (see Fig. 72). Actually, the tests carried out on PETN ($\rho=1.73 \text{ g/cm}^3$) showed that the speed of the process increases monotonically along the length, and sections are observed with subsonic, transonic and supersonic values of velocity.

Cast explosives. The transition of the combustion of cast explosives to detonation was investigated in the already mentioned works of Macek et al. [13, 121] and Price and Wehner [125]. At the same time these investigations in essence were reduced to a study of transition to detonation of a low-speed process. The emergence of detonation was observed, if the explosive (DINA, pentolite 50/50) was placed in durable steel tubes (inside diameter 12.7 mm, external - 31.8 mm) of sufficient length (343 mm). The layout of the experiment and the arrangement

of sensors are shown in Fig. 6b. The velocity of propagation of the reaction front was determined, as a rule, by usual type ionization sensors. The ionization method of recording undoubtedly is lacking that advantage which is given by the optical method, which permits implementation of continuous observation of the development of the process. However, in conjunction with the sensors of compression, which fixed the passage of the compression waves, the methods of recording used made it possible to obtain sufficiently complete information about the investigated process.

In works [121, 125] also the recording of pressure $p(t)$ in the combustion zone was realized with the aid of strain gauges which were stuck to the external surface of the tube near the point of ignition. The calibration of the sensors was conducted under static conditions.

In work [125], set up for the purpose of studying the effect of the shell of the charge on the transition of combustion to detonation and the obtaining of additional information about the low-speed process, besides the methods of study enumerated above they used the high-speed filming of the destruction of the tube and sensors for determining the radial deformation of the external surface of the tube.

The results of the measurement of velocity of propagation of the process, obtained by the method of ionization sensors, are presented in Table 12.

From the data given it follows that the emergence of normal detonation precedes the low-speed (1000-2300 m/s) process, which is spread in 30-80 μ s. Correspondingly the length of the predetonation section changed between 6 and 18 cm, the most typical value was approximately 10 cm. The maximum value of velocity before the emergence of detonation is equal to 2000-2300

Table 12. Velocity change along the length of a charge during transition of the combustion of cast explosives (DINA, pentolite) to detonation.*

h, mm	$D_{12}, \text{mm}/\mu\text{s}$	h_1, mm	$D_{13}, \text{mm}/\mu\text{s}$	h_2, mm	$D_{14}, \text{mm}/\mu\text{s}$	h_3, mm	$D_{15}, \text{mm}/\mu\text{s}$	h_4, mm	$D_{16}, \text{mm}/\mu\text{s}$	h_5, mm	$D_{17}, \text{mm}/\mu\text{s}$
DINA [13]											
32	1,1	25,4	2,3	50,8	7,3	76,2	7,6	152,4	7,6	228,6	—
32	1,1	25,4	1,8	50,8	2,0	76,2	2,0	152,4	7,6	228,6	—
32	1,0	25,4	0,89	50,8	1,4	76,2	0,89	152,4	7,6	228,6	—
38	1,3	19,1	2,0	44,5	7,6	95,3	8,0	136,1	—	—	—
38	2,4	19,1	7,3	44,5	7,8	95,3	7,8	146,1	—	—	—
32	0	19,1	1,1	44,5	7,7	69,9	7,7	120,7	7,1	171,5	—
26	1,6	12,7	0,82	38,1	0	63,5	>2,1	88,9	7,7	111,9	7,7
20	0,91	12,7	1,2	38,1	1,3	63,5	0	88,9	>2,0	114,3	5,1
Pentolite [125]											
33,3	1,95	12,7	2,6	63,5	7,3	114,3	7,1	177,8	7,6	251	—
33,3	1,27	12,7	2,1	63,5	3,4	114,3	7,5	177,8	7,6	251	—
33,3	0,36	12,7	1,37	63,5	3,4	114,3	7,9	177,8	6,9	251	—
33,3	3,6	12,7	1,35	63,5	2,5	114,3	5,8	177,8	6,4	251	—

*h - distance from igniter to the first sensor;
 h_1 - distance from the first sensor to the
 i-sensor; D_{ij} - the average speed between i-
 and j-sensors: $\overline{D_{ij}}$ - velocity on the section
 of transition from low to high velocity; 0 -
 recording absent.

m/s and it is close (somewhat less) to the speed of sound in explosives. It is evident also that the velocity of the process increases along the length, especially in the initial stage. At the same time the authors themselves give another interpretation to the results obtained concerning the nature of the change in the velocity of the process along the length of the charge. Thus in work [13] it is noted that the "observed acceleration is insufficiently developed in order to give proof of the gradual transition to normal stationary detonation," and Price and Wehner [135], referring to the same work, write that "Gibson and Macek demonstrated the existence of the low-speed, but being spread at a constant velocity, mode in tests on the transition of combustion of DINA to detonation."

Taking into account the data in Figs. 72, 77, it is possible to give the following interpretation to these results, which eliminates this contradiction. In the initial stage of propagation of a subsonic process the velocity increases along the length of the charge, and then in proportion to approximation to the speed of sound a saturation of velocity is observed so that the emergence of detonation precedes the section where the process is spread at a virtually constant (transonic) velocity. The transition of the mode being spread at a constant velocity to detonation can be explained, if one takes into account that on the section of the "plateau" of curve $W(p')$ the rise in pressure in the shock wave barely changes the velocity of the NSR.

The transition of a low-speed process to stationary detonation in cast explosives is realized, in the opinion of the authors of [13], abruptly, since the smallest interval of transition was equal to 13 mm, and the corresponding time of approximately 4 μ s. However, the study of the formation of a detonation wave in cast trotyl during impact initiation,

carried out by Dremin and Koldunov [27], showed that the emergence of detonation occurs in the form of a smooth increase in the parameters of the wave up to the detonation. In the tests carried out in work [131], the transition of combustion of cast DINA to detonation also was realized in the form of a smooth build-up of velocity.

The greatest interest lies in the results of simultaneous measurement of velocities of the reaction front and pressure, shown in Fig. 80, from which it follows that the compression waves are propagated in front of the reaction front. From the recording in Fig. 80a, obtained with the use of sensitive (0.8 kbar) sensors of compression, it is apparent that they operated under the action of a weak damping pressure pulse or, possibly, a series of such pulses, which are overtaken by a powerful compression wave (or shock wave) near the place of origin of stationary detonation. The use of coarser sensors of compression (threshold of operation 2 kbar) (Fig. 80b) showed that the emergence of detonation is realized by pressure waves, the parameters of which increase smoothly.

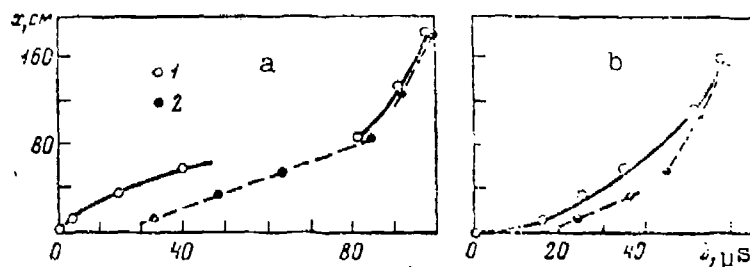


Figure 80. Propagation of the pressure front (1) and reaction front (2) during transition of a low-speed process to detonation. a) DINA; b) pentolite.

Unfortunately, these single and fragmentary bits of information do not make it possible to create a full representation of

the wave picture preceding the transition of a low-speed process to detonation, and only indicate the complex nature of the phenomenon.

In works [13, 121] it was noted that there is vital importance during the transition of combustion to detonation in the rate of pressure buildup dp/dt in the combustion zone. For the investigated explosives the pressure increases exponentially $p=p_0e^{bt}$ (for pentolite $p_0=1$ kbar, $b=8.856 \cdot 10^4$, t - is expressed in seconds). Pressure measurements were conducted up to 4 kbar. In the case when growth in pressure was slower, an increase in the predetonation section or the absence of the emergence of detonation was observed.

The high-speed filming of the tube in conjunction with other methods of recording made it possible to establish [125] that the detonation occurs before the tube is destroyed. In this case the deformation of the tube before destruction was symmetric and noticeable deformation was observed in 28 μs after achievement in the shell of a pressure of 1 kbar. Extrapolation of the curve $p(t)$ for a period of 28 μs allowed the authors to evaluate the pressure at which the tube is destroyed - $p' \approx 20$ kbar. The given value exceeds the critical pressure of initiation of detonation by a shock wave, which turned out to be equal to 11 kbar (for DINA) and 19 kbar (for pentolite),¹ which afforded the possibility to explain the transition of their combustion to detonation.

In the presented works it is tacitly assumed that the

¹Unfortunately, in the work the conditions under which the given values of p_{kp} were obtained are not given.

laminar combustion of explosives converts directly to a low-speed process. This question was not investigated specifically. Therefore there is no firm conviction that the emergence of a low-speed process did not precede the convective combustion on the explosive - shell boundary, similar to that examined in § 23, and this question remains open.

In his first work [121] Macek proposed an elementary theory for the phenomenon which is based on the fact that the transition of the combustion of solid explosives to detonation, just as in gases, is realized by the shock wave which is generated in the unburned explosives as a result of the interference of the compression waves which are initiated by the front of combustion. Subsequently we will call this mechanism gas or "piston."

Such are the basic experimental results which concern the emergence of detonation in high density systems, when transition to detonation is realized in the circuit: laminar combustion - convective combustion - wave low-speed process of explosive conversion - normal high-speed detonation.¹

§ 27. Transition of the Combustion of Low-Density Explosives to Detonation

In this case the transition of combustion to detonation occurs in essence in the circuit: laminar combustion - convective combustion - normal detonation. In durable shells the low-speed process as a rule is absent or of small dimension. The typical optical photographs of the transition of combustion of PETN to detonation are shown in Fig. 81 [14].

¹During the ignition of the charge of a powerful explosive at the enclosed end in a durable shell the section of convective combustion is insignificant along the length.

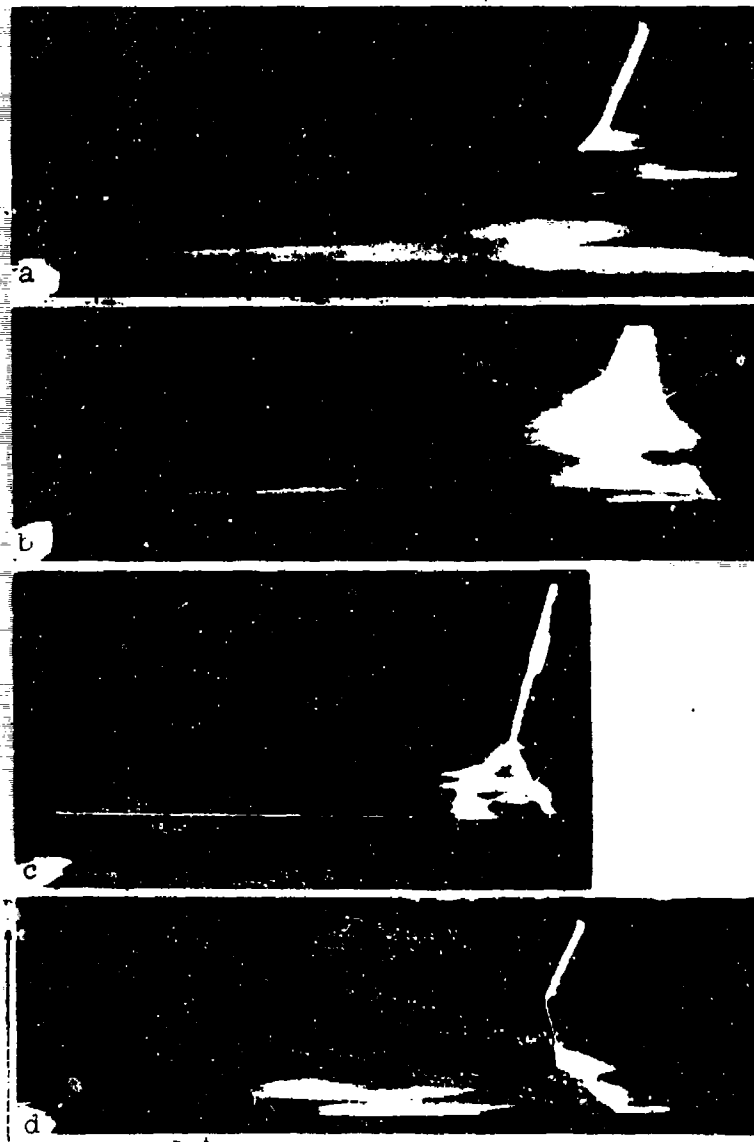


Figure 81. Typical photographs of the transition of combustion of PETN to detonation. a) $D=4700$ m/s; $W=750$ m/s ($\delta=0.56$, $r \approx 500$ μm); b) $D=4300$ m/s, $R=2800$ m/s, $W=800$ m/s ($\delta=0.4$, $r=20$ μm); c) $D=7800$ m/s, $R=3200$ m/s ($\delta=0.80$, $r=20$ μm); d) $D=4700$ m/s, $R'=7800$ m/s, $W=250$ m/s ($\delta=0.56$, $r=500$ μm). 1 - detonation wave (D); 2 - retonation wave in the products of explosion (R) or in the substance (R'); 3 - the process, preceding detonation (W).

1. The characteristic feature of the transition of combustion to detonation of low-density explosives is the development of detonation in front of the convective combustion front. This experimental fact was established for the first time by the Soviet researchers Petrovskiy, Sokolov, and Aksenov [143]. This result is one of the basic arguments in favor of applicability to porous explosives of the "gas" mechanism of transition of combustion to detonation.

From the given photographs it is evident that detonation is preceded by the developed mode of convective combustion with the characteristic "broken" front. This form of notation is caused (see § 23) by the fact that the front of convective combustion is not plane, and the inflammation of the explosive occurs in separate (large) pores which are found in the charge. In powders the detonation appearing in front of the combustion zone usually does not lead to the formation of a detonation wave moving in the opposite direction (to the side of the products of combustion). Between the region of detonation and the combustion zone a section of unreacting substance remains which is fixed on the photographic recording (Fig. 81a, in the form of an interruption of brightness. In work [143] it was shown indirectly that on the section in front of the combustion front a pre-pressing of the explosive occurs. This conclusion was made on the basis of the analysis of the condensed residues of explosives remaining after the tests.

For the purpose of obtaining more complete information about the state of a substance, and first of all the direct proof of pre-pressing in this zone, special tests were carried out [14] in which the detonation wave in explosives was created artificially. The tests were reduced to the following.

Into the investigated explosive charge in the place of

origin of detonation a small quantity (~ 0.1 g) of slightly pre-pressed lead azide was placed. In other respects the test conditions were the same. The compression waves, which move in front of the combustion caused the explosion of the lead which initiated the detonation of explosives of initial density and pre-pressed explosives. The optical recording of one of such tests is presented in Fig. 8ld. One can readily see that the velocity of the retonation wave in explosives substantially exceeds the velocity of the detonation wave. For the powder-like charges of PETN with crystals 0.5 mm in size the velocity of detonation wave is equal to 4700 m/s and corresponds to an initial density $\rho=1.0$ g/cm³, a virtually constant velocity of retonation wave is 7800 m/s and answers to a density of $\rho=1.55$ g/cm³. This result gives direct proof of the existence of a considerable pre-pressing of powder-like explosives in front of the combustion front under the action of compression waves. Specifically, with this is connected, in our opinion, the absence of a retonation wave during the natural emergence of detonation. If we compare the result obtained with the value of the critical pressure of the initiation of detonation, which, according to [150], for PETN ($\rho=1.0$ g/cm³) comprises $p_{кр} = 2.5$ kbar, then we come to the conclusion that the pre-pressing of explosives to a considerable density occurs in a compression wave with comparatively low intensity. This conclusion will agree with that which was obtained in work [33], the authors of which made an analysis of the porous samples of explosives which were preserved after shock loading. It was established that under the influence of a shock wave with an intensity of 1.5-2 kbar simultaneously with the fragmentation of the explosive its compaction from a value of 1.0 to 1.5 g/cm³ occurs.

From the examination of the photograph in Fig. 8ld another interesting result also follows: the boundary, which divides sections with a different detonation velocity, is expressed

quite clearly. This indicates that the compression wave, which causes the detonation of the powder, has a steep leading edge. It is natural that the effect of pre-pressing is especially pronounced at low densities.

We have examined one type of the photographs of the transition of combustion to detonation.

2. In the majority of tests the detonation wave is formed directly near the accelerating front of combustion. In this case in the place of origin of detonation frequently an increase in brightness is observed (Fig. 81b) which is connected, in our opinion, with the development of a local explosion. The thermal explosion of a limited volume of explosive is the direct cause for the development of detonation. The explosion of PETN, which leads to the formation of a detonation wave, was also observed under other test conditions [16].

This fact indicates that the emergence of local explosions has a general nature and is the essential and inherent element of the process of the transition of combustion of explosives to detonation. It was established that during transition of the combustion of PETN to detonation the local explosions occur not only directly near the front of combustion, but also at a certain distance behind the front - in the burning medium (Fig. 81c). Explosion A, which arose in the zone of convective combustion, with a characteristic "broken" front leads to the formation of a shock wave, which, being spread at a rate of 2800 m/s, overtakes the front of combustion and after an insignificant ($\sim 2 \mu\text{s}$) delay causes the detonation of the explosives ($D=7800 \text{ m/s}$). The possibility of the formation of individual volumes of unburned or partially reacted substance which are capable of explosion is completely natural, since the front of convective combustion is not plane and is strongly bent.



Figure 82. Photography of the transition of combustion of a mixture of 10% PS+90% AP to detonation ($r=15 \mu\text{m}$, $\rho=0.65 \text{ g/cm}^3$, $p=1 \text{ atm}$ open tube with a length of 100 cm).
[PS = PS, polystyrene; KXA = AP, ammonium perchlorate]

The emergence of local explosions was observed also during the transition of combustion to detonation of bulk charges of a mixture of ammonium perchlorate with polystyrene (Fig. 82). The feature of these tests, made with the participation of A. V. Obmenin and I. N. Lobanov, lied in the fact that unlike those described above the ignition of the charge was conducted in the atmosphere at the open end, from the side of which a gas-outlet tube of considerable length was located (its diameter was equal to the diameter of the charge). The investigations carried out showed that after ignition convective combustion appeared, which caused the ejection of substance into the free space of the tube. In the tube the volumetric combustion of the rejected substance was the reason for the rapid rise in pressure, the result of which was the development of local explosions in the zone of convective combustion, leading to the detonation of the mixture. In this arrangement of the development of the process the transition of combustion to detonation occurs under conditions of a low-strength shell which surrounds the explosive charge.

It is necessary to note that the emergence of detonation in a burning medium was observed earlier by Petri [9] during the study of the transition of combustion to detonation of the initiating explosive - mercury fulminate.

The newest studies of the transition of the combustion of gas systems to detonation, carried out with the use of Schlieren

methods, showed [138, 141] that the basic reason for the emergence of detonation also is the local explosion of the adiabatically compressed volume of the mixture in front of the turbulent zone of the flame.

Table 13 depicts the characteristic paths of development of an explosion in porous explosives.

Table 13. The typical patterns of development of an explosion in pressed explosives.

State of explosive	Properties of shell	Method of development	Characteristic features
Charges of high density (independent of the initial dispersity of the explosive)	Durable massive shell ($p' > p_{HP}$)*	Laminar combustion - convective combustion - low-speed process - detonation	Abrupt nature of transition of low-speed process to detonation
Charges of low density	Shell with low strength ($p' < p_{HP}$) Durable shell ($p' >> p_{HP}$)	The same, but detonation is absent Laminar combustion - convective combustion - detonation	Stable propagation of low-speed process Detonation wave is formed in front or in immediate proximity of the front of combustion. Essential is the pre-pressing of the explosive before the combustion front. Detonation appears as a result of the development of local explosion in the zone of convective combustion
Charges of explosives of bulk density with particle sizes of several millimeters		Laminar combustion - convective combustion - low-speed process - detonation**	Depending on the properties of the shell a stable low-speed mode is observed (detonation at low velocity with $p' < p_{HP}$)

* p' - the pressure which destroys the shell, p_{HP} - the critical pressure of initiation of the detonation of the charge, surrounded by a shell.

**See [143].

§ 28. Predetonation Section

The quantitative characteristic of the tendency toward the transition of the combustion of explosives to detonation is the extent of the predetonation section L_{np} , i.e., the distance from the point of ignition to the place of origin of detonation. This value makes it possible to compare the different classes of explosives based on their tendency toward the development of detonation.

The measurement of the length of the predetonation section was conducted in works [14, 142-144, 165]. Value L_{np} can be determined easily from continuous optical recordings. However, the use of optical recording is not always possible and substantially complicates the testing. Therefore wide acceptance has been received by a method of determination which is simple in execution [14, 142, 165]. It is based on the analysis of the deformed channel of the thick-walled metal shell, which was not broken in the test. This analysis becomes possible, if the shell after the conducting of the test is cut along the axis of the channel.

Figure 83 is a diagrammatic representation a and photograph b of the channel, deformed after the test, of a thick-walled shell, where A is the point of ignition of the investigated porous sample, AD - predetonation section, DE - the section of detonation.



Figure 83. Diagrammatic representation (a) and photograph (b) of internal channel of the shell after the transition of combustion to detonation.

In the predetonation region the diameter of the channel is increased smoothly and after a certain distance AC takes a constant value which further virtually is not changed. It was established that simultaneously with a change in the form of the channel a change occurs in the color of its internal surface [14]. After the section of the emergence of the inflation of the channel to constant value C a sharp boundary D is observed which is perpendicular to the axis of the charge and separates two regions which are different in color; the bright zone BD, arranged in the predetonation region, from the dark zone DE, which corresponds to the section of detonation. The comparison of the impressions obtained with the optical recording made it possible to establish that boundary D corresponds to the place of origin of detonation. The change in the color is apparently connected with the different nature of deformation of the shell in the predetonation region and on the section of detonation, and also - with the difference in the composition of the explosion products. On the section of detonation the intense destruction of the channel is observed and the formation of deep longitudinal cracks. The intergrowth of cracks partially covers the "bright" zone in the predetonation region.

In a number of cases the diameter of the deformed channel on the section CD of the "bright" zone somewhat exceeds the diameter of the channel on section DE (in Fig. 83a shown by the dotted line). Furthermore, the point of emergence of the inflation of the channel to a constant value does not correspond, as a rule, to the place of origin of detonation ($AC < AD$) (see Fig. 83a). Therefore the determination of the length of the predetonation section based on the emergence of the inflation to a constant value, as this was done in [142], leads to the understating of the true value of L_{np} .

The point of ignition A corresponds, as a rule, to the

beginning of the emergence of convective combustion. During the ignition of the explosive at the enclosed end the stage of laminar combustion is virtually absent as a result of the rapid pressure buildup and achievement of critical separation pressure p_c . In the case of the open end the arrangement of the "embedded charge" was used [14] (see Fig. 2) and the investigated porous explosive was ignited through the layer of the solid (gas-impermeable) substance at a pressure $p \gg p_c$ so that convective combustion appeared immediately. The combustion of the charge in the shell was realized in a bomb with a large free volume, the necessary pressure in which was created by the preliminary combustion of an auxiliary charge.

Let us illustrate the basic characteristic results for homogeneous explosives in an example of PETN, the combustion of which converts to detonation, particularly easily.

Influence of the parameters of the charge of homogeneous explosives. On the curve in Fig. 84 the dependences of the length of the predetonation section on

porosity for PETN with initial particle sizes $r=20 \mu\text{m}$ and $r=500 \mu\text{m}$ are presented. The magnitude of porosity changed in a wide interval from 0.7 to 0.94. The given data

correspond to ignition at the open end in the arrangement just described and are

obtained in a brass shell with a wall thickness of 20 mm. Let us note the presence of spread in the magnitude of the predetonation section, especially in the case of finely crystalline PETN. This required the conducting of a large number of tests, on the basis of the averaging of results of which the curves in Fig. 84 were constructed. The dotted line on the graph in Fig. 84 is

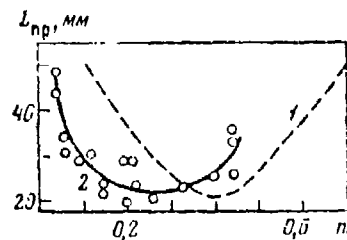


Figure 84. Dependence of the length of the predetonation section on porosity (PETN). 1 - $r=20 \mu\text{m}$; 2 - $r=500 \mu\text{m}$.

used to plot the averaged curve for PETN with $r \approx 20 \mu\text{m}$. From the given data it follows that function $L_{np}(m)$ has a minimum, the location of which with an increase of particle size is displaced into the range of lower values of porosity. At high values of porosity ($m=0.5$) finely crystalline PETN ($r \approx 20 \mu\text{m}$) yields to detonation easier than coarse-crystalline PETN ($r \approx 500 \mu\text{m}$). At low values of porosity a reverse picture is observed. From the graph it is evident that PETN with particle sizes $r \approx 500 \mu\text{m}$ is able to convert to detonation at very low porosity ($m \approx 0.05$), in this case the predetonation section does not exceed 50 mm. A further very insignificant decrease in porosity produces a sharp increase in the length of the predetonation section. The magnitude of porosity, beginning with which an essential increase of L_{np} is observed decreases from 0.1 to 0.05 with an increase of particle size from 20 to 500 μm and corresponds approximately to the identical initial gas permeability of explosives, equal to 10^{-4} darcy. Tests were also carried out with PETN $r \approx 120 \mu\text{m}$. It was shown that the curves of $L_{np}(m)$ for particles with initial size of 120 and 500 μm virtually coincide, with the exception of a small difference at low and high values of porosity. This fact indicates that the porous structures obtained are close to each other, which is connected with the destruction of particles in the process of pressing (see § 4).

The sharp increase in L_{np} at low values of porosity is caused by the emergence of the stable low-speed modes of explosive conversion. Also not surprising is the noticeable spread in the extents of the predetonation section, since, as we saw, the forms of transition to detonation are sufficiently diverse.

A study of the transition of combustion to detonation by homogeneous porous explosives (octogen, cyclonite, PETN, tetryl) was conducted by Griffiths and Grukok [142]. The ignition of the open end of the explosive charge, enclosed in brass shells, was

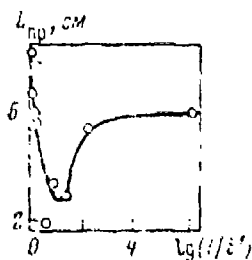


Figure 85. Nature of change in the length of the predetonation section for octogen

realized through the layer of lead styphnate. They investigated the effect of porosity, initial size of explosive particles and the conditions of gas release. Data are given for octogen (Fig. 85) which are constructed in coordinates $L_{np} = \lg(1/t')$, where value t' characterizes the gas permeability of the explosive and depends wholly on the conditions of its determination. Unfortunately, the authors do not give the connection of value $(1/t')$ with porosity and particle size of the explosive. At the same time the general nature of the dependence is outlined well. From the data in Fig. 85 it follows that with a constant initial particle size there is an optimum porosity of explosive, to which the smallest predetonation section corresponds. Thus the presence of a minimum on the curve $L_{np}(m)$ is apparently a characteristic feature of homogeneous explosives.

The decrease of the initial size of particles of the explosive (at a constant pressure of pressing ~ 150 atm) led to a reduction of the predetonation section to a definite limit, whereupon value L_{np} increased. The optimum particle size for octogen and cyclonite turned out to be equal to 124-251 μm , for PETN - 76-124 μm [142].

A study of the transition of combustion to detonation of a wide circle of homogeneous explosives at a constant density (0.9-1.2 gm/cm^3) was conducted in work [165]. A steel tube with inside diameter 6.4-6.8 mm (wall thickness 15 mm) and length of 200-350 mm was used; from the side of ignition a steel plug with a channel 2 mm in diameter was placed. The values obtained for the length of the predetonation section (in cm) are given below:

PETN	Octogen	Cyclonite	DINA	Tetryl	Styphnic acid	Picric acid	Trotyl
1	1-2.5	1.5-3	3-7	4-6	10-12	12-13	>29

It is remarkable that the tendency toward the transition of combustion to detonation for the majority of the studied explosives increases in proportion to the increase in the heat of the explosion.

Systematic studies of the effect of the diameter of charge and conditions of gas release on the emergence of detonation were not made. It is noted only [165] that for low-power explosives (trotyl, picric acid) an increase in the diameter of charge and damping of the open (from the side of ignition) end of the charge led to a contraction in length of the predetonation section. For powerful explosives (PETN, cyclonite) the effect of the indicated parameters is expressed considerably more weakly.

As concerns the role of the shell, then the tests made by us on PETN ($\rho=1.45 \text{ g/cm}^3$, $r=500 \text{ }\mu\text{m}$, $d_s=5 \text{ mm}$) in steel shells with different wall thickness showed that for the transition of combustion to detonation a certain minimum strength of shell was necessary, one such that the condition $p' > p_{kp}$ would be realized. It was established that with a decrease of wall thickness Δ from 17 to 3 mm value L_{np} did not change and it comprised $L_{np}=15 \text{ mm}$. In this case the pressure which is realized in the shell before destruction p' , exceeds p_{kp} . An increase of the predetonation section was observed with $\Delta < 3 \text{ mm}$, when $p' > p_{kp}$. Finally, in thin-walled shells ($\Delta=0.5-1.0 \text{ mm}$; $p' < p_{kp}$) the conversion of combustion to detonation was absent and a low-speed process was spread. During a further decrease of Δ the combustion died out.

Mixtures on a base of ammonium perchlorate [14]. Table 14 depicts the averaged results of several tests of the measurement of the length of the predetonation section for mixture explosives

Table 14. Length of the predetonation section, mm.

Explosive	Porosity		
	0.6	0.45	0.25
Stoichiometric mixture of ammonium perchlorate with polystyrene	85	140	>240
The same with trotyl	60	120	>240
PETN	40	20	30

(particle size of components $r_p \approx 15 \mu\text{m}$) during ignition at the enclosed end. The tests were conducted in steel tubes with walls 15-20 mm in thickness.

For a comparison in this same table data are given for PETN of close dispersity ($r_p \approx 20 \mu\text{m}$). From Table 14 it follows that the nature of the dependence of the length of the predetonation section on porosity for the investigated mixture explosives and homogeneous explosives is different. For mixture explosives an increase in the length of the predetonation section is observed with a decrease in the porosity in the entire investigated interval of change in the latter.

Mixtures on a base of ammonium nitrate. In work [144] a study was made of the transition of combustion to detonation for a number of industrial explosives on a base of ammonium nitrate. The tests were conducted in thick-walled steel tubes with screw-on caps. Charges of bulk density were used which ignited at the closed end of the tube. It is remarkable that the authors were able to obtain the transition of combustion to detonation only in the case when the length of the tube exceeded 1-2 m. The results of the tests are presented in Table 15.

From the examination of the tabulated data it follows that the combustion of mixture explosives on a base of a weaker

Table 15. Magnitude of predetonation section and detonation velocity for some industrial explosives and separate components (trotyl, ammonium nitrate) [144].

Explosive and its composition	Density, g/cm ³	Weight of igniter, g	Diameter of tube, mm	Length of tube, mm	Total number of tests	Including with detonation	Length of predetonation section, mm	Detonation velocity, m/s
Rock ammonite No. 1: 66% NH ₄ NO ₃ (ZhV)* +5% trotyl +24% cyclonite +5% aluminum	1,07	2	23	2000	6	5	<300	4750-5000
Ammonite No. 6: 79% NH ₄ NO ₃ (ZhV) +21% trotyl	1,0	5	48	4000	1	1	>1100	—
Grain granulite 79/21B: 79% NH ₄ NO ₃ +21% trotyl	0,9	8	34	2000	1	1	1200	4500-4800
Dinamon AM-17: 87.7% NH ₄ NO ₃ (ZhV)+10% Al+2.3% oil	0,95-1,05	16	23	2000	2	2	600	4500
Trotyl	1,1	5	48	2000	2	2	500-700	3800
Ammonium nitrate (NH ₄ NO ₃)	0,9	18-25	34	2000	2	2	700	3800
			48	To 6000	2	2	<300	1600-1900
					1	0	—	—
					1	0	—	—
					1	1	800-1000	—
					3	3	300-900	4800-5000
					7	0	—	—

*Water-resistant type of ammonium nitrate, which contains hydrophobic admixture and ferrous compounds.

oxidizer - ammonium nitrate is characterized by considerably less tendency toward transition to detonation than perchlorate compositions. The combustion of pure ammonium nitrate, and also mixtures of it with an inert combustible (dinamon AM-10) do not convert to detonation at tube length up to 6000 mm. The introduction of active combustible - explosives (trotyl, cyclonite) substantially raises the tendency toward the transition of combustion to detonation, nevertheless even for rock ammonite No. 1 the predetonation section exceeds the corresponding value for perchlorate mixtures. It should also be noted that close values of L_{np} are obtained both for pure trotyl and for the industrial explosives which contain in their composition only 21% trotyl (ammonite No. 6 and grain granulite 79/21B). The authors obtained a somewhat unusual effect, which entails the fact that an increase in the diameter of the charge led to an increase in the length of the predetonation section. This result, in the opinion of the authors, is conditioned by the point nature of inflammation (diameter of igniter was 1 cm) and by the formation of the spherical divergent flame front, a result of which is the slower pressure increase in the combustion zone. It is noted that a feature of the transition of the combustion of industrial explosives to detonation is the irregular statistical nature of its emergence.

As a whole it is necessary to emphasize that during the transition of combustion to detonation of mixture explosives a significant role is played not only by the physical, but also the chemical factors (chemical nature of separate components of the mixture). The processes of diffusion mixing are of great significance.

Let us pass to a brief discussion of the results of the transition of the combustion of porous explosives to detonation.

The emergence of detonation in front of the accelerating

front of combustion, and also the pre-pressing of the explosive in the transient area (see Fig. 81a, d) confirm the point of view that the basic reason for the emergence of detonation is the shock wave which is formed as a result of the interference of compression waves, initiated by the combustion front, i.e., in the classical "piston" mechanism. This mechanism was discussed in the literature [121, 142, 143].

From the viewpoint of this mechanism it is possible to explain the nature of the change in the length of the predetonation section L_{np} from porosity m . The basic factor which determines the formation of the shock wave during the ignition of explosives on one of the ends of the tube is the rate of change in time of pressure dp/dt in the combustion zone. The nature of change dp/dt is determined by the burning surface (by the specific surface area of pores and by the rate of their convective ignition), and also by the dependence of the rate of combustion of the explosive on pressure. As it was noted, for homogeneous explosives there is an optimum value of porosity and particle size, at which the length of the predetonation section is minimum. The maximum surface of pores encompassed by combustion corresponds to the optimum value of porosity. In this connection it is necessary to emphasize that for finely crystalline PETN (see Fig. 84) a satisfactory conformity is observed in the values of porosity ($m=0.3-0.5$), at which the specific surface area of pores (see Fig. 14) and rate of convective combustion (see Fig. 61) reach the maximum value. During the explanation of dependence $L_{np}(m)$ for coarse-crystalline PETN it is necessary to consider the fragmentation of particles under the effect of compression waves.

Unlike homogeneous explosives for the investigated mixture explosives the curve $L_{np}(m)$ does not have a minimum. This distinction is connected, in our opinion, with the following facts. If for homogeneous explosives the rate of laminar combustion increases linearly with pressure, then the rate of combustion of

mixture explosives at a pressure of the order of several kilobars does not depend on pressure [23], which naturally leads to a slower increase in pressure dp/dt during the ignition of mixture explosives. Furthermore, with an increase in the density the critical diameter of detonation decreases for homogeneous explosives [137] and increases for mixture explosives [108]. With an increase of density of mixture explosives the critical pressure of the initiation of detonation (see § 29) also is increased sharply.

The aforesaid makes it possible to explain the high absolute values of the length of the predetonation section of mixture explosives and the intense increase of L_{np} with an increase in density which is observed in experiment. During a slow pressure buildup in the combustion zone of mixture explosives the pre-pressing of the substance at a considerable distance along the length of the charge can lead to the fact that the system ceases to be detonation capable, and the emergence of detonation does not occur.

For the construction of the theory of the transition of combustion to detonation it is extremely important to know the wave picture appearing in front of the combustion front, and also the laws governing propagation and interference of the compression waves, which determine the formation of the shock wave of critical intensity. Unfortunately, at present this question is virtually unstudied. The considerations on this question which are contained in different works have not been confirmed experimentally. The difficulties existing here are caused in essence by the absence of data on the laws governing the propagation of weak compression waves in a porous thickening medium.

In conclusion it should be noted that the "piston" mechanism is simplified, greatly idealized. The real mechanism is considerably more complex. First of all it is necessary to

consider the fact that a shock wave of critical intensity can appear as a result of the local explosion of the individual volumes of explosive.

D. EMERGENCE OF DETONATION DURING SHOCK INITIATION

§ 29. Determination of the Critical Pressures of the Initiation of Detonation

The final result of the predetonation development of combustion is the formation of the shock wave which causes the detonation of the explosives, if the wave amplitude reaches a value equal to the critical pressure of initiation of detonation ($p_{кр}$). The analysis of the transition of combustion to detonation is impossible without knowledge of the critical pressures of the initiation of detonation. The initiation of detonation by a shock wave was investigated intensely recently mainly in connection with the determination of the sensitivity of different explosives to the shock effect.

For experimental determination of $p_{кр}$ it is necessary first of all to know the shock adiabatic curve of the explosive, i.e., the connection between pressure and specific volume of the substance on the shock front or, what is the same, the connection between the pressure (velocity of shock wave) and the mass flow rate of the substance. The determination of the shock adiabatic curves (dynamic compressibility) of condensed substances is treated in many works, a survey of which is contained in [140]. As concerns explosives, then mainly the dynamic compressibility of trotyl and cyclonite at a density close to maximum was investigated. In the literature there are very limited data on the compressibility of porous explosives: PETN [150] and ammonium perchlorate [151] of bulk density, and pressed TNT [157]. The recording

of shock adiabatic curves for explosives is a complex and laborious process. Therefore great significance is acquired by the method of calculation of the shock adiabatic curves of explosives.

Generalized shock adiabatic curve. In work [145] it was shown that the dynamic compressibility of a number of metals can be described by a single dependence (generalized shock adiabatic curve), in which only two initial parameters enter - density ρ_0 and the speed of sound. The authors arrived at this conclusion on the basis of the processing of the available experimental data, utilizing in implicit form the law of similarity.

Afanasenkov, Bogomolov, and Voskoboynikov [146] showed the validity of this conclusion for organic substances. It was established that for liquids the experimental data are described by a single dependence of the form

$$D = C_0 \left(2U - 0,1 \frac{U^2}{C_0} \right), \quad (72)$$

where D - the velocity of the shock wave; U - mass flow rate; C_0 - the bulk speed of sound in the initial conditions.

It turned out that the analogous dependence was valid also for cast TNT and pressed cyclonite of high density. This fact, and also the fact that a solid in a shock wave, when the yield point is exceeded can be considered as a liquid, served as the basis for recommending expression (72) as the generalized shock adiabatic curve of organic explosives. The comparison made by the authors of the shock adiabatic curves, calculated from (72) and measured experimentally, showed satisfactory accord. Thus was established [146] the possibility of the construction of the a priori shock adiabatic curve of organic explosives. For the construction of the shock adiabatic curve of individual explosives it is necessary to determine only the bulk speed of sound C_0 .

During the calculation of the bulk speed of sound C_0 in a liquid it is convenient to use Rao's formula:

$$C_0^{1/2} = \frac{c_0}{M} \sum_i y_i B_i \quad (73)$$

where ρ_0 , M - the initial density and the molecular weight of the substance; y_i - number of chemical bonds of this form; B_i - the increments of these bonds.

Value C_0 can also be determined experimentally: by the ultrasonic technique - in a test longitudinal C_l and transverse C_t speed of sound in a solid are measured, and C_0 is calculated from the expression:

$$C_0^2 = C_l^2 - \frac{1}{3} C_t^2 \quad (74)$$

or in tests regarding the isothermal compressibility of the substance.

In work [149] values C_0 were calculated for a number of solid explosives and linear polymers¹, which are given in Table 16.

Mixture systems [146, 168]. During the calculation of the shock adiabatic curve of a nonporous mixture of two (and more) solids it was assumed that the pressure in components at the shock wave front is equalized ($p_{cm} = p_1 = p_2$), and heat exchange between them is absent

$$U_{cm}^2 = aU_1^2 + (1-a)U_2^2 \quad (75)$$

¹Knowledge of C_0 for polymers permits implementation of the calculation of the shock adiabatic curves of mixture powders and different model compositions. The shock adiabatic curve of NH_4ClO_4 is written in the form $D-C_0+1.5U-0.018U^2$.

Table 16. Magnitude of the bulk speed of sound in some explosives and polymeric materials.

Substance	Density, g/cm ³	Bulk speed of sound, m/s		
		according to Rao	on isothermal compressibility	test (ultrasonic technique)
Nitromethane	1,14	1330	—	1346 [149]
Trotyl (liquid)	1,47	1550	—	—
Trotyl (crystal)		2200	2200	2080 [149]
Cyclonite	1,80	2640	2650	—
PETN	1,77	2420	2320	—
Tetryl	1,73	2190	—	—
Ammonium perchlorate	1,95	—	2840	—
Teflon	2,236	1035	1060	—
Polystyrene	1,06	1710	1980	—
Polymethyl methacrylate	1,18	1920	1870	—
Polyethylene	0,917	2970	2120	—

where U_{cm} , U_1 , U_2 - respectively mass flow rate of mixture, first and second components; α - the weight fraction of the first component.

After determining the shock adiabatic curves of components according to (72), it is possible to construct the adiabatic curve of the mixture. On the curve of Fig. 86 a comparison is given of the calculation with experiment for the composition trotyl - cyclonite 30/70.

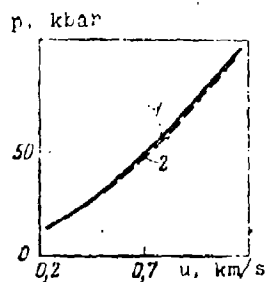


Figure 86. Shock adiabatic curve of the composition trotyl - cyclonite (30/70). 1 - calculation; 2 - experiment.

Porous substances [146]. During the construction of the nonequilibrium shock adiabatic curve of porous substance actually the same considerations and assumptions that are presented above were utilized. A mixture consisting of a solid phase (explosives) and air in pores was examined. Additionally it was assumed that during compression the final air volume was different from zero, and the weight fraction of air was negligible. Then the shock adiabatic curve of the porous substance takes the form

$$U_{\text{inop}}^2 = U_T^2 + p(1 - 1/\gamma)(1/\rho_{0\text{in}} - 1/\rho_{0\text{T}}), \quad (76)$$

where $\gamma = V_0/V$ - the compression ratio of air in pores, $\rho_{0\text{in}}$ - the initial density of the porous substance, $\rho_{0\text{T}}$ - the initial density of the bulk solid explosive. Values p and U_T are assigned by the known shock adiabatic curve of the bulk solid component. It was established [146] that the best agreement of calculation and experiment occurs with $\gamma=7$ (Fig. 87).

With the indicated method a calculation was made of the shock adiabatic curves of porous explosives during the determination of the critical pressures p_{kp} of the initiation of detonation.

Measurement of the critical pressure of initiation of detonation.

There are several methods of determination of p_{kp} , with the content of which it is possible to become acquainted in work [148]. If in early investigations the transmission of detonation from an active charge to passive was realized in essence through the air gap, then in recent years wide acceptance has been

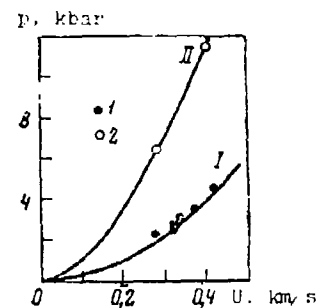


Figure 87 Shock adiabatic curve of porous PETN (I) ($\rho=1.0 \text{ g/cm}^3$) and trotyl (II) ($\rho=1.43 \text{ g/cm}^3$). Lines are calculation, points are experiment: 1 - according to [150]; 2 - [157].

received by the experimental method of determination of p_{kp} , based on the utilization of an inert barrier (metal, plexiglass, etc.). The diagram of the test is presented in Fig. 88a (1 - explosives, 2 - barrier, 3 - active charge, 4 - lens, 5 - detonator), and its graphic interpretation - in Fig. 88b

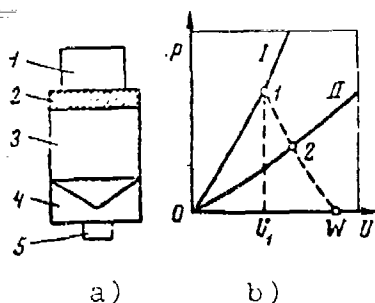


Figure 88. Determination of the critical pressure of initiation of detonation. a) diagram of experiment; b) its graphic interpretation.

charge, 4 - lens, 5 - detonator), and its graphic interpretation - in Fig. 88b (OI - the shock adiabatic curve of the material of the barrier, OII - the shock adiabatic curve of the investigated explosives, 1-2 - the isentrope of expansion of the barrier). During the detonation of active charge into the barrier

a shock wave enters, the pressure in which is determined, if the shock adiabatic curve of the explosive and the dependence of the mass flow rate of the material of the barrier on the properties of the active charge are known. After the approach of the wave to the barrier-investigated explosive boundary conversely a relief wave is spread on the barrier and on the explosive - a shock wave.

The pressure of the shock wave which entered the investigated explosive is determined by the point of intersection 2 of the shock adiabatic curve of the explosive with the isentrope of expansion of the material of the barrier, outpoint from point 1 (isentropes are the mirror reflection of the shock adiabatic curve of the barrier). The critical pressure p_{kp} is defined as the minimum pressure of the shock wave entering the explosive at which the detonation of the charge is excited.

Value p_{kp} depends on the parameters of the charge (density, initial size of particles, diameter). A specific effect can be

exerted by the profile of the initiating shock wave¹.

Let us examine the results of measurement of p_{KP} , obtained in a common test setup (Fig. 88). An active charge of trotyl [147] or of a mixture of TNT + NaCl of different percentage composition [149] was used. The diameter and height of the active charge were 40 and 60-100 mm respectively. For the purpose of obtaining a plane detonation front an explosive lens was utilized. The barrier was a copper plate with a thickness of 5 mm. The passive charge of the investigated explosive (without a shell) had the following dimensions: diameter 20 mm, height 60 mm. Emergence of detonation was fixed by the optical method with photography of the charge from the lateral surface or from the end.

In this experimental setup a study was made of the dependence of the critical pressure of initiation of detonation on relative density for trotyl, cyclonite [147-149], PETN, and also for a stoichiometric mixture of ammonium perchlorate with polystyrene². The findings are presented in Fig. 89.

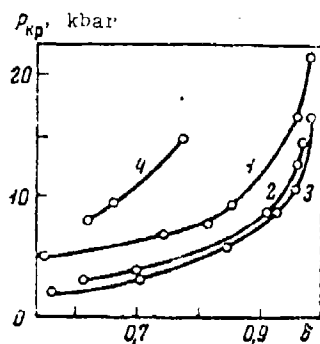


Figure 89. Dependence of the critical pressure of initiation of detonation on porosity. 1 - trotyl, $r < 100 \mu\text{m}$; 2 - cyclonite, $r < 100 \mu\text{m}$; 3 - PETN, $r \approx 20 \mu\text{m}$; 4 - stoichiometric mixture of ammonium perchlorate with polystyrene, $r \approx 15 \mu\text{m}$.

¹In work [149] it is noted that the profile of the initiating shock wave is essential for homogeneous explosives. For porous systems value p_{KP} is determined in essence by the amplitude of the initiating shock wave. In favor of this is the fact that value p_{KP} for charges of porous explosives of identical diameter, obtained by different methods, turn out to be close.

²Dependence of $p_{KP}(\delta)$ for PETN and a mixture system was obtained by A. V. Obmenin.

From them it follows that for the secondary explosives with $\delta < 0.85$ the critical pressure increases weakly with an increase in the density. At high densities ($\delta > 0.85$), which approach the density of a single crystal, p_{HP} increases sharply. It is interesting to note that in accordance with the data in Fig. 13 at a density $\delta > 0.85$ a noticeable decrease in the gas permeability of the charge is observed. Thus the presence in the charge of a small degree of porosity exerts a substantial influence on the sensitivity of the explosive to a shock wave. From the investigated substances for a mixture system the highest value of p_{HP} is characteristic.

One should emphasize that the diameter of the charge of the studied secondary explosives in the entire density range considerably exceeded the critical diameter of detonation (d_{HP}''), for a mixture system (with $\delta \geq 0.75$) it was close to critical.

The partial data available in the literature (for example, see [148]) indicate that near the critical conditions of detonation (with $d_{\text{g}} \approx d_{\text{HP}}''$) an increase is observed in the critical pressure of initiation. With an increase in the diameter of the charge dependence $p_{\text{HP}}(d_{\text{g}})$ weakens, and at $d_{\text{g}} \gg d_{\text{HP}}''$ value p_{HP} in practice does not depend on the diameter of charge. The latter is confirmed by the tests carried out by us with charges of PETN of different diameter (Fig. 90) (for PETN with $\rho = 1.70 \text{ g/cm}^3$, $d_{\text{HP}}'' \approx 0.3 \text{ mm}$). Under conditions when $d_{\text{g}} \gg d_{\text{HP}}''$, value p_{HP} does not depend on the surrounding of the charge with shell of steel or plexiglass.

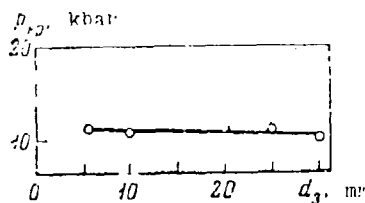
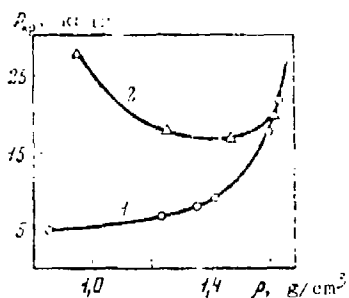


Figure 90. Dependence of the critical pressure of initiation of detonation on the diameter of the charge (PETN $\rho = 1.70 \text{ g/cm}^3$, $r \approx 20 \text{ }\mu\text{m}$).

The account of this circumstance and the fact that in porous explosives the critical pressure of initiation of detonation is determined in essence by wave amplitude (and not by its profile), gives basis to utilize values p_{HP} , obtained in tests on shock initiation, in connection with the conditions of the transition of combustion to detonation.

The initial particle size of the explosive uniquely affects the sensitivity to the shock wave. We have studied dependence $p_{\text{HP}}(\delta)$ for coarse-crystalline trotyl with initial particle sizes $r=0.4-0.8$ mm (charges 20 mm in diameter without a shell, with the exception of the charges of the bulk density, where $d_g=30$ m, were used). The findings are given in Fig. 91, also presented



Dependence of the critical pressure of initiation of detonation on porosity for samples of trotyl of different dispersity. 1 - $r < 0.1$ mm; 2 - 0.4-0.8 mm.

here are results [147-149] for finely crystalline trotyl ($r < 0.1$ mm). As it follows from the results given, an increase in the initial particle size leads to an intensive increase of p_{HP} at low and especially bulk densities of charge. In high density charges the effect of the initial particle size is expressed to a considerably less degree or is completely

absent. A lowering in the sensitivity of coarse-crystalline charges of explosives of bulk density was noted in work [153]. This effect makes it possible to explain why a stable low-speed detonation in powder-like explosives is spread only when using particles of large dimension. Low-speed detonation is shielded in this case from transition to normal detonation by the high value of p_{HP} . For trotyl the pressure in the wave of low-speed detonation (see p. 186) is substantially lower than the directly

measured value of p_{kp} .

What was presented above corresponded to the pressed charges of explosives, which contained open gas-permeable porosity. In order to trace the effect of the physical structure of a charge (the state of aggregation), we compare values of p_{kp} for cast, pressed, molten and liquid explosives (Table 17).

Table 17. Critical pressures of the initiation of detonation for some explosives with different physical structure of charge.

Explosive	Initial density, g/cm ³	Diameter of passive charge, mm	Critical pressure, kbar
Trotyl pressed	1,63	20	22 [147]
Trotyl cast	1,62	20	115 [147]
	1,62	35	57 [147]
	1,62	50	35 [147]
Trotyl molten	1,47	20	110 [147]
PETN pressed	1,73	20	17
PETN crystal	1,77	20	112 [147]
Cyclonite pressed	1,74	20	15 [147]
Cyclonite crystal	1,80	20	160
Nitroglycerin powder	1,58	20	85 [147]
Nitroglycerin liquid	1,60	20	85 [147]
Nitromethane liquid	1,14	20	90 [147]

A tendency is noted, according to which the sensitivity of explosives to shock wave decreases in the order: pressed, cast, liquid explosives.

Attention is drawn to the fact that value p_{kp} for pressed trotyl with open porosity is noticeably lower than for cast of the same density which contains closed pores. The observed distinction is apparently connected with the nature of porosity. This is confirmed by the data of [155], in which it was established that the sensitivity of powders with closed porosity is lower

than with that with opened. Thus the sensitivity of the system to a shock wave depends not only on the presence of porosity, its extent, but also on the nature of porosity. The structure of charge also has a noticeable effect on the formation of the detonation wave.

§ 30. Formation of Detonation Wave

Recently considerable attention has been given to the study of the development of a shock wave into detonation. For this purpose as a rule the velocity of the wave front was measured.

Considerably greater information on the indicated question is obtained in work [27], the authors of which investigated cast finely crystalline and pressed trotyl with initial density of 1.62 and 1.59 g/cm³ respectively. By the electromagnetic method two parameters characterizing the shock wave were determined - velocity of front D and distribution of mass flow rate behind the front in time $U(t)$. They also investigated electroconductivity in spreading shock waves. This made it possible to obtain a sufficiently complete picture about the processes which take place behind a shock wave front. Furthermore the optical recording of the process of emergence of detonation was used.

The amplitude of the initiating shock wave comprised 50, 35, 20 kbar for cast trotyl and 35, 18, 12 kbar for pressed. The last values of pressures were less than p_{HP} and did not cause detonation. The diameter of the passive charge was 60 mm, active (mixture of trotyl with talc of different density) - 80 mm, as the material of the inert barrier plexiglass was used.

The results of the measurements of parameters D and U on the wave front, obtained at different distances L from the barrier - explosive boundary, are presented in Fig. 92, and the oscillograms of the recordings of mass flow rate $U(t)$ - in

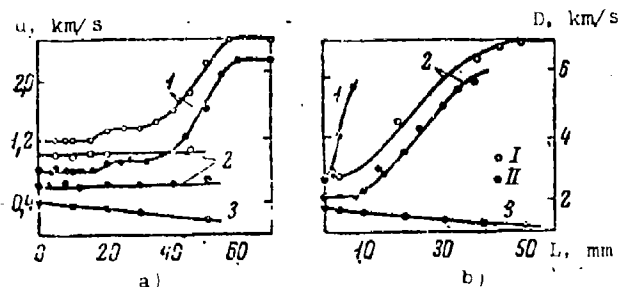


Figure 92. Value of the velocity of shock wave D (I) and mass flow rate of the movement of substance U (II) at different distances L from the barrier - explosive boundary for cast (a) and pressed (b) trotyl. a) 1 - $p=50$; 2 - 35; 3 - 20 kbar; b) 1 - $p=35$; 2 - 18; 3 - 12 kbar.

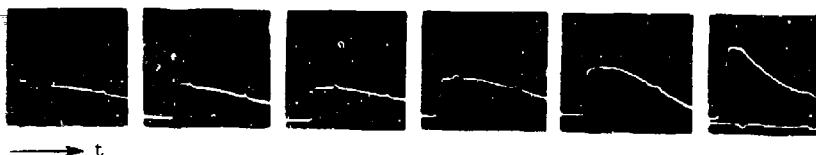


Figure 93. Oscillograms of the recordings of mass flow rate in cast trotyl (interval between markers - $2 \mu s$). $p=50$ kbar, $L=0$; 4; 8; 16; 30; 50 mm.

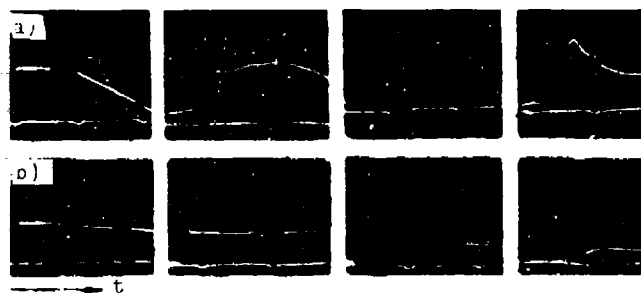


Figure 94. Oscillograms of recordings of the mass flow rate in cast trotyl. a) $p=18$ kbar, $L=0$; 4; 12; 18 mm; b) $p=12$ kbar, $L=0$; 4; 20; 40 mm.

Figs. 93, 94. It is evident that the development of a shock wave up to detonation occurs in the form of a smooth change in the parameters (D and U).

For cast trotyl an initial section is observed where the

parameters of the shock wave which initiates detonation do not change and are assigned by the incoming wave. An increase in the parameters of the wave up to the detonation begins at a certain depth, the magnitude of which decreases with an increase in the amplitude of the initiating wave. With the amplitude of the wave entering the explosive close to critical, the emergence of detonation occurs at a considerable distance from the barrier (thus, for instance, at $p=35$ kbar the normal detonation parameters along the axis of the charge were fixed at a depth $L=120$ mm). Photographic observations of the development of the process showed that in cast trotyl in the stage preceding detonation a brightness is recorded, the intensity of which increases in the course of time. It is interesting that on the initial section the rate of the process, measured according to the optical notations, coincides with the velocity of the shock wave, determined by the electromagnetic method along the axis of the charge. We utilized these data for the explanation of the nature of the low-speed process. As it follows from Fig. 93a, in cast trotyl the shock wave in the initial stage retains a triangular profile, which then is transformed into a profile with a "shell." The indicated change in profile is fixed and with $p < p_{\text{HP}}$ is also connected by the authors with the course of the chemical reaction behind the shock wave front.

In the pressed trotyl (unlike cast) the tendency for an increase in the parameters on the shock wave front, capable of developing to detonation, is observed directly at the interface of the barrier and explosive (Fig. 94a). The profile of the wave on the interface ($z=0$) is different from triangular, observed at the entry of the shock wave into the inert material. During propagation of the shock wave with $p > p_{\text{HP}}$ a profile $U(t)$ is fixed with a "hump," the slope of which rises, which is accompanied by an increase in the mass flow rate on the front U_{ϕ} and apex of the hump U_r (Fig. 94a). With $p < p_{\text{HP}}$ the wave front is eroded, and the velocity of the front becomes lower than the speed of

sound (Fig. 94b).

The measurements of electroconductivity showed that in cast trotyl an increase in conductivity begins directly behind the shock front, while in pressed trotyl the increase in conductivity occurred with a delay.

The entire totality of experimental data obtained testifies to the fact that the process of development of a detonation wave in pressed trotyl is more sensitive to a change in the parameters of the incoming shock wave than in cast trotyl. This experimental result is explained by the authors by the fact that the heat release rate in pressed trotyl depends more strongly on pressure behind the shock front.

According to contemporary representations, the chemical reaction under the influence of a shock wave on porous explosives begins in separate foci - "hot points" and occurs in the form of a thermal explosion. The reason for emergence and existence of a "hot point" is the physicochemical heterogeneity of explosives. The reaction which emerges is spread possibly in the form of combustion to the remaining mass of explosive, which leads to the emergence of a system of compression waves, which amplifies the first shock wave. This produces an increase in the concentration of hot points, pressure in the reaction zone, and as a final result leads to detonation.

At the same time at present reliable information about the processes which proceed in the "hot points" is absent. Also the question concerning how "hot points" are formed remains open. The following possible reasons for the formation of separate foci of the reaction are discussed: the collision of shock waves, elasto-plastic changes behind the shock front with localization of stresses, the discontinuity of flow near heterogeneities, phase transformations, etc.

All this creates major and thus far unsurmounted difficulties during the development of a theory of shock initiation.

In this respect solid (porous) explosives differ from homogeneous (liquid) explosives. In liquid explosives the incoming shock wave is propagated initially as in an inert medium. After a delay on the interface (at the point of entrance of the shock wave) a thermal explosion occurs which leads to the emergence of detonation in the compressed explosive, which overtakes the original shock wave front. Only then is normal detonation spread through the substance.

LIQUID EXPLOSIVES

Working out the problems of the stability of combustion of liquid explosives (ZhVV) [HBB] yielded one of the most interesting sections of combustion theory. The peculiarity here lies in the fact that the theory of the emergence of the effects of instability basically was created prior to their experimental detection and detailed investigation. From the experimental viewpoint, the favorable combination of such properties of ZhVV as optical transparency, stability of density, broad range of possible rates of combustion, and possibility of changing the mobility by small additions of high-polymeric substances, makes it possible to conduct interesting experiments in the observation of the details of the process of combustion.

This section of combustion theory owes its development first of all to K. K. Andreyev, A. F. Belyayev, Ya. B. Zel'dovich, L. D. Landau, and also to their numerous followers and pupils. One should note the prominent position in the world of science which Soviet research holds in this question.

Many questions, illuminated in the present chapter, one way or another were illuminated in Andreyev's monograph [38]. However, a series of works on the questions of the stability of combustion of ZhVV, for one reason or another, did not enter into the monograph [37, 38]. Moreover in light of contemporary concepts about

the mechanism of stability of the combustion of ZhVV new interpretations of known experimental facts appeared. All this makes it possible to hope that this section will be useful from the viewpoint of the summation of the accumulated knowledge and the attempt to interpret the data from common positions.

One should recognize that although the critical conditions of the disturbance of stable combustion of ZhVV have been the object of a relatively large number both of experimental and theoretical works, the question concerning the conditions for the passage of combustion into explosion has been developed very little. Single experimental studies, which do not make it possible to form a final picture of the process have been dedicated to the passage of combustion into explosion. As concerns the theory of the problem, thus far it has not been formulated. Here the works are usually limited to the assumption that combustion beyond the stability limit can lead to autoturbulence, explosion and even detonation. However, the extrapolation of limiting phenomena to ranges of values of parameters lying far beyond the limits, without special substantiation, is not always convincing. As a rule, there are many factors, which contribute to the emergence of nonlinear effects, part of which can have a stabilizing effect.

Relatively new is the question concerning the combustion of heterogeneous mixtures of the type of ZhVV - solid. Nevertheless recent works here have laid good foundations for understanding the mechanism and laws governing the combustion of this class of systems.

In the present section we do not deal at all with problems of the combustion of atomized liquid fuels, which are illuminated in numerous and well-known works, and in general the technical applications of the combustion of ZhVV are outside the scope of this discussion.

CHAPTER VI

THE THEORY OF THE LIMITS OF NORMAL COMBUSTION OF LIQUID EXPLOSIVES

§ 31. Theory of Andreyev - Belyayev and Zel'dovich

The earliest theory of the stability of combustion of explosives, which is also applicable to the case of liquid explosives, was Andreyev - Belyayev's theory, discussed above (Chapter III). Let us recall that its basic conclusion consists of the following: "the possibility of stable combustion at a given pressure is determined by the relationship between the rate of combustion (more precisely, by the rate of gas formation) and the rate of the departure of gases at this pressure or, more correctly speaking, by the relationship between the acceleration of gas inflow and the acceleration of gas consumption under pressure" [38, pg. 297]. In the first approximation, the condition of stable combustion according to Andreyev - Belyayev has the form

$$\frac{1}{A} \frac{d(u; \sigma)}{dp} > 1, \quad (77)$$

where A is the efflux coefficient, which has a value on the order of $7-7.6 \text{ g/cm}^2 \cdot \text{s/atm}$.

The rate of combustion of many (but not all) liquid explosives is linearly dependent on pressure. In connection with this the value

$$B = d(u_1 \rho_1) / dp$$

(78)

turns out to be independent of pressure, i.e. a constant of the given substance.¹ Table 18 depicts the values of B for a series of individual liquid explosives and mixtures, partially taken from work [38].

Table 18. Values of the coefficient, B, atm·g/cm²·s

Substance	B
Nitroglycol, liquid	0.039
Nitroglycol, gelatinized	0.029
Methyl nitrate, liquid	0.133
Nitroglycerin, gelatinized	0.146
Nitroglycol (gelatinized) + PbN ₆ 50/50 wt. %	0.148
Nitroglycol (gelatinized) + PbN ₆ , 40/60 wt. %	0.267
Nitromethane	0.0025
Diglycoldinitrate	0.00246
Ethyl nitrate	0.0064
Nitromethane + 7% by weight of pyroxylin	0.00246

Table 18 shows that the majority of liquid explosives have $B \ll A$ and the ratio A/B is $3 \cdot 10^1 - 6 \cdot 10^2$. This means that for the destabilization of combustion of these substances, according to Andreyev - Belyayev, a surface of combustion must be developed in an appropriate relation to the area of a cross-section of the tube. So considerable an increase in the surface of combustion can arise only under special conditions. This question will be discussed below.

¹We do not deal here with the dependence of B on the size of the charge (which as a rule is weak) and on the initial temperature. The introduction of these parameters changes somewhat the quantitative, but not the qualitative side of the basic conclusions.

Thus, to liquid as well as to solid explosives, during combustion under normal conditions, are inherent those values of the coefficients of the accelerations of gas inflow under pressure, which guarantee stable combustion in the sense of Andreyev - Belyayev's gas-dynamic mechanism.

Experimental studies of Belyayev on the passage of the combustion of liquid explosives (methyl nitrate, etc.) into explosion served as a basis for the development by Ya. B. Zel'dovich [43] of a theoretical model of the stability of combustion of explosives, having a clearly pronounced reaction in the k-phase. The reason for the disturbance of normal combustion in Zel'dovich's model is physicochemical. The essence of the mechanism consists of the following. With an increase in the pressure as a result of a temperature rise of the surface of the liquid the rate of the k-phase reaction increases and the wave of heating goes into the depth of the liquid. The development of vapors and products of the k-phase reaction occurs in the gaseous phase. Since k-phase and g-phase reactions are considered independent it is possible to find a ratio between the activation energy of the k-phase reaction and the heat of vaporization, such that the rate of heating of the liquid will become greater than the rate of its vaporization. Superheating and boiling-up of the liquid will occur in a layer of some thickness, which causes the dispersion of the liquid and its vapors into the zone of the flame. It is thought that in this case conditions can arise for the development of detonation.

A comparison of Zel'dovich's theory with experiment and its discussion are comprehensively presented in Andreyev's monograph [38].

§ 32. Landau's Theory of the Hydrodynamic Stability of Slow Combustion

Landau [73] approached the problem of the stability of combustion from other positions than Andreyev - Belyayev and Zel'dovich. In his theory the gas-phase mechanism of combustion is accepted,

i.e., from the surface of the liquid, vaporization occurs which is supported by heat from chemical reactions in the vapor above the surface. By means of slight disturbances of the surface the stability of the flow of combustion products is examined taking into account the stabilizing effect of gravity and surface tension. In this case, in the first approximation, the thickness of the zone of chemical reaction is disregarded in comparison with the length of the disturbance wave. This also indicates a failure to take into account the processes, which determine the structure of the surface of the discontinuity liquid - gas. The mathematical formulation of the problem of the hydrodynamic stability of the surface of the boundary liquid - gas is independent of the cause of gas generation and even of the cause for its motion. Moreover, Landau's problem is isobaric; the compressibility of the gas is disregarded. As a result solutions of Landau's problem may also be transferred to other models, for example to the motion of a layer of liquid along the surface, the blowout of the mirror of the surface of the liquid by gas flow, etc.

For the determination of the critical conditions for the development of infinitesimal disturbances of the boundary, liquid-vapor, the continuity equation and the Eulerian equation are solved concurrently. It was shown that at a sufficiently high rate $J = u_1 \rho_1$ the process of combustion becomes hydrodynamically unstable: small deformations of the surface are increased. For the stability of the plane form of the front of combustion it is necessary that the roots of the equation

$$\Omega^2 (u_1 + u_2) + 2\Omega k u_1 u_2 + \left[k^2 (u_1 - u_2) + \frac{6k(\rho_1 - \rho_2) + 3k^2}{J} \right] u_1 u_2 = 0 \quad (79)$$

have a negative real part. This gives the following condition for the stability of combustion:

$$J^4 < \frac{12k\rho_1^2 u_2^2}{\rho_1 - \rho_2} = J_*^4 = (u_2^* u_2^*)^4, \quad (80)$$

where u_1 and u_2 are rates of motion of the liquid and the combustion products in a laboratory coordinate system; ρ_1 and ρ_2 are the densities of the liquid and the combustion products; σ is the coefficient of surface tension, $J = u_1 \rho_1 = u_2 \rho_2$ is the mass velocity of combustion; J_* is the mass velocity of combustion under critical conditions (critical rate of combustion), which is equal to $u_2^* \rho_2^*$; g is free-fall acceleration; k is the wave vector of the disturbance of the surface of the liquid; $1/\Omega$ is the characteristic time of development of the disturbance.

Let us examine the basic corollaries of Landau's theory [177-179].

Dimensions of the Most Dangerous Disturbances and the Time of Their Development

We will examine combustion in a container of infinite diameter in order not to limit ourselves initially to the possible dimensions of disturbances. For the determination of the dimensions of the most dangerous disturbances, i.e., the disturbances, which have a small time of development during combustion beyond the stability limit, we use equation (79). Let us introduce the dimensionless values

$$n = \frac{J}{J_*} \sqrt{\frac{\rho_2^*}{\rho_2}}; \quad x = k/k_*; \quad \omega = \frac{\Omega J_*}{2g} \frac{1}{\sqrt{\rho_1 \rho_2^*}}. \quad (81)$$

Here k_* is the wave number of most rapidly growing wave under critical conditions of disturbance. It is equal to

$$k_* = \frac{J_*^2 (\rho_1 - \rho_2)}{2\sigma \rho_1 \rho_2^*} = \sqrt{\frac{g}{\sigma} (\rho_1 - \rho_2^*)} = \frac{2g \rho_1 \rho_2^*}{J_*^2}. \quad (82)$$

With $n > 1$ the disturbances will be amplified, which lie in a certain range of the wave vectors k (or wavelengths λ), which is dependent on the rate of combustion n :

$$n^2 - \sqrt{n^4 - 1} < x = k/k_* = \lambda_*/\lambda < n^2 + \sqrt{n^4 - 1}. \quad (83)$$

With $n^4 \gg 1$ we have $1/2n^2 < x < 2n^2$. Hence it is apparent that with an increase in n (rate of combustion) the interval of the dimensions of the growing disturbances is expanded both to the side of long and to the side of short waves. With $n=1$ the interval contracts into the point $x=1$.

In Landau's problem fine-scale disturbances ($x > n^2 + \sqrt{n^4 - 1}$) are effected by the forces of surface tension, and large-scale disturbances ($x < n^2 - \sqrt{n^4 - 1}$) by the forces of gravity.

In order to determine the dimensions of the most dangerous disturbance, i.e. of the one developing most rapidly, one should find the x_n with which ω acquires the greatest value:

$$x_n = \frac{2}{3}n^2 + \frac{1}{3}\sqrt{4n^4 - 3} \quad \text{with} \quad n-1 \gg \rho_2/\rho_1. \quad (84)$$

Let us designate the time of increase in the disturbance with the wave number x , at the rate n over τ , then

$$\Omega = 1/\tau = \sqrt{g/k} \sqrt{2n^2x^2 - x - x^3}. \quad (85)$$

For the most dangerous disturbance the time of growth τ_{\min} is determined by substitution of the value x_n instead of x . With $n^4 \gg 1$ formulas (84) and (85) are simplified:

$$k_n = 2\pi/\lambda_n = \frac{1}{3}k_0 n^2; \quad 1/\tau_{\min} \approx 1.5(gn^3/J_0) \sqrt{\rho_1 \rho_2}. \quad (86)$$

It is evident that λ_n and τ_n decrease rapidly with an increase in the rate of combustion n . If the rate of combustion slightly exceeds the critical value, i.e., $J/J_* = 1 + \delta$, $\rho_2/\rho_1 \ll \delta \ll 1$, then

$$1/\tau_n \approx 2\sqrt{2g} \sqrt{\rho_1 \rho_2} \sqrt{\delta/J_*}; \quad k_n = k_0 (1 + 4\delta).$$

Near the transition from stable combustion to unstable, the value of a random disturbance changes according to the law $\xi_n = \xi_0 \exp(kz - i\omega t)$. With $n < 1$ $\omega \neq 0$, $z = 0$; with $n > 1$ $\omega = 0$, $z \neq 0$, i.e. in the range of stable conditions disturbances produce damped oscillations of the surface of the liquid, and in the range of unstable conditions the disturbances grow in amplitude, and oscillations are absent.

Table 19. Theoretical values of the parameters λ_n and τ_n .

n	J.J.	λ_n , cm	τ_n , s	λ_n/τ_n , cm/s
1,0	1,0	1,16	∞	0
1,05	1,11	0,97	0,0273	35,5
1,1	1,21	0,85	0,0150	57,5
1,2	1,44	0,67	0,013	62,0
1,4	1,96	0,47	0,0055	85,5
1,6	9,56	0,35	0,0033	102
2	4	0,22	0,00165	133,5

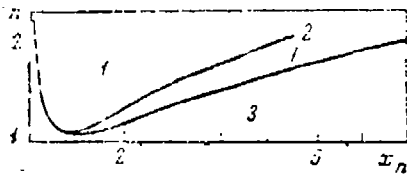


Fig. 95. Unstable region (1), wave numbers of the most dangerous disturbance (2) and the range of absolute stability of combustion (3).

Lower than curve 1 lies the range of absolute stability 3.

Table 19 gives theoretical values of λ_n and τ_n depending on J/J_* for nitroglycol. Values taken are $\rho_1 = 1.49$ g/cm³, $\sigma = 48$ dyn/cm², $\rho_2 = 5 \cdot 10^{-4}$ g/cm³.

Figure 95 shows the unstable region 1 and the wave numbers 2 of the most dangerous disturbance.

Effect of the Diameter and Shape of the Container on the Limit of the Stability of Normal Combustion

The above discussion was conducted on the assumption that the diameter d of the container in which liquid explosives are contained is considerably greater than the characteristic dimensions of the disturbance: $d \gg 1/k_*$.

If the diameter of the container in which the burning liquid is located, is so small that this inequality is not fulfilled, then the dimensions of the most dangerous disturbance λ_d in this case will depend on the diameter and shape of the container, whereupon $\lambda_d < \lambda_*$; $k_* < k_d$; $x_d > 1$.

We will qualitatively analyze the effect of the diameter of the container on the critical condition of combustion $J_d(n_d)$. By using equation (83) it is possible to determine the critical rate of combustion of a liquid in a tube with a diameter of d :

$$n_d = \sqrt{0,5(x_d + 1/x_d)}. \quad (87)$$

Since $x_d > 1$, then $n_d > 1$, i.e. combustion in a narrow container is more stable than in a wide one as a result of the stabilizing effect of the walls.¹ It is clear that in a sufficiently narrow container the dimensions of a dangerous disturbance are proportional to the diameter, but in a sufficiently wide container they do not depend on the diameter: $1/x_d = dk_*$ with $dk_* \ll 1$; $1/x_d = 1$ with $dk_* \gg 1$.

With $x_d^2 \gg 1$ expression (86) is simplified: $n_d^2 = 1/2x_d$ or $n_d^2 = 1/(2dk_*)$. This expression was obtained in Landau's work [73].

Let us represent the dependence of x_d on $k_1 d$ by a broken line: $1/x_d = adk_*$ with $adk_* < 1$; $x_d = 1$ with $adk_* \gg 1$, where a is a constant, which depends on the shape of the container; taking into account (86), we have

$$\begin{aligned} n_d &\approx \sqrt{0,5(adk_* + 1/adk_*)} && \text{with } ak_* d < 1, \\ n_d &= 1 && \text{with } ak_* d > 1. \end{aligned}$$

¹Here, naturally, incidental phenomena, which do not relate to the hydrodynamic situation, such as heating of the liquid with flame by heat transfer through the wall, etc, are not considered.

The dependence of n_d on the dimensionless quantity $k_* d$ must be the overall limit of the stability of combustion of all liquid low-viscosity explosives in containers of identical shape, i.e. n and $k_* d$ are similarity criteria. This follows from the formulation of Landau's problem itself, which makes it self-similar.

The calculation of the proportionality constant a was carried out in work [178] for containers with round- and rectangular-shaped cross-sections.

During combustion in a cylindrical tube, besides conditions on the burning surface, boundary conditions must be satisfied on the walls of the tube where the radial component of the rate is equal to zero. With this condition are determined the possible values of the wave number of the disturbance of the surface k :

$$k = k_{qs} = \alpha_{qs}/R, \quad (88)$$

where α_{qs} are roots of the first derivative of the Bessel function I_q of the first order q ; s is the number of the root; R is the radius of the tube.

The form of the elementary disturbances of the surface $\xi(r, \varphi)$

$$\xi \sim I_q(\alpha_{qs} \cdot r/R) \cos q\varphi, \quad (89)$$

where r is the current radius; φ is the angle, which is determined by values of the whole numbers q (quantity of junction diameters); s (quantity of junction circumferences).

The critical rate of combustion $J_*(R)$ is connected with the diameter of the tube $d=2R$ by equations (80) and (86). Substituting in (86) the expression k in formula (88), we derive a relationship which is correct for combustion in a cylindrical tube

$$u^2 = \frac{J_*^2(R)}{J_*^2} = \frac{1}{2} \left(\frac{\alpha_{qs}}{Rk_*} + \frac{Rk_*}{\alpha_{qs}} \right), \quad k_*^2 = \frac{\rho_0 g}{\sigma}. \quad (87a)$$

In the case of a plane-parallel container $1/2i\pi$ ($i=1, 2, \dots$) enters in (89) instead of α_{qs} and R is a half of the large side of the rectangle of the cross section of the container. At the limit of stability a wave is self-excited, for which α_{qs}/k_*R is closest to unity. Thus, during combustion in a narrow tube ($Rk_* < 1$) at the limit of stability a wave must appear with $s=0$ and $q=1$.

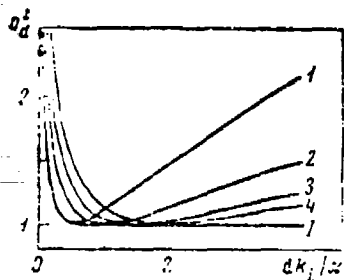


Fig. 96. The dependence of the limits of stable combustion on the given diameter of the container with different harmonics of disturbances 1 - curve of absolute stability; 1 - $i=0.5$; 2 - 1.0; 3 - 1.5; 4 - 2.0.

The dependence of the critical rate of combustion on the radius of the tube (Fig. 96) in the first approximation is material only in narrow tubes:

$$u^2 = J_0^2(R)/J_1^2 = 1 \quad \text{with } Rk_* > 1;$$

$$u^2 = 0.5(R_1/R + R/R_1) \quad \text{with } Rk_* < 1,$$

where $R_1 = \alpha_{10}R_* = 1.84k_*$ (combustion in a round tube) and $R_1 = (1/2)\pi k_* = 1.54k_*$ (for a flat container).

Effect of the Acceleration of Gravity

As follows from formulas (80) and (84), the size of the most dangerous disturbance depends substantially on g , and during its decrease, increases. The acceleration of gravity is of no importance only during combustion in containers of infinite diameter. In limited containers during a decrease in g the role of the factor, which stabilizes long-wave disturbances, passes to the diameter of the container which limits the maximum size of the disturbances. For the analysis of the case $g \rightarrow 0$, disregarding the interaction of gas, liquid and the surface of the container, let us note that

$$J_0^2 \approx 2\alpha_0^2 k_*.$$

In a container of infinite diameter with $g \rightarrow 0$, $k \rightarrow 0$, and therefore $J_0 \rightarrow 0$, i.e., combustion is always unstable to long-wave disturbances.

In a limited container the dimensions of the disturbances are $\lambda_{\max} = d$, and correspondingly $k_{\min} = 1/ad$, where a is const. Substituting k_{\min} in (89), instead of k_1 we derive, that with $g=0$

$$J_0^2 = 2\sigma\rho_s/ad.$$

Comparing this value with the critical rate of combustion under normal conditions

$$(J_0/J_c)^2 = [(\rho_s)_0/(\rho_s)_c] [1/(ak_c d)].$$

Under the assumption $J \sim p^v$ the ratio of critical pressures is $(p_0/p_c)^{2v-1} = 1/(ak_c d)$. Thus, the critical pressure (with $v=1$) is inversely proportional to the diameter of the container. The ratio of the critical pressure, determined under normal conditions in small-diameter tubes p_d ($k_c d \ll 1$), to the critical pressure during free fall p_0 ($g=0$) in a tube of diameter d_0 is equal to: $p_d/p_0 \approx d_0/d$ with $adk_c \ll 1$.

Effect of the Law of the Rate of Combustion of a Liquid

From equation (80) it follows that the value of the critical rate of combustion increases with pressure as

$$J_c = C_1 p^{0.5}, \quad (90)$$

where C_1 is not dependent on pressure. The rate of combustion of explosives can be written as

$$J = B p^v. \quad (91)$$

In liquid substances, as a rule, $v=1$.

Comparing (90) and (91), we have:

$$u' = \frac{J}{J_c} = \frac{B}{C_1} p^{v-0.5}. \quad (92)$$

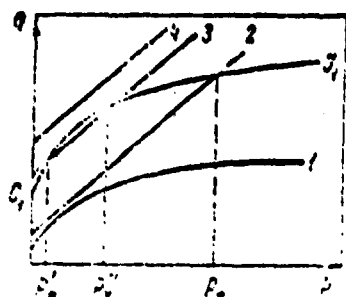


Fig. 97. Diagram of the dependence of the limiting conditions of normal combustion on the form of the equation of the rate of combustion at different pressures.

For stable combustion it is required that $u' < 1$. Depending on the relationship of the coefficients B , C_1 and the value of index ν , in principle, the following situations are possible (Fig. 97):

1) $C_1 > B$, $\nu < 0.5$; at all pressures $J_* > J$ and combustion is stable (curve 1);

2) $C_1 > B$, $\nu > 0.5$; at pressures greater than p_* combustion becomes unstable (curve 2). With $p < p_*$ combustion is stable:

3) $B > C_1$, $\nu > 0.5$; two cases are possible:

a) the curve $i(p)$ intersects $i_*(p)$ at two points. In the interval $p_*' - p_*''$ combustion is unstable, outside the interval it is stable (curve 3); b) the curve $J(p)$ goes above $J_*(p)$ everywhere (curve 4). Combustion is unstable at all pressures.

For calculation of the value of the coefficient C_1 it is possible to use the method, developed by Andreyev [38]. Expression (30) is reorganized with the aid of the introduction of the connection between the parachor P , the surface tension σ , the molecular weight M and the density of the liquid ρ_1 (formula of Bachinski - McLeod $P\rho_1/M = \sigma^4$). As a result of the analysis of the possible variations Andreyev showed that the equation obtained by him

$$J_* \approx 7,91 \rho_2^{0,5} \rho_1^{1,25} (P/M)$$

actually has the form

$$J_* \approx 3p^{0,5},$$

where $3 \approx 0.25 \text{ g/cm}^2 \cdot \text{s} \cdot \text{atm}^{1/2} = \text{const.}$

From the data given by Andreyev on the values P/M it follows that this relation for organic explosives lies within the limits of 1.7-1.95. Taking into account that for the same substances

$\rho_1 = 1.2-1.6 \text{ g/cm}^3$, we derive that according to the formula of Bachinski - McLeod, $\sigma = 17-94 \text{ dyn/cm}$, at an average value equal to $\sim 40 \text{ dyn/cm}^2$. This result shows that the utilization of a parachor is virtually equivalent to the substitution of the usual value σ , which is characteristic for liquids at normal temperature. In view of the very weak dependence of J_* on σ (as $\sigma^{1/4}$) the value of the coefficient C_1 turns out to be actually slightly variable. We use Andreyev's data on the densities of combustion products at $p=1 \text{ atm}$, according to which $\rho_2^0(1 \text{ atm}) = 1.8 \cdot 10^{-4} \text{ g/cm}^3$, and by substitution in (80) together with $\rho_1 = 1.4 \text{ g/cm}^3$ we will obtain

$$J_* = 0.12 \sqrt[4]{3} \sqrt{p}, \text{ g/cm}^2 \cdot \text{s}.$$

During a change in σ within the limits from 40 to 1 dyn/cm, C_1/\sqrt{p} changes within the limits from 0.12 to 0.3 $\text{g/cm}^2 \cdot \text{s}$. Thus, in the first approximation, $C_1 = 0.2 \text{ g/cm}^2 \cdot \text{s} \cdot \text{atm}^{1/2} = \text{const}$, which is close to the coefficient 3. For stability of combustion it is necessary that its rate $J = Bp^v$

$$5Bp^{v-0.5} \leq 1. \tag{92}$$

As can be seen from Table 18, in unthickened liquids the value (5B) at 1 atm is close to unity only in methyl nitrate. As concerns gelatinized explosives, the stability of their combustion will be discussed below.

The question concerning the reality of the existence of noticeable forces of surface tension under conditions of the combustion of noticeable forces of surface tension under conditions of the combustion of a liquid is fundamental. However, experimental observations make it possible to confirm that surface tension during combustion does exist, and its value is considerable. This is substantiated, in particular, by experiments with thermocouples, introduced into the burning liquid: authors [180, 181] observed how liquid is held by a thermojunction and extends to a rather high elevation.

§ 33. The Theory of Levich

If Landau considered the stabilizing effect of the forces of surface tension and gravity, then Levich [74] examined the problem of the hydrodynamic stability of combustion of a viscous liquid. For this the solution was carried out to the Navier-Stokes equations with a number of simplifying assumptions.

The critical condition of Levich has the form

$$J^3 < 3\sqrt{3}g\eta\rho_0^{3/2}\nu_0^{1/2} = J_c^3. \quad (93)$$

The physical sense of expression (93) is discussed below. Let us turn to the basic corollaries of the theory of Levich [74]. Basic laws were found, characterizing the effect of different factors on the emergence and development of instability during the combustion of a viscous Newtonian liquid. For comparison, the basic corollaries of the theories of Landau and Levich are given in Table 20. From the table it is evident that a noticeable viscosity first of all retards the development of the process of unstable combustion and the range of characteristics giving stable combustion is expanded. Specifically, let us note the substantial change in the effect of the diameter of the container, for example with $g=0$, from a dependence of the type $p_* \sim 1/d$ to a dependence of the type $p_* \sim 1/d^2$, which is connected with an increase of the dimensions of the most dangerous disturbance. By comparing the effect of the diameter of the container for cases with a predominant effect of surface tension and viscosity, it is possible to see that with a certain combination of the parameters the passage is feasible for one substance from a dependence of the type $p_* \sim 1/d$ in the range of increased values of the diameter of the container to a dependence of the type $p_* \sim 1/d^2$ with small diameters. However, calculation shows that the transition point for conventional explosives lies in the range of very small diameters.

Table 20. Comparison of characteristic values in the problems of Landau and Levich.

Characteristic	Considerable value	
	σ, g	η, g
Critical rate of combustion	$J_c^4 = \frac{4\sigma g (\rho_1 \rho_2)^2}{\rho_1 - \rho_2}$	$J_c^3 = 3 \sqrt{3} g \rho_1^{1/2} \rho_2^{3/2}$
Characteristic dimensions of the disturbance	$k_c = \frac{2g \rho_1 \rho_2}{J_c^2} = \sqrt{g \rho_1 / \sigma}$	$k_c = \frac{g^{1/2} \rho_1^{1/2}}{2\eta^{1/2}}$
Boundary of the spectrum of the disturbance	$n^2 = \frac{1}{2}(x + 1/x)$	$n^2 = \frac{1}{3}\left(x^2 + \frac{2}{x}\right)$
Dimensions of the most dangerous disturbance	$x = \frac{2}{3}n^2 + \frac{1}{3}\sqrt{4n^4 - 3}$	$12n^4x^2 - 8x^3 - 6n^4x + 6n^2x - 1 = 0$
a) $n = 1 + \delta, \delta \ll 1$	$x = 1 + 4\delta$	$x = 1 + \delta^2$
b) $n^2 \gg 1$	$x = \frac{4}{3}n^2$	$x = \frac{\sqrt{3}}{2}n$
Effect of the diameter of the container	$J_c^2 \sim \frac{3D_c}{d}; p \sim \frac{1}{d}$	$J_c^2 \sim \frac{3D_c}{d}; p \sim \frac{1}{d}$
Time of development of the disturbance	$\Omega = 1/\tau = \sqrt{k_c g} \times \sqrt{2n^2x^2 - x - x^3}$	$\Omega = \frac{\sqrt{k_c g}}{2} \sqrt{-x^2 - 2x - \sqrt{3n^2x^2 - 2x}}$
a) $n = 1 + \delta, \delta \ll 1$	$1/\tau = 2\sqrt{gk_c} \sqrt{\delta}$	$1/\tau = 3\delta \sqrt{k_c g/2}$
b) $n^2 \gg 1$	$1/\tau \sim \sqrt{gk_c} n^3$	$1/\tau \sim n^2 \sqrt{3g}$
Rate of development of the disturbance	$v \sim \lambda/\tau$	
a) $n = 1 + \delta, \delta \ll 1$	$v = 2\sqrt{gk_c} \sqrt{\delta}/(1 + 4\delta)$	$v = 3\sqrt{gk_c} \delta/(1 + \delta^2)$
b) $n^2 \gg 1$	$v = 3\sqrt{gk_c} n/4$	$v = 2\sqrt{3g} n/\sqrt{3}$
Gravitational field is absent ($g=0$)	$J_c^2 \sim \frac{3D_c}{d}; p \sim \frac{1}{d}$	$J_c^2 \sim \frac{\eta^2 D_c}{d^2}; p \sim \frac{1}{d^2}$
Surface tension is absent ($\sigma \rightarrow 0$)	$J_c^3 \sim g \rho_1 \rho_2^2 l^2$	$J_c^3 = 3 \sqrt{3} g \rho_1^{1/2} \rho_2^{3/2}$
a) $\lambda_c < \lambda_{lc}$	$J_c^2 \sim g \rho_1 \rho_2^2 l$	
b) $\lambda_c \ll d$		

§ 34. The Stability of Combustion at Pressures Higher Than the (Thermodynamic) Critical Pressure.

As is known, for liquids there is critical pressure and a critical temperature, the exceeding of which leads to the disappearance of surface tension. The critical pressure of organic explosives

is $p_{kp} = 40-50 \text{ kg/cm}^2$. As concerns the critical temperature, it has not been determined. If one uses the empirical expressions [182, 183] for weakly associated liquids, (which undoubtedly cannot be considered a substantiated method), then a value is obtained on the order of $250-350^\circ\text{C}$. Examining the combustion of liquid explosives at pressures higher than the critical pressure and analyzing Landau's formula, Andreyev comes to the conclusion [38] that stable combustion of these substances with $p > 50 \text{ atm}$ is impossible. If we are limited to the framework of Landau's theory, then the sole factor which stabilizes short-wave disturbances is surface tension, and that is why when $\sigma \rightarrow 0$ they begin to increase. True, it is possible to consider the thickness l_p of the zone of reaction (in Landau's theory it is equal to zero), and to consider that disturbances whose dimensions are less than l_p do not affect combustion. Let us extract the expression for the dimensions of disturbances as $\xi \sim 1/ak_*$, and $l_p \sim \mu_1/u_1$. Utilizing Landau's formula and Table 20, we derive that for satisfaction of the requirement $\xi \leq l_p$ the critical rate of combustion when $\sigma \rightarrow 0$ must be equal to

$$J_* \approx (\sigma \mu_1 / \rho_0^2)^{1/2} \quad (94)$$

With $p_{kp} = 50 \text{ atm}$ $J_* \approx 35 \cdot 10^{-2} \text{ g/cm}^2 \text{ s}$, which is very small.¹

Another factor of the stabilization of short-wave disturbances is the viscosity of the liquid. Under conditions when $\xi \gg l_p$, which enters into the assumption of the theories of Landau and Levich, the fraction of the thoroughly-warmed liquid in the wave of the disturbance is insignificant. As a result of the heating of the surface the surface tension can be lowered to a very low value; however, viscous forces in sub-surface layer will always be in effect. This makes it possible to assert that at pressures higher than critical, the role of the stabilizer of short-wave disturbances may pass to viscosity, and the critical condition of the development of disturbances is the condition of Levich.

¹Let us note that expression (94) is also correct for the combustion of gases.

Conventional organic liquid explosives have, at normal temperature, a viscosity on the order of several centipoise. Estimation of the value J_{η}^* according to the formula of Levich yields with $\eta=10^{-2}$ poise $J_{\eta}^*=0.05\sqrt{p}$ (p , atm; J_{η}^* , g/cm²·s). Thus, during a decrease of σ the role of stabilizer continuously passes to the viscosity and combustion can remain stable even at pressures higher than critical in the sense considered here. However, the coefficient of the root of the pressure (with $\eta=10^{-2}$ poise) proves to be somewhat less in Levich's problem than in Landau's (with $\sigma=30$ dyn/cm). If at the critical (thermodynamic) pressure the rate of combustion is low and calculation according to Landau's formula gives substantially higher values, then the limiting conditions of normal combustion will be determined by Levich's formula. But if J_{η}^* , according to Landau, is expected near the critical pressure, then the limit of normal combustion is determined by the joint action of (decreasing) surface tension and viscosity. With high viscosities, in the sense considered here, the attainment of the critical pressure does not affect the stability of combustion, but it may be apparent for entirely different reasons (through the heat of vaporization of the liquid becoming zero).

The attainment of the critical temperature T_{kp} is a more complex matter. In volatile explosives the temperature of the surface is limited by the boiling point, which increases with an increase in pressure, and the possibility is not excluded of reaching $T=T_{kp}$ both with $p < p_{kp}$ and with $p > p_{kp}$. It is simultaneously necessary to consider that the maximum temperature of the surface T_{η} is limited by the temperature of decomposition of the substance, and inasmuch as conventional explosives decompose at temperatures lower than the calculated $T_{kp}=250-350^{\circ}\text{C}$, T_{η} proves to be below T_{kp} . As a whole the question remains open, since the conditions on the decomposing surface of the liquid are ill-defined. It is possible to assume that precisely this difficulty in attaining T_{kp} makes combustion stable even at pressures higher than p_{kp} .

An increase in the initial temperature T_0 of liquid explosives has a dual effect. First, with an increase in T_0 the rate of combustion of the liquid increases. Simultaneously critical conditions (80) and (93) change in view of the decrease of η and σ (in that measure, in which the temperature of the surface of the burning liquid increases) with an increase in the initial temperature (effect of T_0 on ρ_2 can be disregarded). The analysis of the change in the critical situation depending on T_0 shows that an increase of T_0 substantially lowers the critical pressure p_* and rate J . Taking into account that viscosity depends on temperature exponentially, one should expect a considerably more powerful effect of the initial temperature on the stability of combustion of high-viscosity systems in comparison with non-viscous ones.

§ 35. Critical Value of Reynolds Number During the Combustion of ZhVV

According to Landau's theory [73] the development of instability of the combustion of gases must begin with Reynolds numbers $Re_* \approx 1$. The most recent studies of the stability of gas flames [184, 185] showed that experimental values of Re_* agree well with theory, if as characteristic dimensions we accept the average dimensions of the sections into which the unstable flame is divided. Although the actual values Re_* are $(2-4) \cdot 10^2$, the consideration of the dissipating effects connected with the viscosity of gas, completely removes the contradictions between theory and experiment.

Of doubtless interest is an analogous estimation in the case of combustion of liquid explosives. Utilizing values of J_* calculated above and accepting as the determining dimensions the wavelength of the most rapidly growing disturbance λ_* , for Landau's problem we find

$$Re_* \approx \frac{J_* \lambda_*}{\eta} = \frac{2\pi \sqrt{z}}{\eta} \sqrt[4]{\frac{\sigma^4 (\rho_2^*)^2}{g \rho_1}}$$

The substitution of typical values for the viscosity of the liquid $\eta=2$ cp, $\sigma=30$ dyn/cm, $\rho_2^* = 2 \cdot 10^{-4} \cdot \rho$, g/cm³ gives

$$Re_c \sim 10 \sqrt{p_c} = 10 - 100.$$

Included in the Re number are the characteristics of the liquid, but not of the combustion products. With this we confirm that the development of instability arises precisely in the liquid phase.

Using an analogous method for Levich's problem we obtain

$$Re_c \approx 22 \sqrt{p_c \rho_c} \approx 0,25 \sqrt{p_c} \approx 0,5 - 2.$$

Thus the combustion of liquid explosives as well as the combustion of gases is characterized by critical values of the Re number, calculated from the most rapidly growing disturbance, on the order of units.

In light of the present conclusion the failure becomes understandable of the attempt [186] to connect the emergence of disturbed combustion with attainment in the gaseous phase of a value of Reynolds number of the order 2000, which is characteristic for the transition of the laminar flow of a stream in tubes to a turbulent flow. The authors [186] link the emergence of turbulence with the gaseous phase and accept as the determining dimension the diameter of the tube in which combustion is conducted. However, even the authors [186] make the assumption that the Re number constructed by them does not accurately characterize the phenomenon, and they introduce the effect of heat losses outside the charge as factor of stabilization of combustion.

In certain cases the processing of experimental data using precisely this critical value of Reynolds number, which was constructed with the method given above is of doubtless interest.

§ 36. Interpretation of the Critical Conditions in the Theories of Landau and Levich

For explanation of the physical essence of critical conditions (80) and (93) we will use the method of dimensional analysis, proposed by A. D. Margolin: let us compare the values of forces which stabilize and destabilize a disturbance with characteristic dimensions ξ on the surface of the liquid. Let us take into account that departing from the surface of the disturbance are combustion products (ρ_2, u_2); gravitational force $F_0 \sim \xi^3 g \rho_1$ attempts "to wash away" the disturbance; and the forces of surface tension $F_\sigma \sim \xi \sigma$ and viscosity $F_\nu \sim \xi \eta W$, where W is a rate of "washing out" of the disturbance, attempt to agitate the decomposition of the wave of the disturbance. Hence it follows that in the case of Landau's problem the equilibrium condition (more precisely, the unaccelerated motion or relative equilibrium) takes the form

$$a_1 \xi^3 g \rho_1 + a_2 \eta \xi \approx \xi^2 \rho_2 u_2^2 \quad (95)$$

or

$$\xi_{1,2} = \frac{1}{2a_1 g \rho_1} [\rho_2 u_2^2 \pm \Delta] (a_1, a_2 - \text{const});$$

$$\Delta^2 = (\rho_2 u_2^2)^2 - 4a_2 \eta g \rho_1.$$

Let us take a plus sign before the root and analyze the result. With $J^4 = (u_1 \rho_1)^4 < 4a_2 g \rho_1 \sigma \rho_2^2 = J_*^4$ the expression for ξ becomes complex, which answers the oscillations of the surface with an amplitude of the order $\xi \sim u_1 u_2 / 2a_1 g$. Actually, comparison of (95) with the expression for the wavelength of the disturbance [see equation (83)] $\lambda_n = \lambda_0 \exp(kz - i\omega t)$, which with $n < 1$ and expansion in series near the critical point takes the form $\lambda_n \approx \lambda_0 (1 - i\omega t)$, makes it possible to conclude that $\lambda_0 \sim \xi = u_1 u_2 / 2a_1 g$,

$$\omega t = \sqrt{\frac{4a_2 g \rho_1 \sigma}{\rho_2^2 u_2^4} - 1} = \sqrt{g/k_n} \sqrt{(p./p)^2 - 1},$$

where p_* and k_n are the critical pressure and the wave number of the disturbance. The cessation of oscillations of the surface

occurs at the point $J=J_*$, $\Delta=0$, which is the critical point in Landau's problem, and the condition $J=0$ coincides with formula (80). In this case $R_*=\xi_*=u_1 u_2 / 2a_1 g$. Beyond the limit with $J>J_*$ the growth of ξ occurs in proportion to the increase in the velocity, i.e. combustion becomes unstable. In the limit with $J \gg J_*$ the force of surface tension can be disregarded and $\lim \xi = u_1 u_2 / a_1 g$ with $u_1 \rightarrow \infty$, i.e., the amplitude of the disturbance grows doubly as compared with the value at the stability limit. Let us note that this corresponds to an increase in the surface of combustion of approximately ξ^2 , i.e., approximately fourfold. Value ξ is the limiting dimension, giving an extreme estimation, and all disturbances with an amplitude of less than ξ are possible.

An analogous discussion for Levich's problem is complicated by the fact that we do not know beforehand the rate of the "washing out" of the disturbance W . Therefore from the analysis of the solution to the equation

$$\rho_2 u_2^2 \xi^2 = a_3 \rho_1 g \xi^3 + a_4 \eta \xi W,$$

$$\xi_{1,2} = \frac{1}{3a_3 g \rho_1} \left[\rho_2 u_2^2 \pm \sqrt{\rho_2^2 u_2^4 - 4a_4 \eta g \rho_1 W} \right] \quad (96)$$

the critical condition $u_2^4 \rho_2^2 = 4a_4 \eta g \rho_1 W$, by analogy with Landau's problem, we will identify with the solution of Levich (93), whence with an accuracy to the factor of the order $\sqrt{2/a_4}$ we have $W \sim \sqrt{u_1 u_2}$.

As in Landau's problem, at rates of combustion less than critical, equilibrium is reached through oscillations of the surface, and beyond the limit of stable combustion the amplitude of the disturbance grows in proportion to the increase in the rate of combustion.

The introduction of the rate of motion of the disturbance, which is the pulsating rate of the motion of the disturbance in liquid, makes it possible to express ξ_* as $\xi_* = W^2 / 2a_1 g$. Comparison with Table 20 shows that ξ_* is the dimension of the most dangerous disturbance, which grows at the limit of stability.

Above, for the examination of the amplitude of the disturbances we used only one value ξ , corresponding to a minus sign before the root, i.e., we examined a long-wave disturbance. The second value of the amplitude is the dimension of a short-wave disturbance which decreases with an increase in the rate of combustion, which makes it possible to draw a conclusion about the expansion of the spectrum of the possible values ξ with an increase in the rate of combustion.

In the range of values of the parameters, where $F_{\sigma} = F_{\eta}$, stabilization of combustion will occur because of the action of both forces.

Thus, Landau's critical conditions correspond to the moment when the forces of surface tension (or forces of viscosity in Levich's problem) cease to stabilize the motion of the surface and its vibration converts to a continuous increase of the amplitude of the disturbance.

It is interesting to note that stabilization by forces of viscosity in comparison with the forces of surface tension becomes predominant in proportion to the increase in the rate of combustion, since $F_{\eta}/F_{\sigma} \sim J\eta/\sigma\sqrt{\rho_1\rho_2}$, i.e., at high rates, combustion in essence is stabilized by viscosity.

The examination conducted makes it possible to accept ξ_{σ}^0 for the supercritical range as a measure of the amplitude of the disturbance in Landau's problem; and in Levich's problem, $\xi_{\eta}^0 \sim \sqrt{\eta W/g\rho_1}$. For combustion up to the limit of stability the measure of the amplitude of the disturbances is the value $u_1 u_2/g$. As the measure of the rate of motion of the disturbance one should take $W \sim \sqrt{u_1 u_2}$ during combustion beyond the limit of stability and $u_1 \rho_1$ in the precritical range.

§ 37. Features of the Behavior of Gelatinous Systems

Conventional liquid explosives are Newtonian systems. The rate of their deformation is directly proportional to the applied stress. However, with the thickening of liquid explosives by high polymers upon introduction of the dispersed phase, they, as a rule, become non-Newtonian or even viscous-plastic systems. In non-Newtonian liquids the sliding rate increases with stress according to the power law with index s more than one, i.e., the viscosity of such a system depends on the applied load. In connection with this for non-Newtonian liquids in Levich's problem it is necessary to use η , which corresponds to the disturbing stress $F \sim \rho_1 (u_1 u_2)_{*} = J_{*}^2 / \rho_2$. By substitution in Levich's formula (93) of the expression for η in the form $\eta = \eta_0 F^{-s}$ we find that the critical condition in this case takes the form

$$J_{*}^{3+2s} = 3 \sqrt[3]{\eta_0 g \rho_1^{1+2s} \rho_2^{(1-2s)}}. \quad (97)$$

Many gelatinous explosives exhibit plastic properties which in the simplest case are described by the model of Bingham's body [187, 189]. Bingham's body is characterized by the so-called flow point γ_0 . With shear stress F less than γ_0 there is no flow, the gel behaves as a solid. The experimentally obtained values γ_0 depend on the type of gel and lie within the limits $10^2 - 10^5$ dyn/cm² [188]. For plastic gels the limiting value of the rate of normal combustion with $\gamma_0 \gg \eta' g \rho_1 \rho_2 / J^2$ is $J_{*} = \sqrt{\gamma_0 \rho_1}$ and with $\gamma_0 \ll \eta' g \rho_1 \rho_2 / J^2$ is determined with Levich's formula (93). Here η' is the plastic viscosity.

In gelatinous systems there is dynamic surface tension, which exceeds static surface tension several times. For some systems even an ultradynamic surface tension is characteristic, which reaches 300 dyn/cm instead of the usual 30. This fact can become a rather important factor for stabilizing the disturbance, in particular during the excitation of instability with high-frequency oscillations, including those generated by the very process of

combustion [189]. As concerns the critical values of the rates of combustion, in view of the weak dependence on σ and η they can increase several times with an increase in σ or η by an order. Furthermore, the absolute values of these values change, which determine the change of factors stabilizing combustion.

§ 38. Artificial Disturbances Under Subcritical Conditions of Combustion

For subcritical conditions of combustion disturbances with an amplitude more than $\xi_{\sigma}^0 = \sqrt{\sigma/g\rho_1}$ (or $\xi_{\eta}^0 = \sqrt{\eta W/g\rho_1}$) can be only artificial, since combustion itself cannot generate them. These disturbances can be introduced from without, for example during the ignition of explosives by agitation of their container or by another method. An artificial disturbance can either "spread" to a value, comparable with "natural" disturbances, or burn out.

With low viscosity, if $\xi < \sqrt{\sigma/g\rho_1}$, then the disturbances do not break up; taking into account the results of § 36, it is possible to confirm that oscillation of the surface occurs with simultaneous combustion, whereupon $t_r < t_p$. If $\xi \gg \sqrt{\sigma/g\rho_1}$, then the disturbances spread over time of the order $t_r \sim \xi/W$. Comparison of t_p with the time of combustion of the disturbance $t_p \sim \xi/u_1$ makes it possible to conclude that with $u_1 < \sqrt[4]{\sigma g/4\rho_1} \sim 5-10$ cm/s and $\xi \gg \xi_{\sigma}^0 t_r > t_p$. Thus, large artificial disturbances under subcritical conditions virtually always burn out in time of the order $(\xi - \xi^0)/u_1$ up to dimensions of the order ξ^0 , and then they behave as natural disturbances. With high viscosity, the time of combustion of the disturbance is greater than the time of spreading, and pulsations of the surface must be absent.

Thus, in the case of nonviscous liquids artificial disturbances spread faster than they burn, whereas in the case of high-viscosity liquids the situation is reversed. Hence follows the different mechanism of the destruction of an artificial disturbance in the

subcritical range: spreading in nonviscous and burnout in high-viscosity liquids.

Near critical conditions an artificial disturbance is able "to swing" the surface of combustion to the limiting amplitude, whereas under favorable conditions (absence of disturbing effects) the range of amplitudes can not go beyond the limits of infinitesimal disturbances and combustion will go smoothly. Under these conditions a powerful external disturbance can cause turbulence of the flow of combustion products and initiate disturbed combustion which will be extinguished through oscillatory conditions. All of this can influence the recorded rate of combustion. As follows from that which was presented, a disturbance with an amplitude $\xi > \xi^0$ is powerful. Immediately let us note that in many instances this is a very low value, and in experiments special measures must be undertaken if we want to investigate the phenomenon in the pure form. Specifically, the bubbles of gas dissolved in the liquid are capable of becoming the source of a "large" disturbance.

If conditions are such, that both σ and n are small (low-viscosity liquid, low surface tension, high temperature of the surface of combustion, etc.), then the time of the spreading of the disturbance ξ will comprise $t_p \sim \sqrt{2\xi/g}$.

Theory does not give the connection of the oscillation frequency of the surface with the parameters of combustion. Qualitatively, however, it is possible to expect the following. In proportion to the approach to the critical point, oscillations of the surface of combustion, caused by disturbances, will die out slower and slower, since the equilibrium (without oscillations) is reached in the approach to the critical point from the side of lower rates of combustion. In the early stage of the precritical range the fading of pulsations occurs rapidly and the initial disturbances are dissipated, without introducing distortions into the development of the process of combustion.

§ 39. Features of Combustion in the Precritical Range

In the precritical range of combustion, as the analysis in the preceding sections of the chapter showed, the time of the combustion of disturbances generated by the process of combustion, frequently proves to be less or comparable to the time of the spreading of the disturbances. Oscillations of the surface of combustion during the simultaneous motion of disturbance waves create the convective mixing of a layer of the liquid of some thickness, adjacent to the surface of combustion. Disturbances of the surface amplify heat exchange in the surface layer and are capable of expanding the thoroughly-warmed layer because of the supplementing of conductive heat transfer by convective [38]. If weak agitation of the surface of liquid is able to increase the entrance of vapors into the gaseous phase, which can be observed in substances with a hot flame, then the intense intermixing of the near-surface layer can cool the thoroughly-warmed layer, and also the zone of the chemical reaction to such a degree, that the conditions of thermal equilibrium will be destroyed and combustion will die out.

In limiting situations the intense agitation (mixing) of the thoroughly-warmed layer of liquid with the underlying cold masses leads to heat loss from the reaction layer. This creates the prerequisites for a paradoxical effect: the emergence of the disturbance of the liquid near the stability limit, there, where there are oscillations of the surface and a spreading of the disturbances, which may lead to an increase in the critical diameter of combustion $d_{кр}$. Beyond the stability limit where oscillations are absent, the indicated phenomenon is impossible.

It is logical to assume that if the amplitude of the disturbances is considerably greater than the thickness of the thoroughly-warmed layer, and time of the combustion of the disturbance is greater than the time of spreading t_p , then one may expect the effect of oscillations of the surface on $d_{кр}$, and in the case when

$t_r < t_p$ damping is possible. Comparing the thickness of the thoroughly-warmed layer $l \sim \kappa_1 / u_1$ with $\xi \sim u_1 u_2 / g$ (where κ_1 is the coefficient of thermal conductivity of liquid explosives), we find that the condition for the emergence of the considered effect is the satisfaction of the inequalities $u_1^3 \gg \kappa_1 \rho_2 g / \rho_1$; $t_r > t_p$.

The precritical range of combustion, characterized by fluctuations of the surface of the liquid, also exhibits the peculiarity, that in it the rate of combustion is increased several times in comparison with the normal rate (without fluctuations of the surface) because of deformation of the surface of combustion, and the value of the rate itself depends on the introduction of artificial disturbances of combustion from without. The passage through the critical point removes the uncertainty of the size of the surface of combustion; the transition must be characterized by a sharp discontinuity in the dependence of the rate of combustion on pressure, since beyond the stability limit oscillations with limited amplitude are changed (according to Landau's theory) by an increase in the amplitude of the disturbance without oscillations. All this makes it possible to consider it natural that between the range where $\kappa_1 / u_1 > (u_1 u_2 / g)$ (disturbances do not affect combustion) and the critical point, the recorded average rate of combustion of a charge of liquid explosives can lie within the limits from the normal rate to a rate increased 2-4 times (proportionally to an increase in the surface of combustion as a result of its deformation during oscillations).

The decomposition of the standing wave of the disturbances (appearance of an imaginary part in expressions for the value of the amplitude of the disturbance) in the subcritical range of combustion gives rise to a progressive or rotary wave which, as though "overflowing" departs from the point with the greatest local pressure. Since a pressure drop is generated by the combustion of the disturbance waves themselves, for a measure of the rate of motion of such waves let us accept the rate of "spreading". This means that in a round container where the wave will rotate, the

rotation frequency depends on the diameter of the container d and the rate of combustion as $f \sim W/d \sim u_1 \sqrt{\rho_1} / d \rho_2 \sim \sqrt{p}/d$. In a plane container one should expect the emergence of a traveling wave whose rate will be of the order $W \sim \sqrt{u_1 u_2}$.

§ 40. The Possibility of the Emergence of Turbulence in the Molten Layer of a Burning Solid Explosive

Sometimes the agitation of the surface molten layer of burning solid fusing explosives is considered as one of the important factors, which contribute to the transition of combustion to disturbance and explosion [85]. Using dimensional equations, let us estimate the possibility of the emergence of the indicated effect.

From dimensional considerations it may be concluded that for developing a disturbance the thickness of the layer of fusion l_n must exceed the value of the order of the wavelength of the disturbance ξ . Since

$$l_n \sim \frac{\kappa_1}{u_1} \ln T'; \quad \xi \sim \frac{u u_2}{g}; \quad T' = \frac{T_* - T_{nn}}{T_{nn} - T_0},$$

where T_* , T_{nn} , T_0 are temperatures respectively of the surface of the burning explosive, of fusion of the explosive and the initial temperature of the charge, then $l_n \gg \xi$ is equivalent to the condition

$$a_1 \kappa_1 g \rho_1^2 \ln T' \gg J^2,$$

where a_1 is a constant.

If in the layer of fusion of the explosive stabilization of the disturbance is effected by the forces of viscosity, then for developing a disturbance it is necessary that the rate of combustion exceed the critical value according to Levich [formula (93)]. The necessary condition of the disturbance of the combustion of fusion takes the form

$$a_1 \kappa_1 g \rho_1^2 \ln T' > J^0 > 3 \sqrt{3} \eta \rho_1^{1/2} p_*^{1/2}, \quad (98)$$

or

$$\frac{a_1 \kappa_1 p_*^{1/2}}{3 \sqrt{3} \eta \rho_1^{1/2}} \ln T' > 1, \quad (99)$$

which (in order of values) answers the condition

$$\eta \sqrt{p_*} \ll a_2$$

(η , poise; p_* , atm; $a_2 = \text{const} \approx 1$). With $\eta > 1$ poise $p_* \ll 1$ atm, and considerable pressures p_* are possible only with $\eta < 1$ poise. However, as noted above, with $\eta < 1$ poise the basic stabilizing effect is exerted by surface tension. In this case instead of (99) the inequality $a_2 u_1 / p_* \gg 1$ is obtained, where a_2 is a constant of the order of one; u_1 is the linear rate of combustion; p_* , atm. Such an inequality is never satisfied in the range $p_* > 1$ atm, since $u_1 = B p_*^v$, where $B = 10^{-1} - 10^{-2}$ cm/s · atm^{1/v}, $v \leq 1$.

Thus, the development of disturbances in the layer of fusion is unreal. Only at initial temperatures, very close to the melting point, $T_0 \approx T_{\text{пл}}$, when the substance is practically all liquefied, can the considered effect occur, since in this case there will be no fundamental difference from a viscous liquid.

§ 41. Combustion Stability Under Variable Pressure [179]

During the combustion of liquid explosives under conditions of rising pressure a significant role is played by the relation of the growth time of the disturbance t_0 and of the time of the change in pressure t . If $t_0 \gg t$, then the disturbances do not have time to develop, and with $t_0 \ll t$ combustion will be similar to combustion under constant pressure. It is possible to consider that the criterion of stability during combustion under conditions of rising pressure is the expression

$$t_0/t \approx \text{const} \approx 1. \quad (100)$$

Since t_0 rapidly decreases during a pressure increase (see Table 20), it is sufficient to examine the criterion (100) near the critical conditions, which are characteristic for combustion under constant pressure (Landau's theory and Levich's theory). Let the critical pressure under conditions of rising pressure be p_{HP} , and the corresponding rate J_2 . Then

$$1/t = \dot{r} \sim \frac{1}{p_{HP}} \left(\frac{dp_{HP}}{dt} \right)_r; \quad t_0(p_{HP}).$$

With $n=J/J_* = 1+\delta$, $\delta \ll 1$, we obtain:

a) in the case of low viscosity (with $u_1 \sim p$):

$$2\dot{r} \sqrt{\delta g k_0} = 2\dot{r} \sqrt{\delta g^{1/2} \rho_1^{1/2} / \rho_1^{1/2}} \sim 2\dot{r} \sqrt{\rho_1^{1/2} g^{1/2}} \sqrt{(p_{HP} - p_0) / 2p_0} \approx \text{const} \approx 1; \quad (101)$$

b) in the case of high-viscosity systems:

$$3/2 \dot{r} \delta \sqrt{g k_0} = \frac{3}{2\sqrt{2}} \dot{r} \eta^{-1/2} g_1^{1/2} \rho_1^{1/2} (p_{HP} - p_0) / p_0 \approx \text{const} \approx 1. \quad (102)$$

In the particular case during the combustion of a charge of liquid explosives in a manometer bomb under the law of the combustion of explosives of the form $u_1 = Bp^\nu$, the characteristic time of pressure change is

$$\dot{r} = 1/t = V \rho_2^0 / B S p \rho_1 = V M p^{1-\nu} / B S R T_2 \rho_1,$$

where S is the area of the surface of combustion; V is the volume of the bomb; T_2 is the temperature of the combustion products; R is a gas constant; M is the molecular weight; for many liquid explosives $\nu=1$.

In other words, in a manometer bomb with low viscosity and $\nu=1$

$$(p_{HP} - p_0) / p_0 \sim (S/V)^2,$$

and with high viscosity and $\nu=1$

$$(p_{HP} - p_0) p_0 \sim (S/V).$$

When $V \rightarrow \infty$, $p_{kp} \rightarrow p_*$, i.e. the combustion proceeds analogously to the case of a bomb of constant pressure. Thus, during the combustion of liquid explosives in a manometer bomb the critical pressure p_{kp} turns out to be all the greater than p_* , the faster the pressure buildup occurs in the volume of combustion, whereupon viscous systems, other conditions being equal, yield a large difference ($p_{kp} - p_*$) in comparison with low-viscosity explosives.

For illustration of the obtained result we will turn to the diagram in Fig. 98. Here p_* is the critical pressure of normal combustion under conditions $\dot{p}=0$, i.e. of combustion in a bomb of constant pressure, p is the current pressure, τ is time.

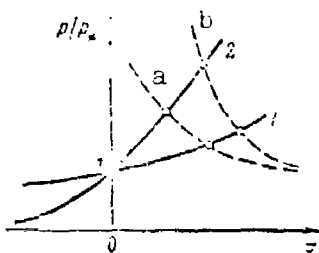


Fig. 98. Effect of the rate change of pressure in the volume of combustion on the critical pressure of normal combustion.

Let us assume two experiments with different rates of pressure buildup in the volume of the bomb: \dot{p}_1 and \dot{p}_2 (curves 1 and 2), whereupon $\dot{p}_1 < \dot{p}_2$. We will begin counting time from the moment $p=p_*$. In coordinates $p/p_* - \tau$ the dependences of the time of development of the disturbances in Landau's problem (curve a) and in Levich's problem (curve b) have the form of hyperbolas, which asymptotically approach $p/p_*=1$ with $t \rightarrow \infty$. According to (101) and (102) and Table 20, curve b lies in the range of higher values of time and proceeds more steeply than curve a. The collision points of curves 1 and 2 with curves a and b determine the value of the critical pressure which will be observed during combustion under rising pressure. In this case the faster the pressure increases, the higher is the critical pressure, and at equal \dot{p} high-viscosity systems (Levich's problem) give higher values of p_{kp} than low-viscosity systems (Landau's problem).

§ 42. Questions of the Theory of Combustion of Liquid Explosives Beyond the Stability Limit

The theories of the hydrodynamic combustion stability of liquid explosives of L. D. Landau and V. G. Levich in the form presented above provide a stability criterion, but they cannot predict the nature of the process above the critical pressure. In this sense a theory of developed disturbed combustion has not yet been created.

Let us examine the picture of the flow of combustion products of a disturbed liquid substance. In this case we will use the results of corresponding discussions, carried out for gas flames [185] taking into account the fact that unlike gas systems where $\rho_1 = \rho_2$, in the case of liquid substances $\rho_1 \gg \rho_2$.

Flow of Combustion Products During Disturbed Combustion

During the combustion of the flat undisturbed surface of a liquid the flow of combustion products is irrotational and (disregarding lateral effects) one-dimensional. However, beyond the stability limit the picture of flow changes sharply. Emerging from the deformed surface of the liquid, the products of vaporization, during expansion in the process of reaction, can form vortices, since the flow of gas becomes three-dimensional and is not barotropic. Calculations [185, 190] show that the vortices are formed over the surface of flame unevenly. The greatest intensity of vortex formation appears near the bending points of the deformed shape. This process is illustrated by the diagram in Fig. 99, taken from [185]. As can be seen from the diagram, vortices attempt to expand the gas flow (with flame) in such a way that the convex sections move forward, and the concave sections remain, i.e. the initial disturbances increase. The vortices produce a disturbance of pressure whose gradient is directed across the flame from convex places to concave ones. The distance from the surface of the

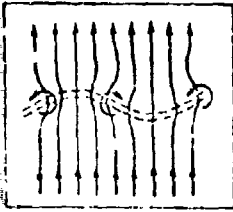


Fig. 99. Diagram of the formation of vortices in combustion products as a result of the deformation of the front of the flame.

liquid to the turning place of the lines of flow depends on the degree of thermal expansion in the flame and increases with an increase in u_2 . Hence it follows that the higher the pressure, the nearer to the surface of liquid the vortices are formed.

The existence and the behavior of a gas flame reproduce, in an enlarged form, the picture of the arrival of vapors from the surface of the liquid. The oscillations of the surface, mixing of the surface of the thoroughly-warmed layer by disturbance waves; all this is immediately reflected in the flame. At the moments and in the ranges of intensification of vapor formation occur the deflection of the gas flame from the surface of the liquid and the drift of the flame from the flow of vapors. A decrease in the arrival of vapors leads to the approach to the surface by the flame which is spreading on the vapor flow; this leads to an increased arrival of heat from the flame to the liquid and the acceleration of vapor formation. Pulsations of the gas flame appear.

As noted above, the theory does not provide a connection between pulsations, surface irregularities during the development of disturbed combustion and stability conditions. It is possible to assume that the dimensions of inequalities during developed disturbed combustion are connected with the dimensions of the most dangerous disturbances, which are derived in stability theory. An analogous phenomenon occurs in so-called cellular gas flames [184, 185], where the size of a cell is connected with the dimensions of the most rapidly growing disturbance. It is possible to visualize that basically some disturbances increase for which t (characteristic) is minimal under given conditions, and their increase suppresses the development of other disturbances. When disturbances reach sufficiently large amplitude, their growth ceases due to nonlinear processes and a constant rate of disturbed combustion is established.

It is necessary to note one very important fact [177]. The theories of hydrodynamic stability have been developed in linear approximation, and that is why they are accurate with infinitesimal amplitudes of the disturbances.

The instability of a flame in this approximation still does not mean that its autoturbulence must arise. With an increase in disturbances nonlinear effects can appear, which will stabilize deformations of the surface of combustion and prevent the further development of disturbances.

According to conclusions from Landau's theory, beyond the stability limit an increase in the amplitude of the most dangerous disturbance λ_n occurs. With an increase of n the size of λ_n decreases rapidly, as well as the time of its development. If the value of the disturbance λ_n is great in comparison with the width of the combustion zone (and only this case is examined by Landau's and Levich's theory of the limits of stable combustion), then together with the surface of the liquid the surface of the chemical gas-phase reaction is deformed (here is meant the zone of reaction in the vapors nearest to the surface of liquid, which most strongly affects the rate of combustion in volatile systems). Actually, the comparison of the times of the development of disturbances t and of the relaxation of the process of combustion t_r shows that always $t > t_r$. It is clear that an increase in the surface of combustion must involve an increase in the mass rate of combustion. The effect of deformation of the surface of the burning liquid on the rate of combustion has been noted by a number of authors [37, 191].

It is interesting to note that upon transition through the critical rate the recorded rate of combustion had to grow with a jump, since immediately after $u=1$ the surface of combustion begins to be developed because of an increase in the amplitude of the most dangerous disturbances.

Since in Landau's and Levich's theory precisely this increase in the amplitude of the disturbances determines the development of the process of combustion (and consequently its regularity), it is necessary to examine the question of how strongly the disturbance of the surface can develop.

In Landau's and Levich's model the increase in the amplitude of disturbances is not limited. However, in actuality there are factors which substantially limit this increase. So, the amplitude of the deformation of the surface of the liquid, which grows, according to the model of Landau and Levich, from an infinitesimal disturbance, is limited from above by the energy of the disturbing effect of the flow of combustion products. The amplitude of such a disturbance ξ is connected with the rate of flow as

$$\xi g \rho_1 \approx \frac{1}{2} \rho_2 u_2^2,$$

that gives $\xi < u_1 u_2 / 2g$.

At the critical point $\xi = \xi_* = (u_1 u_2)_* / 2g = \lambda_* = 2\pi / k_*$. The values k_* are calculated above.

Artificial disturbances with an amplitude of more than $u_1 u_2 / g$ will "spread" to these dimensions,¹ and then their evolution will not differ from the development of spontaneous disturbances. With respect to this form of disturbances in the sense considered here the conclusions of § 37 are applicable.

¹It should be noted that the effect of the interaction of the liquid with the walls of its container is not considered here. In the case of small diameters of the container and high adhesive force of liquid (for example viscous, gelatinous) the material of the container acquires a very significant factor, which interferes with spreading.

The Separation of Drops from the Burning Surface of Liquid

Let us pass to the discussion of a very important phenomenon for the unstable combustion of liquids : the separation of drops from the surface of liquid by the flow blowing on it.

The formulation of the problem of the separation of drops from the surface of liquid coincides with the problem, solved by Landau [73] and Levich [74], if instead of the rate of combustion we examine the speed of the flow which is blowing out. By putting to use the methods of dimensional theory, this can be shown in the following manner.

If the dimension of the drops, being separated from the surface of the liquid, is r_K , the speed of the flow which is blowing out is u_2 , density ρ_2 , and the density of liquid ρ_1 , then the force, which acts on the surface of the liquid from the side of the flow is

$$F_K \sim \rho_2 u_2^2 r_K^2, \quad r_K \sim u_1 u_2 / g.$$

The force of surface tension, which resists separation,

$$F_\sigma \sim \sigma r_K.$$

If viscous forces impede separation, then

$$F_\eta \sim \eta u_2 r_K.$$

Comparing F_K with F_σ or F_η , we obtain the critical conditions of separation $F_\sigma / F_K \approx 1$ and $F_\eta / F_K \approx 1$, which coincide with an accuracy to constant factors with the criteria of Landau and Levich respectively. This, the satisfaction of these criteria denotes the beginning of the process of separation of drops from the surface of liquid. It is simultaneously known that the entrainment of drops of liquid becomes noticeable, when rate of evaporation reaches a value of the order $5 \cdot 10^{-2} \text{ g/cm}^2 \cdot \text{s}$ [192], which is a very low value, considerably less than the usual level of the rate of combustion.

This phenomenon can introduce a supplemental contribution into the process of the removal of the drops of liquid to the gaseous phase.

The flow of combustion products along the surface of the liquid appears as a result of vortex formation and the 3-dimensional nature of the picture of the flow of products. The separation of drops occurs from the wave crests of the disturbances, during which the irregularity of the surface facilitates this process. The action of the swirled gas flow on the surface of the liquid smooths its contour.

The higher the rate of combustion in comparison with the critical, the more the minute disturbances are able to develop on the surface of the burning liquid. Simultaneously the rate of flow increases. Actually the disturbances are not able to grow, and the process of vaporization in essence is replaced by the separation and entrainment into the gas flame of microdroplets of liquid. The thoroughly-warmed layer in the liquid phase virtually disappears. Actually, with $u_1=10$ cm/s, which is realized experimentally [38, 193], the thickness of the thoroughly-warmed layer of liquid would be $\sim 1 \mu$, and time of presence in it $\sim 10^{-5}$ s, which is too small to consider that any substance can burn under such conditions by the usual thermal conductivity mechanism, whereas the experiment confirms: the capability for disturbed high-speed combustion is practically independent of the chemical nature of the liquid explosives. From the viewpoint of the initial liquid substance during combustion beyond the stability limit thermomechanical erosion occurs with the subsequent treatment of the explosive in the vortex flame.

It is interesting to note that the picture of combustion beyond the stability limit can depend strongly on the mechanism of combustion. We build all discussions on the assumption of the gas-phase prominent reaction of combustion. If an explosive, during its combustion, undergoes significant k-phase reactions, then it is possible to expect a number of complications of the picture.

Specifically, the disturbance of thermal equilibrium in the k-phase can lead to the fading of combustion upon transition to developed disturbed conditions, or the inhibition of ignition up to failure.

Rate of Combustion of ZhVV Beyond the Stability Limit

The introduction of the hypothesis that the treatment of a liquid explosives, stripped off by the flow of swirled gas, occurs in the turbulent high-temperature flame, makes it possible to solve the problem of the value of the rate of disturbed combustion. The fact is that in a turbulent flame the kinetic peculiarities of an explosive fall back to the second plane and the reaction rate in the flame is very great and does not limit the treatment of the initial substance. The limiting stage becomes the growth of disturbances and inequalities which "are cut off" by the vortex flow and taken away into the flame for combustion. Hence it follows that the rate of combustion under disturbed conditions u_T is limited by the rate of growth of the disturbances, i.e.

$$u_T \sim v_n = \lambda_n / \tau_n, \quad (103)$$

where λ_n and τ_n are the dimension and time of the development of the most dangerous disturbance (see Table 20), v_n is the rate of its increase.

In view of the unwieldiness of the expression for u_T in the general form let us observe initially the evolution of value u_T using data of the calculation for nitroglycol (see Table 19). In Fig. 100 value v_n is built in logarithmic scale depending on J/J_n . Upon transition through $n=1$, the value v_n grows sharply from zero. The slope of curve $\bar{v} = d(\ln u_T) / d(\ln n)$, which characterizes the dependence $v_n \sim n^{\bar{v}}$, decreases from ∞ through intermediate values to $\bar{v}=0.5$. Approach to $v=0.5$ proceeds asymptotically in proportion to the increase in n and is satisfied with $n \gg 1$.

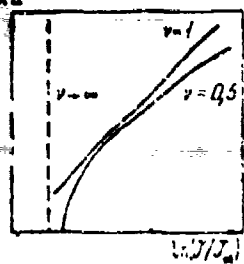


Fig. 100. Dependence of rate of combustion beyond the stability limit on $n=J/J_*$ for nitroglycol.

An expression for the limiting ($n \gg 1$) form of the dependence u_T on the parameters of combustion can be obtained from the following physical prerequisites. The limiting value of the rate of combustion will be proportional to rate of the escape of liquid from surface and is limited by the energy of the flow. This makes it possible to write, that at the limit:

with

$$(J/J_*) \sqrt{\rho_2^* u_1^*} \gg 1, (u_T - u_1)^2 \rho_1 \approx \rho_2 u_1^2; \quad (104)$$

$$(u_T - u_1) \approx u_1 \sqrt{\rho_1 / \rho_2},$$

where $u_1 = B p^v$ is the normal rate of combustion of the liquid in the absence of disturbances.

It is convenient to introduce critical values of the rate of combustion and pressure u_1^* and p_* , after which the form of the expression for the rate will be the following:

$$u_T = B \left[p^v + \sqrt{\frac{\rho_2}{\rho_1}} p^{v-0.5} \right] = a (p/p_*)^v + a_1 (p/p_*)^{v-0.5}$$

with

$$u_T \gg u_1 \quad u_T = a_1 \frac{u_1^*}{p_*^{v-0.5}} \cdot p^{v-0.5}, \quad (105)$$

where a, a_1 are constants.

Thus, the rate of developed disturbed combustion depends on the value of the critical parameters $u_1^*/p_*^{v-0.5}$ and on pressure to the degree $(v-0.5)$. Comparing this result with the data calculated for nitroglycol (see Fig. 100), we are convinced that the limiting form $u_T(p)$, obtained from expression (103) and using (104) coincide. The same result of course is obtained from Table 20 for $n^4 \gg 1$.

If under these conditions of combustion λ_n calculated for a container of infinite diameter will not be realized, then the

increase of value v_n will take place more slowly, i.e., one should expect that for arrival at the limiting dependence $u_T(n)$ higher values of J/J_* will have to be reached.

For the most dangerous disturbance the rate v_n can be written in the form

$$v_n = 2\pi \sqrt{g/k_*} \cdot (x\tau)^{-1} = 2\pi\varphi \sqrt{g/k_*}, \quad \varphi = 1/2\pi.$$

The value of φ does not depend on the properties of the explosive (they affect the value of k_*). This makes it possible to construct universal dependences $\varphi(J/J_*)$ for Landau's problem - φ_δ and for Levich's problem - φ_η . From the comparison of curves $\varphi_\sigma(J/J_*)$ and $\varphi_\eta(J/J_*)$ it follows that in the case of viscous systems the arrival at the asymptotic dependence occurs more slowly.

It is very probable that in view of $\sigma \rightarrow 0$ during the approach of the temperature of the surface of the liquid and the pressure to critical values the transition occurs of the dependence $\varphi(n)$ with the curve φ_σ to φ_η , which leads to the later arrival of the rate of disturbed combustion at the limiting dependence.

• Formula (104), from other considerations, was obtained for the first time by A. D. Margolin.

• The difficulty in using expression (104) lies in the fact that for determining the rate of combustion far from the limit it is necessary to consider that in the absence of disturbances (repression of them by one method or another) the rate law, characteristic for subcritical conditions, remains in force. The constant a must be determined experimentally. It reflects the ability of liquid to be split up into drops and also the kinetic of the reaction of the latter.

Let us note that expression (103), correctly, is outside of the dependence on the predominant factor of stabilization, be it surface tension or viscosity. Only the value of the critical values changes.

Thus, beyond the stability limit combustion takes place by the mechanism of the separation of drops and their combustion in the vortex gas flame. Due to the vortex nature of flows in the gas, the flame becomes turbulent, with a high degree of homogeneity of the temperature on the flame, caused by the recirculation of gas. The vortices of high-temperature gas separate drops of liquid from the disturbances and throw them into the gas at a temperature equal to the final temperature, where accelerated heating and combustion of the liquid occurs. Combustion bears a truly turbulent nature. The energy source of process as a whole is the gaseous phase. The recirculation of the final high-temperature combustion products provides the high effectiveness of the process of combustion. Since u_T depends on final temperature and the composition of combustion products through the dependence on ρ_2 , the absolute value u_T (other conditions being equal) must be more in systems with an increased value $\sqrt{RT_2/M}$, where M is the molecular weight of the combustion products, R is the universal gas constant, T_2 is temperature of gas. Hence it follows that in mixtures of liquid explosives the maximum of the rate of disturbed combustion must occur near the stoichiometric relationship of the components (see § 44).

From that which was presented above it also follows that during combustion beyond the stability limit particles of the original substance pass continuously into the flame.

The vortex motion of gas is able to create clusters of drops, the thermal explosion of which can become the reason for the initiation of an explosion and, apparently, even of the development of detonation of the charge of liquid explosives. This scheme of the initiation of explosion is proposed in practically all works dedicated to this question. Unfortunately, the absence of direct experimental proofs and the severe difficulties of obtaining them force us to examine the possibility of the realization of such a mechanism only indirectly.

CHAPTER VII

EXPERIMENTAL STUDIES OF THE HYDRODYNAMIC COMBUSTION STABILITY OF ZhVV

The most detailed survey of the experimental works dedicated to the analysis of combustion stability of ZhVV [HBB - liquid explosive] and to the transition of their combustion into an explosion is contained in K. K. Andreyev's monograph [38], and when this is expedient we will limit ourselves to reference to this book. However, [38] does not include all the works, or the comparison of theory and experiments is presented incompletely.

§ 43. Methods of Studying the Combustion of ZhVV

There is no need to prove the great influence of the method of experiment on the results obtained and, consequently, also the conclusions from the investigation. The theory of the hydrodynamic combustion stability of ZhVV is constructed under the assumption of the infinitesimal dimensions of the acting disturbances in comparison with the thickness of the combustion front. Unfortunately, in the experiments for checking the theory this requirement is difficult to fulfill, since the permissible dimensions of disturbances introduced by the ignition system turn out to be very small. Furthermore, only sometimes is the necessary information about the parameters of ZhVV and combustion products available. All this to a certain extent impedes the quantitative comparison of theory and the results of experiments.

During the study of combustion of ZhVV the usual methods of determination of the basic parameters of explosives and powders are used [18]. The combustion of ZhVV takes place in bombs of constant (more precisely, slightly changing) pressure both at normal and at elevated temperatures, in manometer bombs, and also Andreyev tubes. The time (rate) of combustion is found by the methods of burning wires, photo-cinema-recording, and at low velocities of the process - by the measurement of burn-up time with the aid of a stopwatch.

The method of ignition is of great significance. Usually heated electric spirals, immersed directly into the tested substance, are used. For facilitation of ignition the use of a transition layer made of gelatinized nitroglycol, diglycoldinitrate, etc. is useful. However, even an interlayer made from gelatin does not ensure the absence of end disturbances which is required by theory. The best results in the solution to this problem are obtained by the following method. On the surface of the investigated substance a layer of slowly burning liquid 5-7 mm high is poured. It has a specific gravity which is less than that of the studied ZhVV. In this case it is necessary that the auxiliary ZhVV under these experimental conditions would burn normally. It is convenient to use the following ZhVV: at pressures up to 80 atm - ethyl nitrate ($\rho_1 \approx 1.1 \text{ g/cm}^3$), at pressures between 50 and 130 atm - nitromethane ($\rho_1 \approx 1.12 \text{ g/cm}^3$).

Another method for ensuring the undisturbed nature of ignition entails the utilization of a manometer bomb: the inflammation of the charge at a low pressure, far from the limit of stable burning, at a sufficiently low rate of pressure buildup in the bomb makes it possible to attain the damping of the external disturbances, connected with the ignition of explosives, by the moment of achievement of the investigated pressure range.

During the study of the temperature distribution in the burning ZhVV a significant difficulty appears: the liquid envelops

the joint of the thermocouple at the moment of the exit of the latter from the condensed phase into gaseous, and this introduces known distortions. Nevertheless the maximum temperature and the shape of the heating wave in the k-phase can be recorded with a good reproducibility.

Of great interest were the observations of the state of the burning ZhVV which were made through the layer of liquid using the layout in Fig. 101. The charge of ZhVV was poured into a glass tube with a flat bottom 3. Through a prism with an angle of 45° a high-speed movie camera 4 is used to photograph the layer of liquid with a height on the order of the depth of focus near the plane of focusing 2. At filming speeds on the order of 2000 frames in 1 s with 1.5-3 enlargement it is possible to obtain useful information about the dynamics of behavior of the burning liquid [178]. Stereo filming (two cameras arranged at an angle of 90° to each other) made it possible to fix the spin motion of the flame [177].

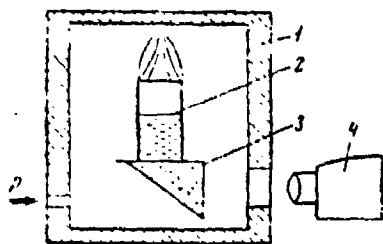


Figure 101. Diagram of photographing of combustion of a ZhVV through the lower end of the charge: 1 - bomb; 2 - surface of the burning liquid; 3 - prism with angle of 45° ; 4 - movie camera; p - supply of pressure.

The study of the transition of the combustion of ZhVV into an explosion was initially conducted in Andreyev tubes [37], later [191] bombs of constant pressure with high-speed photoregistration of combustion were used. Some experiments were set up in manometer bombs.

An increase in the viscosity of ZhVV as a rule is done by dissolution of the appropriate high polymer (usually pyroxylin or polymethyl methacrylate).

In work [177] a track method was proposed for the study of unsteady combustion. Its essence lies in the fact that in the investigated ZhVV (in work [177] this was nitroglycol) a minute quantity (0.01-0.02%) of dye is dissolved, for example nigrosine (black organic dye). After the combustion of the ZhVV with this addition on the walls of the cup a track remains which reproduces the form of movement of the flame and reflects its interaction with the flow of the ebbing vapors of the explosive. An analogous method of observation is applied during the investigation of shock waves and spinning detonation.

§ 44. Laws Governing the Combustion of ZhVV

The typical pattern of changes in the combustion behavior of ZhVV under constant external pressure depending on the magnitude of the latter has been described repeatedly [38]. In a general form it is possible to present the following sequence of processes observed during the study of combustion in pressure dependence:

1. Range of smooth burning. It is characterized by an even flame front, by the stationary propagation of combustion. The dependence of rate of combustion on pressure here is usually very close to linear.
2. Near-critical transition region of combustion. In the beginning of this region at low pressures during careful ignition (through the interlayer of liquid) here it is possible to obtain metastable normal values of combustion rate which satisfy the dependences for the range of smooth burning. In certain cases it was possible to fix the damping of the initial disturbance on the path in 5-10 mm and transition to the normal rate of combustion. The picture of combustion in this case will be usual and stable, and only special methods (track) make it possible to reveal the features of combustion. However, intensive ignition (for example directly from an electric spiral) initiates the disturbed combustion of the liquid. As a rule, but not always, pulsations of flame

appear, the average rate of combustion increases maximally by 2-4 times. Observations from the end through the layer of liquid [178] prove the existence of the different modes of vibrations of the surface.

3. Range of developed turbulent combustion (supercritical area). For this mode of combustion are characteristic first of all very high rates of combustion, a diffuse front of combustion, fine-scale flame-generated turbulence. Near the limit the dependence of combustion rate on pressure is much more strongly linear. During intense ignition the transition of combustion to explosion is feasible.

Clearly it is not always possible to isolate all the indicated modes of combustion, since some can be missing (areas 1 and 2), or they can occupy a narrow interval of pressures or overlap. Let us pass to the examination of the indicated modes of combustion.

Smooth Burning

Beginning from the pressure at which the ignition of ZhVV in a container of given diameter occurs (it is caused by thermal factors) and up to a certain pressure which is different for different ZhVV, a slow uniform combustion is observed. Thus according to the data of Andreyev [38], nitroglycol at a diameter of glass tube of 3-4 mm burns stably at pressures of more than half an atmosphere, and with 1 atm the rate is approximately 2 cm/min. In this case the combustion front is even, the flame, as a rule, is weakly luminous, its temperature is relatively low. Reactions in the flame do not go to the end, only the most active stages are realized. This flame is called initial.

In proportion to the increase in pressure the degree of completion of the reactions of combustion increases, the temperature of the flame is increased, and at a certain considerable distance from the surface a high-temperature secondary flame appears. The

appearance of the secondary flame is not reflected either on the velocity of combustion or on its dependence on pressure.

The rate of the smooth burning of ZhVV at a given pressure, as all explosives in general, depends on the initial temperature, increasing with an increase in the latter, and also on the diameter of the container in which the combustion takes place. The influence of the diameter of the container was examined in a number of works [38, 186, 195], and from different points of view. Apparently one should consider first of all two phenomena: the influence of the meniscus of the liquid on the true surface area of combustion and heat transfer into the liquid on the walls of the tube from the flame and from the liquid through the walls outside (heat loss). In work [195], and also [186], the influence of the meniscus was considered experimentally, but this did not give any interesting results. Apparently, the most important are the effects of heat exchange. In this case the heat transfer on the walls from the hot secondary flame leads to the heating of the ZhVV and an increase in velocity, but a decrease in the diameter contributes to the strengthening of the effect. Specifically by this effect we are inclined to explain the higher rate of combustion of a number of investigated ZhVV (Fig. 102) in containers of small diameter. Heat transfer outside is especially important at low rates of combustion with incomplete heat release. Simultaneously an increase in the diameter of the container lowers heat losses from the gaseous phase and contributes to the course of secondary reactions. It has been experimentally established that an increase in the diameter of the container lowers the magnitude of pressure for the appearance of the secondary flame [37]. Filming shows that in the range of smooth burning the artificial disturbances of the burning surface of a ZhVV die out rapidly.

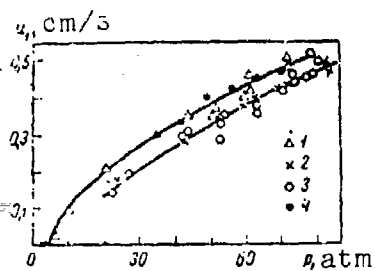


Figure 102. Influence of the tube diameter on the rate of smooth burning of ethyl nitrate: 1 - $d=3.8$; 2 - 5; 3 - 7; 4 - 3 mm.

Near-Critical Range of Combustion

Theory gives a stability criterion, but it cannot predict the details of the process near the critical pressure. The tests showed that if during smooth burning the surface of the liquid within the limits of resolution of photographic recording is smooth, then in the near-critical range the picture of combustion is substantially different. Upon reaching of a certain rate of combustion the surface of the ZhVV begins to be distorted. It is reproduced during photoregistration by an eroded undulating line; the flame at times is approached at a high speed and again thrust back, or it arrives in rotation; the rate of combustion increases sharply and combustion becomes nonuniform. During a pressure increase the blurring of the surface decreases, and the dimension of inequalities decreases. High-speed filming shows that the process of the emergence of flame pulsations begins precisely from the disturbance of the surface of the liquid. On the basis of observations of drops of ZhVV which move from the surface into the zone of the flame, in work [177] the conclusion was made that the agitation of gas flow begins from the surface. Figure 103 shows the frames of the high-speed filming of the unstable combustion of nitroglycol in a container with a rectangular cross section of $10 \times 2 \text{ mm}^2$. The liquid is seemingly pumped from side to side, and over its surface an interference wave of less dimensions passes. The period of the basic wave form is $\sim 0.2 \text{ s}$. Soon after inflammation the first and second harmonics of such fluctuations were observed. Bandwidth, which corresponds to the surface of the liquid, is changed, which indicates the fluctuations of the surface in the direction of the smaller dimension of the container.

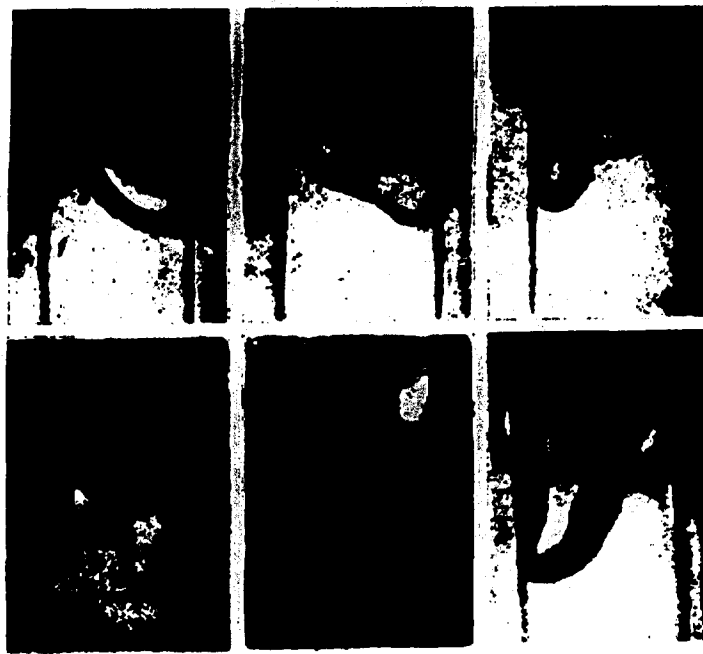


Figure 103. Frames from the filming of the combustion of nitroglycol in a container of rectangular cross section 2×10 mm: 1 - substance; 2 - surface of liquid; 3 - flame.

Figure 104a shows three half-waves, which were formed during the combustion of nitroglycol in a container of rectangular cross section, while Fig. 104b gives a motion-picture frame which shows the shape of surface, characteristic for the combustion of liquid DINA and diglycoldnitrate.

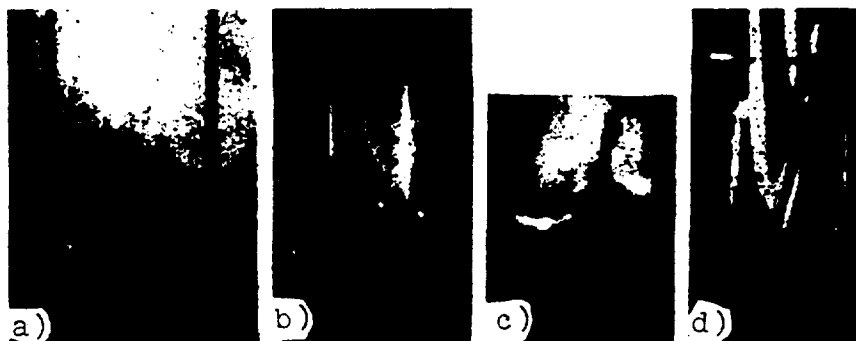


Figure 104. The motion-picture frames of the combustion of ZhVV: a) nitroglycol, container 2×10 mm, three half-waves on the burning surface; b) motion-picture frame of spin combustion (diglycoldinitrate) in a circular cup; c) the formation of a "fountain" in the center of a tube (diglycoldinitrate); d) the separation of drops from a curved surface (ethyl nitrate, 110 atm).

Generally during unstable combustion several characteristic forms of surface distortions are observed. These can be divided into three basic types [186, 196, 197].

1. The surface of the burning liquid accomplishes fluctuations in a vertical direction; into the zone of the flame from the wave crests avalanches of drops are broken away and they flare up in the flame. The secondary flame fluctuates, periodically approaches the surface of liquid and draws back from it (Fig. 105a). Energy for the maintaining of fluctuations can come both from the gas flame and from the flare-ups of drops ejected into the flame. A characteristic example of such a type of distortion is given by nitroglycol.

2. In a number of cases in the near-critical range of combustion the surface of the burning liquid begins to accomplish a spin motion, when the flame as if "screwed itself" into a column of ZhVV which is absorbed by the rotating surface. A surface of ZhVV appears which is arranged almost parallel to the normal direction of movement of the combustion products. From this surface into the flame the drops of liquid broken away by the gas flow are ejected (Fig. 104, 105). Typical examples of this form of combustion are given by diglycoldinitrate, supercooled DINA, and some mixtures on a base of nitric acid. It is interesting to note that with low mobility of ZhVV (thickened nitroglycerin, according to Andreyev) the spiral pitch described by the flame can be considerably greater than the diameter of the container and comparable with the height of the column of ZhVV. In such cases, as a rule, an explosion appears (see § 48).

The spin state of motion of the burning surface of the liquid, according to observations [186], never converts to oscillatory conditions, whereas the reverse version is feasible. According to the observations of Chuyko, by the use of different forms of ignition of diglycoldinitrate it is possible to obtain both a simple and a "two-headed" spin, when the flame is divided off into

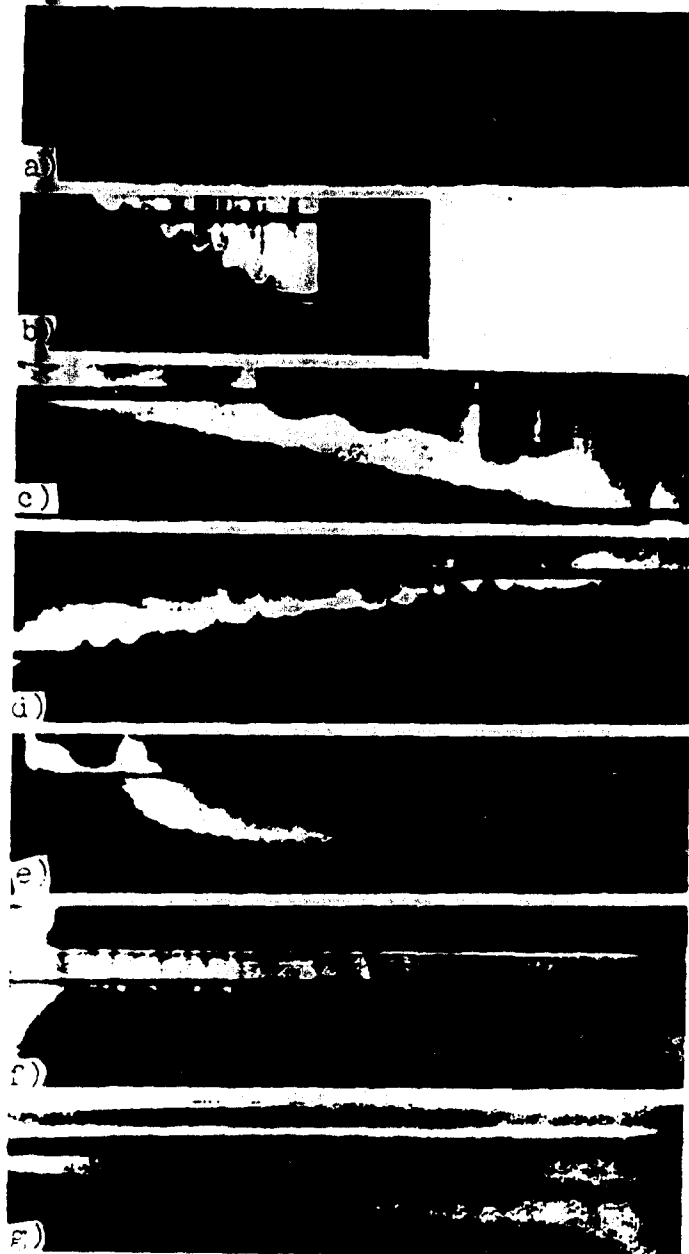


Figure 105. Phototraces of the combustion of ZhVV: a) nitroglycol, $d=5$ mm, $p=15$ atm, pulsation of flame; b) diglycoldinitrate, $d=5$ mm, $p=58$ atm, two-headed spin, injection of drops into flame from wave crests; c) diglycoldinitrate, $d=3.3$ mm, $p=68$ atm, two-headed spin; d) ethyl nitrate, $d=5$ mm, $p=110$ atm, fine-scale pulsations of flame; e) nitromethane, $d=8$ mm, $p=155$ atm, attenuation of oscillations of surface and transition to smooth burning; f) nitroglycol, $d=7$ mm, manometer bomb, after smooth burning the pulsations of the surface of liquid in the flame appeared, sharp acceleration of combustion, with $p=35$ atm explosion developed; g) nitroglycol, $d=3$ mm, $p=15$ atm, near the bottom combustion is accelerated as a result of the heating of liquid on the walls of the cup.

two rotating [spins].

3. The third type of phenomena was described by Whittacker [198] as the formation of "filaments" of liquid, heaving upward on the wall of the tube, when the surface accomplishes wave motion and pumps liquid on the filaments into the zone of the flame. Maksimov and Bayrash [196] observed, apparently, this same mode of combustion and called it spouting. The difference of their data from the observations of Whittacker is in the absence of the apparent movement of the surface of the liquid, and also in the fact that the liquid heaved upward in the center of the container and not on the wall (see Fig. 104c). In both cases as a result of the destruction of the liquid jet into the zone of the flame a large mass of drops was ejected and its accelerated combustion ensured a high rate of combustion. In work [186] the transition to the "spouting" mode of combustion was observed at elevated pressures, after spin motion ceased, while in work [196] - after the oscillatory process.

All the investigators come to the conclusion that in essence the observed increase in the rate of combustion in the near-critical range is connected with the development of the burning surface. In accordance with estimation (see § 38), the excess of the observed rate of combustion above the value obtained by the extrapolation of data on slow combustion on the near-critical range is 2-4 times. The disturbances introduced by inflammation die out in the precritical range slowly. As a result errors are possible when the initial (connected with ignition) fluctuation of the surface is accepted as natural, which is especially difficult to distinguish at low heights of charges and intensive igniting pulses. Figure 105e gives the phototrace of the combustion of nitromethane in the near-critical area, which illustrates this position. The oscillatory state of motion of the surface which emerges from the igniting spiral dies out after a certain time (mainly because of a reduction of oscillation amplitude, but not an increase in their frequency), and smooth burning is established.

The influence of the diameter of the container on the phenomena which take place in the near-critical area of combustion can be illustrated in an example of nitroglycol and ethyl nitrate (see Fig. 113) [38, 197]. An increase in the diameter of the container leads to an increase in the rate of combustion, which is expressed especially clearly in nitroglycol.

A detailed study of the transient area showed [38, 197] that the transition from straight line $u(p)$ for smooth burning to the straight line of developed turbulent combustion occurs on a complex curve. As a rule the spread of the experimental data here is great. For nitroglycol, nitroglycerin, and DINA the rates in this area are greater than this would correspond to the straight line of turbulent combustion; for diglycoldinitrate, nitromethane, and ethyl nitrate in narrow tubes (4-5 mm.) it proves to be somewhat lower. Among the mixtures on a base of nitric acid both forms of transient dependence are encountered. According to Andreyev [30], these features are apparently connected with the dual influence of turbulence on combustion: destroying the thoroughly warmed layer, it impedes combustion and can even lead to its fading. On the other hand, increasing the contact surface between the gaseous combustion products and the liquid, turbulence can accelerate combustion. This leads to the appearance of very interesting effects. Thus in the experiments of Andreyev and Bepalov [199] a considerable (2-3 times) increase was revealed in the critical diameter of combustion d_c of gelatinized nitroglycerin (3.2-5%) upon transition to the excited mode of combustion. The greater the viscosity of gelatin, the more weakly the increase d_c is expressed. In the case of nitroglycol the picture was not as sharp, although in the beginning of the near-critical area the fading of combustion was frequently observed with diameters greater than usual by several times.

In light of the possible effect of the disturbances of the burning surface on the process of combustion (especially near the limit) there is no lack of interest in the attempt to connect with

this effect some facts which are still lacking their own interpretation.

In the works of Whittacker, et al. [186, 198] it was revealed that on the curves of $u(p)$ of the mixtures of nitric acid with a number of organic combustibles (2-nitropropane, etc.) a "jump" of dependence is observed at a certain pressure (Fig. 106), if the diameter of the tube in which the ZhVV is ignited was small (3-4 mm). With an increase in the diameter of the tube (5, 6 and 8 mm) the "jump" disappears, but dependence $u(p)$ in a smooth manner continues the curve for pressures higher than the point of "jump." The introduction of 0.5% of polymethyl methacrylate as thickener for the system led to the disappearance of jump and increased the temperature of the surface by $\sim 40^\circ\text{C}$. In spite of the scalene experiments, the authors of [186, 198] could only conclude that at the point of "jump" some change in the mechanism of combustion occurs which is not described by the existing theories of combustion.

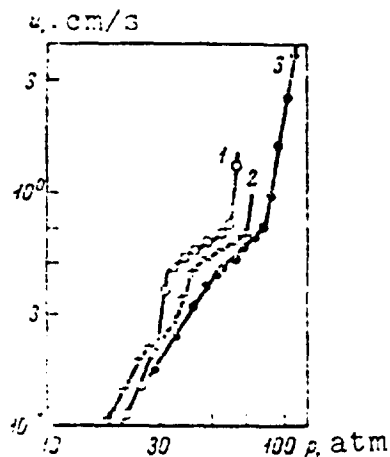


Figure 106. Dependence of the rate of combustion of mixture ZhVV on pressure [186]: 1 - nitric acid (99%) - nitroethane; 2 - nitric acid (99%) - nitromethane; 3 - nitric acid (95%) - nitropropane.

Later a whole series of works was published on the combustion of hydrazine (see survey in the book [38]). According to Antoine [200], in an interval of pressures 1-14 atm the rate of combustion of hydrazine of 100% concentration in a cup 5.6 mm in diameter answers to the equation $u_1 = 0.026p^{0.5}$ mm/s. At pressures above 14

atm the rate of combustion is proportional first to pressure in degree of 0.75, and then of the first degree. In proportion to the increase in the diameter of the cup the area of combustion with dependence $u_1 \sim p^{0.5}$ is narrowed, and at a diameter equal to 12.7 mm the transition to the curve (Fig. 107) occurs at 4 atm.

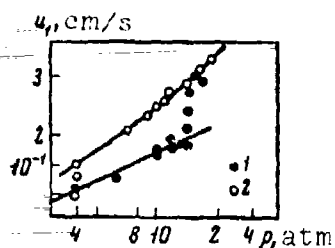


Figure 107. Dependence of the rate of combustion of hydrazine on pressure and diameter of the container [200]: 1 - $d=4$ mm; 2 - $d=12.7$ mm.

Antoine does not find a satisfactory explanation for the phenomenon, although he notes a certain change in the nature of brightness of the flame and its intensity (lowered brightness of radiation of the flame in the range of combustion up to the "jump" of the curve). He also observes a weak turbulence of the surface and indicated that despite the fact that as a whole the combustion was stationary, the points of surface described a spiral in proportion to the combustion of the substance.

Let us discuss the data of [198, 200], on the strength of the results in § 39. During the combustion of a low-viscosity liquid the maximum amplitude of disturbance which can be created by the process of combustion (lower than the stability limit according to Landau) is determined as the height of the liquid column, which balances the dynamic pressure of the ebbing combustion products (see § 38):

$$\xi_0 \sim u_1 u_2 \cdot 2g.$$

It is obvious that disturbances of amplitude greater than ξ_0 cannot arise. If an amplitude is of an order and less than ξ_0 , then combustion can support this disturbance. For this it is necessary

to create a non-univariate nature of flow of combustion products at the burning surface, which is not an exceptional phenomenon. Further, according to § 39, at a thickness of the combustion zone l greater than ξ_0 , the disturbance will reflect on the rate of combustion. Since $l \sim \kappa_1 u_1$, then condition $\xi_0 \gg l$ answers to a rate of combustion:

$$u_1^* = \sqrt[3]{2g\kappa_1\rho_2/\rho_1}, \quad \text{or} \quad \frac{u_1^*}{\sqrt[3]{p_1}} = \sqrt[3]{2g\kappa_1\rho_2^0/\rho_1^0}. \quad (106)$$

Thus at a rate of combustion $u_1 > u_1^*$ the "natural" disturbances of a burning surface are able to change the rate of combustion.

The phenomenon of the fading out of combustion during the emergence of pulsations of the flame is observed, in particular, during the combustion of nitroglycerin and liquid (95°C) PETN. The dependence $u(p)$ for methyl nitrate undergoes a fracture with displacement (Fig. 108), according to Andreyev [37], and also for a number of other both liquid and solid melting substances. Not excluding the possibility of other interpretations which, in particular, for nitroglycerin and PETN are presented extensively in Andreyev's monograph [38], we compare the experimental and calculation data for these substances. Table 21 gives the experimental values of the rates of combustion and pressure which correspond to the fracture of the curve $u_1(p)$, and for nitroglycerin and PETN - to the end of burning. For a convenience the values of magnitude $D = u_1^* \sqrt[3]{p_1}$ are compared, which according to formula (106) depends only on the thermophysical characteristics of the combustion of substances. In this case it turns out that in the cases of mixtures on a base of nitric acid, PETN and hydrazine in a container 12.7 mm in diameter coincidence of experiment and estimation is observed. For the agreement of data on nitroglycerin it is required to consider that at $p \approx 0,6$ atm the temperature of combustion products is somewhat lowered, and their composition is shifted to the side of the formation of higher molecular fragments. If we lead the resulting density of combustion products to 1 atm,

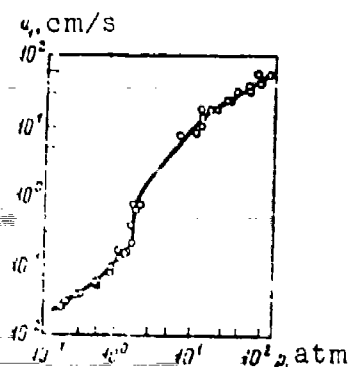


Figure 108. Dependence $u(p)$ for methyl nitrate, $d=5$ mm. Data from [38] (to $p=2$ atm) and [206].

Table 21. Determination of the position of the point of emergence of pulsations.

Substance	Experiment			Calculation	Literature
	p_0	u_0	D	D_0	
Hydrazine ($d=12.7$ mm)	4	0,05	0,053	0,056	[200]
Nitric acid - 2-nitropropane	16	0,163	0,0635	0,0695	[185]
Nitric acid - nitroethane	30	0,22	0,0707	0,0707	[198]
Nitric acid - dioxane	11	0,16	0,0805	0,0805	[198]
PETN	1	0,047	0,047	0,051	[55]

then it must comprise $\sim 4.3 \cdot 10^{-4}$ g/cm³ in comparison with that experimentally determined by combustion at 1 atm of a value of order $2.1 \cdot 10^4$ g/cm³ [30].

The appearance of pulsations at moment $\xi_0 = l$ can be presented in the following form. With $\xi_0 \ll l$ the disturbances lie within the combustion zone (heated layer) and do not cause substantial changes in the rate of combustion. With $\xi_0 > l$ together with the disturbance of the surface there is a sagging in the zone of the gas-phase reaction and the rate of combustion increases proportional to the increase in the surface. The most powerful effect one should expect with $l \approx \xi_0$, when the destruction of the heated layer can lead to the dying out of combustion, which also is observed in the case of nitroglycerin.

Limiting Conditions of Smooth Burning

Until recently, following K. K. Andreyev's basic works in this area, the near-critical area of combustion isolated by us was related to true turbulent combustion, i.e., as the maximum velocity of smooth burning a velocity was accepted, above which pulsations of flame and other unstable phenomena were observed. In light of the considerations given above and also of the experimental data, which show the existence of an area of metastable combustion appearing in the absence of forcing disturbances of the surface of the liquid, it was justified to conduct a finer separation of combustion behavior. One should isolate the precritical mode (artificial oscillations of the surface die out) and near supercritical, where the disturbances of surface increase from infinitesimal, and their decay is caused by nonlinear effects. Virtually this separation according to the available experimental data can be made only sometimes, since the bulk of information is obtained under conditions when there was powerful initial disturbance.

In accordance with theory, the critical point will be that rate of combustion, higher than which oscillations are absent, and only an increase of disturbances in amplitude occurs. Experimentally this point must be determined under conditions which eliminate the influence of artificial disturbances. The process which corresponds to combustion in the supercritical area is characterized by a powerful and monotonic dependence of rate of combustion on pressure (at least close to the limit), and the precritical area couples it with the area of dependence of slow combustion on pressure. This fact in conjunction with the photoregistration of combustion makes it possible to find the critical point with sufficient certainty.

From the aforesaid it follows that the result of the experiment in the near-critical range depends strongly on the method of investigation and first of all on the dimension of the initial disturbance. Figure 105f shows the phototrace of the combustion

of nitroglycol in a manometer bomb. Ignition was conducted at 1 atm, when the disturbance of the surface dies out rapidly and pressure rises slowly because of accumulation in volume of the combustion products of ZhVV. With this setting of the experiment the normal burning surface is retained in a considerable part of the range of pressures, where with the standard test variant excited combustion occurs. Thus in this case the pulsations of the surface rose at ~19 atm, whereas according to [37] with the usual method of experimentation they were already noted at ~13 atm. Analogous observations are made in work [186]. By the use of the method of inflammation through the layer of slow-burning liquid (ethyl nitrate) it was possible here to obtain smooth burning in the area where sharp inflammation causes oscillatory combustion behavior. In this case the rates of combustion lied on a continuation of curve $u(p)$, obtained by the extrapolation of data on smooth burning in the range of precritical pressures.

For low-viscosity ZhVV the critical pressure p_* , at which the self-turbulence of combustion begins under conditions of the experiments at a constant pressure, when there are finite disturbances caused by the ignition process, differs little (by 20-30%) from the critical pressure p_{kp} , obtained under conditions of combustion in a manometer bomb when there are only infinitesimal random disturbances. This result shows that the conditions of stability of combustion of low-viscosity liquids are virtually identical for infinitesimal and finite disturbances. Consequently, the conclusions of the theory, obtained for infinitesimal disturbances, are suitable for the evaluation of combustion stability to finite disturbances.

According to experiments on nitroglycol the time, during which in our experiments in a manometer bomb the pressure rose from p_* to p_{kp} was from 0.2 to ~1 s (cups 7 mm in diameter). Calculation time of the development of disturbances (see Table 20) with $n=1.1$ comprises approximately 0.2 s. In another series of experiments we attempted to determine the time of development of disturbances under conditions of combustion under constant pressure. For this the inflammation of nitroglycol was done through a layer of ethyl

nitrate which as carefully as possible was poured on the surface of the investigated explosives. The basic difficulty here consisted of the account of the burnout of the boundary layer of the mixture of nitroglycol and ethyl nitrate. It was possible to establish that experimental times of development of instability are approximately 3-7 times greater than calculated, and the nature of their change depending on n will agree with theoretical.

The influence of the diameter of the container on the value of the ultimate pressure of smooth burning was investigated in an example of nitroglycol [178]. In Fig. 109 the points are experimental, the curve is constructed according to equation (87) for a round container.

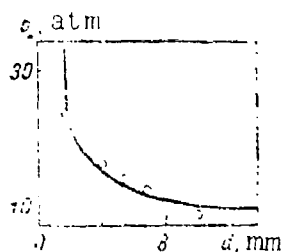


Figure 109. Influence of the diameter of the cup on the ultimate pressure of the smooth burning of nitroglycol.

During the study of the combustion of ethyl nitrate in cups 3, 8, 5 and 7 mm in diameter maximum velocities 0.55, 0.5, and 0.45 cm/s were achieved respectively at a pressure of 82-85 atm. Similar results are obtained for diglycoldinitrate: in cups of the same diameters the maximum velocities were equal to from 0.7 to 0.6 cm/s, and pressure 52-60 atm. It is doubtless that the influence of side effects (heat transfer on the walls of the cup, heat loss outside, etc.) for slowly burning substances with a relatively low combustion temperature, which are ethyl nitrate and diglycoldinitrate, turn out to be much more significant than for nitroglycol. Moreover for the indicated two substances the critical velocity is reached, apparently, at pressures higher than the critical thermodynamic, which complicates the picture even more. In work [186] during transition from a round container with a

diameter of 3.7 mm to plane with a section $10 \times 1 \text{ mm}^2$ the ultimate pressure of smooth burning decreased more strongly than the size of the container decreased (10/3.7 times), which is logical to connect with the strengthening of heat transfer from flame on the walls of the container and the overheating of substance which was connected with this.

The influence of initial temperature on the limit of smooth burning of nitroglycol [201] proved to be in agreement with theory. At a pressure of 12.3 atm the transition answers to the rate of combustion of $0.645 \text{ g/cm}^2\text{s}$ and a temperature of ZhVV equal to 47°C . A pressure of 17.5 atm is sufficient for transition to turbulent combustion at 23°C , which answers to a rate of $0.75 \text{ g/cm}^2\text{s}$. In accordance with equation (80) the relationship $J_* \sqrt{P_*} \sim C^*$ takes place. In this case C^* is equal to 0.184 and 0.179 units respectively.

Let us examine the question concerning the conformity of the experimental and calculated critical conditions of smooth burning. This comparison for some substances has already been made in Andreyev's monograph [38] and it was shown that in a number of cases very satisfactory accord is observed between theory and these experiments. Let us make a supplementary comparison of the values, which characterize the limiting conditions of smooth burning, where n for a number of inviscid substances, which have a high value of critical pressure [apparently exceeding the critical conditions also for the formula of Levich (93) (Table 22)]. For the comparison we utilize value $C^* = J_* \sqrt{P_*}$, the value of which according to Landau's theory we designate C_1 , and according to the theory of Levich - C_2 .

In Table 22 pressure is given in atmospheres, J_* - in grams per 1 cm^2 in 1 s. The following abbreviations are accepted: NGL [НГЛ - nitroglycol]; MTN [МТН - methyl nitrate]; DGDN [ДГДН - diglycoldinitrate]; ETN [ЭТН - ethyl nitrate]; NM [НМ - nitromethane]; TEGDN [ТЭГДН - triethyleneglycoldinitrate];

Table 22. The limiting conditions of smooth burning of inviscid ZhVV.

Substance	Experiment			Calculation		literature
	p_*	J_*	C^*	C_1^*	C_2^*	
НГТ, 20° C, $d = 5 \mu\text{M}$	19	0,9	0,2	0,18	0,07	[38]
НГТ, 23° C, $d = 4 \mu\text{M}$	17,5	0,75	0,18	0,18	0,07	[201]
НГТ, 47° C, $d = 4 \mu\text{M}$	12,3	0,63	0,18	0,18	(0,06)	[201]
МГН, 60° C	1	0,2	0,2	(0,2)	(0,06)	[30]
ТММ, 20° C	1,75	0,32	0,24	0,28	0,07	[38]
ДГДН, $d = 5 \mu\text{M}$	85	1,38	0,15	0,32	0,15	[197]
ЭТН, $d = 7 \mu\text{M}$	115	0,67	0,063	0,23	0,06	[197]
ВМ, $d = 8 \mu$	185	0,56	0,037	0,24	0,037	(1)
ДНА	51	1,11	0,136	(0,26)	(0,14)	(2)
ТОГН	50	1	0,14	(0,3)	(0,15)	[211]
ЭТН/ДГДН (1:1)	115	1,11	0,12	0,29	0,087	[197]
ДГДН	72	1,43	0,17	(0,2)	(0,29)	[38]
ТММ + benzene	4,2	0,385	0,19	(0,2)	(0,07)	[265]
ТММ + ВМ (3:2)	3	0,28	0,164	(0,2)	(0,07)	(1)
PETN, 100° C	8,2	0,55	0,19	(0,2)	(0,15)	[85]
НГН	1,38	0,29	0,252	0,33	0,3	[199]

DNGTs [ДНГЦ - dinitroglycerin]; TNM [ТММ - tetranitromethane]; NB [ВМ - nitrobenzene], (1) the results of the authors; (2) A. P. Glazkova's data on supercooled substance [222], in the calculation of C_2^* a viscosity of 30 cp is accepted. Numbers in brackets are rough estimate. For NGTs [НГЦ - nitroglycerin] p_* is accepted according to the data of [199] and corresponds to the limit of smooth burning under conditions of slowly increasing pressure. The rate of combustion of NGTs is calculated according to the equation $u = 0.23 p_*^{0.765} \text{ g/cm}^2 \cdot \text{s}$.

Table 23 depicts the results of the processing of data from [186, 198] on the combustion of mixture ZhVV on a base of nitric acid. In view of the absence of those constants necessary for the calculation only the value $u_* \sqrt{p_*} = C_0^*$ constructed according to experimental data is given. If we accept $\eta = 1 \text{ cp}$, $\sigma = 16 \text{ dyn/cm}$ (nitric acid), then calculated $C_1^* = 0.18 \text{ units}$, and $C_2^* = 0.66 \text{ units}$.

The comparison of the data of Table 22 and 23 with theory is done conveniently based on the values of relation $J_* \sqrt{p_*}$. During the calculation of coefficient C_1^* it proves to be (§ 32) on the

Table 23. The limiting conditions of smooth burning of mixtures of nitric acid and a combustible [186, 198].

Combustible	c _{HNO₃}	u _{lim} cm/s	p _{lim} atm	C _{lim} *
Nitromethane	99	0,6	55	0,065
Nitroethane	99	0,71	97	0,072
1-nitropropane	99	0,68	83	0,073
2-nitropropane + 0.5%	99	0,67	66	0,082
Lucite				
Dioxane	99	0,60	21	0,122
Isobutyric acid	99	0,9	33	0,099
2-nitropropane	100	1,3	56	0,174
•	97	0,7	69	0,084
•	95	0,7	76	0,075
•	90	0,63	125	0,055

order of 0.12-0.3 units, whereas coefficient C_2^* is equal to (§ 33) 0.03-0.20 units. Comparing these values with those experimentally found, we see that if p_* is more than 50 atm, then the experiment will agree better with C_2^* , but with small p_* value C^* is nearer to C_1^* . This fact serves as confirmation of the considerations developed in § 34, namely: with p_* larger than critical thermodynamic for a given liquid, when surface tension decreases, the stabilizing role gradually transfers to viscosity forces. At low pressures the flame stabilization is connected mainly with the action of the forces of surface tension.

Further confirmation of the Landau-Levich theory was obtained in experiments on combustion under conditions when the value of the overloads acting on the liquid changed, i.e., with $g' \neq 9.8 \text{ m/s}^2$. Initially the experiment [197] was set up on the combustion of nitroglycol under conditions of free drop ($g=0$) at 1 atm. It was established that in a container 5 mm in diameter the agitation of combustion did not occur. Comparison with theory showed [177] that the flame stabilization was ensured in these experiments because of the small diameter of the container. For development of instability combustion must flow in a container with a diameter on the order of 1 m. Earlier it has already been indicated [37] that the checking of Landau's theory was possible also by means of

setting up tests with $g' \gg 9.8 \text{ m/s}^2$, i.e., under conditions of overloads. Such tests were carried out by Ordzhonikidze, Margolin and Pokhil [202]. Nitroglycol was used; combustion was conducted in a test tube 5.5 mm in diameter. With $g'=g$, i.e. under normal conditions, p_* was equal to 12 atm. During combustion under an overload equal to 300 g, the nitroglycol burned stably in the entire investigated interval of pressures (to 140 atm). The rate of combustion corresponded to values obtained by the extrapolation of the curve of slow combustion at pressures below 12 atm under normal conditions, and at 140 atm it was 3.3 cm/s. The calculation according to Landau's theory [equation (80)] shows that with 300 g the transition to turbulent mode should be expected at ~ 250 atm. In accordance with theory (see Table 20) it turned out that

$$p_* \sim \sqrt{g}.$$

Combustion of Liquid Explosives
(ZhVV) [HBB] Beyond Stability
Limit

The combustion of ZhVV beyond stability limit is characterized first of all by the high velocities of the propagation of the process, by the strong dependence of rate of combustion on pressure; as a rule, the diameter of the container in which the combustion is conducted substantially affects the rate of combustion.

Figures 110, 111 as an illustration give the curves of $u(p)$ for several liquid explosives and mixtures. The typical rates of combustion are from 1 to 100 cm/s, while the index ν , as a function $u(p)$ frequently proves to be even more than one. A. D. Margolin and V. M. Margulis carried out the processing of experimental data in coordinates $u/u_* - (p/p_* - 1)$ corresponding to the theoretical dependence (§ 42) $u_T(p)$. It proved to be (Fig. 112) that far from the limit ($n \gg 5$) the dependence of the rate of turbulent combustion on pressure agrees with the predictions of the theory.

The effect of the diameter of the container d on the rate of turbulent combustion near the limit is illustrated in Fig. 113, which is constructed according to the data in work [197] for nitroglycol. In the range of pressures 20-60 atm there occurs the relationship $u_T = 0.15 + 0.032(p - 20) \times (d - 1.7)$ cm/s (where p is in atm and d in mm). Assuming that in the turbulent region the rate of combustion linearly increases with an increase in the diameter of the container, while in the normal mode as a result of the effect of heat transfer in the walls of container it somewhat decreases, then from Fig. 113 it follows that higher than a pressure of 20 atm truly turbulent combustion occurs.

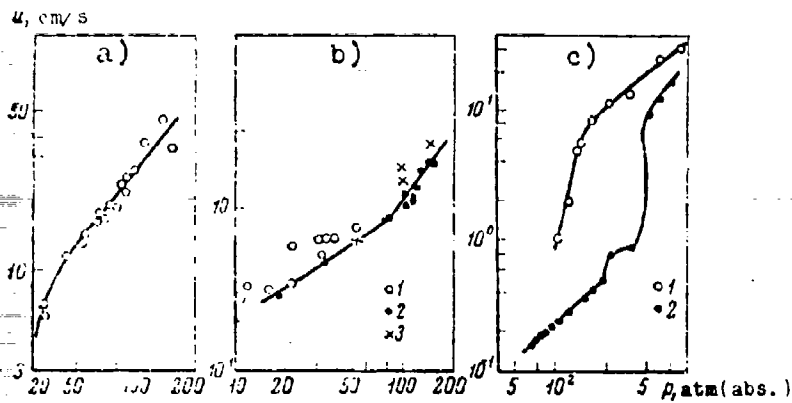


Figure 110. Dependences $u(p)$ for individual substances. a) nitroglycol, $d=5$ mm [206]; b) DINA (data of Glazkova): 1 - supercooled; 2 - solid; 3 - DINA with addition of 30% of colloxylin [pyroxylin]. c) 1 - nitromethane, according to the data in [191] and the authors; 2 - ethylnitrate, according to data in [191] and the authors.

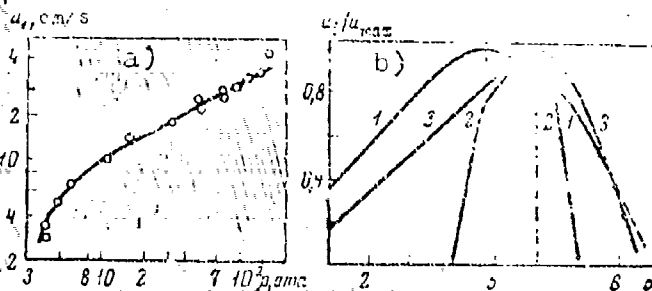


Figure 111. Rates of combustion of mixed ZhVV. a) TNM-nitrobenzene (60-40), $d=4$ mm; b) TNM-butanol with different relationships of components and pressures: 1 - 1 atm; 2 - 2 atm; 3 - 40 atm, current rates are related to the maximum value of u_{max} ; u_{max} are equal: at 1 atm to 0.07, at 2 atm - 2.6, with 40 atm - 42 cm/s. [$p_{atm} = atm(abs.)$].

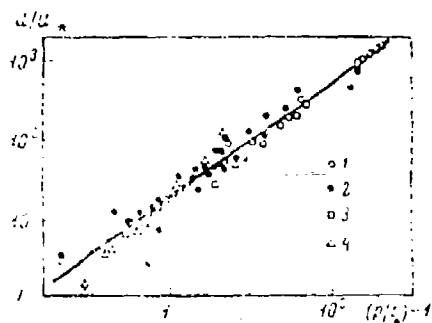


Figure 112

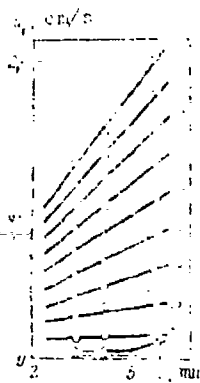


Figure 113

Figure 112. Generalized dependence of the rate of combustion of ZhVV in turbulent conditions 1 - methyl nitrate [191, 206]; 2 - nitroglycol [191, 193, 197, 206]; 3 - ethylnitrate [191, 197]; 4 - diglycoldinitrate [197].

Figure 113. The rate of turbulent combustion of nitroglycol depending on the diameter of beaker at constant pressures. Numerals on curves designate pressure in atm.

In work [186], during the study of the combustion of ZhVV mixtures on the basis of nitric acid it was also established that in the range of turbulent combustion the rate of combustion increases with an increase in the diameter of the container. Furthermore, it turned out that in aluminum tubes the rate of combustion was 2-3 times greater than in pyrex tubes, and in shells of ballistite powder the rates were still higher. During the study of the combustion of nitroglycerin far from the limit [191] the rate of combustion increased as \sqrt{d} with a change in the diameter of the container in the interval of from 5 to 9 mm.

The effect of the initial temperature on the turbulent combustion of ZhVV was studied by Tereshkin and Andreyev [201]. Simultaneously with a decrease in the pressure of the transition to the turbulent combustion mode the dependence of the rate of turbulent combustion on pressure increases.

The effect of the initial temperature weakens in proportion to removal from the limit. The processing of the data of Tereshkin shows that if at a pressure of 17.5 atm the rate of turbulent combustion increases as the absolute temperature to a degree of 1.63, then with a pressure of 53.5 atm this degree decreases to ~0.68. It is logical to connect this fact with the specific character of the mechanism of turbulent combustion of ZhVV: far from the limit of normal burning the rate is determined mainly by the energy of the combustion products, which increases as a root square from the final temperature of combustion [see equation (104)].

In experiments with nitromethane, as noted above, it is possible to observe the damped oscillations of the surface of the liquid. The calculated frequency of the natural oscillations is equal to ~15 Hz. For the combustion of nitromethane there was obtained at 134 atm - 12 Hz; at 155 atm - 12 Hz; 208 atm - 24 Hz. These data show that during combustion with an increase of pressure (rate of combustion) the excitation of different modes of oscillations is possible, which throws off the rhythm of the change in frequencies which were recorded in the experiments.

In several works the attempts were made to find the correlation between the observed oscillation frequencies of burning surface (and their corresponding flame pulsations) under such experimental conditions as pressure, the diameter of the container etc. [186, 196]. The obtained results turned out to be contradictory. So, in work [196] a drop in the oscillation frequency of the surface of the burning methyl nitrate was observed whereas during the study of the combustion of a mixture of tetranitromethane with nitrobenzene, taken in ratio 60:40 weight %, flame pulsations were observed with a constant frequency which increased as a function of pressure as $f \sim p^{0.65}$. In work [197], the observation of the combustion of nitroglycol gave a set of

frequencies, in which a tendency toward a drop in the period of pulsations with an increase in the pressure is marked. It is very possible that in these works the authors recorded in different ranges of combustion the parameters of different types of periodic distortions of the surface of the liquids which, as was shown above (§ 38), change differently as a function of pressure. Maximov's work [196] on the oscillation frequencies of the burning surface of methyl nitrate are described sufficiently well by the expression $f \sim 1/u_1$ and are related to combustion somewhat above the critical point. During the study of the spin instability of the burning surface between the angular rate of rotation ω and pressure by Andreyev and Tereshkin (using liquid trotyl as an example) and work [186] the dependence in the form $\omega = a - bp$ was observed, where a and b are certain constants. Thus, with pressure increase the rotation frequency decreases, and at a certain value of pressure, the motion must cease, which was also observed experimentally.

For a study of the picture of the motion of the surface of combustion, in work [177] the tracing method (introduction of dye to the investigated substance) was used. Figure 114 shows photographs of the small tubes in which was conducted the combustion of nitroglycol with an addition of 0.02% of nigrosine (a black soluble in alcohol organic dye). On the internal walls of the small tubes 2.5 mm in diameter (Fig. 114a) after combustion 20 atm a track remained in the form of wavy spirals, having an approximately constant step. With an increase in the pressure the spiral pitch decreases. So, with $p=20$ atm it is equal to ~ 2 mm, at 22 atm it is equal to ~ 1.4 mm. The maximum length of the wave at 20 atm is equal to ~ 8 mm, and at 22 atm to ~ 5 mm. Besides those indicated, more short waves are observed. On the wall of a small tube 4 mm in diameter (Fig. 114b) after combustion at 18 atm a track in the form of the complex entanglement of lines, resembling a grid remained. The size of the cell is equal to

3×3 mm. Such cells are obtained when the wave amplitude is approximately equal to the spiral pitch. Apparently, the observed tracks reproduce the form of the motion of the flame and reflect its interaction with the flow of the ebbing vapors of the explosive.



Figure 114. Photographs of beakers after the combustion in them of nitroglycol with the addition of dye: a) $d=2.5$ mm, $p=24$ atm; b) $d=4$ mm, $p=18$ atm.

The dimensions of the disturbances during unsteady combustion can be estimated on motion-picture frames. This estimation of the wavelength gives the value 2-8 mm (nitroglycol, diglycoldinitrate, nitromethane). Waves on the order of 1 mm long are observed less confidently. Thus, the order of value corresponds to the size dimensions of the most rapidly growing disturbances predicted by the theory (see Table 19).

In light of contemporary ideas about the stability of the gas flow of combustion products, which flows from the disturbed surface, the emergence of the spin motion of the flame - surface system reflects the result predicted by the theory. Actually, in the case under consideration the stable forms of motion are either the rotating flow or the circular vortex.

Usually for observation of the nature of the combustion of ZhVV, film is applied from the side through the transparent walls of the container. In work [178] the method was applied of filming from the end through the layer of burning liquid. For this a plane transparent bottom was attached to the glass and the test

tube was placed on a prism at an angle of 45° , through which the photographing was conducted (see Fig. 101). The entire assembly was mounted in a vessel of constant pressure; photographing was done by a high-speed movie camera. Two substances were investigated - nitroglycol and diglycoldinitrate, for which the critical pressures of the emergence of unsteady combustion were equal respectively to about 15 and 54 atm (in a test tube 6 mm in diameter). Since photographing was conducted in intrinsic radiation, the refraction of the light on the surface of liquid revealed its structure. Figure 115a shows typical frames (1-10) of the filming of the combustion in unstable conditions. The examination of the motion-picture frames shows that Fig. 115a - 1 can be compared with mode $q=1, s=0$ (one nodal diameter; Fig. 115a - 2 with mode $q=2, s=0$ (two nodal diameters). Other frames correspond to the more complex combination modes. Frame 1 is most widely propagated: this form of disturbance is encountered in almost all films for both substances. The photographs obtained during the combustion of diglycoldinitrate do not differ in appearance from the photographs of the combustion of nitroglycol. However, an examination of the motion-picture films showed that in this substance a rotational motion of the flame occurs, which is caused by the wave on the surface of the liquid moving along the circumference of the tube. In the developed mode of unsteady combustion, the peculiar process of the complication of the form of the disturbances is observed. Two semicircles appear, each of which is then divided into halves, whereupon the process of division is accelerated, and a complex picture of the combination of the different modes of motion is rapidly formed. Figure 115b shows consecutive frames of the filming of this process of division during the combustion of diglycolnitrate under a pressure of 62 atm in a tube 6 mm in diameter. Besides the noted modes, radial pulsations of the liquid are sometimes also observed (Fig 115a-5).

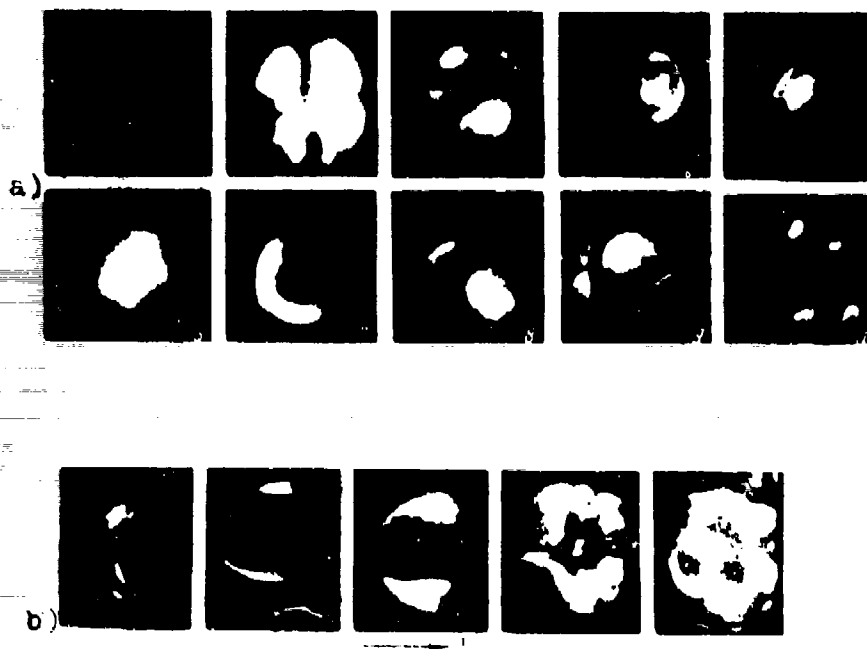


Figure 115. Motion-picture frames of the surface of 2hVV during combustion beyond stability limit. a) different types of surface structure; b) the development of instability during the combustion of diglycoldinitrate (62 atm, $d=6$ mm).

With an increase in pressure (of the rate of combustion), the dimensions of the separate elements of the disturbances decrease, and the large nonuniformities disappear, which seemingly are comprised of separate pieces of the picture of the surface. Filming from the end makes it possible to evaluate time of the development of the disturbances. So, in the case shown in Fig. 115, it amounted to about 15 milliseconds. The photographs of the surface of the liquid, which burns in the disturbed mode, were made under conditions when the velocity of propagation of the combustion exceeded the normal by ten times. However, the increase in the burning surface recorded in the photographs is small, not more than 2-3 times. Probably the surface visible in some photographs is covered with small waves. All the same, the increase in the rate of combustion of by ten times in comparison with the normal cannot be explained by trivial geometric reasons.

It was necessary to assume that the height of the separate waves was ten times greater than the distance between the waves. Therefore it may be concluded that the agitated combustion of the liquid is turbulent.

§ 45. Combustion of ZhVV Mixtures

Homogeneous stable mixtures of liquid components, such as tetranitromethane (TNM) [TNM] and fuel, in many instances behave analogously with individual liquid explosives. They can burn in the normal mode, which fluctuates and is turbulent, the critical conditions of the transition to turbulent conditions being described by Landau's theory. However, there are some distinctions which appear with a specific coincidence of circumstances. Most basic is the effect of the distinction in the volatility of components and their densities, which create the prerequisite for the fractional, nonsimultaneous depletion of the components. In the absence of reactions in the condensed phase, the rate of combustion will depend on the composition of the mixture in the gaseous phase. As a result of the divisibility of vaporization, this composition can differ significantly from the initial, which occurs in the k-phase.

If we investigate the combustion of mixtures of TNM at 1 atm in air with such fuels as ethyl ether, benzene, acetone, etc., then during the combustion of several mixtures depleted by the oxidizer at 1 atm in tubes (quartz, glass, metal) the following phenomenon is observed. Initially, with ignition from a source of moderate temperature a small pale flame is formed which hangs above a section of the tube, corresponding mainly to the combustion of the fuel with air. The rate of the dropping of the level of the liquid mixture is very low and amounts to several hundredths of a millimeter per second. Then suddenly within tube appears a bright transparent high-temperature flame,

the base of which almost rests on the surface of the liquid. An intense wave motion on the surface of mixture occurs and the rate of combustion increases by more than an order (photo of Fig. 116a). A rapid flame is formed as a result of the combustion of the mixture of vapors, which almost corresponds to that which was established in the initial composition. The heating of the surface layer of the liquid directly from the flame, and also through the walls, which transmit heat from the flame, makes it possible to vaporize at a sufficient rate the difficult volatile component (TNM) as well. The use of a powerful igniter makes it possible to obtain immediately the mode of rapid combustion, whereas low-power ignition leads to a two-mode process. One should also keep in mind that the maximum speed of rapid combustion in normal (nonturbulent) conditions corresponds approximately to the stoichiometric relationship of the components, while a large surplus of TNM makes the mixture noncombustible. The observation of the dynamics of the process reveals the existence of a near-surface layer of intense mixing (the so-called "homolayer" [204]), which occupies the height of an order of one to one and one-half diameters of the container. On some mixtures the streams which descend from the mixing layer are clearly visible. During the passage of "rapid" combustion from the walls of the tube inward, the waves which form in tubes 10-30 mm in diameter cells on the order of 1-3 mm in size will move away (see Fig. 116b). By introducing the heat-conducting rod into the liquid, it is possible to accelerate the appearance of "rapid" combustion. If we then remove the rod, the combustion is continued in "rapid" conditions.

In the mixing layer a rearrangement of the composition of the mixture occurs. As a result of the accelerated consumption of the more highly volatile component (for example, in the mixture of TNM with benzene the benzene departs) the ratio of the components

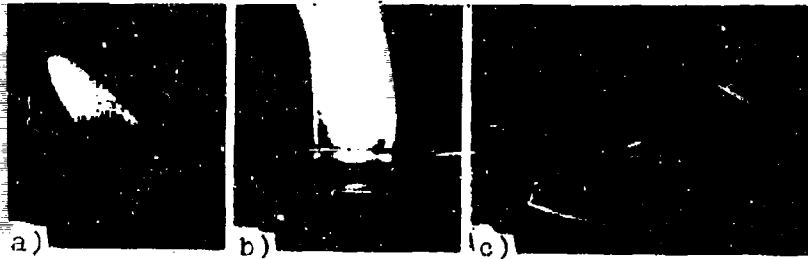


Figure 116. Photographs of the combustion of mixed ZhVV at 1 atm: a) "slow"; b) "rapid" mode of combustion of a mixture of TNM and acetone; c) cells on the surface of the burning mixture of TNM-acetone ($d=12$ mm).

changes. There is simultaneously a reconstruction of the rate of combustion, temperature, etc. The thickening of the mixture impedes convection, and the thickness of the layer of mixing decreases. The intensity of the mixing depends on the relationship of the densities of the components. In experiments on TNM and fuel the density of the oxidizer was always higher and the volatility lower. If the density of the fuel was higher, stationary combustion would become impossible in view of the accumulation on the surface of the less volatile and not independently combustible tetranitromethane.

The rearrangement of the composition of the mixture in the process of combustion is proven by the following facts. During combustion in the tube of a mixture, for example TNM with benzene, toward the end of the combustion, there occurs the accumulation of a brown layer with a thickness of several millimeters, which is mainly TNM. In another experiment, a mixture of TNM with a heptane of a composition, close to stoichiometric, began to burn at 1 atm at a rate on the order of 0.2 mm/s, and then the rate gradually decreased and combustion was extinguished, then there still remained 10-15 mm of liquid in the test tube. Direct experiments showed that the remaining mixture was not capable of combustion as a result of re-enrichment by tetranitromethane.

The combustion mode of the mixtures is determined by the dynamic equilibrium between the process of vaporization of the components, the convective mixing in the near-surface layer and the speed of the reaction in the vapor phase.

The questions of combustion and transition to the explosion of mixture liquid systems are investigated more profoundly and comprehensively in Gol'binder's works [205]. He gave considerable attention to the process of the rearrangement of the composition of the mixture as a result of the fractional vaporization of the components, and also to the role of chemical factors (presence of the reactions between components, the formation of active intermediate compounds, etc.). Gol'binder indicates that the difference between the behavior of liquid mixtures and individual ZhVV is not always observed, since frequently the mixtures form chemical complexes in the liquid phase, either azeotropes or constantly evaporating mixtures. With an increase in pressure the differences become less noticeable, since the change of the composition of liquid and vapor in the process of combustion is impeded.

The mechanism of the transition of the combustion of liquid mixtures to explosion and detonation, according to Gol'binder, involves the formation of a gas-vapor-drop suspension (two-phase mixture). According to Andreyev [38], this layer can be stable with a thickness somewhat less than critical. The sharp acceleration of gas formation begins when the critical thickness of the layer of two-phase suspended matter, which is found in the gaseous phase above the burning surface is exceeded. Acceleration can be the consequence of a flash or detonation, or any intermediate mode of explosion-like combustion of the suspension. The existence of an upper limit of the detonation of mixtures, based on pressure, is treated in this examination as the consequence of a decrease in the thickness of the layer of the two-phase suspended matter: with an increase in pressure, the dispersion of drops during the

gaseous phase increases, but the full time of their combustion is also shortened which limits the maximum attainable thickness of the layer of the suspension. This question is discussed in monograph [38], where there are references to a series of works.

We also do not examine the results of investigations of those self-igniting liquid mixtures which are described and discussed in the works of Gol'binder [205] and Andreyev [38].

§ 46. Combustion of Viscous Systems

The stabilizing effect of the thickening of liquid explosives and systems is well known and has long been utilized, including in technology. A detailed discussion of many aspects of this question can be found, for example, in Andreev's works [38, 199]. In a qualitative respect, the effect of an increase in viscosity corresponds to the predictions of the theory of Levich [74]; however, the quantitative side of the question has been only very slightly studied. In Whittaker's work [186] a mixed system (nitric acid- 2-nitropropane) was thickened by the addition of the high polymer "lucite." It was established, that the higher the viscosity of the mixture, the higher the pressure (rate of combustion) at which occurs the transition to the turbulent combustion mode. In this case the critical pressure increased in proportion to viscosity to a degree of 0.148. Let us recall that in Levich's theory [74] this index is equal to 0.33. However, the analysis of Whittaker's data shows that the viscosity of the system was insufficient (less than one poise), and therefore surface tension had to exert the basic stabilizing correction. Consequently, the data of the experiment must be correlated in accordance with Landau's theory [73]. In Table 24 Whittaker's results are processed by the calculation of the relation $u_* / \sqrt{p_*}$, which follows from Landau's theory [73] with constant values

for the quantities of surface tension and density¹. In view of the small quantity of the used thickening additive this is not presented as a rough assumption. As can be seen from Table 24, relationship $u_* / \sqrt{\rho_*} \approx \text{const}$ is fulfilled by Landau very well and Whittaker's results can be considered as a confirmation of the validity of the theory. Let us note that Levich's relationship [74] does not describe these data.

Table 24. Processing of the data of work [186].

Content of "Lucite", %	η (35°C), nS	u_* , cm/s	p_* , atm	$u_* / \sqrt{\rho_*}$
0,0	0,70	0,645	55,0	1,0
0,1	1,80	0,655	75,9	0,85
0,3	4,60	0,736	55,2	0,87
0,5	12,61	0,782	100,2	0,85
0,75	35,0	0,815	125,4	0,85

Apparently, Chuyko and Ivashkin (IKhF [ИХФ - Institute of Chemical Physics] of the AN USSR, 1968) in their experiments investigated the combustion stability of a mixture of tetranitromethane (TNM) with benzene, taken in a volume ratio of 3:1 and thickened by additions of polymethyl methacrylate (PMMA) [ПММА]. It was established that this liquid-viscous system is non-Newtonian. By viscosity measurement at different shear stresses with the subsequent extrapolation to stresses of an order $(\rho_2 u_2^2)_*$, which corresponds to the disturbing conditions at the critical point of normal burning, it was possible to make a relatively correct comparison of the theory with the experiment. The combustion of mixtures was conducted in an apparatus with only slight pressure variations in beakers 6 mm in diameter. Table 25 gives results of the experiments, and also the critical values of the rates of combustion J_* calculated from the formulas of Landau and Levich.

¹A relative value has been derived which is standardized at a value for a system without an addition.

As was noted above, the viscosity was determined by extrapolation, in view of the small difference in the values $(\rho_2 u_2^2)_*$ for the different systems, it virtually corresponds to a shearing stress of an order of 1 dyne/cm². Also included are the results of an investigation of the mixtures, which contain an addition of aluminum powder, which created the supplementary thickening effect. If we exclude data on a mixture with 5% PMMA, then Levich's formula gives the critical value of velocity which is on the average two times less than that observed experimentally. The calculated speed, according to Landau's formula, and with the utilization of all data, on the average exceeds the experimental by 25%. In this case it was accepted that the surface tension of the system was constant (30 dynes per centimeter); this may be an insufficiently good approximation. Thus, in this case it was not possible to make an unequivocal selection between theories; both give approximately an identical degree of correlation with the experiment.

Table 25. Limits of the normal burning of viscous systems.

Concent of PMMA, weight	Experiment			Calculation J	
	u_{cr}	J.	p., atm	according to Landau's formula	according to Levich's formula
1	9	0,28	3	0,433	0,065
2	32	0,42	8	0,71	0,165
3	2·10 ³	0,77	10	0,79	0,725
5	5·10 ⁴	1,36	36	1,5	18,7
2 + 5 Al	135	0,615	11	0,83	0,31
3 + 10 Al	—	2,38	56	1,67	—

The combustion of these mixtures of TNM with benzene was also studied at elevated pressures when it goes into turbulent conditions. One of the interesting results here proved to be the effect of the method of the ignition of the mixture on the rate of combustion. Ignition from a slightly incandescent electrospiral led to rates of combustion several (2-5) times less than with ignition from a tablet of ballistite powder

(Fig. 117). The comparison of mixtures varying in viscosity shows that this difference decreases in proportion to the thickening of the system by a high polymer, while the most viscous mixtures virtually do not react to the method of ignition. The explanation of this phenomenon, apparently, is connected with the fact that the excitation of combustion from an intense source (powder tablet) leads to a powerful distortion of the combustion surface which cannot be rapidly attenuated in view of the increased viscosity of the system, and combustion develops on the disturbed surface. The stability of this process can easily be destroyed. The great increase in the viscosity of the system blocks the surface distortion of the charge from the action of the igniter; the method of ignition becomes unimportant. The effect is greatest, when the time of the fading of the disturbance of surface is comparable to the burn-up time of the sample (see also further experiments on combustion under increasing pressure). The data given in Fig. 117 on the rates of combustion, excited by the high intensity source of ignition, correspond to the linear increase in the value of the average speed of turbulent combustion from pressure.

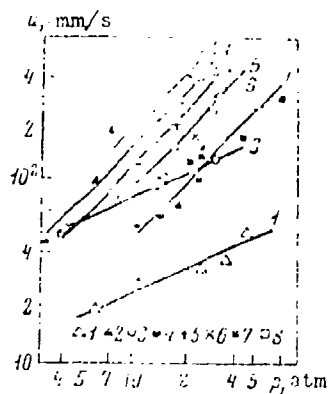


Figure 117. Rates of combustion of mixtures of TNM-benzene (3:1) depending on the quantity of thickener (polymethyl methacrylate), pressure and the method of ignition:

1 and 3 - ignition from spiral; the remaining are from the tablet of powder; 1 and 2 - 1% of PMMA; 3 and 4 - without thickening; 5 - 0.5% of PMMA; 6 - 2% of PMMA; 7 - 2% of PMMA+5% Al; 8 - 3% of PMMA. On curves 1 and 3 index $\nu=0.5$, on remaining curves $\nu=1$.

The experimental data obtained with soft initiation correspond to the much weaker dependence of the rate of turbulent combustion on the pressure: for an unthickened mixture of TNM with benzene and a mixture with 1% PMMA the rate increases as $p^{0.5}$, i.e., it corresponds to the theory of the turbulent combustion of liquid systems examined in § 41. It is necessary to assume that the emergence of the first of the conditions of turbulent combustion of liquid with the strong dependence of velocity on pressure examined here corresponds to cases of the rapid transition of combustion to explosion which were repeatedly observed by many researchers with the intense ignition of ZhVV [38, 191, 206].

In light of these data let us examine the mechanism of the effect of the height of the tube above the surface of the liquid, which was noted by a number of researchers. Under high-speed turbulent conditions, the burnout of the suspension of drops far from the surface and torn away from the surface of the liquid, for example to the extent of the vessel (short tube), leads to the loss of part of the flow energy of the combustion products; the quantity of drops re-entering the flame is limited. An increase in the length of the tube above the surface makes it possible to utilize more fully the flow energy for separating the drops from the surface of the initial liquid, and with disequilibrium - to lead to the explosion of the drop-gas mixture (§ 48). The more reactive the system, the higher its combustion temperature, the higher the energy of the gas flow, the less the critical value of the length of the tube above the burning surface, the more easily the explosion occurs with intense ignition. The role of the viscosity is also clear: when the thickening of the mixture raises the critical shear stress to a value which exceeds the shearing stress of the turbulent flow of the combustion products, the hypersonic mode of turbulent combustion becomes impossible. For non-Newtonian systems it is also necessary to consider the dependence of the mechanical characteristics on the loading rate.

The introduction to the liquid substances of small quantities of thickening additives frequently changes the rate of combustion and its pressure dependence both in normal and in turbulent combustion modes, especially with low concentrations of the additives. With an increase in the viscosity, the effect rapidly decreases. For example, the processing of Whitaker's data [186] shows that with lucite contents in the mixture nitric acid - 2-nitropropane equal to 0; 0.1; 0.3 and 0.75% at 40 atm, rate of combustion is respectively 3.9; 3.4, 2.55 and 2.4 mm/s, while at 70 atm it is equal to 6.5; 5.8; 4.8 and 4.6 mm/s. The combustion of nitromethane with additions of 2.8, 4.2, 7 and 9.8% of pyroxylin, according to N. V. Parfenov's experiments, at 50 atm is 1.80, 1.68, 1.42, and 1.20 mm/s. Let us note that the unthickened nitromethane under these conditions burns at a rate of 1.5 mm/s. The difference in the effect of the addition of pyroxylin and lucite is connected with a difference in their combustibilities. The rate of combustion of pyroxylin is higher than that of nitromethane, and lucite is actually inert. In experiments with nitromethane, the net result of the introduction of an addition is the competing effect of two factors: an increase in velocity and power of the mixture with the introduction of the active thickener and a decrease in the velocity as a result of an increase in the viscosity of the system. The thickening of the mixture decreases the near-surface layer, heated thoroughly to a temperature close to the boiling point (decomposition), as a result of the suppression of convective mixing.

Viscosity effect on the velocity of combustion beyond the stability limit is virtually not investigated. It was established that the rate of the turbulent combustion of the colloxylin-thickened -nitroglycol depends on a pressure less than the unthickened substance, while the velocity is lower, the difference increasing in proportion to removal from the limit. The rate of the turbulent combustion of the mixture TNM-benzene (see Fig. 110a)

on the whole decreases with an increase in the viscosity of the system; however, the form of pressure dependence is virtually retained. It can be approximated by the equation $u=Bp$, where coefficient B decreases with an increase in viscosity.

A special case is the combustion of low-melting solids under conditions when there is a considerable melting layer. Theory shows (§ 40) that the agitation of combustion according to the Landau - Levich mechanism is possible only under exceptional circumstances (temperature of the substance close to melting point). The known experiments of Popova and Andreyev [85] on molten PETN showed that the picture of combustion actually corresponds to Landau's and the critical rate of combustion agrees sufficiently well with the calculated value. Glaskova's experiments [222] on supercooled DINA also confirmed that the molten explosives behave analogously to liquid systems. As concerns the agitation of the combustion of solid fusing substances by the Landau - Levich mechanism, Popova's experiments were dedicated to this question [85]; she observed the fading of the combustion of solid PETN after the pulsation which accompanied ignition. It is obvious that the melting layer burned out in this case in the turbulent conditions, not having had time to transfer the heat to the depth of the charge, in consequence of which the melting was not renewed in continuous form and combustion was extinguished. As a result of the indicated circumstance, the undamped mode of turbulent combustion of solid fusing explosives is not possible by the Landau - Levich mechanism. However, the abnormally large melting layer formed, for example, during very weak and prolonged ignition, can burn out in turbulent conditions, including in the form of a flash or explosion-like process. One of the possible methods of checking the theories is the study of combustion under increasing pressure. According to the results obtained in § 41,

high-viscosity mixtures under these conditions can burn normally to pressures which noticeably exceed critical p_* , determined with combustion under constant pressure. Experiments with nitroglycol showed that at rates of pressure buildup to 20 at/s it is possible to exceed p_* by not more than 20%, which agrees with the predictions of the theory. On a system of TNM - benzene with an addition of 2% PMMA and 5% aluminum powder experiments were conducted for the purpose of checking the theory for viscous systems. Combustion was conducted in a manometer bomb with a recording of the curve of the change in the pressure over time $p(t)$. Under conditions of combustion under constant pressure, for this mixture $p_*=11$ atm. Figure 118a shows the dependence of the critical pressure p_{κ} , found according to the experiments in the manometer bomb, from the given rate of pressure buildup $r=(1/p)(dp/dt)$ in the volume of the bomb, calculated from the recording of $p(t)$ in the section ahead of the interruption of normal combustion. As the curve shows, at low speeds of pressure buildup, the well expressed effect forecast by the theory is observed: in the manometer bomb p_{κ} exceeds p_* and increases with an increase in r . The processing of the data of the experiment leads to an expression in the form $(p_{\kappa}-p_*)p_*^{-1}r\eta^{-1/2} = \text{const}$. Since the mixture investigated is a non-Newtonian liquid, its viscosity depends on the rate of the application of shear stress, i.e., $\eta=\eta(\dot{\gamma})$. If $\eta \propto \dot{\gamma}$, the data of the experiment agree with the predictions of the theory [formula (102)]. Actual form of $\eta(\dot{\gamma})$ is not known.

Let us pass to the section of the dependence $p_{\kappa}(\dot{\gamma})$ at increased rates of growth of pressure. The experiment shows that with $\dot{\gamma} > 3.1/\text{s}$ the condition $p_{\kappa} < p_*$ is observed. Filming made it possible to establish that in these experiments the initial disturbance, created by an igniter (black powder) did not go out and turbulent combustion developed on the uneven surface

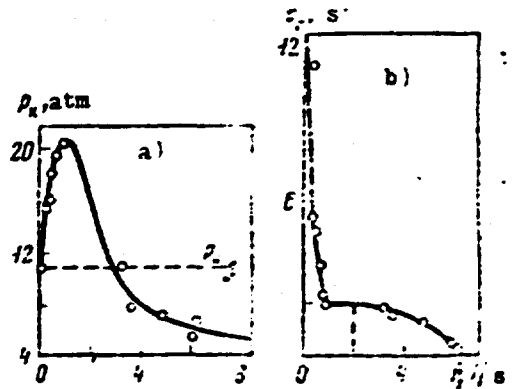


Figure 118. Effect of the relative rate of the increase in pressure r . a) the critical combustion pressure of the mixture TNM - benzene (3:1) with addition of 2% PMMA, 5% Al in manometer bomb; b) time of the development of the unsteady combustion of the same mixture.

as a further deepening of surface irregularities. In experiments with small rates of pressure growth, the initial disturbances of surface were damped, and there was always a section of combustion with a smooth surface. Figure 118b shows the dependence of the combustion period of the mixture to the moment of reaching p_H . A comparison of Fig. 118a and 118b makes it possible to establish that the characteristic time of the fading of the disturbances of the surface of the investigated system is approximately $\sqrt{2}$ s. If the rate of pressure buildup was so great that the disturbances were not damped,¹ p_H proved to be less than p_* . With the development of instability from normal burning $p_H > p_*$. In the experiments $p_H/p_* \approx 1.85$ is reached. Further thickening of the system will contribute to an increase in this ratio (at equal rates of growth of pressure),

¹This is equivalent to the requirement that the time of the combustion of the sample be comparable (or less) with the time of fading of the disturbance of the surface of the mixture.

but simultaneously the time of the fading of the initial disturbances will increase, which can hinder the attainment of high values of p_H/p_* . Utilizing known methods of ignition without significant disturbances, the curve $p_H/p_*=f(r)$ can be continued into the area of high pressure buildup rates.

§ 47. Combustion of ZhVV Charges With Heat Conducting Elements

With the determination of the rate of combustion of explosives, we frequently encounter the distorting effect of the shell of the charge on the results of the measurements. It was noted long ago that in metallic, not too massive shells, the rate of combustion of explosive charges proves to be more than in an environment of materials which conduct heat poorly [38]. An explanation of the effect of heat-conducting walls has already been given in Andreyev's works [37]. A charge shell which conducts heat well (for example, a metallic one) makes it possible to increase the heat flux into unburned substance because of the selection and heat transfers from the high temperature zone to the bypass of the gaseous phase of the combustion products of the charge which conduct heat poorly. The heat transmitted along the wall is spent for an increase in the initial temperature of the charge in the sub-surface layers, which as a result of the dependence of the rate of combustion on the temperature of the explosives, leads to an increase in the average rate of combustion of the charge. It is understandable that the higher the rate of combustion, the less the quantity of heat that can be transmitted into the bypass of the front of combustion via the heat-conducting element. In this case a larger than usual value is acquired by such factors as the temperature distribution in the gaseous phase, the presence of reactions in the k phase (temperature sensitivity of the rate of combustion), etc. In experiments with liquid explosives, placed in beakers (metal, quartz, glass), frequently at the end of combustion at a low rate effervescences of the liquid are observed which are accompanied by a flash. So, with the measurement of the temperature at the bottom of a beaker of nitroglycol, which burned at 5 atm, we recorded an increase in temperature long before the approach of the combustion front of more than

100°C. "End" effects are caused by the fact that the absence of heat withdrawal leads to a heatswell in the limited volume of the shell and, as a result, to a progressive heating of the terminal volume of the liquid (see Fig. 105g).

The first experiment described in literature with a heat-conducting element introduced for the strengthening of the heat transfer from the gas into the condensed phase was conducted by Kostin (cited in [37]). A copper rod introduced into the test tube of burning nitroglycol sharply accelerated combustion. At the present time, the introduction of heat-conducting elements into explosive charges and solid rocket propellants have become one of the physical methods of controlling their combustion rate [201].

We repeated I. D. Kostin's experiments (together with A. D. Margolin and F. S. Sokolovsky) on a TNM - benzene mixture, taken in the ratio 3:1 (1 atm). A change in the material of the wall of the shell of the charge (glass, brass, aluminum) was reflected in the rate of combustion, at the moment of the emergence of the mode of "rapid" combustion (see § 45), and also in the nature of the convective current of the mixture in the near-surface layer. In this case, for example, in an aluminum thin-walled shell the "rapid" combustion mode appears almost right after ignition, and in a quartz shell - after the combustion of the liquid column one to one and one-half diameter in height. The waves, which form a similarity to Binara's cells (see Fig. 116c) will move away from the walls of the container inward. The wave motion in the metal shell is brighter and is more intense than in quartz. In proportion to the thickening of the mixture the wave motion is damped; a high-viscosity mixture burns out faster at the walls and forms a cone with the apex upward.

Into the mixture, burned in a quartz cup, a copper rod was

introduced. Observations of the dynamics of the process revealed an intense convective current in the liquid beginning at the rod. The rate of combustion increased, and the transition to the "rapid" combustion mode was accelerated. The small thickening of the mixture unexpectedly led to explosions. It turned out that near the rod in the near-surface layer there occurs the formation of bubbles of the gas which is a mixture of the vapors of the initial liquid and of the decomposition products (indicated by changed in the color). In proportion to heating, the quantity of bubbles increased, and the accumulation of a foamy layer, whose burst was recorded as an explosion, occurred. The local nature of the phenomenon is clearly seen from the fact that frequently after the explosion the test tube turned out to be intact, the rod was ejected, and combustion continued to be propagated. Especially intense explosions occurred when the rod was introduced into the liquid to a small depth ("end" effect). The role of thickening of this case is reduced to the difficulty of convective heat exchange with the cold layers of the liquid, which leads to an overheating of the limited volume of the mixture, its decomposition and explosion.

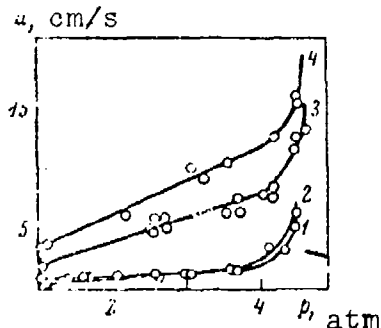


Figure 119. The dependence of the rate of combustion on the pressure of a stoichiometric mixture of TNM - benzene. 1 - plexiglass test tube without plates; 2 - steel plates with a thickness of 0.1 mm; 3 - copper plates with a thickness of 1.5 mm; 4 - copper plates with a thickness of 0.5 mm.

The systematic study of the effect of heat-conducting elements on the hydrodynamic combustion stability of ZhVV was undertaken in work [208] using as an example the stoichiometric

mixture of TNM with benzene. In the experiments rectangular plexiglass or quartz test tubes with a section of $5 \times 6 \text{ mm}^2$ were utilized; in part of the experiments thin copper or steel strips which served as heat-conducting elements were placed on two of the walls. The results of the experiments are shown in Fig. 119, from which it is evident that the metallic plates noticeably increase the rate of combustion in subcritical conditions as well as the critical rate of combustion; however, the critical pressure of the transition to turbulent conditions remains unchanged. Hence it follows that the effect of the introduction of the heat-conducting elements entails an increase in the effective rate of combustion of the mixture; at the same time the combustion stability of the liquid mixture is determined by the intrinsic fundamental rate. It is appropriate to note that in the case of powder-like systems the critical conditions of the disturbance of normal burning are also determined by the fundamental rate of combustion and do not depend on the physical effects, which lead to an increase in the recorded rate of combustion.

Let us examine the phenomena which accompany the combustion of a liquid mixture into which a heat-conducting element is introduced, being guided by the data in work [208]. The heat is spread along the element from the zone of the flame into the depth of the liquid. The heating of the layers of the mixture adjacent to the element causes the appearance of convective currents within the liquid.

The heating of certain near-surface layer forces it to burn at an accelerated rate. However, at pressures lower than the critical for the transition to turbulent conditions the burning up of the reheated layer of the mixture converts to the calm combustion of the unheated liquid, since for it the normal mode of combustion is characteristic under these conditions. The warm-up period of the new near-surface layer of the liquid

follows again because of the heat of transmission along the element, and the picture is repeated. The fluctuating combustion mode appears, the average speed of which will be above normal because of the acceleration of the combustion of the reheated layer of the mixture. The turbulent combustion, not alternating with periods of normal burning, can develop only after the critical pressure of transition for the initial mixture is exceeded in the experiment. In work [208] the described sequence of the phenomena was confirmed experimentally by the method of high-speed filming.

The effect of the heat-conducting element logically depends on the relationship of the thermal diffusivity of its material and the $ZhVV$ and also on the temperature combustion rate coefficient of the latter. In the case of liquid mixtures with significantly differing volatilities there can arise the amplifying pulsations of the phenomenon of fractional burnout. With the re-enrichment of the surface layer of the mixture the component incapable of independent combustion, the damping combustion is possible, which we observed experimentally during the investigation (1 atm) of a mixture of TNM with ethyl ether which was somewhat re-enriched by the oxidizer.

Thus, the steady state of turbulent combustion is feasible only when the critical value is exceeded by the fundamental rate of combustion, which also determines the independence of the critical pressure from the presence of the heat-conducting elements.

We do not examine here the possible catalytic effect of the surface of the heat-conducting element, which sometimes can substantially influence the average rate of combustion of liquid explosives.

§ 48. Means of Transition from Excited Combustion to Explosion

The phenomenon of the transition of combustion to explosion and detonation has always been the final goal toward which researchers of the mechanism of unsteady combustion have strived. The fundamental works on this question are those of K. K. Andreyev, A. F. Belyayev and their coworkers. Their views are most fully reflected in monographs [37] and [59]. Nevertheless, it is necessary to state that this section of combustion theory is still weakly developed, both theoretically and experimentally. Many propositions remain hypotheses which do not have quantitative substantiation.

The theory of the turbulent (agitated) combustion of liquid explosives presented in the preceding sections makes it possible to approach somewhat a solution to the problem of the conditions of transition from the combustion ZhVV to the explosion, although it is not possible to give a final answer, above all in view of the absence of the necessary experimental studies.

The Andreyev-Belyayev Mechanism

As was mentioned in the beginning of the chapter, the transition from combustion to explosion according to the Andreyev-Belyayev mechanism can occur if the acceleration of gas formation with pressure exceeds the critical value at combustion.

The physical meaning of this assertion is clear from an examination of the expression for pressure in the volume of a container (tube) which contains the burning explosives. If the diameter of the charge is equal to the diameter of the tube, then with $u_1 = Bp^v$ $p_T = (B\rho_1/A)^{1/(1-v)}$. Hence, it follows that with $B\rho_1/A > 1$ and $v \approx 1$, pressure p_T increases indefinitely until the shell of charge is destroyed, i.e., until explosion. Since $A \approx 7.4 \text{ g/cm}^2 \cdot \text{s} \cdot \text{atm}$, the condition of the explosion of the charge

will be the requirements $B\rho_1 > 7.4 \text{ g/cm}^2 \cdot \text{s} \cdot \text{atm}$ $\nu \approx 1$. If $\nu > 1$, the disequilibrium occurs if the pressure exceeds value $p_{HP} = (A/B\rho_1)^{1/(1-\nu)}$ (curve of m_2^+ in Fig. 120).

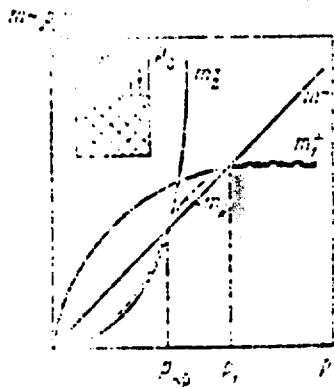


Figure 120. Balance of gas inflow with the supersonic discharge of the combustion products.

With $\nu < 1$, even with $B\rho_1/A > 1$ pressure p_1 will exist, which corresponds to the equilibrium of gas inflow and gas outflow. With $\nu < 1$ and $B\rho_1/A \leq 1$, the pressure p_T will be virtually equal to the external pressure p_0 .

As was established in the preceding paragraph, the dependence of the rate of turbulent combustion of liquid explosives on pressure initially has an index $\bar{\nu}$ more than one; then it passes all intermediate values and at high n it approaches $\bar{\nu} = \nu_0 - 0.5$, where ν_0 characterizes undisturbed combustion. With liquid explosives $\nu_0 \approx 1$, and consequently the developed turbulent combustion mode has the dependence $u_T(p)$ in the form $u_T = Bp^{0.5}$. Hence it follows that the combustion in the developed turbulent conditions, from the viewpoint of the Andreyev-Belyayev mechanism, must be stable, with $p_1 = \left(\frac{Ba_1}{A} \frac{\rho_1^{1/2}}{(\rho_2^0)^{1/2}} \right)^2$ where ρ_2^0 is the density of the combustion products, reduced to 1 atm. It is interesting to compare this conclusion with the data of work [191] (see § 49).

In the transition zone between $n=1$ and $n \gg 1$ there is a pressure range where the index $\bar{\nu} \geq 1$. If condition $B_T\rho_1 > A$ is satisfied here, then there appears the possibility of the disequilibrium of the gas inflow and the gas outflow. However, if the shell of the container with the explosives is sufficiently durable, then the pressure in it will grow until the mode of developed excited

combustion is established for which $\bar{v} < 1$. This is illustrated by the curve m_* in Fig. 102. Here with $p < p_1$, the gas inflow is greater than the gas discharge, and pressure in the shell increases. However, there occurs further the transition to the saturating branch ($\bar{v} < 1$) and in the final analysis the equilibrium pressure p_1 is established. Of course, the shell can be destroyed before the achievement of pressure p_1 , and this will be recorded as an explosion.

We have discussed only one condition of the transition of combustion to explosion for the Andreyev-Belyayev mechanism. Another requirement is $\rho_1 B > A$. In the developed mode of excited combustion $B_T = B\sqrt{\rho_1/\rho_2} = 10^2 B$. A comparison of this value with the data in Table 18 and value A shows that the methyl nitrate possesses $B_T \rho_1 / A > 1$ and for it, $p_1 = 3.5$ atm, whereas other substances are located near the limit. Important here is even not the order, but the numerical value of the coefficient a_1 , etc. In other words, depending on the details of the situation, both $B_T \rho_1 > A$ and the subcritical combustion mode can be realized. So, careless ignition, which contributes an additional increase to the burning surface of 2-3 times, the difficulty of the gas outflow, let us say, by a decrease in the section of the flow of the products of combustion in comparison with the surface area of the charge, etc. - all this will facilitate the explosion.

It is important to emphasize the following fact. The study of the problem in the Andreyev-Belyayev theory is conducted on the assumption that the whole substance manages to react within the limits of the container confining the liquid. If a considerable fraction of the substance is taken out (for example, in the form of drops) and reacts far from tube, the generation of gas from the combustion of this quantity of explosives does not enter into the balance of the gases which determines pressure at the surface. The height h of the container which contains liquid

explosives which will ensure the combustion efficiency of the drops, separated by the flow from the surface, obviously, must be not less than h_* , where

$$h > h_* \approx \tau_m u_2 = \tau_m \frac{B_T}{V_P} \frac{1}{V \rho_2^2} \quad (107)$$

In the first approximation, τ_m is determined by the kinetics of the reaction of the substance and is proportional to the size of the drops to the degree of the second order, while with simple burnout this degree is equal to one.

From the viewpoint of the balance of gas inflow and gas outflow, the developed mode of excited combustion should be stable. This conclusion follows on the assumption that the disturbances develop from infinitesimal disturbances generated with the very process of combustion, i.e., their amplitude $\xi \ll u_2^2/g$. As concerns larger artificial disturbances, as was established in § 39, they burn with "spreading".

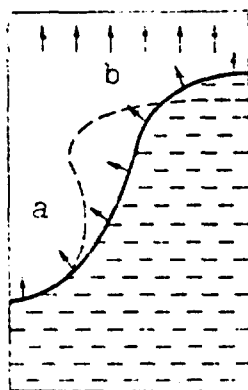


Figure 121. Evolution of large-scale disturbance of the burning surface of the liquid.

Let us assume that at the moment of intense ignition of the liquid, at some moment the indentation (Fig. 121) was formed. In area a the pressure will be more than in area b. The excess pressure will begin to squeeze out the liquid from the container, to splash it, and the ignition of the drops by the high-temperature flame can occur in the form of an explosion. Moreover, the wave

can turn out to be unstable, and instead of spreading, the break of its crest will occur (dashed curve in Fig. 121). As a result, within the liquid there will prove to be an isolated volume of

combustion, which, increasing, will destroy the enveloping fluid. The external picture will be represented by the explosion of the charge.

Thus, the most favorable conditions for developing instability, according to Andreyev-Belyayev, occur near the limit of normal burning, when the mode of excited combustion is not yet developed. Far from the limit, according to Landau-Levich, the combustion in the sense considered is stable ($\bar{v} < 1$); however, it is necessary to eliminate the external artificial disturbances more than $\sim u_T^2/g$ in size, which can become the reason for local explosions.

Thermal Explosion of a Suspension of Drops of ZhVV in the Gaseous Phase

In view of the powerful turbulence, the temperature of the combustion products is close to maximum and is almost constant with regard to the flame jet. This provides a rapid course of the gas-phase reactions as a result of the exponential dependence of their rate on the temperature. As was already mentioned above, the thermal explosion of a drop suspension very frequently is considered as the initial stage of the development of an explosion and even as the detonation of the charge. Let us discuss this question in somewhat more detail.

The concentration of the drops of the explosives in the gaseous phase c_H can be taken as proportional to the rate of turbulent combustion. Taking into account that with 1 cm^2 for time τ_H , there emerges into the gaseous phase $u_1 \rho_1 \tau_H$ grams of the substance, which is distributed in the gas column $u_2 \tau_H$ in height, we obtain $c_H = \rho_2 \text{ g/cm}^3$.

To evaluate the conditions of the thermal explosion of suspended matter, we utilize the fact established in work [209]: the critical conditions of the self-ignition of the aggregate of the particles have the same form as the critical conditions

for a single particle, but with a changed heat-transfer coefficient. A peculiarity is the fact that the thermal explosion of the aggregate of the drops occurs under conditions of the interference of the particles. Furthermore, according to [209], in the first approximation, the presence of the stages of the heating and vaporization of the drops of the liquid explosives leads to a change in the numerical value of the critical value of the Franck-Kamenetskiy δ_* . This makes it possible to write the critical condition of the thermal explosion in the form

$$\delta_{**} = \frac{E}{RT_0^2} \frac{Q\rho_1}{\lambda_1} \frac{(Nu)_{\kappa}}{Nu} L^2 \psi \geq \text{const} = \delta_*, \quad (108)$$

where E - activation energy; T_0 is the temperature of the medium; ψ - reaction rate; R - universal gas constant; λ_1 - the coefficient of the thermal conductivity of the drop; Q - the heat of reaction of the explosive, $(Nu)_{\kappa}$, Nu - Nusselt numbers for the heat transfer from the particles to the gas and from the gas to the walls, respectively; L - the typical dimension of the container (diameter); δ_* - critical value.

Thus, the thermal explosion of a suspension of drops is feasible with the fulfillment of the relationship in (108). It includes in particular, the value of the diameter of the container, so that with an increase in the area of the section the thermal explosion is facilitated. Let us note that, according to [209], the ignition point of the particles does not depend in this case on their size.

Under condition in (108) it is assumed that all drops pulled from the surface are located in the suspension. One should also consider the effect of the burnout of the suspended matter for the time of the induction of the thermal explosion [210; 211]. In the first approximation, it is possible to consider that it is sufficient to satisfy conditions (107) and (108), wherein as τ_{H} one should take the induction period of the thermal explosion, since the time of the burst τ_{B} is considerably shorter than τ_{H} .

It is worth noting one fact which sometimes is the source of errors. A decrease in the degree of dispersion of the particles, which is introduced during the gaseous phase from the surface by itself, causes only a change in the height of flame jet, but cannot lead to a disturbance of the balance of the gas inflow and gas discharge. Actually, the gas inflow is connected only with the quantity of that reprocessed into the products of combustion of the original substance; and without the introduction of any supplementary mechanism of the essential acceleration of the combustion of the drops of ZhVV and the effect of the process of the combustion of the suspension on the supply of drops from the surface, it is not possible to unbalance the process. Let us recall that the interruption of the drops is determined by the kinetic energy of the combustion products $\rho_2 u_2^2$.

The positive feedback of the process of the combustion of the drops with the process of the separation of the drops from the burning surface can be accomplished only through a pressure increase in the container since the velocity of the combustion products after the achievement of the completeness of combustion (and with $v=1$) no longer changes. The rise of the pressure in the container is possible if the time of the reaction of drops is shorter than the time of the discharge of the combustion products, i.e., $D/v < h/C_3$, where v is the effective speed of the reaction (combustion) of the drops with a size D ; h is the height of the free part of the tube above the surface of the liquid, C_3 - the speed of sound in the combustion products. Taking $h=1$ cm, $C_3=10^5$ cm/s, $D=10^{-3}$ cm, we calculate that $v=10^2$ cm/s. The normal rate of combustion roughly is $u_1=3 \cdot 10^{-2} p$ cm/s. Taking into account the possible heating of a drop, we find that rates of 100 cm/s correspond to $p=10^4$ atm. Thus, simple thermal conductive combustion of the drops at moderate pressures is not able to create a pressure jump above the burning surface. Let us note that the heating time of a drop with a diameter of D is $\sim D^2/4Nu_1$, and with $D=10^{-3}$ cm is $\sim 2 \cdot 10^{-4}$ s, which is more than $h/C_3=10^{-5}$ s.

It is interesting to compare this time with the time of transition from combustion to explosion obtained in work [19]] (see § 49).

Generally speaking the question concerning the actual sizes of the drops of suspended matter remains open, since the initial (torn from the surface) drops of ZhVW can be crushed in the gas flow. This moment is discussed in Mayer's work [216].

The distance to the combustion point of the drops from the surface exceeds the value which is characteristic of the normal process κ_1/u_1 , since from the surface of the liquid moves not the prepared steam, but cold drops.

We will turn to the question concerning the consequences of the thermal explosion of the suspension. Considering the explosion of drops to be instantaneous, i.e., is fulfilled $(u_2/C_3) (\tau_{\text{ш}}/\tau_{\text{в}} \geq 1)$, where C_3 is the speed of sound in the products of combustion, we can estimate that excess pressure which appears in the flame jet. Since in 1 cm^3 there are contained $c_{\text{ж}} = \rho_2 = \rho_2^0 p_0$ grams of the liquid explosive, with a complete transformation their temperature increases from an initial T_0 to T_2 - the final temperature of the explosive conversion, and the density will change from ρ_1 to ρ_2 . The increase Δp of the pressure in the combustion products will be

$$\Delta p = p - p_0 = c_{\text{ж}} RT_2/M \approx p_0.$$

This value can prove to be so considerable that the container will be destroyed and process will occur as an explosion. The effect of the gradient of excess pressure on the original substance is able to destroy the liquid, to atomize it, and thereby make the process of combustion self-accelerating. To this contributes the fact (which we did not consider above) that the actual distribution of the concentration of the drops in the flame jet is not homogeneous as a result of the vortex flame condition. Therefore, the thermal explosion can appear

in separate isolated sources, in the same way as this is frequently observed in gas turbulent flames [185]. The difference consists in the hundred times higher local pressure increases, which appear with the combustion of drop suspensions. The noted nonuniformity of the distribution leads to the fact that the streams of the products of the thermal explosion will affect the surface of liquid, disturbing its uniformity.

If the time of the development of thermal explosion is not too short, and it is possible to disregard the outflow of gas from the container for the time of the reaction (this means that $u_2 \tau_{\text{th}} / C_3 / \tau_B < 1$), then the pressure in the container will take a value on the order of $p_B \leq (\rho_2 B_T / A \rho_2^0)^{2/3}$. If the initial pressure was much less than p_B , the result of the combustion of the suspension will look like an explosion. At high pressures the process occurs in the form of a flash.

It is very important to pay attention to the following fact. At higher than critical thermodynamic pressures, after the heating of the drops of liquid to a temperature higher than the critical T_{HP} , their "pulse" vaporization with the subsequent combustion of vapors occurs. By the moment T_{HP} is reached, it manages to evaporate a total of ~5% of the mass of the drop [203]. This phenomenon in many respects can contribute to the transition of the turbulent combustion of ZhVV to the explosion through processes in the vapor phase.

Cavitation Excitation of the Explosion of ZhVV

In work [2] Belyayev advanced the hypothesis according to which the dynamic lowering in the pressure above the burning surface of the liquid can lead (through the effervescence of the substance, in Belyayev's view) to the initiation of detonation. The basis for this assumption were the observations that the combustion of methyl nitrate, stable at 1 atm and 40°C, converts

to detonation if we lower the pressure in the process of combustion. A further line of reasoning, in light of contemporary ideas, took a noncorresponding course and there occurred the substitution for the question concerning the role of rapid pressure relief of the question concerning the explosion of a mixture of the vapors of methyl nitrate with air. There is a detailed discussion of this (the second) question in Andreyev's books [37, 38], and we will not dwell on it here.

We will turn to the essence of A. F. Belyayev's hypothesis. It has been established by works of recent years [212-214] that comparatively small changes in pressure can cause cavitation and explosion in some ZhVV. According to the works of Gordeyev [213], the excitation of explosion occurs during collapse of sufficiently large cavitation recesses (caverns). In this case the basis of the mechanism is composed of the heating and ignition of the vapors of the liquid in the mixture contained in a cavern with the dissolved gases as a result of their rapid compression. Taking into account that the heating T_1/T_0 of the vapors is proportional to the compression p_1/p_0 to the degree of $(\gamma-1)/\gamma$, where γ is the polytropic exponent, it proves to be advantageous, with this compression stress, for achieving a high final temperature T_1 , to have a small initial pressure of the vapors p_0 . At the same time, if the volatility is very low, the vapor pressure turns out to be negligible, and the heating and flash of the vapor will be insufficient for the initiation of the explosion. It is important to emphasize [70] that the heating as a result of the compression of a chemically active gas, which the vapor of an explosive is, is more dangerous than the compression of inert gas pockets, since the temperature of the compressed reactive gas will be higher a result of the heat release from the chemical reactions.

The size of the cavitation bubble has the greatest significance. The small bubbles are cooled so rapidly that the compression of the vapors occurs virtually in isothermal conditions.

For the essential heating of a bubble with inert gas it is necessary [70] that the time of the compression of the gas $t_1 \sim \sqrt{p/\dot{p}}$, where \dot{p} is the rate of pressure buildup, be less than the cooling time t_2 :

$$t_2/t_1 \approx d^2 \dot{p} / 4 Nu \kappa_2 \rho \gg 1.$$

Here κ_2 is the temperature conductivity contained in the bubble; d - the average value of the diameter of the bubble; Nu - Nusselt number for the heat emission from the bubble into the liquid.

With $d \sim 10^{-4}$ cm it is necessary to have $\dot{p}/p > 10^5 \text{ s}^{-1}$, i.e., compression must occur for an extremely short time. The heating of the compressed gas is $T_1/T_0 = (p_1/p_0)^{(\gamma-1)/\gamma}$. The condition of the thermal explosion of the reactive gas in the first approximation, takes the form

$$(d^2 \rho_2 Q_2 E k_0 / 2RT_0^2 Nu) \exp(-E/RT_1) \gg 1,$$

where k_0 is the pre-exponent; Q_2 is the thermal effect of the chemical transformation; d - the size of the caverns; ρ_2 - the vapor density of ZhVV in the bubble-cavern which is proportional to the vapor pressure p_0 . One should consider that $p_0 = a_1 - a_2/T_0$, where a_1 and a_2 are constants of this substance and T_0 is the absolute temperature.

Thus, as a function of the volatility of the liquid and the kinetics of the reaction of its vapors there is a critical dimension of the cavitation bubble which can become the source of the initiation of the explosion with this compression of the bubble. Gordeyev indicates [213] that any explosive liquid can be exploded with the collapse in it of a cavitation bubble, the initial size of which is equal to the critical value or exceeds it. However, practically, in view of the difference in the physicochemical properties of the liquids, they all cannot be initiated by cavitation. Substances which have low speeds of

reaction of the vapors, a very low or too high a volatility are characterized by such large critical dimensions of the cavitation bubble which virtually cannot arise.

Gordeyev and Matveyev studied [215] the initiation of an explosion by cavitation (at 1 atm) of the following ZhVV: nitroglycerin (NG) [HГU], tetranitromethane (TNM) [THM] nitromethane (NM) [HM], solutions of benzene, heptane, methanol in TNM, a solution of methane in liquid oxygen (at the boiling point of nitrogen) and a heterogeneous system of solid acetylene-liquid oxygen (also at the boiling point of nitrogen). An original procedure was developed for creating large cavitation recesses, which made it possible for the first time to study the phenomena in detail. A test tube was utilized with a fitted piston under which the investigated substance was introduced. A liquid seal in the form of a coniform funnel filled with the explosives made it possible to insulate the liquid under the piston from the effect of atmospheric pressure for several milliseconds. The rapid extraction of the piston creates a tensile stress in the liquid, the compactness of the explosives is disturbed, and caverns are formed¹. An explosion was excited with the collapse of the cavitation bubbles in the solutions of benzene or heptane in tetranitromethane. In technical NG it was possible to excite explosions by applying a piston with a tapered point.

Study of the effect of the initial temperature [215] gave the following results. A solution of benzene in TNM at a temperature of less than 10°C and up to the temperature of precipitation of the crystal residue constantly produced explosions.

¹It is necessary to note that the tensile strength of liquids very strongly depends on the content of the dissolved gases. In this case the saturation of the liquid by the gas sharply lowers its strength and contributes to cavitation.

At 20°C excitation of the explosion occurred in one third of the experiments. The pressure of vapors p_0 is at 20°C, $p_0=30$ mm Hg, and at 10°C, $p_0=17$ mm Hg. An increase in the temperature up to 40°C ($p_0=70$ mm Hg.) decreased the excitation frequency of an explosion to 3/20. At 60°C ($p_0=160$ mm Hg) not one of the 20 experiments produced an explosion. The solution of heptane in TNM routinely exploded at a temperature less than 2°C ($p_0=3$ mm Hg.). At 20°C ($p_0=14$ mm Hg) the frequency of explosion was 2/50, and at 40°C ($p_0=200$ mm Hg) not one of the 100 experiments produced explosions. The solution of methanol in TNM turned out to be insensitive to the cavitation excitation of explosion in the temperature range 10-50°C ($p_0=40-280$ mm Hg).

Experiments were carried out on technical and purified NG at elevated temperatures. There is great interest, both from the theoretical and the practical point of view, in the fact that purified NG, in spite of a very low vapor pressure (less than 0.5 mm Hg), routinely produced explosions. The technical product at 70°C exploded in two experiments of the twenty, but at lower temperatures it was insensitive to cavitation excitation.

Undoubtedly, there the kinetic side of the process was revealed here: the vapors of the purified nitroglycerin easily produced a thermal explosion as a result of their high reactivity. As concerns the contaminated product, developing a thermal explosion in its cavitation recesses requires that the initial temperature of product be raised at least to 70°C. An important observation is [215] that the purified NG, after the exposure of the surface of the liquid in air for several hours, becomes insensitive, while the pressure of its vapors is raised.

The cavitation mechanism of the excitation of the explosion must be considered as one of the causes of the explosions of liquid explosives during careless ignition, especially with experimental ZhVV for combustion in a closed volume. A free-burning igniter, as well as a flash of the thick thoroughly warmed layer of the

explosives, gives rise to acoustical oscillations whose propagation can cause the cavitation of the liquid and contribute to the explosion of the charge.

We will again turn to Belyayev's work on the excitation of an explosion of methyl nitrate [2], and also to the supplemental work of Andreyev [37]. It was established that the ignition of the vapors of methyl nitrate, and also a mixture of the vapors with air with a content of methyl nitrate of more than 70% produces a powerful explosion. Moreover, it was also possible to produce an explosion of the liquid methyl nitrate itself with the ignition of the vapor-air mixture above the surface of the liquid. Examining the results of these experiments, Andreyev [37] notes that the explosion of the gaseous vapors is able to create a small, but sufficient for the initiation of detonation, rise in pressure. It would be possible to assume that the jump in pressure created by the gas explosion creates the acoustic fluctuations of the liquid, its cavitation, and the excitation of the explosion by the mechanism described above.

However, there are experimental observations which show that the excitation of an explosion can occur in another way. Thus, we conducted the combustion of nitroglycol under conditions of a bomb of a small ($\sim 200 \text{ cm}^3$) constant volume. Nitroglycol was placed in beakers with a diameter of 5 and a height of 30 mm. With the ignition of the explosive from a charge of black powder, which burned for a time on the order of 50 milliseconds, we routinely obtained an explosion of entire charge above the surface of ZhVV. However, it was sufficient to shield the surface of the liquid by a layer of nitroglycol gelatin or to place a transition layer from the slowly burning nitroglycerin powder, as the excitation of normal burning occurred. But if the spiral was placed deep into the liquid, an explosion occurred again. In the absence of special experiments it is not possible to deny the probability of the cavitation excitation of an explosion.

However, the stabilizing role of a thin layer of gelatin is insufficiently clear. Apparently, gelatin impeded the destruction of the surface by the streams of the products of the combustion of the igniter. The question concerning the role of cavitation in the process of the excitation of an explosion and the propagation of low-speed detonation processes ZhVV is minutely examined in works [122, 212, 214, 215, 217]. The mechanism of the excitation of an explosion through cavitation, in view of the weak impulses necessary for its accomplishment apparently one is of the most widely accepted ways of achieving the transition of combustion of ZhVV to explosion. Unfortunately, at present there are no experimental studies of its realization under varied conditions of combustion.

The turbulent combustion of ZhVV beyond the stability limit, as we noted above, leads to the initiation of vortices in the gaseous phase. If, as a result of those or other reasons, the steady state of vortex formation is disrupted, the rarefaction wave from the gaseous phase will go into the liquid. However, the pressure of the initiation of turbulent combustion, as a rule, is 10 atm and more. As a result, the essential compression of the cavitation bubbles is difficult to achieve and this makes the cavitation mechanism of the excitation of an explosion through the pulsations of pressure in the combustion products only slightly probable. At the same time, some quick-burning liquids which produce excited combustion at low pressures (methyl nitrate, mixtures of tetranitromethane with a number of hydrocarbon fuels), can prove to be the objects of a cavitation explosion.

§ 49. Transition of the Combustion of ZhVV at High Pressures to Explosion

The thorough investigation of Dubovitskiy and Bachman [191] of the transition of the combustion of a number of nitroesters at high pressures to detonation is the only work on this problem. Bombs of constant pressure were used, which made it possible to

conduct the experiments at pressures of up to 800 atm. Two drum photorecorders (for the low-speed and detonation explosive processes) provided the photorecording of the dynamics of the combustion. Furthermore, the authors of work [191] utilized high-speed (2-4 thousand frames per second) filming. Let us consider some results of this work.

1. It was established that "the transition of the combustion of methyl nitrate to detonation (combustion in thin-walled glass tubes with an inside diameter of 5 and a height of $h_0=20$ mm) is observed only in the range of pressures $70 \leq p \leq 350$ atm, above 350 atm and up to 800 atm only combustion at the speed of several meters per second occurred".

2. The combustion of nitroglycol¹ at pressures higher than 50 atm occurred in two stages. If the first of them was characterized by a sharp photoregistration front, and as a whole, by the relative constancy of the speed relative to the height of a liquid column, then at the second stage, which occurred only with $h_0 > 40-60$ mm, either a combustion mode different from the first appeared or detonation abruptly occurred.

3. It was established that the transition of almost uniform combustion to explosion occurs in a time of $\leq 10^{-3}$ s, which corresponds to the combustion of a layer of nitroglycol 1-2 mm thick.

4. With heights of the charge less than a certain limiting value h_* detonation never occurred, while with $h > h_*$ the probability of its excitation no longer depended on the height but increased with an increase in the diameter of the charge d and in the pressure

¹Analogous observations were also made during the study of the combustion of methyl nitrate and nitroglycerin.

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On a section of 20-30 d the velocity is usually sufficiently constant relative to height, while the fading of the process was never observed.

7. In separate experiments in wide ($d > 5$ mm) test tubes the branching of the leading slightly glowing wave was observed, which exited with a velocity of 700-750 m/s (against 400-500 m/s in the primary front) and which formed an area of weak brightness in front of the primary detonation front. In one of the experiments, the branching-off wave, after reflection from the bottom of the test tube, caused the detonation of the charge, which was always spreading at the same velocity, 400-500 m/s, towards the primary front.

8. The thickening and strengthening of the walls of the test tube did not affect the ceiling of the appearance of detonation, did not change the rate of the almost uniform combustion; but it noticeably increased the rate of the unsteady detonation, as well as the squeezing of the lead column which was laid under the test tube to provide evidence of the intensity of the explosive process.

We will turn to the interpretation of the results. According to the point of view of the authors [191], with the combustion of ZhVV beyond stability limit "the conditions necessary for the appearance of detonation can be created in separate very small volumes of liquid explosives located near the combustion front". As proof, the results of the high-speed filming of the combustion are presented, which demonstrate the existence of the greatly bent (usually cone-shaped) flame front. Since the dynamic pressure of the combustion products of ZhVV ebbing from the bent surface are able to equalize a very large liquid column, and in view of the nonuniform nature of ignition, the asymmetric displacement of the liquid from the test tube and the formation of a bent front of combustion is a natural corollary. Further, a parallel is drawn between the excitation of detonation with a shock and the

frictions from the local sources of heating and by the process of the unsteady combustion of the liquid. It is assumed that as a result of the great bend of the combustion front, isolated volumes of high-temperature combustion products can be formed in front of it. The development of combustion within this volume increases the pressure and the temperature. If they have time to achieve sufficiently high values before the destruction of the source, the emergence of detonation is possible.

We will discuss briefly those views which were developed in work [191] itself. In light of current data, it is possible to make some additions.

The nature of the detonation processes of the ZhVV, which were observed in work [191], provides a basis for an assumption about the leading role of a cavitation type of process. Specifically, this is indicated by the powerful effect of the thickness of shell on the rate of the process.

From our point of view, the source of the acoustic jolts of the test tube with ZhVV is the sound vibrations, which appear with the discharge of the combustion products from the test tube. The thickening of the wall of the test tube, the setting of the test tube into a steel shell - all this contributes to the transmission of the sound vibrations from the opening of the tube into the liquid. With $h \approx 5$ cm, $p_0 = 200$ atm(abs.) $u_1 = 80$ cm/s, $\rho_1 = 1.5$ g/cm³, the oscillation frequency will be $f \approx u_2/h = 700$ Hz. The acoustic jolts of nitroglycol, apparently, create small cavitation bubbles, the continuity of the liquid is disturbed, and the process of combustion becomes, in the known sense, similar to the combustion of porous powder-like charges. A comparison of the observations made in work [191] with the results of the study of low-speed detonation processes [122, 212] reveals much in common.

The photorecording of the work in [191] can be interpreted as proof of the uneven, cellular structure of flame front. In this case the characteristic dimension of the separate cells proves to be of the order 0.2-0.5 mm (at pressure 350 atm). Utilizing data from Tables 19 and 20, and taking into account that the critical pressure in nitroglycol is equal approximately to 17 atm, we find

$$\xi_n \approx \frac{1.16 \cdot 3 \cdot 17}{4 \cdot 350} = 0.4 \text{ mm},$$

which corresponds to the experiment.

It is indisputable that the method of ignition exerts a great effect on the recorded mode of the propagation of the unstable combustion mode. Only the use of transient charges from the normally burning substances makes it possible to avoid the effect of the powerful disturbance, which is the process of ignition, on the detailed picture of the development of combustion, since in the distant supercritical area of combustion the powerful disturbances are not able to be damped.

The critical height of the charge, which was discovered in work [191], lower than which detonation did not appear, can be identified with the height of the combustion of the suspension of drops of the liquid raised from the surface. In that case the combustion time of the suspension, with $h_* = 5$ cm, $\tau_{\text{wh}}/u_2 = = h_0 p_2 / (\rho u)_{\text{T}} = 2 \cdot 10^{-3}$ s. With the diameter of a drop on the order of 0.2 mm (the wavelength of the most rapidly growing disturbance), the rate of combustion of the drop is $\theta \approx 20$ cm/s. Extrapolation of the normal rate of combustion of nitroglycol up to 200 atm gives $u_1 = 5.2$ cm/s. The calculation of the heating of the drop does not make a decisive change in this figure. Thus, it is possible to assume that either the crushed drops, whose size is less than ξ_n , enter into the gaseous phase, or that the mechanism of their combustion is not thermal conductive, but explosive.

In favor of the assumption regarding the excitation of the detonation of the explosives through a thermal explosion of the suspension of drops in the gaseous phase, there is also the fact of the effect of the diameter of the charge on the detail of the detonation, which is characteristic for the "collective effect" of the thermal explosion of the aggregate of the particles. Let us note that the height of the charge affects the excitation frequency of the detonation independently of the diameter of charge, which does not contradict formula (108) (see also § 48).

The abrupt nature of the appearance of detonation agrees with the hypotheses regarding the development of an explosion through the thermal explosion of the particles of the explosive and of the intermediate products of combustion in the gaseous phase, under conditions when the initial liquid is prepared by jolts of the test tube by acoustic vibrations generated by the discharge of the combustion products. It is possible to identify the branching wave departing ahead of the primary front with the propagation of the cavitation front, and the weak brightness with the heating of the cavitizing bubbles. Current methods of study would indisputably be able to be introduced certainly into this question.

It is appropriate to remember the following. Leypunskiy and Korotkov conducted the combustion of nitroglycol at pressures up to 2000 atm and established that with the careful pumping out of the dissolved air from the liquid, the combustion occurs without transition to explosion or detonation and has a rate of the order of several meters per second. Since in their experiments Leypunskiy and Korotkov used a manometer bomb, ignition was conducted at low pressures, which indisputably contributed (together with the removal of air bubbles) to the elimination of external disturbances and to an increase in the tensile strength of the ZhVV and, as a result, to an increase in the stability of the turbulent combustion.

Everything that has been said does not eliminate the possibility of the development, under adequate conditions, of detonation from a source of the combustion formed within the liquid. The question consists only of how the source is created. A beautiful example of the significant mechanism of excitation of the detonation of ZhVV is presented by I. A. Voskoboynikov's experiments (IKhF AN SSSR, 1962) which were conducted on a stoichiometric mixture of tetranitromethane and nitrobenzene. A drop of metallic sodium, which was put into the test tube with the mixture served as the source of ignition. A photorecording shows that low-speed combustion initially appears near the drop of sodium. The inertial forces provide for a short time (~ 50 μ s) the possibility of the development within the mixture of an insulated center of combustion of the mixture of TNM with nitrobenzene makes it possible for disturbed combustion to develop at those low pressures (2-5 atm) and short times which characterize the given experiment. As the photorecording of the process shows a detonation wave, which occurs at a rate on the order of 7000 m/s appears in the mixture. This experiment visually demonstrates the possibility, in principle, of the emergence of detonation from an insulated center of combustion within liquid explosives, although for a final solution to the question supplementary investigations are necessary.

§ 50. The Combustion of Two-Phase Systems

In work [218] the experimental and theoretical study of the combustion of the simplest model of a two-phase porous charge - slotted charge, was conducted. The slotted charge consisted of two plane-parallel plates between which the liquid was filled. One of the plates (or both) was prepared from powder. With normal combustion the liquid impedes the penetration of the flame into the clearance, and the powder plate burns from the end. Under specific conditions the flat surface of the liquid becomes unstable, waves appear on it, and drops and streams, which are taken away by the flow fo the combustion products are formed. The revealed fresh sections of the powder plate are ignited, and the combustion is spread into the depth of the slot. The described picture reminds one of the turbulent combustion of liquid explosives with the difference being that the energy source in this case is the combustion of the exposed part of the lateral surface of the slot. The theory of turbulent combustion of the slotted charge of the powder filled with liquid is formulated [219] analogous with the theory of the turbulent combustion of liquid explosives.

Theory of Combustion of Two-Phase Systems

The following model of turbulent combustion is accepted. The pulsations of the rate of combustion products, equal in order of magnitude to the average flow rate of the gas, cause pulsations of the rate of the liquid. The revealed surface of the plates is instantly ignited. The rate of turbulent combustion in the first approximation is equal to the pulsating rate of motion of the liquid. Upon transition of the turbulent motion from the gas into the liquid, the pulsations of pressure (but not rate) are retained; therefore, the boundary condition on the burning surface takes the form

$$p_2 W_2^2 = p_1 W_1^2 + k_1 v_1^2 + k_2 g_1^2 + k_3 \rho_1 v_1^2 / \delta^2, \quad (109)$$

where W_1 is the pulsating rate in the liquid; W_2 - pulsating gas rate; ρ_1 - density of the liquid; ρ_2 - gas density; ξ - scale of turbulence; σ - coefficient of surface tension; g - acceleration of gravity; η - viscosity of the liquid; δ - width of gap of slot; k_1, k_2, k_3 - coefficients.

The pulsating rate of the gas flow, which has the scale ξ , is proportional to the rate of gas flow at this distance from the surface, i.e.,

$$W_2 = k_0 J \xi^2 \delta, \quad (109a)$$

where k_0 is the coefficient; J - the mass rate of combustion of the powder.

After substituting formula (109a) into equation (109), we will obtain the equation

$$(\rho_1 \xi \delta)^2 W_1^2 = \rho_1 W_2^2 + k_1 \sigma \xi^3 + k_2 \rho_1 g \xi^3 + k_3 \eta W_2 \xi \delta^2, \quad (110)$$

$n=1$ or 2 - the quantity of powder plates.

Actually there is a whole spectrum of pulsations. The development of pulsations with a different wavelength ξ occurs at a different rate. The rate of turbulent combustion is determined, first of all, by the pulsations which are developed at a maximum rate. An analysis of equation (109) shows that with an increase in ξ the pulsating rate is continuously increased; therefore, the most important for our purposes are pulsations with the maximum length of the wave, i.e., with $\xi=L$, where L is width of the slot. After substituting L for ξ into equation (109), we will obtain the quadratic equation relative to W_1 , from which W_1 as a function of pressure, dimensions of the slot and rate of combustion of the powder is determined. The critical condition of the emergence of turbulent combustion ensues from equation (110) with $\xi=L$ and $W_1=0$.

With the sufficiently large diameter of the charge L

$$L \geq \sqrt{\alpha k_1 / \rho_1 g k_2} \quad (111)$$

[condition (111) is fulfilled with $L > 5$ mm] the expression for the boundary of transition from the laminar to turbulent combustion mode takes the form

$$n^2 J^2 / \rho_2 = (k_1 / k_0^2) (\rho_1). \quad (112)$$

After substituting $J = B p^v$ and $\rho_2 = a p$ into this expression, we obtain the critical pressure of the transition

$$p_{cr} = (a k_2 \rho_1 g \delta^2 B^2 k_0^2 J^2)^{1/(2v-1)}. \quad (113)$$

In the solution to equation (110) it is possible to isolate two limiting cases. In the case of the relatively low speeds of turbulent combustion the last term in the first part of equation (110) considerably exceeds the first term, i.e., the viscous forces is more than the inertial

$$W_1 = ALJ^2 n^2 / \eta \rho_1 - C \rho_1 g \delta^2 / \eta \quad (114)$$

with

$$\frac{k_0}{k_2} \sqrt{\rho_1 / \rho_2} \delta J n / \eta < 1. \quad (115)$$

Here

$$A = k_0^2 / k_2; \quad C = k_2 / k_2.$$

If it is possible to disregard the viscous forces in comparison with the inertial and gravitational forces in the case of very high rates of turbulent combustion, then

$$W_1 = k_0 J L n / \delta \sqrt{\rho_1 \rho_2}$$

with

$$\frac{k_0}{k_3} \sqrt{\frac{\rho_1}{\rho_2} \frac{\delta J n}{\eta}} > 1; \frac{k_0^2 J^2 n^2 L}{k_2 \rho_1 \rho_2 g \delta^2} > 1.$$

Experiments in [218] were conducted in the bomb of constant pressure in the atmosphere of nitrogen. The charge consisted of two plane-parallel plates between which liquid was filled. One of the plates was of powder and the second - plexiglass, through which the filming was produced, or the recording on a moving-image camera occurred. The width of plates was 10 to 37 mm, height, 60 mm, thickness, 2 mm, and the clearance between the plates, 0.1-0.8 mm. It was established that the combustion of this charge can pass both in the normal mode when the presence of the slot, filled with liquid, does not affect the rate of combustion of the charge, and also in the turbulent mode when the flame rate many times exceeds the normal rate.

The filming and photorecording showed that in identical experimental conditions the value of the turbulent rate is repeated from one experiment to the next and does not depend on the length of the charge.

Investigated in [218] was the dependence of the rate of combustion of the slotted charge of the nitroglycerin powder ($u_1 = 0.47 p^{0.75}$ cm/s with $1 \text{ kg/cm}^2 < p < 150 \text{ kg/cm}^2$) on pressure in the bomb. The clearance between the plates was filled with water. Estimates show that in these experiments condition (115) was always satisfied; therefore, with the experiment it is necessary to compare the theoretical value of rate of combustion computed according to formula (114) with $n=1$. The constant coefficients A and C, which enter into formula (113), were determined in the following way.

In accordance with equation (114) all the experimental results were plotted (Fig. 122) in the dimensionless coordinates $W_1 \eta / \rho_1 g \delta^2$ and $L J^2 / \rho_1 \rho_2 g \delta^2$ and lay on one straight line. The coefficient A is

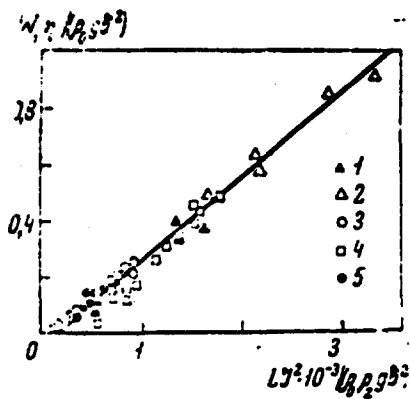


Figure 122

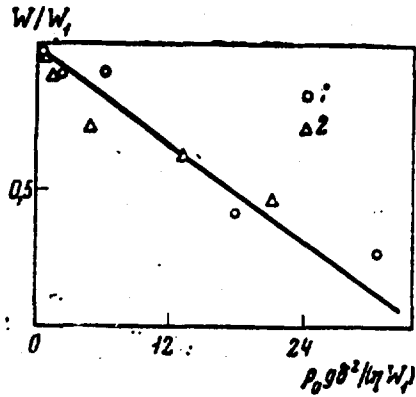


Figure 123

Figure. 122. Generalized curve for the rate of turbulent combustion of slotted charges 1 - $\delta=37$ mm, $L=0.37$ mm; 2 - $\delta=20$ mm, $L=0.2$ mm; 3 - $\delta=20$ mm, $L=0.37$ mm; 4 - $\delta=10$ mm, $L=0.2$ mm; 5 - $\delta=10$ mm, $L=0.37$ mm.

Figure 123. Dependence of the rate of turbulent combustion on the clearance of the slot 1 - $L=10$ mm, $p=100$ atm; 2 - $L=20$ mm, $p=60$ atm.

equal to the tangent of the slope angle of the straight line. Calculations give the value $A=3 \cdot 10^{-4}$. The coefficient C is determined by the value of the segment intercepted by the straight line on the axis of the ordinates is equal to $3 \cdot 10^{-2}$.

An increase in the clearance (Fig. 123) and also an increase in the viscosity of the liquid lead to a decrease in the rate of turbulent combustion, while an increase in the width of the slot produces an increase in the rate.

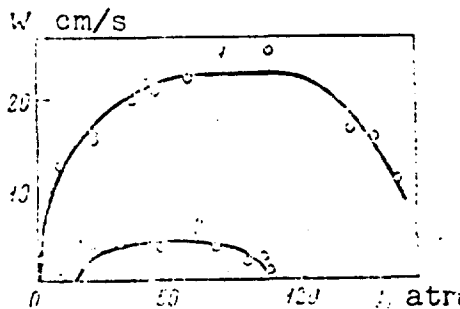


Figure. 124. Experimental dependences of the rate of turbulent combustion on pressure for powders with variable ν greater and less than 0.5.

From an analysis of equations (110) and (114), it follows that with the combustion of the slotted charges of the powder with $\nu > 0.5$ the turbulent combustion mode begins when the pressure exceeds the critical value. With a further growth in pressure an increase in the rate of turbulent combustion occurs. But if $\nu < 0.5$, then the theory predicts that the turbulent mode must begin with a lowering of the pressure lower than the critical value, and the rate of turbulent combustion must be increased with a decrease in the pressure. This conclusion of theory was checked experimentally. Figure 124 gives dependences of the rate of combustion of the slotted charge on pressure. Curve 1 refers to the powder, the rate of combustion of which is determined by expression $u_1 = 0.56 p^{0.28}$ cm/s at 10 atm $< p < 140$ atm, and curve 2 - to the powder with $u_1 = 0.32 p^{0.17}$ cm/s at 15 atm $< p < 140$ atm. In the interval of pressures from 1 to 10-15 atm the value ν varied from 1 to 0.28 for the first powder and from 0.8 to 0.17 for the second.

The experimental dependences given on Fig. 124 qualitatively agree with the conclusions of the theory. At low pressures, since $\nu > 0.5$, an increase in the rate of turbulent combustion with an increase in the pressure occurs, and at high pressures ($\nu < 0.5$) the turbulent combustion is attenuated with an increase in pressure.

As regards the measured values of the turbulent rate, they were below the calculated values. This is explained by the fact that here the slot was filled with kerosene, which, unlike water, wets the powder. Therefore, formed on the surface of powder is the liquid film the thickness of which depends on the rate of motion of the liquid and its parameters [220], which also leads to a deceleration of the turbulent combustion [218]. The checkout experiments showed that in all cases when the nonwetting liquid, in filling the slot, was substituted by the wetting liquid (kerosene, alcohol), a decrease in the rate of the turbulent combustion of several times was observed.

Experimental Studies of the Combustion of Two-Phase Systems

With the filling of the porous charge with liquid, there can be formed the movable two-phase system whose combustion is accomplished by a number of interesting laws. Depending on the ability of the components of the system to burn, and also on their physico-chemical properties, the stable or excited turbulent combustion mode appears.

According to Andreyev [37], the mixtures of black powder with nitroglycerin (NG) [HГЦ] (content of NG from 10 to 60%) at atmospheric pressure burned normally, whereupon the rates of combustion were below the calculated additive value. The concentrations of NG used in the experiments did not provide mobility to the system, and its combustion did not differ from the laws governing the combustion of the usual heterogeneous systems.

There is great interest in the experiments of Kondrikov [87, 221], who investigated the behavior of a number of initiating explosives in the mixture with the gelatinized nitroesters. It was revealed that at atmospheric or moderately increased pressure the combustion is unstable: with ignition either the extinction of combustion or explosion occurs. The pressure increase stabilizes the combustion and makes it stable. Thus, the mixture of the weakly gelatinized nitroglycerol with 10% by weight of lead azide in charges 5 mm in diameter begins to burn stably at pressures higher than $p_{HP} = 6$ atm at a rate virtually equal to the rate of combustion of gelatin. An increase in the content of the lead azide (up to 75% by weight) leads to an increase in p_{HP} , whereupon, according to [221], $p_{HP} = 4.10 \exp(1.32 m) \text{ kg/cm}^2$, where m is the content of the lead azide in the mixture (g/cm^3). The rate of combustion of the mixtures is approximately proportional to the pressure, and coefficient B in equation $u_1 = Bp^v$ has a dependence on m of the same form as p_{HP} (Fig. 125).

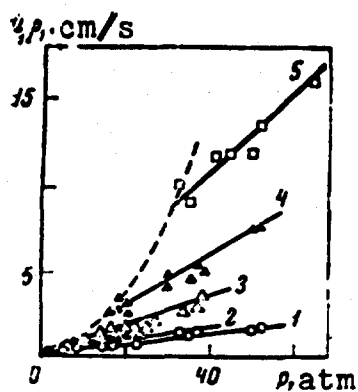


Figure 125

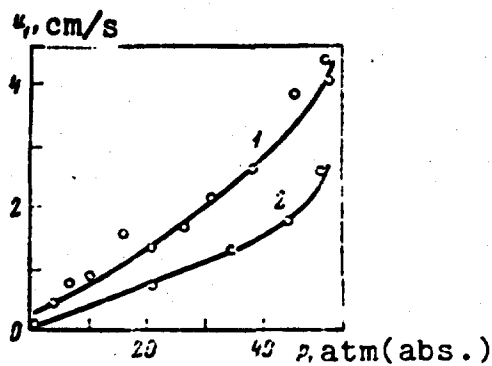


Figure 126

Figure 125. Effect of pressure on the rate of combustion of mixtures of the lead azide with gelatinized nitroglycerin. Content of lead azide: 1 - 0; 2 - 10; 3 - 30; 4 - 50; 5 - 60%. Above the dashed curve the mixtures are exploded or extinguished [221].

Figure 126. Effect of pressure on the rate of combustion of mixtures of lead styphnate with the gelatinized nitroglycerol. 1 - 50; 2 - 30%.

Mixtures of lead azide with other liquid nitroesters and also mixtures of nitroesters with lead styphnate (Fig. 126) and potassium picrate (Fig. 127) as a whole give the same pattern of the effect of pressure on the possibility of the stable combustion of mixture, only the most standard for them is the attention of combustion. It was noted that contributing to the emergence of the explosion was the ignition of the mixtures directly by an incandescent spiral and the presence in the mixture of lumps of the initiating substance.

The explanation of such peculiar behavior of the mixtures in work [221] is based on the hypothesis about the emergence of the explosion of the suspended matter of a sufficiently large number of particles of explosives dispersed from surface of the charge. In this case it is assumed that the determining factor in the process of the emergence of the explosion is not the pressure by itself, but the "thickness of the thoroughly heated and reacting layer and the duration of its existence."

Another approach to the explanation of the peculiar region of the unsteady combustion of heterogeneous mixtures, which contain the free-burning solids, is of interest. First of all, in accordance with data [87, 221] let us assume that the combustion of pure lead azide easily converts to an explosion (apparently, through the intense dispersion and explosion of the suspended matter of the particles). With the low content of the azide in the mixture with the nitroester, each particle is the drain of heat with respect to the nitroester surrounding it. The "pores" between the particles are filled with the liquid, which can burn if the thermal equilibrium in the thoroughly heated layer is balanced. In other words, the "diameter of the pores" must correspond to the rate of combustion of the liquid at this pressure approximately just as the critical diameter of combustion d_{kp} does. At low rates of combustion the "diameter of the pores" can prove to be (and thus was obtained in B. N. Kondrikov's experiments) small and insufficient for the stationary combustion of the liquid base. Combustion is hindered also by the mixing noted in work [221] of the thoroughly heated layer by microflashes of single ignited particles of explosives. The thermal nature of the phenomenon is indicated by the fact of the effect of the diameter of the charge whose decrease always contributed to the attenuation of combustion. As a result of the action of the enumerated factors, with ignition by a weak source there occurs attenuation after the burnout (or flash) of the thoroughly heated layer, and the intense ignition leads to the vaporization of the liquid explosive; the unprotected initiating substance is uncovered and there follows an explosion by the mechanism inherent in the pure lead azide. At the high pressures when the rate of combustion are sufficiently great, there appears the independent combustion of liquid "framework" of the mixture, and the particles of the lead azide will be carried into the gaseous phase where they burn one at a time. An increase in the content of the solid phase (with a constant particle size) decreases the diameter d_n of the "pores" filled with liquid as $d_n \sim (1-\Delta)/\Delta$, where Δ is the volumetric content of

the solid phase. After considering that for stable combustion it is necessary that $d_{\Gamma} > d_{\kappa p}$, and, according to [221], $d_{\kappa p} \sim p^{-\psi}$, where $\psi=0.6-1.48$ and on the average $\psi=1$, we will obtain

$$p_{\kappa p} \Delta / (1 - \Delta) \approx \text{const}, \quad p_{\kappa p} d_{\alpha} \approx \text{const}. \quad (116)$$

The processing of data [221] with the use of formula (116) shows that this expression naturally describes the experimental data.

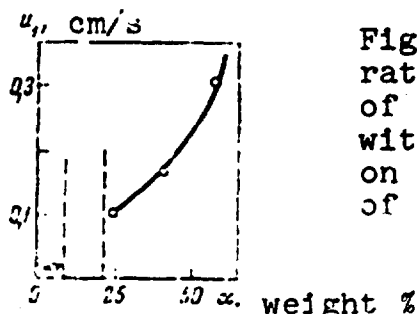


Figure 127. Dependence of the rate of combustion (at 1 atm) of mixtures of potassium picrate with gelatinized diglycoldihydrate on the composition. α - content of potassium picrate.

If the assumed has foundation, then an increase, for example, in the initial temperature of the mixture must decrease the pressure retention of unsteady combustion as a result of an increase in the rate of combustion of the ZhVV and decrease in its $d_{\kappa p}$. A change particle size D of the solid phase with its constant content must affect d_{Γ} in terms of the measurement of the effective diameter of the liquid layers, whereupon it is possible to expect with $\Delta=\text{const}$ the fulfillment of relation $p_{\kappa p} D=\text{const}$.

A good illustration to the effect of the dimension of container consists of experiments [221] on the combustion of the mixture of nitroglycerin with the lead azide in the ratio of 50:50 weight %. As is known [38, 120], nitroglycerin in a certain range of pressures does not burn, which is explained, according to Andreyev, by the intense agitation of the thoroughly heated layer by the Landau-Levich mechanism. The lead azide in pure form does not burn at all but explodes. The thickening of the nitroglycerin by lead azide makes it possible to observe stable combustion.

Moreover, by the developed mode of the excited combustion this addition lowers the rate of combustion of NG by approximately 2 times. An analogous effect is revealed on the mixture of liquid nitroglycol with lead azide. The introduction of the concept about the effective diameter of the liquid layers in a mixture with a solid filler makes it possible to explain these facts by the dependence of limiting conditions on the diameter (thickness) of the liquid layer.

Conducted in work [219] is research on the combustion behavior two-phase, solid-liquid, explosive charges. The glass tube was filled with grains of NG powder ($u_1 = 0.47 \cdot p^{0.76}$ cm/s with $1 \text{ kgf/cm}^2 < p < 150 \text{ kgf/cm}^2$) or ammonium perchlorate. The gaps between the grains were filled with liquid: water, alcohol, gasoline, glycerin. The charge was burned in a bomb in the atmosphere of nitrogen at pressures of 1 to 120 kg/cm².

Figure 128 shows the dependence of pressure on the rate of combustion of the charge, which consists of cylindrical grains (diameter of the grains is equal to its height) of nitroglycerin powder, which are placed into tubes with an inside diameter of 6.5 mm. The charges were filled with water or alcohol; the liquid occupied 30-40 volumetric % of the charge. At pressures above p_{kp} the combustion occurred in the turbulent mode at high rates considerably exceeding the normal rate of combustion of the powder itself. At pressures below p_{kp} the combustion is not sustained, since the water (or alcohol) fills the burning grains and interferes with the flame from spreading from one grain to the next. It is evident that the rate of combustion of the water-filled charges is higher than the rate of those filled with alcohol, which wets the powder considerably better than does water. With an increase in the diameter of the tube, the rate of combustion is first increased, and then it remains constant.

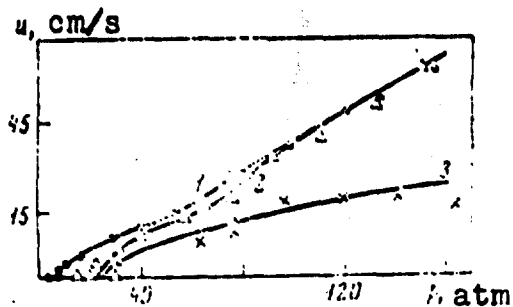


Figure 128. Dependence of pressure on the rate of combustion of two-phase charges, nitroglycerin powder and liquid. 1 - grain 1 mm in diameter with water; 2 - grain 3 mm in diameter with water; 3 - grain 1 mm in diameter with alcohol.

For research on the effect of the viscosity of the filling liquid the solution of a different concentration of glycerin in the water was used. With an increase in the viscosity of the filling liquid, the rate of the turbulent combustion at first does not change, but then sharply falls (Fig. 129) to attenuation or the normal rate of combustion of the powder grains with a motionless filler.

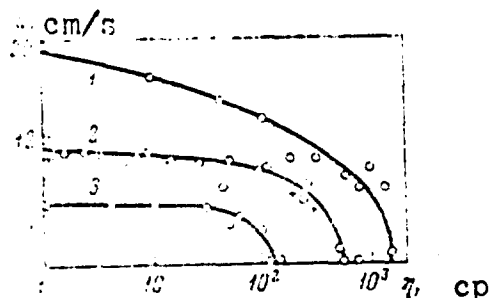


Figure 129. Dependence of the rate of combustion of two-phase charges of NG powder (diameter of grain, 1 mm) on the viscosity of the filling liquid. 1 - 80; 2 - 50; 3 - 25 atm(abs.). Crosses are experimental data for grain 3 mm in diameter at 50 atm(abs.).

Turbulent combustion is observed in the mixture of grains of ammonium perchlorate with gasoline (20% by weight) (Fig. 130). With a size decrease of particles of perchlorate, the rate of turbulent combustion decreases. As is known, the rate of the laminar combustion of mixtures of ammonium perchlorate with solid fuels is increased with a size decrease of particles of the oxidizer [44]. On the same curve (Fig. 130) the rate of combustion of the mixture of ammonium perchlorate with the gasoline thickened by rubber (rubber cement) is carried out. It is evident that the turbulent combustion of the mixture of the oxidizer with the mobile liquid fuel is spread considerably more rapidly than that of the smooth burning of the mixture with viscous fuel. The rate

of combustion of the mixture with rubber cement is approximately equal to the rate of combustion of the mixtures of ammonium perchlorate with solid organic fuels [44].

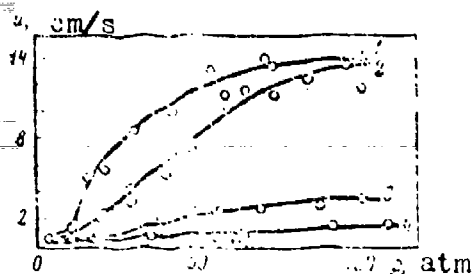


Figure 130. Dependence of the rate of combustion of the two-phase charges of ammonium perchlorate with gasoline (1-3) and rubber cement (4-5) with different grain sizes of ammonium perchlorate. 1 and 5 - 1-1.6 mm; 2 - 0.25-0.63 mm; 3 and 4 - 0.1-0.25 mm.

The experiments presented show that turbulent combustion can occur in two-phase systems which consist of powder-like explosives filled with liquid and powders and also in charges of a solid oxidizer and liquid fuel.

It is possible to visualize the emergence of turbulent combustion in the following manner: under certain conditions the stable combustion becomes unstable, the gaseous products of combustions penetrate the pores of the charge, displacing the liquid and igniting the walls of the pores. The displaced liquid in other places is ejected into the flow of the combustion products, the zone of the flame advances because of convective current along the pores, but not due to the heating of fresh portions of the substance along the mechanism of the conductive heat transfer. Photographs show that the leading edge of turbulent combustion leaves behind the zone which consists of the burning grains of explosives and pores between which the liquid is already removed. On grains the fluid film whose thickness depends on the rate of motion and on parameters of the liquid must remain [220].

The presence of the mechanical bond between the particles affects the course of turbulent combustion. The water-filled

charge from grains of powder, glued together with the aid of acetone, burns faster than a similar bulk charge. Let us note that the gluing of the particles exerts the same effect on the combustion of the porous (filled by gas) powder-like charges. The dispersion of unglued particles of the charge, obviously, decreases the intensity of the effect of combustion products on the fresh mixture. In systems which consist of components not capable of independent combustion, the combustion is spread over the boundary of their contact.

The photorecordings of the development of the process in different systems show that with the turbulent combustion mode near the critical pressure, the liquid is ejected from the slotted charge by a fountain located in the middle of the slot or near its edge. With the developed turbulent combustion (rate exceeds the normal by 10-30 times) the liquid is ejected in the form of fine streams and drops. It is not difficult here to see the analogy with the turbulent combustion of liquid individual substances and mixtures (see § 44).

The presence of the dry section of the slot above the surface of the liquid contributes to the development of turbulent combustion, but the rate of turbulent combustion in this case is not changed. An increase in the length of the dry section of the slot up to a certain value facilitates the emergence of turbulent combustion due to an increase in the rate of flow of combustion products in the clearance.

Extremely interesting are the data of Whittaker [198], who investigated the question concerning the role of volatility of components in an example of mixtures of nitric acid with solid fuels. For the passage of stationary stable combustion, according to Whittaker, it is necessary that the rate of evaporation of all components be equal to the rate of combustion. It was established that the mixture of nitric acid with α -dinitrobenzene was incapable of stable combustion, but at high pressures it burns in the turbulent mode. For a comparison, subjected to testing was the mixture of

nitric acid and sebacnitrile, which has an elasticity of the vapors at 45°C equal to 1 μ , which coincides with the elasticity of vapors of dinitrobenzene. This mixture also proved to be incapable of burning normally, but after 154 atm it is ignited and burns in the turbulent mode. Thus, mixtures with the very low pressure of the vapors have only the region of the turbulent combustion mode when particles and drops of the mixture enter into the high-temperature flame and vaporize there, sustaining in the flame the initial relationship of the components. In the mode of normal combustion the temperature is too small for ensuring the transport of the low-volatile component into the g-phase.

Although Whittaker's experiments were carried out on mixtures with solid fuel, their essence remains valid also for liquid components. Thus, mixtures of TNM with fuel, re-enriched by an oxidizer, do not burn at low pressures. But if we conduct combustion at increased pressures, then they burn in the turbulent mode up to the end.

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