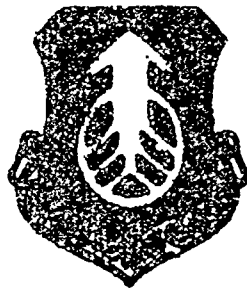


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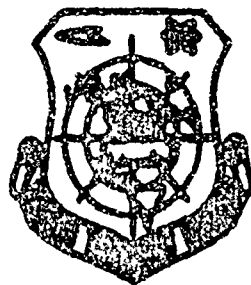
FOREIGN TECHNOLOGY DIVISION



DETONATION WAVES IN CONDENSED MEDIA

by

A. N. Dremin, S. D. Savrov, V. S. Trofimov, and
K. K. Shvedov



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Block	Italic	Transliteration	Block	Italic	Transliteration
A a	A a	A, a	P p	P p	H, h
B b	B b	B, b	C c	C c	S, s
D d	D d	V, v	T t	T t	T, t
F f	F f	G, g	Y y	Y y	U, u
K k	K k	L, l	Q q	Q q	F, f
E e	E e	Ya, ye; E, e*	X x	X x	Kh, kh
M m	M m	Zh, zh	H h	H h	Ts, ts
S s	S s	Z, z	Ch	Ch	Ch, ch
N n	N n	I, i	Sh	Sh	Sh, sh
O o	O o	Y, y	Shch	Shch	Shch, shch
U u	U u	K, k	’	’	’
Y y	Y y	L, l	Y y	Y y	Y, y
’	’	N, n	’	’	’
’	’	H, h	’	’	’
’	’	O, o	’	’	’
’	’	P, p	’	’	’

* ye initially, after vowels, and after y, b; e elsewhere.
 When written as E in Russian, transliterate as yE or E.
 The use of diacritical marks is preferred, but such marks
 may be omitted when expediency dictates.

This monograph generalizes the results of original research by the authors on the structure of the detonation front and the limit conditions of excitation and propagation of detonation in condensed media. Much attention is also paid to the general state of the theory of detonation.

The book is designed for technical and engineering personnel and scientific workers, involved with research and the use of explosives.

There are 4 tables, 101 illustrations, and 146 bibliographic designations.

Responsible editors:

Academician N. H. Semenov and
Academician Ya. B. Zel'dovich

FOREWORD

This book puts forth the results of research on the theory of detonation of condensed media, conducted at a branch of the Institute of Chemical Physics of the Academy of Sciences of the USSR. The book is designed for scientific personnel and engineers involved with research and practical work on detonation, and also for students and graduate students, specializing in the theory of the physics of combustion and explosions.

The use of condensed explosives is at the present time becoming more and more widespread. This can be explained by the growing interest of investigators in the phenomenon of detonation.

The basic underlying ideas in the development of concepts on the mechanism of detonation, which stimulated widespread formulation of experimental research, belong to the Soviet scientists: Ya. B. Zel'dovich, Yu. B. Khariton and K. I. Shchelkin. The names of these scientists are connected with ideas of a physical model of a detonation wave, with the limits of excitation and propagation of detonation and of the universal instability of a detonation front in homogeneous explosive media.

The present book gives further development to problems of the theory of detonation for condensed explosives. Such a possibility has arisen as a result of the fact that at present, thanks to

new methods of research and to the perfection of experimental technology, important new experimental data have been obtained in the cited direction.

In the introduction the basic problems of the study of detonation of condensed explosives are briefly formulated. The phenomenological theory of detonation is expounded in Chapter I as applied to condensed explosives: the classical theory, the theory of Zel'dovich and the theory of a quasi-stationary detonation front. Chapter II gives the results of investigations of the mechanism of the initiation of detonation in liquid and solid explosives by shock waves. An account is given here of the voluminous experimental data on the structure of flows during the formation of detonation. Chapter III takes up the results of investigations of the process of detonation in liquid explosives. This chapter examines the experiments in which it was established that in a number of liquid explosives the detonation front has a heterogeneous pulsating character and gives qualitative explanations to the limits of the existence of such detonation. Chapter IV generalizes the results of investigations of the process of detonation in solid explosives. Chapter V examines the nature of the critical diameter. Special attention is here given to the study of pulsations of the surface dimension of the detonation front in liquid explosives.

The authors express their deep gratitude to Academician N. N. Semenov for his support of this research at its start and his continuous interest in the results during the investigations, to Academician Ya. B. Zel'dovich for his numerous discussions of the results, valuable observations and advice during the investigations and for his work on the manuscript, to correspondent members A. I. Buzikis and R. I. Soloukhin, and also to P. I. Dubovitskiy, Ya. K. Troshin, L. V. Dubnov, V. V. Nitrofanov and M. Ye. Topchiyan for numerous interesting and useful discussions on the theory of

detonation in connection with the authors' own experimental results and data.

The authors consider it their pleasant duty to thank O. K. Rozanov, G. A. Adadurov, S. A. Koldunov, V. A. Verstennikov, and A. N. Mikhaylov, who participated in the investigation.

INTRODUCTION

The most basic organization of theoretical research on the detonation of condensed media consists in the determination of the connection of the basic characteristics of a detonation wave with the original physical-chemical properties of an explosive. For the solution of this problem it is necessary to answer the following questions:

1. What kind of physical model of the detonation wave is there?
2. How does the structure of the front of the detonation determine the limits of its excitation and propagation?
3. How are the rates of the chemical reactions in the condensed medium related with the intensity of the shock compression?
4. What kind of equation do we have for the state of the condensed explosives and the product of their detonation?

The classical hydrodynamic theory of detonation of gases, the creation of which involves the names of Mikhel'son, Chapman and Jouget, suggested a model in conformance to which the detonation wave is a shock wave with negligibly small time of chemical conversion at the front. If a shock wave is propagated in a

nonexplosive media, then directly behind its front the velocity of the flow of matter is less than the velocity of propagation of the excitations. In the case of a shock wave without an external support ("plunger") the excitation behind the front is a vacuum, and therefore such waves attenuate. To explain the constancy of the rate of detonation as a shock wave it is necessary, consequently, to allow that the speed of the products of explosion behind its front be greater than or equal to the speed of sound. Chapman and Jouget advanced the hypothesis, according to which the speed of the outflow of products of an explosion is equal to the speed of sound.

The laws of conservation of mass, momentum and energy with the transfer of matter through a detonation front together with the equation of state of the gases contain five unknown parameters of a detonation wave. The Chapman-Jouget hypothesis gave the fifth efficient equation. Therefore, the coincidence of the detonation parameters calculated on the basis of the hydrodynamic theory and experimental values was viewed as confirmation of the correctness of the Chapman-Jouget hypothesis and of the concept of detonation as a shock wave. The solution of the problem of the applicability of the hydrodynamic theory to detonation of condensed media was made more difficult because of the absence of an equation of state of their explosion products. Therefore, for calculations various equations of state or equivalent equations of state, but in different form, were employed. It turned out that the results of calculating the parameters of detonation, with the exception of the temperature, were in good correspondence with experimentation. In conformance with these results few investigators were left who doubted the applicability of the hydrodynamic theory to detonation both of condensed media as well as of gases.

In the use of condensed explosives in technology detonation is most frequently propagated under conditions far from extreme. In this case the width of the zone of chemical reaction on its front is disregardably small in comparison with the characteristic

dimensions of the charge. Therefore, for calculating the dynamic parameters of a stationary detonation wave the classical hydrodynamic theory is perfectly adequate.

Since the classical hydrodynamic theory postulated that the reaction occurs so quickly, that it is not a controlling factor for the propagation of detonation, this theory could not give clarification of the limits. In essence, because of this reason there was also no complete theoretical basis given for the principle of selection of the detonation rate, since for this proof, as consequences showed, there were necessary representations on the mechanisms of the detonation conversion, on the structure of the reaction zone (each representation of the mechanism of a detonation conversion obviously requires its own proof for the principle of selection of the detonation rate).

The hydrodynamic theory of detonation received further development in the work of Zel'dovich (somewhat later analogous results were obtained in the works of Heilmann and Dering). The new theory proposed a physical model for the detonation front. In particular, it was shown that in the zone of reaction of a detonation wave there must exist elevated pressures, corresponding to the gas state behind the front of the shock wave, which is propagated with the speed of the detonation. According to this model the shock front causes ignition of the substance. In proportion to the occurrence of the reaction the volume of gas increases, while the pressure drops to values which correspond to a certain state of the explosion product. The region of elevated pressures at the front of the detonation wave became known as the "khimpik" (chemical peak). For this mechanism of the detonation conversion the proof of the validity of the Chapman-Jouget hypothesis was successful. The most important conclusion of Zel'dovich's theory - the existence of the chemical peak at the front of detonation wave - subsequently received experimental confirmation in the investigation of the detonation of gases and condensed media. These results were a

convincing confirmation of the validity of the theory. Subsequent occurrences showed, however, that this theory also is not universal.

For all the investigated gas mixtures and for a number of liquid explosives a pulsating character of the detonation front was established. In these explosives, and also in solid explosives, the original physical-mechanical structure of which it is non-homogeneous, the zone of heat liberation at the front of detonation waves is turbulent. It is obvious that the theoretical basis for the principle of selection of the detonation rate, obtained for a one-dimensional wave, is not applicable in this case. For a nonunivariate detonation front it should be recalculated anew.

In connection with the opening of a pulsating (nonunivariate) detonation in homogeneous media the problem of a physical model on the front of a detonation wave or of the structure of the zone of heat liberation again became the important factor in the theory. It was experimentally established that the interaction of the front of the shock wave with the following region of self-ignition leads to complex nonstationary hydrodynamic processes, as a result of which the detonation in homogeneous media, apparently, also "selects" the method of propagation: pulsating or one-dimensional. This fact, besides the independent interest, led to the necessity for a completely different treatment of phenomena on the limits of propagation of detonation and during its excitation by a shock wave.

Fundamental information on the process of detonation of condensed media is currently being produced by experimentation. As a result of this investigations in general, including those conducted in this book, have a fragmentary character and require additional calculations, presently inaccessible due to the absence of reliable information on the equation of state of condensed explosives, their explosion products and of the kinetics of reactions, which occur under conditions of detonation pressures and temperatures.

Attempts to construct an equation of state for explosive products have been made for a long time. However, in the majority of cases these theoretical investigations led to the writing of an equation of state with many unknown parameters, which were calculated on the basis of experimental data on the dependence of the dynamic parameters of detonation (speed, pressure) on the initial density of the explosives. Naturally, in these calculations the Chapman-Jouget principle of selection for the detonation rate was used. The value of such calculations for the theory of detonation is small. A criterion for the successful application of the hydrodynamic theory should be the coincidence of the experimental values of detonation parameters with the results of calculation carried out on the basis of independent data. The problem has not yet been solved in such a form.

The measurement of the temperature might give important information on the state of the detonation products. With these aims the use of optical methods, which are apparently the only ones possible, have met with considerable difficulties. In experiments, especially with liquid explosives, the luminescence of the detonation front has been successfully observed without difficulty. To evaluate the chromatic and luminosity characteristics of the temperature of the detonation products it is necessary to obtain information on the radiative and absorptive capacities of the detonation products in the Chapman-Jouget plane which characterize the dynamic parameters of the detonation wave. However, there has been no success in obtaining the spectra of these detonation products, when the chemical reaction is basically completed. When observing detonation from the side this is inhibited by the effect of lateral unloading. When observing the process from the end of the charge using spectral equipment the identification of the radiation spectrum of the zone of heat liberation at the front with the radiative power of the detonation products appears indeterminate.

The narrowness of the zone of chemical reaction during detonation of liquid explosives does not simplify the problem, since there is a corresponding increase in the temperature gradient in the region of detonation ignition, which can greatly distort the relative and absolute distribution of radiation energy from the region of detonation products. It is known that optical methods of measuring luminosity and chromatic temperature are applicable only for objects homogeneous in temperature. In a number of liquid explosives the detonation front is also pulsating, and its luminescence corresponds to a set of local flashes on the front, which follow with great rapidity. Obviously, in this case the origin of the spectrum of detonation has an even more complex nature.

CHAPTER I

A PHENOMENOLOGICAL DESCRIPTION
OF DETONATION

Detonation is one of the processes by which the chemical conversion of explosives and of combustible mixtures takes place. This process, similar to combustion, is characterized by the fact that the chemical reaction takes place in the entire volume of the substance not simultaneously, but propagates successively from layer to layer. During detonation and combustion in the substance there is a shift in the chemical conversion front, which depending on the occurring process is also called the detonation front or the combustion front and within the limits of which the substance passes through all the intermediate stages from the initial state to the products of reaction (Fig. 1).

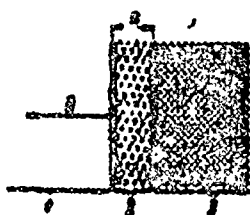


Fig. 1. Diagram explaining the process of detonation and combustion. 1 - original substance; 2 - zone of chemical conversion; 3 - reaction products; a) width of the zone of chemical conversion; D - normal rate of propagation of the front in the substance.

Combustion and detonation are distinguished from one another by the fact that in the first case the normal rate of movement of the front of chemical conversion D is less than the speed of sound in the initial substance, while in the second case it exceeds this

speed. Detonation may be propagated under conditions of an isolated, closed system. From this follows the definition of detonation. Detonation is the process of supersonic propagation of the front of chemical conversion in a substance, which may occur without any interaction with the surrounding medium.

Chemical conversion of a substance during detonation is simultaneously accompanied by the movement of the medium, which arises as a result of the difference in the specific volumes of the initial substance and of the products of reaction under one and the same pressure (or due to a difference in pressures with identical specific volumes). In turn, the mechanical movement affects the state of the substance within the limits of the detonation front and, in the final analysis, the rate of the chemical conversion. Consequently, detonation is not only a chemical, but also a gas dynamic process. Moreover, it is precisely the laws of gas dynamics, it turns out, which determine the rate of movement of the detonation front in the substance, as well as many other aspects of the detonation process.

In the general case to determine the conditions of the chemical conversion of a substance it would be necessary to solve the mutual system of equations of gas dynamics and chemical kinetics. But this problem, apparently, can be solved only for the simplest systems. On the other hand, many basic conclusions on the movements of the detonation front can be made from a gas-dynamic analysis of the properties of the suggested solution. Such an analysis is a subject of the phenomenological theory of detonation.

§ 1. Classification of the Theory of Detonation

The classical theory of detonation, developed in the works of Mikhel'son [1], Chapman [2] and Jouget [3], is occupied by a range of problems, for which no significant role is played by the final

width of the chemical conversion zone (see Fig. 1). Then, this theory views the detonation front simply as a surface of discontinuity, which divides the initial substance from the reaction product. The limits of applicability of the classical theory will be explained further.

The movement of the detonation front in the substance, as any movement, is subject to the laws of the preservation of mass, momentum and energy. The use of these laws is significantly simplified, if we consider that the detonation front as a result of its supersonic speed cannot send the perturbation forward. Therefore, the initial medium remains unperturbed right up to the start of the chemical conversion. In this way, during detonation only the reaction products can influence the mechanical movement. Assuming that the initial substance and the product are isotropic media, and drawing on considerations of symmetry, it is not difficult to show that the speed of the just formed reaction products, which is henceforth designated as u , is directed along the normal to the detonation front. We will take this as its positive direction, which coincides with the direction of propagation of the detonation.

Let us examine the detonation of the physically and infinitely small material volume, conceivably separated from the medium. Let us assume that at first it was a straight cylinder, the axis of which is perpendicular to the surface of the detonation front (Fig. 2). If the detonation front passed through the entire cylinder for time t , then the initial volume and the mass of the substance were equal to σDt and $\rho_0 \sigma Dt$, respectively, where σ is the area of the base of the cylinder, and ρ_0 is the initial density of the medium. The base of the cylinder, through which the detonation front entered, shifts with a reaction product speed u , and therefore for time t the height of the cylinder is reduced by the value ut . Consequently, the volume of the reaction product is equal to $\sigma(D - u)t$, and their mass is equal to $\rho_0 \sigma(D - u)t$, where

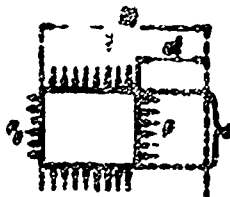


Fig. 2. For the derivation of laws of conservation of mass, momentum and energy for a detonation front. The broken line designates the position of part of the boundary of the cylinder and of the detonation front at the initial moment in time.

ρ is the density of the product. Equating the mass of the products to the mass of the initial substance, we find

$$\rho_0 D = \rho (D - u) = j. \quad (1)$$

Here j is the density of the flow of matter through the surface of the detonation front, i.e., the mass of the substance, which reacts per unit of time in a section of the detonation front of unit area.

Sometimes it is convenient to represent equation (1) in another equivalent form:

$$s = \rho_0 D (V_0 - V) = j (V_0 - V), \quad (2)$$

where $V_0 = 1/\rho_0$ and $V = 1/\rho$ are the specific volumes of the initial substance and of the products, respectively. Each of the equations (1) and (2) expresses the law of conservation of mass.

Let us apply the law of conservation of momentum to the divided cylinder. During time t the initially resting substance acquires a quantity of movement $\rho_0 D u t$. This quantity of movement arises under the influence of pressure, which the surrounding medium exerts on the cylinder's boundaries. If we designate by P_0 and P the pressure in the initial substance and in the products, respectively, then the total force acting on the cylinder during its detonation is constant and equal to $(P - P_0)$, since the forces acting on the lateral boundary of the cylinder are counterbalanced. By equating the momentum of force $(P - P_0) s t$ to the increment of the quantity of movement, we find

$$\rho_0 D_0 = P - P_0 \quad (3)$$

With the aid of the equation for the law of conservation of mass (2) we can give the last equation another form, which will play an important role in the theory:

$$P = \frac{P_0 - P_0}{V_0 - V}. \quad (4)$$

Equations (3) and (4) are called equations of conservation of momentum.

Let us examine the law of conservation of energy. Let us designate by E_0 and E the specific (per unit mass) internal energy of the initial substance and of the products, respectively. We will assume that both values are measured from one and the same arbitrary zero level and include both the energy of kinetic movement and of the interaction of molecules, as well as the latent chemical portion of energy. In the case where the initial substance and the products of reaction are thermodynamically identical, the chemical energy can be separated in the form of the independent term Q . This is also done, for example, in the examination of detonation in gases. In the general case such separation of the chemical energy does not have to be done uniquely, and therefore in the discussions of the theoretical problems we will not do this.

Besides the internal energy, the reaction products still possess specific kinetic energy $-u^2/2$, on account of which the total change in energy of the separated volumes during its detonation can be represented in the form

$$\rho_0 D_0 (E - E_0 + u^2/2).$$

Generally speaking, a divided cylinder changes its energy both as a result of change in volume, as well as because of the transfer of heat from the surrounding medium. However, in an examination

of detonation of condensed media diffusion and heat conductivity are disregarded, since these processes are slow and, apparently, do not succeed in making a significant contribution to the energy of the formed products for the times which are characteristic for detonation. Taking this into consideration, let us equate the change in energy only to the work of external forces P_{out} . Considering the equation of the law of conservation of momentum (3), we get

$$\rho_0 D(E - E_0) = P_{out} - \rho_0 D \frac{u^2}{2} = \frac{P + P_0}{2} (V_0 - V) f.$$

From the last expression with the aid of the equation of conservation of mass (2) we exclude D and u and arrive at the following form of the equation of conservation of energy:

$$E - E_0 = \frac{P + P_0}{2} (V_0 - V), \quad (5)$$

which differs from the preceding, in that it contains only thermodynamic values. The presence of such an equation shows that with given parameters of the initial state of the medium (P_0 , V_0 , E_0), not every state of the reaction products can be achieved in the process of detonation.

Let us analyze the conclusion of the equations of conservation of mass, momentum and energy with the purpose of their extension to the case of a plane stationary detonation front with a terminal width a (see Fig. 1). The detonation front is called stationary if its normal speed D , width a , as well as propagated distribution within its limits of density ρ , specific momentum ρu and specific energy E do not change with time.

From a stationary detonation front it follows that its front and rear boundaries pass through the above separated infinitely small cylinder during one and the same time t . This means, just as before, that the initial and terminal volumes of the cylinder

are equal to $\sigma D t$ and $\sigma(D - u)t$, respectively. From this the above deduced derivation of the equation for the conservation of mass is obtained directly. The momentum and energy, included in the unit area of a detonation front, as a result of its passage through the cylinder do not change. This may be viewed as the equality of the total interaction between the cylinder and the detonation front to zero. Consequently, the divided cylinder acquires momentum and energy in the final analysis only as a result of the forces which act upon it outside the detonation front. However, only this was used above in the derivation of equations of the laws of conservation of momentum and energy. Thus, the derived equations for the conservation of mass, momentum and energy are valid not only for the surface of discontinuity, but also for a stationary detonation front of finite width.

In connection with the fact that the chemical reaction ordinarily takes place for a finite time, the actual detonation front must have a finite width. Consequently, the classical theory of detonation, on the basis of which lie the equations of the laws of conservation of mass, momentum, and energy (1)-(5), strictly speaking, are applicable only to a flat stationary detonation front. In practice this means that the characteristic dimensions of the charge L and the radius of curvature of a detonation front R significantly exceed its width: $L \gg a$, $R \gg a$. Moreover, a change in the speed of the front D must be insignificant during time a/D , i.e., $dD/dt \times a/D \ll D$. Detonation which occurs under these conditions is called ideal. Thus, the classical theory is a theory of ideal detonation.

Our further conclusions will rest on the assumption that the products of reaction exist in a state of thermodynamic equilibrium. In this case their specific internal energy is a function only of P and V :

$$E = E(P, V). \quad (6)$$

For example, if these products satisfy the equation of state of an ideal gas, then

$$E = \frac{PV}{\gamma - 1} + Q, \quad (6a)$$

where $\gamma = c_p/c_v$ is the ratio of specific heat with constant P and V, respectively. The quantity Q is a constant, which depends on the chemical composition of the gas and the selection of the zero reading level of the energy. As a rule, this level is selected so that for the products

$$Q = 0. \quad (7)$$

From the existence of relationship (6) it follows that a certain curve in plane P-V, which is called the detonation adiabatic curve (Fig. 3), corresponds to the equation of the conservation of energy (5). It can be shown [4] that with sufficiently general assumptions on the equation of the state of the products the qualitative form of the detonation adiabatic curve is in all cases the same. Therefore, the basic conclusions of the possible theory of detonation may be illustrated by the example, when the detonation products conform to the equation of state of an ideal gas.

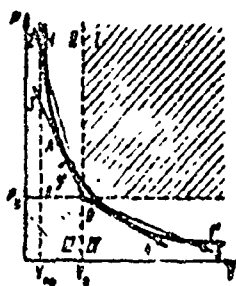


Fig. 3. Investigating the properties of the detonation adiabatic curve. 1(1') - supposed position of the detonation adiabatic curve; 2, 3, 4, 5 - Mikhel'son's curves.

Independent of whether the initial medium is gaseous, the following designation can be introduced:

$$E_0 = \frac{P_0 V_0}{\gamma - 1} + Q_0. \quad (8)$$

From equations (8), (7) and (6a) it follows that the value Q_0 is the specific isobaric-isochoric thermal effect of the reaction, i.e., the quantity of heat, which would be liberated as a result of the occurrence of the chemical reaction at constant pressure and volume values:

$$P = P_0, V = V_0.$$

From this same equation it follows that the given value in the general case depends on P_0 and V_0 . This may be a constant only in the case where the initial medium is also an ideal gas, and with the same value of γ , as in the products.

Substituting expressions (6a), (7) and (8) into equation ..., after simple transformations we obtain

$$P = \frac{2(\gamma-1)Q_0 + P_0(\gamma+1)V_0 - (\gamma-1)V_1}{(\gamma+1)V - (\gamma-1)V_0}. \quad (9)$$

Examination of this expression shows that it immediately conforms to the shape of the curve represented in Fig. 3. In particular, this curve has a vertical asymptote when

$$V = V_{np} = \frac{\gamma-1}{\gamma+1}V_0. \quad (10)$$

V_{np} is the limiting volume, to which the products may be compressed during detonation.

The lines of the rays exiting from point P_0, V_0 correspond to the equation of the law of conservation of momentum (4) in this same plane P - V . They are called Mikhel'son's curves. The tangent of the slope angle of each of Mikhel'son's curves is equal to j^2 . Consequently, only Mikhel'son's curves with positive slope ($\text{tg } \phi > 0$) may correspond to the actual process of detonation. For this reason it is possible to exclude from further examination quadrants I and III of planes P, V (see Fig. 3) as responding to

the imaginary value of the plane of the flow of substance j through the detonation front. It is also possible to show that the chemical conversion regimes, which cannot exist as stationary under conditions of a closed isolated system, corresponds to quadrant IV. Such a process is called deflagration. Thus, only points of quadrant II of plane P-V can respond to detonation.

With a fixed rate of detonation D the actual state of the products directly behind the detonation front can be described by the point of intersection of the detonation adiabatic curve and the corresponding curve of Mikhel'son. From Fig. 3 it is clear that in the general case there are two such points (for example, the points of intersection of line 2 with curve 1), i.e., the laws of conservation of momentum and energy permit two types of detonation at one and the same speed D . Detonation which corresponds to a large pressure value in the products is called overcompressed or strong detonation, while that which corresponds to a lesser value is called undercompressed or weak detonation. The lowest detonation rate, at which Mikhel'son's curve has only one common point A with the detonation adiabatic curve, is called the normal. In conformance with the classification of detonation regimes the segment of the detonation adiabatic curve, lying above point A, is called its strong branch, while the segment situated below is called the weak branch.

It can be shown (for example, see [4]) that in overcompressed detonation the reaction products relative to the detonation front move with subsonic speed. In undercompressed detonation this speed is supersonic. In the case of normal detonation the relative speed of the products is precisely equal to the speed of sound. Let us prove, in particular, the last assertion.

It is known that the speed of sound c is determined by the following expression:

$$c^2 = -V^2 \left(\frac{\partial p}{\partial V} \right)_s. \quad (11)$$

where S is the specific entropy. On the other hand, the unknown relative speed of the products $D - u$ using the equations of the laws of the conservation of mass (1) and momentum (4) is expressed by the slope of Mikhel'son's curve:

$$(D - u)^2 = -V^2 \frac{P - P_0}{V_0 - V}. \quad (12)$$

Thus, it is necessary to prove that at point A Mikhel'son's curve touches not only the detonation adiabatic curve, but also the isentrope. With this aim let us differentiate expression (5) with respect to V along the detonation adiabatic curve. As a result of simple transformations with the use of thermodynamic identities we will find

$$T \left(\frac{dS}{dV} \right)_V \left[\left(\frac{dP}{dV} \right)_V - \left(\frac{dP}{dV} \right)_S \right] = \frac{V_0 - V}{V} \left[\left(\frac{dP}{dV} \right)_V - \frac{P - P_0}{V_0 - V} \right], \quad (13)$$

where T is the absolute temperature; dP/dV is the derivative along the detonation adiabatic curve.

From the last equality it follows that at point A the simultaneous touching of the detonation adiabatic curve, of the isentrope and of Mikhel'son's curve does in fact take place, i.e., $c^2 = (D - u)^2$.

As can be seen from the foregoing examination, the laws of conservation of mass, momentum and energy permit any rate of detonation D , as long as it is not less than the minimum value corresponding to normal detonation. It thus seems as if the self-sustaining detonation front can have any speed, beginning with the normal and higher. However, experience shows that each explosive has its own definite detonation rate. Consequently, there must exist a mechanism, which selects only one definite speed from the set of speeds permissible by the laws of conservation.

Even Jouget pointed out [3] that overcompressed self-sustaining detonation cannot be stationary. He proceeded from the fact that with such detonation the products are removed from the detonation front at subsonic speed. Because of this the rarefaction wave has the possibility of overtaking the detonation front and making it nonstationary. The rarefaction wave can be eliminated, if the detonation products are supported from behind using some kind of plunger, which moves in the direction of propagation of the detonation. However, such a regime will still not be self-supporting, and its speed will be determined not only by the mechanism of the detonation conversion, but also by the external source.

Thus, using simple considerations it can be shown that self-supporting detonation can be either normal or undercompressed detonation. However, more definite conclusions of the regime of this detonation, without introducing information on the structure of its front, cannot be made. Therefore, the problem of the nature of the detonation speed within the framework of the classical theory is solved on the basis of the additional assumption, called the Chapman-Jouget selection hypothesis or principles. According to this principle, self-supporting detonation is normal, i.e., its front relative to its own products moves at the speed of sound.

The Chapman-Jouget hypothesis allows us to calculate the detonation rate and other parameters of the detonation front, if the parameters of the initial state of the substance P_0 , V_0 , E_0 , as well as the dependence $E = E(P, V)$ for the products, are given. According to the state of the detonation adiabatic curve is plotted and the slope of the Mikhel'son curve, corresponding to point of tangency A , is found.

For example, let us determine the detonation rate D for the case where the products are an ideal gas. For this let us substitute into the equation of the detonation adiabatic curve (9) the value P , expressed with the aid of the equation of the law of conservation of momentum (4):

$$P = \frac{P_0}{V_0} (V_0 - V) + P_0 \quad (14)$$

As a result of this substitution a quadratic equation relative to V , depending on D as on the parameter, is obtained. From the known principles such a value D will be found, with which the equation has only one root. The obtained value, obviously, will also be the desired detonation rate. For simplicity let us examine the case where the value P_0 in comparison with P can be disregarded. Assuming in expressions (9) and (14) $P_0 = 0$, we will come to the following quadratic equation relative to V :

$$\frac{(\gamma+1)D^2}{V_0^2} V^2 - 2 \frac{\gamma D^2}{V_0} V + 2(\gamma-1)Q_0 - (\gamma-1)D^2 = 0. \quad (15)$$

The condition where this equation has only one solution will have the form

$$D^2 - 2(\gamma-1)D^2 Q_0 = 0 \quad (16)$$

Hence, throwing out the physically inapplicable value $D = 0$, we find

$$D = \sqrt{2(\gamma-1)Q_0}. \quad (17)$$

In conformance with equation (17), the detonation rate, and consequently, also all the other parameters of the detonation front are determined by the heat of reaction Q_0 . It should be emphasized that here not an ordinary isobaric-isothermic heat effect is understood (i.e., determined with constants P and T), but an isobaric-isochoric heat effect. These two values are significantly different and equal to one another only in exclusive cases, when as a result of the occurrence of the reaction at constant pressure P and T simultaneously manage to be maintained constant. This, for example, is possible if the products of detonation (PD) and the initial medium are described by the equation of the state of an ideal gas with one and the same value γ .

The role of the isobaric-isochoric heat effect of the reaction was here established for a particular form of the equation of the state of the PD. However, it is difficult to show that even in the general case it is this value that is decisive for the detonation process. Considering the observation made, henceforth by the term heat effect of the reaction we will always mean precisely the isobaric-isochoric heat effect.

The obtained conclusions were illustrated in an example, in which the PD were assumed to be an ideal gas. Actually, such an assumption can be justified only in the case, where the initial explosive has a very low density. For example, if it appears to be an ideal gas or else if it is a very porous condensed medium. In contrast to the last example ordinary explosives have a density of 1-2 g/cm³. In conformance with the equation of the law of conservation of momentum (4) the density of the product is even higher. Consequently, they cannot be described by the equation of state of an ideal gas.

The nonideality of the detonation products, in particular, is manifested in the dependence of the rate of detonation of condensed explosives on the initial density ρ_0 , which was discovered experimentally by the very first investigators of detonation. Actually, according to equation (8), $E_0 = Q_0$ when $P_0 = 0$. Since the initial energy does not depend on the density (the porosity) of the substance, the detonation rate, according to formula (17) would also not have to depend on ρ_0 in the case where the products were an ideal gas.

The first attempts at taking into account the nonideality of the detonation products were undertaken with the use of Abel's equation of state [5-12]:

$$P(d - a) = RT, \quad (18)$$

where α is the characteristic volume of the molecules or the covolume. However, it is not difficult to see that the detonation adiabatic curve corresponding to this equation of state can be obtained from equation (9) by substitution of V by $V - \alpha$. Consequently, in this case also for the detonation rate we come to formula (17). Hence it follows that for an explanation of the dependence of $D(p_0)$ the covolume must be considered as a variable value. Its dependence on the various parameters are examined in works [13-21].

The variability of the covolume suggests that in the structure of the equation of state of the PD a significant role is played by the forces of the elastic interaction between the molecules. Landau and Stanyukovich were the first to point this out. They suggested a basically new approach to the structure of the equation of state of PD [22]. Proceeding from the fact that with the enormous pressures existing in the detonation products, each molecule vibrates predominantly around a certain equilibrium position, these authors suggested that the equation of state of PD be examined by methods of the physics of solids. Equations for pressure and specific energy are represented in the form of sums of the elastic and thermal terms:

$$P = P_v(V) + P_t(V, T) = \frac{A}{V^n} + \frac{BT}{V}, \quad (19)$$

$$E = E_v(V) + E_t(V, T) = \frac{A}{(n+1)V^{n+1}} + C_v T, \quad (20)$$

where A , E , n , C_v are constants.

Using equations (19) and (20), it is possible to express the detonation rate through the parameters of the initial explosive ρ_1 , Q_0 [23]. We will not stop here on this point. Let us only note that the obtained expression differs significantly from (17) and is similar to the latter only in the fact that in a general case D is proportional to $\sqrt{Q_0}$, if we assume $E_0 = Q_0$. All the subsequent works [23-36] on the determination of the equation of

state of PD rests on the basic work of Landau and Stanyukovich [22] and are dedicated basically to the determination of expressions (19) and (20) from experimental data.

In works [22, 23] it is shown how, proceeding from the dependence of $D(\rho_0)$, to determine the constants of equations (19) and (20). More accurate results [32-34] are obtained with the use of not only this dependence, but also the values of the parameters of detonation at the Chapman-Jouget point. A special place is occupied by works [35, 36], in which the equation of state of PD is determined on the strength of experimental data on the impact compressibility of separate chemical components of the products. A detailed analysis of certain works on the equation of state of detonation products of condensed explosives may be found in review articles [37, 38].

Thus, the classical theory of detonation at the present time allows us not only in principle, but also in practice to calculate the parameters of detonation waves in condensed media. However, this calculation is based on the Chapman-Jouget hypothesis, and the classical theory cannot answer the question, as to why precisely this principle, and not some other principle of selection is implemented. The problem of the selection principle, as Zel'dovich first demonstrated [39], must be solved on the basis of the concrete assumption of the structure of the detonation front.

§ 2. The Theory of Zel'dovich

Let us examine from the position of gas dynamics the structure of a stationary detonation front in a homogeneous medium. Here we will assume that the flow in the reaction zone is one-dimensional. Therefore, it is necessary to write one-dimensional equations for the conservation of mass, momentum, and energy for this narrow zone. However, it turns out that if within its boundaries the viscosity, thermoconductivity, and diffusion are disregarded,

then the desired equations will be the equations (1)-(5) derived above. Actually, with the assumptions made intermediate reaction products differ from the terminal products only by the absence of chemical equilibrium, which is in no way reflected in the equations of conservation. Therefore, using the same considerations which allowed us to generalize the equations mentioned for the case of a plane stationary detonation front we can establish their application for any portion of this front, which comprises an arbitrary portion of its width.

Within the limits of the reaction zone the specific internal energy E can be assumed to be a function of only three variables:

$$E = E(P, V, k), \quad (21)$$

where k is a value, which somehow reflects the chemical composition, and which for brevity is therefore henceforth called the composition. It is possible, for example, to use as the composition the set of independent concentrations of chemical components in the reacting mixture. From this example it is clear that in the general case a composition k is determined not by one, but by several numbers.

Differentiating (21) with respect to the composition, we obtain an expression for the heat effect of the reaction with constants P and V :

$$dQ = - \left(\frac{\partial E}{\partial k} \right)_{P, V} dk \quad (22)$$

Henceforth for simplicity we will assume that the sign of the heat effect depends only on k , although its absolute value may also be a function of P and V .

In the equation of the law of conservation of energy (5), by replacing E by the function $E = E(P, V, k)$ and assuming k to be a constant parameter, we will arrive at an expression, which can be

called the equation of the intermediate detonation adiabatic curve of constant composition:

$$E(P, V, k) - E_0 = \frac{P - P_0}{\gamma} (V_0 - V). \quad (23)$$

The detonation adiabatic curve, corresponding to the state of the final reaction products, for the sake of distinction we shall call the equilibrium adiabatic curve. Let us note that the substitution into equation (23) of the final value of the composition $k = k_1$ for the actual detonation front, generally speaking, does not produce an equation of the equilibrium detonation adiabatic curve, since the equilibrium composition may be a function of P and V .

It is not difficult to show that the intermediate adiabatic curve of constant composition has the same properties as the equilibrium detonation adiabatic curve. For this, it is sufficient to repeat the corresponding calculations of [4], having replaced the equilibrium isentrope and the speed of sound

$$s = \sqrt{-V \left(\frac{\partial P}{\partial V} \right)_k}$$

by the isentrope of constant composition and the so-called frozen speed of sound:

$$c_s = \sqrt{-V^2 \left(\frac{\partial P}{\partial V} \right)_{k,0}}. \quad (24)$$

Let us explain the physical meaning of these concepts.

If a reacting mixture of arbitrary composition k , existing in state P, V , is quickly adiabatically compressed or expanded by the infinitely small value dV , then its state will be displaced with respect to the isentrope of constant composition, since the latter cannot instantaneously react to the change in the external conditions. Let us select on plane P - V the random point A (Fig. 4).



Fig. 4. Relative distribution of equilibrium isentrope AB and the isentrope of constant composition AC.

Let us draw the equilibrium isentrope AB through this point and let us determine with respect to it the position of the isentrope of constant composition k . If after fast compression by dV the composition remains equilibrium, then the isentrope of constant composition coincides with the equilibrium isentrope. Conversely, point C or C_1 will correspond to the new state, which is required to be established.

Since in the new state the composition k is not an equilibrium composition, it will strive (relax) to a new equilibrium value. Rapid compression led to an increase in pressure when $S = \text{const}$. Consequently, in conformance with Le Chatelier's principle in the process of relaxation the pressure will drop. Since this process is accompanied by a rise in entropy, point D, corresponding to the equilibrium state, turns out to be higher than the isentrope AB. In this case D may come to the new equilibrium state only from point C. Consequently, the isentrope of constant composition may proceed only more abruptly than the equilibrium isentrope, i.e.,

$$\left(\frac{\partial P}{\partial V}\right)_{k,1} > \left(\frac{\partial P}{\partial V}\right)_k \quad (25)$$

$$c_1 > c_k \quad (26)$$

It can be demonstrated that infinitely small perturbations are propagated in the medium with velocity c_3 . This conclusion is also valid in the case where the medium is in the equilibrium state.

In connection with this arises the question of whether it is necessary in Jouget's proof of the impossibility of overcompressed detonation to replace the equilibrium speed of sound with the frozen one? This question should be answered in the negative. The fact is that the rarefaction wave, propagating in the medium, is expanded in space with time, and the expansion of the substance at the front of this wave occurs more and more smoothly. Therefore, the basic rarefaction is propagated in the medium with the equilibrium speed of sound, while the perturbation moving away in front with velocity c_3 attenuates. Thus, in examining a stationary regime it should be kept in mind that the rarefaction wave is propagated in the products with the equilibrium speed of sound. However, it can be noted that if a sufficiently strong perturbation is created in the products, it is capable of penetrating within the limits of the reaction zone, i.e., with respect to strong perturbations the normal detonation front is overcompressed.

With the substitution of the value $k = k_0$ into the equation of the intermediate detonation adiabatic curve there is obtained an equation of the impact adiabatic curve, which is related with the movement in the medium of the surface of discontinuity without a reaction. Such a surface of discontinuity is called a shock front. For the latter all the above obtained equations of conservation (1)-(5) are valid, therefore the shock front may be viewed as a particular case of an overcompressed detonation front.

Let us now apply the equations of conservation of mass, momentum and energy to determine the structure of the detonation front. Figure 5 represents the relative distribution of the equilibrium detonation adiabatic curve p and the intermediate detonation adiabatic curves of constant composition k , where the greater value of the subscript corresponds to the larger amount of liberated heat (the shock adiabatic curve of the initial explosive corresponds to the composition k_0).

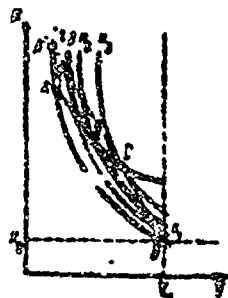


Fig. 5. Relative distribution of the equilibrium detonation adiabat curve p and detonation adiabat curve of intermediate composition with a chemical reaction exothermic from start to finish.

In accordance with the equation of conservation of momentum (4) the point depicting the thermodynamic state of the medium (the point of the state) must slide along one of Mikhel'son's curves, until it reaches the equilibrium detonation adiabat curve. If it were lifted from position O , then only the equilibrium points lying on the weak branch of the indicated detonation adiabat curve would be accessible to it. Therefore, depending on the concrete mechanism of occurrence of the reaction not only a normal, but even any regime of undercompressed detonation might take place. If however, the phenomena of transfer and the transmission of radiant energy within the limits of the detonation front are assumed to be negligibly small, then only a single mechanism of initiation of the chemical reaction remains - shock compression of the substance. Therefore the forward border of the reaction zone must be the shock front, which transfers the state of the medium abruptly from point O to point A or any other point A' , lying above the shock adiabat curve.

From position A or A' in proportion to the occurrence of the chemical reaction the point of the state along the corresponding Mikhel'son curve transfers to position B or B' with the decrease in pressure. Thus, within the limits of the detonation front a zone of increased pressure, called the chemical peak (Fig. 6), must exist. The propagated pressure distribution in the chemical peak depends on the kinetics of occurrence of the chemical reaction.

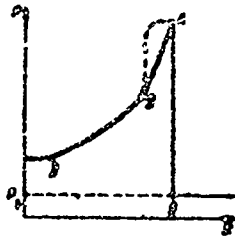


Fig. 6. Distribution of pressure in a normal detonation wave in the case of a quick reaction from start to finish (the continuous line) and at the start of a slow, and then accelerating reaction (dotted line).
BD - nonstationary rarefaction wave. The designation does the same as in Fig. 5.

A further shifting of the point of state from position B or B' along the Mikhel'son curve is impossible, since movement below must occur on the equilibrium isentrope, and movement above would denote a shock compression of the products. The latter is also impossible, since the shock front is propagated with supersonic speed, while at point B and above the following condition is fulfilled

$$c > D - u. \quad (27)$$

Hence it follows that the points of type C, lying on the weak branch of the equilibrium detonation adiabatic curve, are unachievable in the case under consideration, and condition (27) is the necessary condition for the stationary propagation of the detonation front.

On the other hand, on the strength of the incompatibility of the overcompressed front with the rarefaction wave, we obtained the above second necessary condition for the existence of a stationary self-supporting regime:

$$c \leq D - u. \quad (28)$$

These two conditions do not contradict one another only when

$$c = D - u, \quad (29)$$

i.e., with the fulfillment of the Chapman-Jouget selection principle. Let us emphasize that this principle is implemented with respect to the equilibrium speed of sound, and relative to the frozen speed c_3 the regime is overcompressed.

Let us examine another case, where the chemical reaction during the change of the composition from k_0 to a certain k_1 is exothermic, and from k_1 to the equilibrium composition - endothermic. Such a reaction may, for example, exist, if in the reacting mixture two independent chemical reactions go with heat liberation of equal signs, where the endothermic reaction has a lower speed. Figure 7 represents the corresponding diagram of the relative position of the detonation adiabatic curve. Now the lowest speed of detonation is determined by the slope of Mikhel'son's curve OA tangent to the detonation adiabatic curve of intermediate composition k_1 , in which the sign of heat liberation changes. Hence it is immediately obvious that in any regime the detonation front is propagated with a speed higher than normal. In other words, the Chapman-Jouget principle is not implemented in this case.

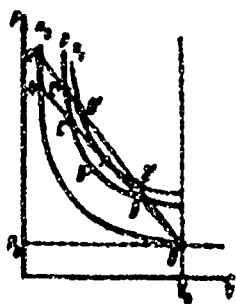


Fig. 7. Relative position of the equilibrium detonation adiabatic curve p , shock adiabatic curve k_0 and detonation adiabatic curve of maximum heat liberation k_1 .

Let us examine the change of state within the limits of such a detonation front. Just as in the first case (see Fig. 5), the point of the state of a substance shifts along Mikhel'son's curve from position A or A' to position B or B' (see Fig. 7). During this process the pressure falls, i.e., once again there is a chemical peak. From position B' a further shifting of the point of

state downward is impossible, since the intermediate detonation adiabatic curve of composition k_1 lies above all the other detonation adiabatic curves. Consequently, from position B' the point of state will shift along Mikhel'son's curve only upward - to the equilibrium position C'. Let us note that, passing from above downward through point C', the reacting mixture had no equilibrium composition, but a certain intermediate composition between k_0 and k_1 . In contrast to B' from position B the further movement of the point of state along Mikhel'son's curve is possible both to the side of a pressure increase, to position C, as well as to the side of its further decrease, to position D, to which undercompressed detonation corresponds. It is precisely such detonation which will be self-propagating in the case under consideration.

For a more visualizable representation of the structure of an undercompressed detonation front let us assume that behind the detonation front in the products a shock front is transmitted, each time of greater amplitude, until finally the undercompressed regime transfers to an overcompressed regime. Figure 8 represents the pressure distribution in a detonation wave for the three cases analyzed above, mainly, when points D, C, and C' correspond to the final state of the products.

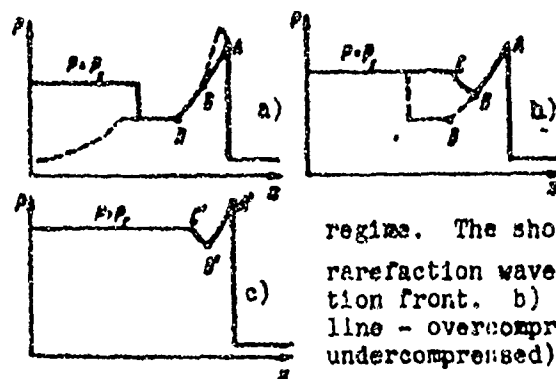


Fig. 8. Pressure profiles in detonation waves in the case of change of sign of the heat liberation at the end of the reaction zone.

a) Undercompressed regime. The shock waves with $P < P_C$ and the rarefaction waves are absent from the detonation front. b) Mixed regime (the continuous line - overcompressed, the dotted line - undercompressed). A shock wave with $P = P_C$

can be represented at any distance from the detonation front. c) Overcompressed regime. The detonation front cannot be separated from the shock wave with $P > P_C$.

Let us now assume that behind the shock front there first occurs the absorption of heat, for example, as a result of the endothermic reaction or the process of relaxation. Then from point A or A' (see Figs. 5 and 7) the point of state will at first go along Mikhel'son's curve upward, which will lead to a smooth rise in the pressure in the chemical peak. In other words, the forward part of the detonation front will have an "avalanche," which is shown for the example by the dashed line in Fig. 8a.

Concluding our discussion of the structure of a detonation wave with various heat liberation regimes, let us note that in all instances, except that corresponding to Fig. 8a (segment BD), the point of state intersects the strong branches of the intermediate detonation adiabatic curves, i.e., in these cases the flow of matter relative to the detonation front is subsonic in the reaction zone and perturbations from it enter the shock front. As pertains to segment BD, the flow corresponding to it must be supersonic (this is because of the frozen speed of sound). Thus, Zel'dovich's theory not only permits us to substantiate the Chapman-Jouget selection principle, but also to point out possible divergences from this principle depending on the kinetics of the chemical reaction within the limits of the detonation front.

§ 3. On the Theory of an Uneven Front

The theory examined in the preceding paragraph shows that if we assume the flow within the reaction zone boundaries to be one-dimensional, then the corresponding solution of a common system of equations of the gas dynamics and of the chemical kinetics will always exist. Therefore, from first glance it can be shown that the problem of the structure of the detonation front, at least in homogeneous explosives, is in principle solved and for its actual determination it is necessary only to find sufficiently accurate equations of the chemical kinetics and to determine the necessary constants. However, as is pointed out in the work of Zel'dovich

[39], the existence of a solution still does not denote that it corresponds to the actually existing process of detonation. The fact is that a solution, obtained on the assumption of a one-dimensional flow in the reaction zone, can turn out to be unstable with respect to small perturbations.

An investigation of the stability of the detonation front with respect to the small perturbations was first undertaken by Shchëlkın [40]. Subsequent works [41-44] showed that in the majority of cases during the detonation of gases a smooth detonation front, corresponding to Zel'dovich's theory, is actually unstable. The most basically formulated and solved problem in the general form on the stability of the detonation front is in work [45]. However, neither this, nor other works permit us to draw definite conclusions on the stability of the detonation front in the case of condensed explosives. The application of the theory to this case is complicated by the fact that the equations of state of the reacting medium and the kinetics of the chemical reaction are unknown for it. Therefore, in this book concepts on the instability of a smooth detonation front are developed on the basis of experimental data.

In the case of instability of a smooth detonation front Zel'dovich's theory is obviously inapplicable, and the problems of its structure and of the justification of the Chapman-Jouget selection principle must be solved anew. As long as the equations of the chemical kinetics for conditions of detonation are unknown, the problem of the detail structure of the detonation front cannot be solved. However, even now it is possible to examine the averaged structure of the reaction zone from a general standpoint. In works [46, 47] there is an analysis of the application of the laws of conservation of averaged mass, momentum and energy to the case of gas detonation on the assumption of isotropic flow turbulence in the reaction zone. In work [48] it is shown that by selecting a method of averaging of the flow parameters the equations of conservation for an arbitrary medium can be given the form of

these same equations of a one-dimensional flow (1)-(5), if by the pressure and specific internal energy we mean the following formal values:

$$P_0 = \bar{P} + \overline{\rho u'^2_x} \quad (30)$$

$$E_0 = \bar{E} + \overline{\rho \frac{u'^2}{2}} \quad (31)$$

and by the density and speed - the corresponding average values $\bar{\rho}$ and \bar{u} . In the last expressions the line above denotes averaging with respect to time at a given point of space in the coordinate system, related with the detonation front. The vector u' and its component u'_x , directed along the detonation propagation, represent the pulsation of the flow velocity, i.e., the difference between momentary and the average velocity.

Thus, in the case of a turbulent reaction zone the internal energy should mean the sum of the internal energy proper and of the turbulent movement of the medium. In just the same way the pressure should be understood to mean the sum of the thermodynamic pressure and the dynamic head $\rho u'^2_x$. Let us note that pressure P_0 may be measured by a monometer, which possesses a sufficiently large time constant, if its sensor shifts together with the medium with the average speed of its movement. Furthermore in work [48] it was shown that it is possible to select in this way the values which characterize the flow turbulence in the reaction zone, and that they will formally behave as components of the chemical composition k . In other words, the process of the emergence and subsequent attenuation of turbulence during detonation can be viewed as the occurrence of the chemical reaction and it is possible to even calculate the heat liberation of the latter. From this viewpoint the reaction zone should be understood to mean the entire region, within the confines of which not only does the chemical reaction go to completion, but also where the total attenuation of the flow turbulence occurs.

The proposed method of averaging allows us to solve the problem of the structure of a detonation wave with a turbulent reaction zone in precisely the same way as was done in the theory of Zel'dovich. In particular, it was shown in [48] that if the Grüneisen coefficient for the product satisfies the inequality

$$\Gamma = \gamma \left(\frac{\partial p}{\partial E} \right)_\nu > \frac{2}{3}, \quad (32)$$

then the heat liberation as a result of the formal components of the chemical composition is positive. If the purely chemical part of the heat liberation is also positive, then the detonation will have a normal regime.

The idea of conditions (32) can be clarified on the basis of the following simple considerations. Let us assume that with the attenuation of the turbulence, when the latter can be considered isotropic, a unit volume, which will henceforth remain constant, is liberated from the medium. On account of the fact that it is isolated, the energy contained in it E_0 (the sum of the internal and of the kinetic energy) also does not change with time. Therefore the reduction in the kinetic energy is exactly equal to the increase in the internal energy:

$$\frac{1}{3} \frac{d\overline{u^2}}{dt} = -dE. \quad (33)$$

In accordance with the change in the kinetic and internal parts of the total energy there is a change in the average pressure and in the dynamic head, i.e., the components of the formal pressure. Taking into account the fact that

$$\begin{aligned} dP &= \frac{1}{\gamma} dE, \\ d\overline{u^2} &= \frac{2}{3} dE. \end{aligned}$$

and paying attention to equality (33), we find

$$dP_0 = \left(\Gamma - \frac{2}{3} \right) d\bar{E} / \bar{V}. \quad (34)$$

Since with the attenuation of the turbulence E increases, with the observation of condition $\Gamma > 2/3$ P_0 also increases. However, this also means that in the given case the process of attenuation of the turbulence must be formally considered to be an exothermic reaction.

In the discussed theory, by analogy with the theory of Zel'dovich, the justification of the Chapman-Jouget selection principle is basically related with the assumption that in the process of the reaction and the attenuation of the turbulence the medium goes to a state of thermodynamic equilibrium while expanding (the corresponding point P_0, \bar{V} slides along Mikhel'son's curve downward). With a turbulent reaction zone the disregardable smallness of the phenomena of transfer does not necessarily lead to the desired direction of movement of point P_0, \bar{V} along Mikhel'son's curve. Therefore, the mentioned assumption must theoretically be justified for each concrete structure of an uneven detonation front or must be directly checked experimentally. For example, to determine the distribution of \bar{V} within the limits of the reaction zone it is possible to measure the profile of the mass velocity \bar{u} and to then make use of the law of conservation of mass (1). Running a few steps ahead, we will note that in almost all instances, when such measurement has been done successfully, it was discovered that the reacting medium approaches the equilibrium state right during the process of expansion.

The pressure and energy within the limits of the detonation front, as a rule, are determined indirectly through other values with the aid of the laws of conservation of momentum (4) and energy (5). In the case of a turbulent reaction zone P and E , do not enter into these equations, but rather P_0 and E_0 , and therefore in indirect measurements not the thermodynamic, but the formal pressure and energy are determined, which should always be kept in mind.

CHAPTER 11

EXCITATION OF DETONATION BY SHOCK WAVE

The usual method of initiating detonation in a condensed explosive substance is the creation in this substance of a shock wave of sufficient intensity from the detonator capsule in conjunction with the booster charge.

Detonation may also be caused by friction, a beam of light, burning in a closed volume, shaking of the charge, striking of particles and pieces, a light pulse, etc. However, even under these conditions formation of detonation occurs as a result of the emergence in the final stages of a transition process of the nonstationary shock wave with ignition, which also passes into a stationary detonation wave.

The study of the phenomenon of the transition of a shock wave into detonation touches on the basic problems of detonation of condensed systems. On the one hand, this is a problem of a mechanism of the emergence and occurrence of a chemical reaction which ensures total heat liberation in the explosive for relatively short times of the shock loading. On the other hand, it is a problem concerning the structure of hydrodynamic flows under nonstationary conditions, which form the detonation wave.

The number of experimental works on the observation of a detailed picture of deformation of a detonation wave is small. There are significantly more works dedicated to the solution of applied problems of the susceptibility of the explosives to detonation depending on their aggregate state, density, dispersity, presence of sensitizing and retarding additives, etc. The dynamic parameters of the initiating shock wave were ordinarily not measured here, and the susceptibility to detonation was characterized in relative values. Most frequently this was the width of a plate made of an inert material, which divided the active charge from the investigated material, through which the detonation was still capable of being transferred [49]. In similar experiments using a photoregister it was discovered that detonation in a passive charge begins at a certain distance from the inert boundary, which increased in proportion to the increase in the width of the boundary or the decrease in the size of the initiating charge. In certain experiments the phenomenon of the propagation of detonation in the opposite direction from the site of emergence ("retonation") was also detected.

An explanation of these results encounters significant difficulties. The presence of a delay in the initiation and the emergence of a retonation wave from outside recalls the picture of the predetonation period in the transition of combustion into detonation in gaseous mixtures [23]. In connection with this until this time numerous attempts have been made [53-58] to examine the phenomenon approximately according to the following outline.

The shock wave causes ignition of the substance with a certain delay. A pressure rise as a result of the developed reaction leads to the emergence of a series of compression waves, which overtake the front of the initiating shock wave and increase its amplitude. The amplitude of the shock wave increases continually until it reaches a value which corresponds to normal detonation. In this way it is supposed that the difference with

the classical idea of the transition of combustion into detonation [23] consists only in the fact that the shock wave, originating under the effect of the accelerating front of combustion, is replaced by a shock wave from the active charge. It is obvious that such a transference of the model of the transition of combustion to detonation for clarification of the development of the initiating shock wave is connected with misunderstanding. In the scheme of the transition of combustion to detonation the accumulation of compression waves leads to the formation of a shock wave with an amplitude sufficient for self ignition of the gas. The appearance of such a shock wave is identified with the manifestation of detonation [23]. The more precise problem of the transition of such a shock wave to detonation is not examined in detail, and it is precisely this that is the essence of the problem of shock initiation.

The theoretical problem of nonstationary interaction of the region of self-ignition with the front of the shock wave has remained until the present time an open question even for gaseous mixtures. The specifics of the reactions in a condensed medium complicate a strict formulation of the problem even more.

1. The Initiation of Liquid Explosives

Today the majority of investigators assume that the occurrence of the chemical reaction in a shock-compressed homogeneous explosive has a thermal nature. In spite of the fact that precise calculations on the value of the shock warm-up are so far uncomplicated, approximate evaluations [58, 59] testify to the actual possibility of the heat-up of liquid to temperatures of self-ignition in the shock wave with a pressure on the order of 100,000 atm. The effect of the elastic part of the energy of the shock compression on the weight of the chemical reaction remains indeterminate. It should be kept in mind that on the front of the detonation of powerful liquid explosives the pressure in the medium may reach a significantly greater value, at which

in principle a qualitative change in the mechanism of the chemical reaction is possible [23].

A decisive characteristic of the thermal nature of the chemical reaction, which can be described, for example, by Arrhenius kinetics, is the presence of the abrupt self-acceleration of the reaction under adiabatic conditions, manifested in the self-ignition of the substance after a certain delay time and in the strong dependence of this time on the initial parameters. A concrete reason in favor of the assumption of the thermal nature might also be the analogy in the processes of excitation and propagation of detonation of homogeneous condensed explosives and gaseous mixtures.

In the experimental works of Campbell, et al. [60] using speed photography and electrical probes ultrafast phenomenon in the initiation of detonation in certain liquid explosives was detected. It was established that the initiating shock wave is propagated through the liquid explosive for a certain time at a slightly falling rate, as in an inert medium. After a certain time of delay the shock wave suddenly transfers to detonation, where at the initial moment this detonation is over-compressed. In observing the process from the end of the charge in a transparent liquid explosive - nitromethane - there was registered the occurrence of a weak luminescence shortly before the transition of the shock wave into detonation.

A scheme for setting up the experiment for the observation of the process of initiation in nitromethane, similar to the setup of Campbell, et al. [60], is shown in Fig. 9. As the inert boundary, cutting off the incandescent products of detonation of the active charge, a set of plates made from Plexiglas is used. The transparency of the Plexiglas allows us, during observation of the process from the end of the charge, to record on a photo-scanner the flashes of the air gaps during the passage of the shock wave through the boundary. Since the shock adiabatic

curve of the Plexiglas is known [61], it is possible to calculate the mass velocity, density and pressure in this shock wave. Moreover, the shock adiabatic curve of nitromethane is also known [62]. Therefore, with the method of reflection [63] it is not difficult to calculate the wave and mass velocity, pressure and density in the initiating shock wave.

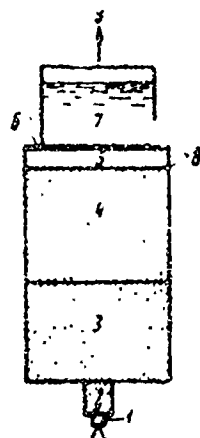


Fig. 9. Setup of the experiment for observing the formation of detonation on the excitation boundary. 1 - Detonator capsule; 2 - booster charge; 3 - explosive lens; 4 - table of pressed trotyl 100 mm in diameter; 5 and 6 - Plexiglas plates; 7 - container with liquid explosive; 8 - air gaps; 9 - direction of the optical axis of the photoregister.

The selection on the pressure amplitude necessary for initiation occurs with a change in the initial density of the charge made from pressed trotyl. Fine regulation of the pressure in the initiated wave allows us to obtain a delay in the transition of the shock wave into detonation of up to 10 μ s. Photoscanning of one of the experiments, conducted according to this setup, is given in Fig. 10. The initial velocity of the shock wave in nitromethane in this experiment amounted to 4.2 km/s, while the pressure in the wave was 78,000 atm. In the photoscanner one can see how after a certain time after the entry of the shock wave into the nitromethane in the shock-compressed liquid there arises a relatively weak luminescence, which has a constant intensity and after a certain time is suddenly changed by the luminescence of the detonation of the nitromethane. (The rate of normal detonation in nitromethane is 6.3 km/s, and the initial density is 1.14 g/cm³.) Using ionization sensors [60] it was

established that the emergence of conductivity on the limit of the division of the inert boundary and the nitromethane corresponds to the start of this luminescence. Using the same senses there was success in recording the fact that the zone of conductivity, which apparently arises as a result of the chemical reaction, propagates with high speed behind the shock wave and overtakes it.



Fig. 10. Photoscanning of the luminescence during initiation of nitromethane according to the system shown in Fig. 9. 1 - Illumination of the air gaps during the passage of the shock wave; 2 - moment of entry of the shock wave into the liquid; 3 - luminescence in the area of shock-compressed liquid; 4 - luminescence of normal detonation of nitromethane; 5 - area of overcompression in the detonation of nitromethane; 6 - illumination of the detonation products during their escape from the free surface of the liquid explosive.

The observed ultrafast perturbation, accompanied by weak luminescence, corresponds, as Chaiken suggested [64], to the detonation of the preliminarily compressed and heated shock wave of nitromethane, which arises under the effect of the thermal explosion on the boundary of the section, occurring after a definite period of induction. The detonation rate here, according to the hydrodynamic model, must be higher than normal due to the preliminary compression of the substance by the shock wave.

Considering this wave as standard, Chaiken suggested a space-time calculation system for its speed from the known dynamic parameters of the initiating shock wave and according to the data of photo-scanning (Fig. 11).

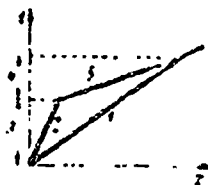


Fig. 11. Chaiken's scheme for calculating the rate of detonation of a shock-compressed substance according to photo-scanning data. 1 - Propagation of the front of the initiating shock wave; 2 - movement of the surface of the boundary made from inert material; 3 - delay of the thermal explosion on the boundary surface; 4 - time of weak luminescence behind the shock wave; 5 - propagation of detonation in a liquid preliminarily compressed by a shock wave; 6 - normal detonation.

Since there were no direct proofs of the detonation nature of the ultrafast perturbation, Jacobs [65] was limited by the assumption of the existence of a "secondary shock wave in the liquid as a result of the reaction." In contrast to these authors Cook [66] found in experiments on the initiation of detonation of nitromethane confirmation of his hypothesis on the existence of a "thermal pulse," which put in doubt the validity of the hydrodynamic theory of detonation.

Thus, the basic problems in the investigation of the mechanism of shock initiation of homogeneous media are the following:

1. To what degree does the nature of the second wave correspond to Chaiken's hypothesis?
2. Under what conditions and in what way does the ultrafast wave arise? In particular, is the formation of this second wave characteristic for the shock initiation of all liquid explosives?

3. How do we determine the sensitivity of homogeneous condensed explosives for a shock wave?

Let us examine these problems one at a time.

1. If, according to Cnaiken, we assume that the ultrafast wave corresponds to detonation of shock-compressed nitromethane, then it is possible from the calculated or measured speed of this detonation to estimate the parameters of the shock wave on its front, corresponding to the hydrodynamic model. The calculation scheme is shown in Fig. 12. It turns out that even for the smallest values of measured wave velocities [60, 67] with the use of the adiabatic curve of double compression (understated estimate) the pressure on the shock front of the detonation, corresponding to a one-dimensional hydrodynamic Zel'dovich model, must be around 1 million atm. The density jump here must not exceed the density jump on the front of normal detonation by less than 2 times.

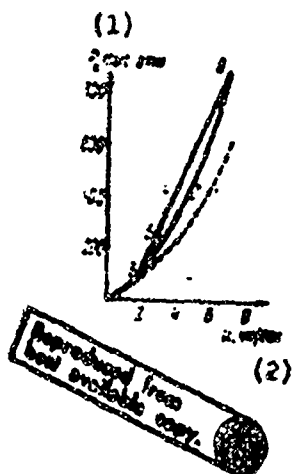


Fig. 12. Estimating the parameters of a shock wave on the detonation front of a shock-compressed substance.
 1 - Extrapolated shock adiabatic curve of nitromethane, measured up to pressures of 80,000 atm; 2 - adiabatic curve of a double shock compression; 3 - parameters of an initiating shock wave; 4 - ray, corresponding to the speed of the second wave, equal to 8.4 km/s relative to the moving boundary of the active charge; 5 - parameters of the second wave; 6 - pressure on the detonation front of a shock-compressed liquid explosive.
 KEY: (1) P, thousands of atm; (2) u, km/s.

From works [68, 69] it is known that the front of normal detonation, as well as inert shock waves in liquid reflect well the light of an extraneous light source. Therefore, attempts might be made to detect the shock wave on the front of an ultrafast detonation by the reflected-light method. Since the density jump, calculated above for a shock front of an ultrafast

detonation, is large, correspondingly the coefficient of light reflection from this wave must also be large.

The shock wave preceding the ultrafast detonation is in nitromethane practically completely transparent. This conclusion follows from the experiments on the observation of light reflection from the border of the boundary, covered by a thin reflecting aluminum layer, through the layer of shock-compressed nitromethane [70]. The transparency of the liquid behind the shock front is also witnessed by the constancy of the luminescence of the second wave during its propagation to the front. Experiments were set up with light reflection (Fig. 13). The initiation delay selected in these experiments was large enough, so that the reflected light from the initiating shock wave would not impede the observation of the light reflection from the second wave, which had a convex shape in our experiments. The angular dimension of the light source was 0.2 rad to obtain a sufficiently large reflection in the convex "mirror," corresponding to the second wave. It was found that the light is reflected well both from the shock detonation wave, as well as from the normal detonation wave, and from the second wave there is no light reflection (Fig. 1). In the explanation of this fact several versions are permissible.

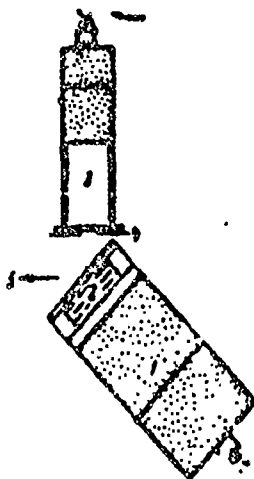


Fig. 13. Formulation of an experiment with light reflection. 1 - Active charge; 2 - transparent container with liquid explosive; 3 - explosive light source, consisting of an explosive lens, a pressed hexogen tablet and a glass tube with argon; 4 - light source diaphragm (15 mm - width aperture, cut in the screen of perpendicular projection of the inlet opening of the photoregister); (5) - direction of the axis of the photoregister.

The high pressures of the dynamic parameters on the front of the second wave, obtained through calculation, allow us to assume that the thermal component in the energy of the shock compression is also large. The high temperature of the shock warm-up on the front of the detonation, propagating along the precompressed and heated front up to temperatures, close to self ignition for the substance, must lead to the minimum possible times of chemical reaction on this front. If ignition on the front occurs here after a time on the order of 10^{-10} s, then the distance from the forward shock front up to the flame must be less than the wavelength of the light ($5 \cdot 10^{-5}$ cm). It is possible that the forward front of such detonation does not, in practice, also have to reflect light from an extraneous source. Also not excluded is the fact that with such enormous pressures the kinetics of the heat liberation is not thermal and the pressure directly affects the chemical conversion. In this case the reflective capability of the detonation front becomes indeterminate. And, finally, the last assumption consists in the fact that the second wave, in general, does not have a clear-cut forward front and is not detonation.

To explain the nature of the ultrafast wave a direct measurement of the profile of the hydrodynamic flows behind the initiating shock wave was made. An electromagnetic device was used, the principle of which is based on the registration of the electromotive force, arising in the sensor made from a thin foil, attracted by the shock or detonation wave to a perpendicularly constant magnetic field [71] (Fig. 14). A typical recording of the flow rate in an experiment with nitromethane is shown in Fig. 15. The sensor was set up at a certain distance from the barrier limit. An initiation delay was selected, such that the shock wave attracted the sensor until the approach of the ultrafast wave to it. As can be seen from the oscillogram, the ultrafast wave has an abrupt leading edge. The mass velocity on the front of the first shock wave is 1.6 km/s, and the additional jump of the mass velocity in the second wave is 1.2 km/s in a regime of initiation with a delay of 2-3 μ s.

The curvature of the leading edge of the ultrashort wave bears witness in favor of the assumption of its detonation character. For the calculation of the parameters of this wave, applying the loss of conservation to the surfaces of the hydrodynamic discontinuity, in work [67] it was learned that the pressure on its front amounts to 250,000 atm with a pressure in the initiating shock wave of 80,000 atm. The chemical reaction zone on the front of this wave, evidently, is so narrow, that it is not noticed on the oscillograms. The detonation character of the second wave is to an even greater degree attested to by the drop in pressure behind the front of this wave due to the escape of the detonation products. It was established that in proportion to the increase in the layer of substance detonated in this wave the pressure profile behind the wave becomes smoother in conformance with the one-dimensional theory of the escape of detonation products.

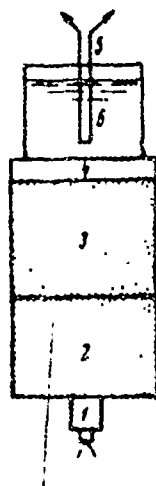


Fig. 14. Mounting of the charge for measuring the profile of velocity of the medium during shock initiation by the electromagnetic method. 1 - Initiator; 2 - explosive lens; 3 - trotyl tablet; 4 - plate made from paraffin; 5 - sensor made from aluminum foil, 0.03 mm thick; 6 - liquid explosive.

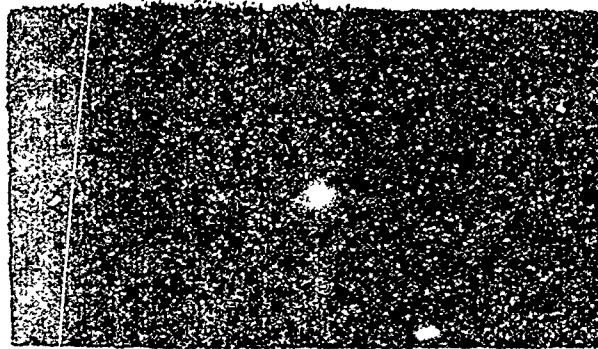


Fig. 15. Oscillogram of the mass velocity during initiation of detonation in nitromethane. 1 - Speed of the medium behind the front of the initiating shock wave; 2 - increase in the flow velocity under the effect of the second wave.

The abrupt pressure drop immediately behind the front allows us also to express certain considerations relative to the fulfillment of the Chapman-Zhugre selection principle for the detonation of a shock-compressed substance. It is known that a regime of overcompressed detonation cannot exist without external support, and therefore in our case this regime does not exist. A regime of undercompressed detonation, which in principle may exist, for example, as a result of radiation or anomalous thermoconductivity is distinguished by the fact that the flow velocity behind the front of the wave is greater than the velocity of propagation of perturbations in the detonation products. In this case directly behind the zone of chemical reaction in the wave an area of constant parameters must exist, since the rarefaction wave remains behind the front of the detonation wave. No such region of constant parameters was discovered on the oscillograms. Therefore, one may assert that the Chapman-Zhugre selection principle for this detonation is carried out with good accuracy. Hence it follows that with a constant initial density such a wave must be stationary, as is also postulated in Chaiken's hypothesis.

It was earlier pointed out that an initiating shock wave during the period of induction behaves as if inert. Thus, the ultrafast detonation, arising from the thermal explosion, is propagated through the compressed substance, which has a practically constant density. Since the propagation of the detonation does not depend on the method of its initiation, it is possible to excite an ultrafast wave artificially. For this, with the usual charge setup (See Fig. 9) on the boundary - nitromethane interface there is set up a gas bubble, a grain of explosive or a metal wire. When the shock wave leaves the boundary at this site there occurs practically without delay a thermal explosion, which causes the detonation of the compressed substance. The shock wave is selected with such an amplitude, that the independent thermal explosion must occur with a long delay. The variation in the delay in initiation is accompanied by an extremely slight change in the parameters of the initiating wave.

The arising detonation is propagated along the interface in the compressed explosive with a velocity almost constant for a certain time and is directly registered on the photoscanner (Figs. 16, 17). Thus, it was successfully established that the process of propagation of the ultrafast detonation is stationary, and its velocity was measured, without using Chaiken's space-time system. For nitromethane, precompressed by a shock wave to a pressure of 80,000 atm, the detonation rate is 8.1 km/s. For a mixture of nitromethane with acetone in a ratio of 75:25 at the same pressure this velocity equals 6.3 km/s. The drop in the speed with the reduction in the heat content helps to confirm the validity of Chaiken's hypothesis on the conformance of this detonation to the hydrodynamic model. It is interesting to note, however, that the calculation of the speed according to the space-time system, suggested by Chaiken, leads to untrue results. The speed of the "second" wave in the mixture turns out to be greater than the speed of this wave in undiluted nitromethane. The reasons for the incorrectness of the calculation procedure will be explained below.

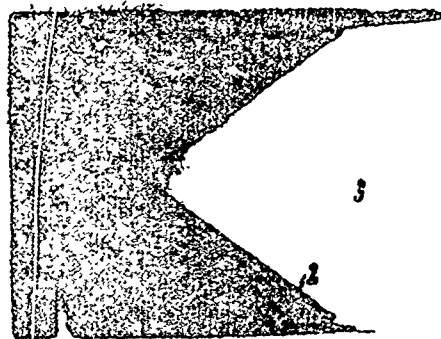


Fig. 16. Photoscan of an experiment of the direct measurement of the detonation rate of a shock-compressed explosive using an artificial ignition initiator in the shock wave. 1 - Explosion of a miniature explosive charge, placed on the interface, under the action of the shock wave; 2 - propagation of detonation through a shock-compressed explosive along the interface; 3 - luminescence of normal detonation.



Fig. 17. Diagram of the propagation of ultrafast detonation of an explosive with its artificial excitation. 1 - Surface of the boundary; 2 - front of the initiating shock wave; 3 - front of the detonation of the shock-compressed layer; 4 - front of normal detonation; 5 - site of explosion of the miniature charge.

In concluding the analysis of the ultrafast phenomenon in nitromethane we will emphasize that the initiating shock wave creates a layer of denser substance, the ignition of which causes the independent detonation of this layer, which then transfers to the detonation of the unexcited liquid explosive. The formation of the ultrafast detonation complex, corresponding to the hydrodynamic model, takes place behind the front of the initiating shock wave; with the transition to the uncompressed explosive this complex is only restructured in conformance with the other value of the initial density.

2. The study of nitroglycerine, dinitroglycerine and tetranitromethane has shown that all these substances on the boundary of excitation behave similar to nitromethane. The threshold pressures differ considerably: for nitroglycerine it is 120,000 atm, and for tetranitromethane - 70,000 atm.

Nitroglycerine and dinitroglycerine, being viscous liquids, can contain in the suspended state air bubbles, water drops and other contaminants. This circumstance, according to Campbell's observations [60] for nitromethane, can qualitatively distort the picture of the formation of detonation as a result of premature ignition of the explosive at the sites of interaction of the shock wave with these inclusions. It was noted that for nonhomogeneities of the initial structure there exists a certain critical dimension (0.3 mm), above which premature detonation takes place. In the case of nitroglycerine there was actually detected a certain peculiarity, consisting in the emergence of a weak luminescence - "aureole" (Fig. II) with the departure of the shock wave, which is maintained right up to the onset of detonation. This luminescence is also observed in a shock wave with an amplitude, insufficient for the excitation of detonation. It may be distinguished that it consists of a multitude of ignition foci, which are recorded on the photoscanner in the form of thin luminescence bands.

Additional experiments with light reflection from the boundary limit have shown that such a focal ignition does not lead to noticeable light absorption, from which the conclusion can be drawn that the quantity of reacting explosive and the corresponding additional heat liberation are insignificant. It is obvious that the foci have dimensions which are less than critical. Therefore, nitroglycerine also possesses properties of a homogeneous liquid explosive, manifested in the formation of ultrafast detonation. Direct measurement of the rate of this detonation by the method described above produces for it

a value of 10.2 km/s with a pressure of 115,000 atm in the shock wave. The density of the nitroglycerine behind the shock wave is 2.3 g/cm^3 . Hence, from approximate estimates, the pressure in the detonation in the compressed nitroglycerine must be higher than 500,000 atm. Apparently, this is the most powerful detonation of those encountered in the experiment.

In all the observed cases the luminescence of the detonation of a shock-compressed explosive turned out to be significantly weaker in comparison with the luminescence of normal detonation. Even Khariton [72] pointed that with an increase in the initial density the temperature of the products of detonation must fall, since a large part of the liberated chemical energy is here transferred to elastic energy of the products. This effect is also predicted by the quantitative calculations on the basis of the equation of state of Landau-Stanyukovich [73]. It is possible that the observed phenomena also serves as experimental confirmation of these assumptions.

For an answer to the question, in what manner does the formation of detonation of a compressed substance under the effect of a thermal explosion take place, it is necessary primarily to clarify the characteristics of the thermal explosion behind the shock wave. The theory of a thermal explosion ordinarily operates with quantitative characteristics of the process in the state of pre-explosion heating. A calculation of the parameters in the process of the explosion itself is practically inadmissible, especially, as a result of the indeterminacy of the activation energy, the specific heat value, the form of the equation of state of the condensed medium, etc. There is no need of such calculations in the majority of practical cases, since the time of the explosion itself turns out to be immeasurably less relative to the time of the induction period.

For the process of heat liberation behind the shock wave very short times are characteristic - millionths of a second. Under such conditions, when the problem of the limitingly small times for the occurrence of the chemical reaction becomes acute, the explosion time "proper" may be of the same order with the time of the induction period. It turns out that certain peculiarities of heat liberation under such conditions can be described by the very simple theory of adiabatic nonstationary thermal explosion, in producing the concept of a "degenerated" thermal explosion [74, 75].

The physical concept of "degeneration" consists in the fact that at the high initial speed of the chemical reaction there occurs the effect of "burn out" of the substance, since up to the moment of the explosion a considerable part of the substance is consumed, as a result of which the explosive effect becomes weakened. The achievement of such conditions is characterized by two parameters

$$\beta = \frac{RT_0}{E} \text{ and } \gamma = \frac{cHT_0^2}{QE}, \quad (35)$$

where T_0 is the initial temperature; E is the energy of activation; R is the gas constant; c is the specific heat; Q is the heat content.

When $\gamma \ll 1$ and $\beta \ll 1$ the thermal explosion is normal with induction period much greater than the time of explosion itself. If these conditions are not fulfilled, then the thermal explosion is degenerated. In this case it is difficult to speak of the induction period and of the time of the explosion itself, since the occurrence of the reaction in time does not possess the sharply expressed effect of self-acceleration, leading to the explosive liberation of energy with a delay. A rough estimate of the parameters β and γ for the conditions of shock initiation in nitromethane (pressure 80,000 atm, $T_0 \sim 1000^\circ\text{K}$ [60], $c = 0.3$ cal/g·deg, $E \sim 50$ kcal, $Q \sim 1$ kcal/g) produces $\gamma = 0.012$ and $\beta = 0.04$.

Since for a normal explosion the values of γ and β comprise 0.01-0.001 [75], from the estimates introduced it follows that under conditions of shock initiation of nitromethane the kinetics of the heat liberation are close to degeneration. The thermal explosion under actual conditions is accompanied by the expansion of the reaction product in the explosion stage of the process, which must lead to deviation from the adiabatic scheme of calculation to the side of still greater "degeneration."

It is obvious that with a certain degree of degeneration in the shock wave the hydrodynamic effect of the explosion behind its front can be weakened so much that a smooth pressure rise will not lead to the formation of detonation of the shock-compressed substance in the region between the shock front and the zone of self ignition.

Depending on the degree of degeneration one should apparently anticipate a certain connection between the time of the thermal explosion, which occurs with a certain delay, and the time of formation of detonation of the shock-compressed substance. These times in turn determine the size of the area at the section boundaries, where this transition process takes place.

A detailed picture of the formation of the ultrafast detonation cannot be observed in an experiment. However, in experiments with the reflection of light in nitromethane [70] it was discovered that the light reflection from the boundary limit disappears shortly before the occurrence of the luminescence of the ultrafast wave. In analogous phenomenon is observed in nitroglycerine (Fig. III).

Apparently, the loss of transparency of the liquid is caused by the start of the violent chemical reaction in the initial stages of the developing thermal explosion. The time interval from the start of darkening of the substance to the emergence of luminescence or the second wave corresponds to the time of its

formation under the effect of the thermal explosion. This phenomenon, testifying to the noticeable degree of degeneration of heat liberation behind the shock wave, is especially well expressed in tetranitromethane. It was established that with slight initiation delays in tetranitromethane there is generally observed the formation of preluminescence, corresponding to the second wave (Fig. 18). Experiments with the reflection of light indicate that the shock wave is nontransparent immediately after it passes into the substance (Fig. IV). At lower pressures and with significantly greater initiation delays the detonation of shock-compressed nitromethane is observed, but the duration of its luminescence is small, since it is formed at a significant distance from the boundary limit, and its travel time to the front is small.

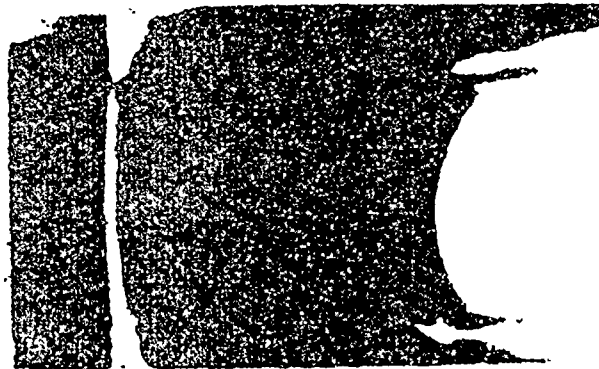
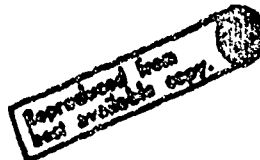


Fig. 18. Photostatic of the luminescence during initiation of tetranitromethane. 1 - Moment of entrance of the shock wave into the nitromethane; 2 - moment of formation of detonation in unperturbed liquid (luminescence of the second wave is absent); 3 - luminescence of normal detonation.



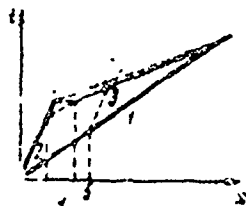


Fig. 19. Chaiken's space-time diagram with calculation of the final time of thermal explosion on the boundary surface.
 1 - Propagation of the initiating shock wave; 2 - movement of the boundary surface; 3 - propagation of detonation of a shock-compressed explosive according to the data of direct measurement of its speed; 4 - region of formation of detonation of a shock-compressed substance under the effect of an adiabatic thermal explosion on the liquid explosive - inert boundary interface; 5 - movement of a thin foil placed a certain distance from the boundary surface.

A good illustration of the presence of a region of formation of a second wave under the effect of the thermal explosion is the divergence of the directly measured ultrafast speeds with the calculation results according to Chaiken's scheme. Apparently, the method of end photoscanning can give correct information for the calculation of the speed of the second wave, if we exclude from the observations the region of formation of detonation of the compressed substance. This is being successfully achieved by placing bans of thin nontransparent foil a certain distance from the boundary limit (Fig. 19). Photoscanning of the process from the end of the charge is shown in Fig. V. From the known distance of the foil from the boundary and the time of passage of the second wave from the foil to the shock front it is not difficult to calculate the speed of the second wave. The result coincides with the direct measurements shown above.

The formation of detonation of a compressed substance behind the shock wave, as follows from the conducted experiments, must occur in those shock waves, in which there is "normal" kinetics of heat liberation. With given equations of state of the liquid explosives and intensity of the shock wave from the active charge, which determine the value of the initial temperature behind the shock front, the possibility of the formation of ultrafast speed will be reduced with the reduction of the heat content of the

explosive (for example, with its dilution by an inert solvent with similar dynamic properties). The approach to the degenerate case occurs as a result of the increase in the parameter γ . The same thing must take place with a significant increase in the amplitude of the shock wave (increase in δ and γ as a result of the increase in T_0).

An ultrafast wave may also be absent in the case where the reaction behind the shock wave is complex and the final stage of the process of heat liberation is for some reason drawn out. The achievement of such conditions with the aid of the above-cited qualitative considerations is naturally difficult to foresee. The detailed mechanism of the formation of detonation of a shock-compressed substance under the effect of thermal explosion requires additional investigation.

3. From the foregoing experiments it was observed that for each liquid explosive in the formulation of the experiments, shown in Fig. 1, there exists a certain pressure amplitude, lower than which detonation does not take place. Of interest is the clarification of the problem of how the limiting amplitude of the initiating shock wave is determined. If the shock wave is rectilinear (of infinite length), then on the assumption of the formal correspondence of the speed of the chemical reaction to Arrhenius' law with any amplitude of the parameters of the initiating shock wave ignition must take place. The single limitation here may be only the presence of such enormous delay times inadmissible for the technology of shock initiation, during which the phenomena of thermal conductivity can occur.

Under actual conditions it must always be a question of shock wave parameters falling in time. The speed of this fall is determined basically by the characteristic dispersion time of the products of the explosion of the active charge, which is proportional to its linear dimension. The amplitude of the parameters is determined by the pressure in the products on the

detonation front and by the equation of state of the loaded substance.

Thus, the limiting conditions for initiation of detonation are reduced to the problem of the adiabatic thermal explosion under conditions of the temperature falling in time with its fixed initial value. If the thermal explosion on the interface takes place, then detonation arises, and if it does not occur, then the substance does not detonate. With a strong degree of degeneration of heat liberation behind the shock wave, when an ultrafast wave after ignition is not formed, this criterion is unacceptable. However, as the experiment shows with the ordinary setup of experiments on shock initiation (see Fig. 9), within the boundary conditions of citation the detonation of the compressed substance always takes place.

Since the dependence of the delay of the appearance of detonation on the temperature in liquid explosives is very strong [60], it is clear from physical considerations that at any value of the initial temperature one may find such a rate of temperature drop with time that at any moment in time the delay of the explosion will exceed the substance's "own lifetime" in the shock-compressed state. This case corresponds to the separation of the thermal explosion, which under such conditions generally does not take place. More precisely the separation condition may be characterized thus: the separation of ignition takes place, if the rate of fall of the parameters of the shock wave as a result of the rarefaction wave from the side of the active charge is sufficient for the cooling arising in the process of adiabatic expansion of the compressed substance to be able to completely compensate for the self-heating of the medium as a result of the chemical reaction.

This consideration can also be illustrated by a rough calculation. The induction period τ is proportional to $\exp(E/RT)$. Hence

$$\frac{d\tau}{\tau} = -\frac{E}{RT^2} \cdot dT.$$

Let us assume that the temperature in the shock wave falls according to the exponential law

$$T = T_0 \exp(-\alpha t),$$

where α is a constant, determining the rate of fall of the temperature in the shock wave from its initial value T_0 , and t is time.

The condition of separation of ignition have the following form: $d\tau/dt > 1$. From a comparison of all these equations the conditions of separation may be represented as

$$\tau > \frac{1}{\alpha} \frac{RT_0}{E} = \text{const} \cdot \frac{RT_0}{E} \cdot \exp\left(-\frac{E}{RT_0}\right).$$

Hence it is clear that with large τ and correspondingly small T separation is achieved with a lower rate of fall of the temperature in time.

With the given geometry of the active system, determining the rate of fall of parameters of the initiating shock wave in time, there exists a certain value of the amplitude of these parameters, below which separation takes place. This effect also determines the threshold of sensitivity of the liquid explosive to shock initiation. With an increase in the parameters of the active charge the amplitude of the limiting pressure, initiating detonation in the liquid explosive, must be reduced (and the maximum possible delay of initiation is increased). It is important to note that in determining the separation conditions an initial chemical reaction rate is generally figured, which is determined by the

temperature of the shock compression and by the value of the activation energy. The heat content of the substance in the expression for the induction period is a secondary term [74]. Therefore, the sensitivity of the liquid explosive to shock initiation must be practically independent of the value of its heat content. The phenomenon of reaction separation during shock initiation not only determines the sensitivity limit of the explosive to shock initiation; it is also manifested in the picture of the formation of detonation above the limit.

Under actual conditions the initiating shock wave, as a result of the effect of lateral rarefaction waves on the detonation of the active charge, is somewhat convex. The attenuation of the front along the periphery of the charge occurs more quickly. Therefore, more favorable conditions for ignition are created along the axis of the charge. In proportion to the distance from the center of the charge in a radial direction delays in ignition increase, while in the peripheral segments combustion undergoes separation. As a result of this the nonaxial segments of the shock-compressed substance on the interface do not explode independently, rather they detonate under the effect of the ultrafast wave coming from the center.

Combustion behind the shock wave is a necessary, but insufficient condition for the excitation of detonation. If the heat content of the liquid explosive is so small that the pressure in the products of normal detonation turns out to be less than the limiting pressure in the shock wave, still capable of causing combustion, stationary detonation under the effect of detonation of the shock-compressed substance does not take place. This was experimentally discovered in mixtures of nitromethane with acetone, having a pulsating detonation front. An explanation of this effect requires the introduction of specific information on the structure of the pulsating detonation front and will be given below.

Also of interest is the question as to under what conditions will the shock wave with the ignition and with subsequent detonation of the compressed substance ensure the creation of stationary detonation, having a one-dimensional zone of chemical reaction. Such a formulation of the problem is naturally somewhat abstract, since the conditions of existence have until now not been investigated under the actual conditions of a one-dimensional detonation wave. In spite of the cited indeterminacy, it is apparent that for sufficiently powerful explosives inflammation of the substance behind the shock wave is a necessary and sufficient condition for the formation of detonation.

Summarizing the results on shock initiation, one must note the following. An examination of the nonstationary interaction of the front of a flat shock wave with the region of inflammation is the classical object of theoretical research. In the stationary version such a complex coincides with Zel'dovich's model for the front of a detonation wave. Under nonstationary conditions new phenomena have been discovered experimentally: the possibility of the formation of independent detonation of the shock-compressed medium, the tendency of combustion behind the shock wave to the separation effect, the possibility of degenerated regimes of heat liberation in the shock wave. It is to be expected that these phenomena greatly determine the variety of the nonstationary processes on the front of a stationary detonation wave.

§ 2. Initiation of Solid Explosives

Solid explosives (bulk, pressed, poured) in the majority of cases have significantly greater detonation sensitivity in comparison with homogeneous liquid explosives. The pressure in the shock wave, initiating the detonation, in a number of systems does not exceed 10,000 atm. Under such pressures the shock heating of the particles is insufficient to create conditions for quick occurrence of the reaction within the particles [59].

It is obvious that the high sensitivity of porous solid explosives is a direct consequence of the nonhomogeneity of the initial physical-mechanical structure. For example, trotyl, the chemical properties of which are maintained with the change in its aggregate state, is much more sensitive to a shock wave in the pressed form in comparison with a cast or molten form with identical initial density. Therefore, it is assumed that a decisive role in heat liberation behind the initiating shock wave in bulk and pressed charges is played by the focal mechanism of occurrence of the chemical reaction.

A shock wave, passing through the explosive with a certain initial structure, creates regions of local heating, in which ignition takes place. An additional pressure rise in the medium because of gas liberation at the foci increases the amplitude of the shock wave, which in turn leads to a further increase in the rate of heat liberation behind the front. To this time there is no one viewpoint on the mechanism of formation of reaction foci.

In works [55, 59, 76] an important role is contributed to adiabatic heating of gas inclusions, which can ignite the surrounding substance. The streams of reaction products, which are capable of penetrating into an uncompressed medium and of creating ignition foci during deceleration, can have a significant effect. Active centers of reaction can arise also because of the intense friction and the plastic flows during the breakdown of the initial structure of the substance by the shock wave [77]. Moreover, local heating must be created because of the microcumulative effects during a sudden closing of the pores in the front of the shock wave, because of the radiational heating of the thin layers of explosive by the radiation of an incandescent gas bubble [78], etc.

The propagation of reaction from the focus to the surrounding medium may occur in two ways: through the additional shock heating under the effect of a focal thermal explosion or through the combustion of particles from the surface. For detonation processes short times are characteristic, and wave processes, it would appear, have high probability. In work [79] for heterogeneous individual explosives there was shown the possibility of a hydrodynamic method of the formation and effect of "hot spots." However, in domestic literature until the present time [55, 59] preference has been given to the mechanism of the rapid burning of particles in a shock wave [72]. A shock wave, as will be shown below, can crumble particles through micron sizes, which in principle can successfully burn for short periods of time. Moreover, a witness of the fact that diffusion processes may participate in detonation conversion is the detonation of mixed explosives.

From the considerations on the possible mechanisms of formation of ignition foci follows the conclusion of the special role of the front of a shock wave for heat liberation in a porous explosive. In homogeneous systems the region of ignition behind the shock wave significantly exceeds the width of the front itself, which has an order of several angstroms [80]. In powders the characteristic times of crumbling and packing of the substance in the front may turn out to be of the same order as the times of ignition at the foci.

If the heat liberation in a wave, after the inflammation of the foci at the front, takes place as a result of shock perturbations, then the main part of the energy will be liberated in the direct vicinity of the front right up to the limiting pressures of the initiating shock wave. According to another mechanism the heat liberation should have a smoother character as a result of the gradual burning out of the substance from the foci, formed at the front.

In proportion to the propagation of the shock wave in a powder explosive the dynamic parameters at its front vary within wide limits from the initial pressure to values, corresponding to a detonation front. Here the substitution of the mechanism of formation of "hot spots" is permissible, since with the increase in parameters an ever greater role will be played by homogeneous shock heating. The reaction times on the front of a shock wave, which has a speed close to the speed of stationary detonation, becomes so small, that particularly strenuous requirements are imposed on the mechanism of transfer of energy from the foci by the heat conductivity and diffusion.

The literature contains almost no direct experimental data on the nature of focal heat liberation in a shock wave. To the present, however, rather a large amount of information has been collected on the macroscopic picture of the formation of detonation from a shock wave. In work [81] in experiments using a photorecorder, and also with the aid of ionization sensors it was established that in solid explosives the initiating shock wave after its passage into the substance begins to increase its speed. The gradual rise in speed is accomplished by the smooth transition to detonation. From this fact, that a shock wave is accelerated from its very start in contrast to liquid explosives, the authors of work [81] concluded that in solid explosives the reaction begins in the direct vicinity of the front of the shock wave in the defects and nonhomogeneities of the explosive.

Significantly more information on the structure of the hydrodynamic flows during acceleration of a shock wave is produced by observation of the profile of the mass velocity by the electromagnetic method. Experiments [82-84] detected a great variety in the picture of the flow behind the shock wave for charges made from trotyl of various structures (Fig. 20). Similar experiments were conducted with hexogene, tetranitromethylaniline and pentaerythritol tetranitrate. These experiments allow us to draw the important conclusion that the qualitative picture

of the transfer of the shock wave to detonation is unequivocally determined by the physical-mechanical structure of the substance.

For bulk explosives the presence of a falling pressure profile behind the front of the shock wave is characteristic, while the amplitude of the front rises continuously and relatively quickly. In a pressed explosive in proportion to the development of the process behind the front of the wave there arises an additional increase in the mass velocity, testifying to the pressure rise at a certain distance behind the front. Such a character of focal heat liberation in a pressed explosive can create the effect of overcompression of detonation at the moment of its formation similar to the case examined above with the formation of detonation in tetranitromethane (see Fig. 18). One can assume that such a phenomenon took place in the experiments of Jacob [77]. The picture of the transition process in poured trotyl was characterized by the constancy of the mass velocity in the vicinity of the front of the shock wave in the initial stages of its development up to detonation.

The character of the mass velocity profiles behind the front of a shock wave were substances different in their initial physical structure in the region directly preceding the formation of detonation becomes identical. In this region there is noted a sharp rise in the parameters at the front. Figure 21 shows graphs of the change in pressure on the front of the shock waves for trotyl, obtained on the bases of measurements of wave and mass velocities in the depth of the charge. In the region of rapid increase of the parameters at the front in all systems in the oscillograms of mass velocity (see Fig. 20) there is observed a drop in the mass velocity directly behind the front of the shock wave. The occurrence of a peak is observed, apparently a chemical peak of the hydrodynamic model of normal detonation. With a further smooth increase in the parameters of the initiating wave right up to values corresponding to stationary detonation the form of the profile is almost unchanged. The parameters at the

front of the shock wave reach values corresponding to the parameters on the shock front of normal detonation, earlier than the reaction zone characteristic for normal detonation is formed.

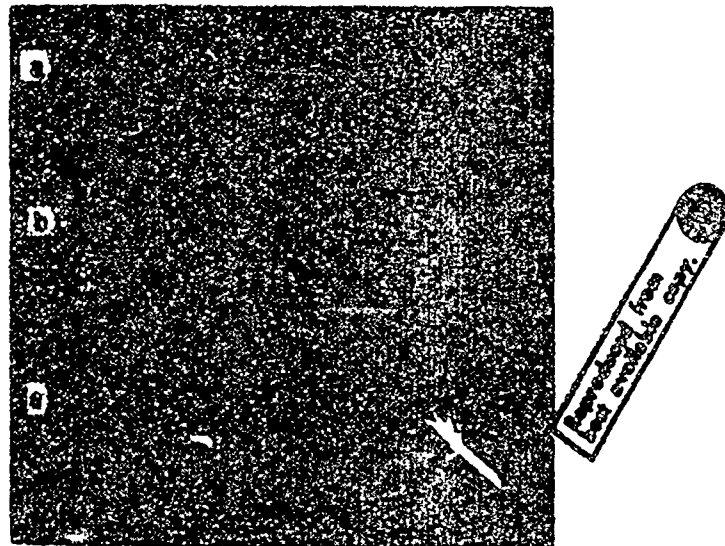


Fig. 20. Oscillograms of the profile of the flow of substance behind the front of the initiating shock wave in trotyl of various structures: a - Cast small-crystal trotyl ($\rho_0 = 1.62 \text{ g/cm}^3$); b - pressed trotyl ($\rho_0 = 1.59 \text{ g/cm}^3$); c - bulk trotyl ($\rho_0 = 1.0 \text{ g/cm}^3$), grain size of 0.5 mm. Numbers under the oscillograms - distance of the sensor from the boundary (in cm). Distance between the time marks on the oscillograms correspond to 2 μs .

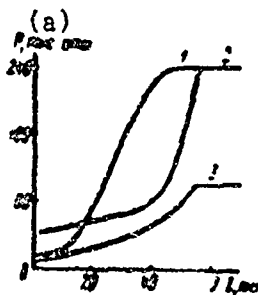


Fig. 21. Pressure at the front of shock waves, causing detonation of pressed (1), cast (2), and bulk (3) trotyl depending on the distance traveled by the waves. KEY: (a) P, thousands of atmospheres.

In the literature there have many discussions of the problem of the possibility of the emergence of retonation waves during the formation of detonation in solid explosives. In particular, these waves were observed during the photorecording of the lateral dispersion of reaction products in the region of the initiating shock wave [53, 54]. However, numerous experiments using the electromagnetic method clarified that along the axis of the charge no retonation waves are observed. The presence of a retonation wave should have been manifested on the oscillograms of the mass velocity in the form of a sharp negative signal. At the same time retonation waves are actually observed with optical observation of the processes of transition from the lateral surface of the charge in pressed trotyl. A comparison of these results forces us to conclude that in this case a special detonation process takes place in the lateral layers of the charge, subjected to the effect of the lateral rarefaction wave. It is obvious that this phenomenon has no direct relationship to the mechanism of initiation of detonation of solid explosives, and its similarity with the mechanism of the emergence of retonation in gas media during the transition of combustion to detonation has no basis.

Observation of the process of initiation of detonation by the optical method in a solid opaque substance from a lateral surface of the charge generally cannot be a sufficiently reliable method of investigation. Thus, for example, as a result of the lateral loading the front of the shock wave is distorted. After the formation of detonation inside the charge its front is also convex. When this wave emerges on the lateral surface, there is recorded an excess in the rate of propagation of luminescence on the lateral surface, which could mistakenly be taken as a real excess at the moment of formation of detonation [52, 54].

Let us stop briefly on the limits of excitation of detonation of solid explosives by a shock wave. An important peculiarity

of the excitation of detonation in solid explosives is the fact that the distance, at which the shock wave becomes detonation, can be very significant, right up to several diameters of the initiated charge. Under such conditions the lateral loading in this charge exerts a significant influence on the transition process and to a considerable degree masks the effect of the active charge, which has a decisive effect on the sensitivity of liquid explosives. Hence it follows that the length of the transition region at the limit of excitation can depend on the diameter of the passive charge and the presence of a shell. A characteristic part of the transition processes in solid explosives is the falling profile of the mass velocity behind the shock wave front, the velocity of which is still far from the velocity of normal detonation. This testifies to the fact that heat liberation in the shock wave occurs close to the front and is not complete.

Thus, if for liquid explosives the criterion of transition of a shock wave into detonation is a homogeneous thermal explosion, which can also occur with a shock wave attenuating in amplitude, then in solid nonhomogeneous explosives the criterion for the formation of detonation is the nonattenuation of the initiating shock wave. This condition is ensured in the case where the pressure rise as a result of the focal heat liberation behind the front compensates for the pressure drop as a result of the rarefaction of the substance behind the shock front. With a given physical-chemical structure of the charge the effect of the activity of the foci must depend on the heat content of the explosive. Therefore, heat content is a basic parameter of sensitivity of solid explosives (in contrast to liquid explosives), namely, the greater the heat content of the substance, the higher its sensitivity. On the other hand, kinetic properties, determine the sensitivity of liquid explosives (explosion effects), during focal heat liberation deviate to a second place and for the sensitivity of nonhomogeneous explosives they play no decisive role. The problem of the connection of the rate of focal heat

liberation in a shock wave with a concrete representation of the mechanism of the formation, multiplication and dissolution of the "hot spots" must be the subject of further study.

Admitting the results to the consideration of the problem of shock initiation of detonation in condensed explosives, one should conclude that in phenomena of detonation formation in homogeneous and heterogeneous explosives, it is difficult to find general traits, which would produce a basis for the construction of a single theoretical model of the transition processes. Therefore, one can assume as unjustified the attempts to construct a universal one-dimensional model of the transition of a shock wave into detonation [65, 85-88], in which both results - the gradual increase in the speed and its excess - can be obtained by varying the formal kinetics. Such a formal system of generalization of the experimental results cannot produce solid physical representations of the phenomenon, since with its use one cannot take into account the effects of the initial structure of the substance on the picture of the transition, nor can one foresee the possibility of incomplete liberation behind the shock front.

CHAPTER III

THE MECHANISM OF THE PROPAGATION OF DETONATION IN LIQUID EXPLOSIVES

The process of liberation of chemical energy at the front of a detonation wave inhomogeneous condensed media is a most inaccessible region for experimental investigation. In particular, due to the exclusive smallness of the times of detonation conversion and the destruction action of detonation to the shell many of the optical methods of diagnostics (schlieren method, photo scanning of the occurrences behind the front, spectroscopic measurement of the temperature profile in the detonation products and so forth) are inapplicable.

Until recently information on the zone of chemical reaction on the front of detonation in liquid explosives was almost completely lacking. For a long time it was suggested [23, 55, 59] that the reaction mechanism in the detonation of liquid explosives did not differ from the reaction mechanism in gaseous detonation and corresponded to the one-dimensional model of Zel'dovich. Such a possibility was confirmed by calculations of shock heating in a condensed medium [89]. In conformance with this, the problem of building a quantitative theory of the detonation front was reduced to the clarification of the kinetics of the chemical reactions for complex organic molecules under conditions of very high pressures, to the consideration of the possibility of changing the form of the equation of state in the process of heat liberation, to the calculation of the distribution of liberated chemical energy into

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elastic and thermal portion, and to an analysis of the regularities of the expansion of the reacting condensed medium and so forth. After the solution of these problems we would succeed in calculating the pressure profile in the zone of chemical reaction.

The discovery of the pulsating nature of the detonation front in these mixtures far from the boundary [90, 91] led to a new formulation of the problem of the mechanism of detonation even for a homogeneous condensed medium. Notably, since with the simplest form of kinetics of the chemical reaction ignition behind the shock wave is accompanied by complex nonstationary processes, the study of these hydrodynamic phenomena on the front of the wave acquire primary importance, inasmuch as it is precisely they that determine the structure of the detonation front and its limits of propagation.

The kinetic problem in such a formulation amounts to the determination of the possibility of the existence of an induction period for ignition behind the shock front and to the calculation of the dependence of its value on the initial temperature. These data are at least sufficient, according to the existing theory [41, 42, 90], to answer the question, whether the zone of chemical reaction on the front of detonation is pulsating or one-dimensional.

The first information on the zone of chemical reaction in liquid explosives was obtained after it was successful in greatly "stretching" in time the process of heat liberation on the front of the dilution of certain liquid explosives with an inert liquid. The direct recording of the luminescence of the front of the detonation of a transparent charge (Fig. 22) successfully demonstrated the clearly expressed pulsating character of the zone of chemical reaction (Fig. VI). It turned out that the pulsating character is also observed with the dilution of nitroglycerin with methyl alcohol, glyceride alcohol nitrite with acetone and so forth. A surprising similarity was noted here between the observed picture of the pulsations on the front with the phenomena taking place in

gaseous detonation [91]. Hence it follows that the specifics of heat liberation in a condensed medium do not lead to significant peculiarities in the process of propagation of detonation, and the theory of the phenomenon for liquid explosives and gases must be common for both to a significant degree.

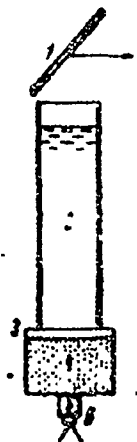


Fig. 22. Formulation of the experiment for observation of luminescence of the detonation front in a liquid explosive. 1 - mirror; 2 - liquid explosive in a metal tube; 3 - plate made from plexiglass; 4 - explosive "lens," creating a flat shock wave; 5 - booster charge; 6 - capsule.

The recording of the transverse pulsations on the front using head-on photo scanning is possible only close to the limits of detonation propagation, in mixtures with relatively low heat content. With the enrichment (an increase in the heat content) of the mixture the size of the inhomogeneities, i.e., the characteristic size of the grid on the photo scan of the luminescence of the detonation front, is abruptly reduced and in mixtures, far from the limit, becomes unsolvable photochronographically. In connection with this, doubts may arise as to the existence of a pulsating zone of detonation far from the limits. It can also be assumed that transverse perturbations on the front arise during shock initiation as a result of the roughness of the initiating shock wave, created by the active charge through the inert boundary with an insufficiently polished surface.

The experiment with light reflection gives an unambiguous answer to both problems. The presence of transverse perturbations on the front of detonation must lead to roughness of the surface of the leading shock front of detonation. Light reflection from such

a "hilly" surface must bear a nonregular character in contrast to the regular light reflection from an inert shock wave, which leads to a mirror reflection of the aperture of the light source on its surface [68]. The irregular character of the reflection is manifested in the blurring of the edges of the "image" of the aperture of the explosive light source.

The result of the experiment with light reflection in initiated nitromethane is shown in Fig. VII. The scheme of conducting the experiment was given in Fig. 13. Detonation under the conditions of this experiment was propagated far from the limits (the size of the charge was much greater than the limit), but the image of the aperture of the light source, taken in the form of a film, was obtained blurred on its front, which bears witness to the roughness of the detonation front. At the same time the initiating shock wave reflects light regularly and, consequently, is smooth. Therefore, the method of initiation is not the reason for the appearance of a pulsating detonation front. It is interesting to note that the pulsating rough detonation wave is formed from a smooth initiating shock wave practically instantaneous without the passing over of detonation which is overcompressed at the initial moment to a regime of a stationary one-dimensional wave with the subsequent restructuring of the one-dimensional "classical" complex to the pulsating zone of chemical reaction. Conversely, one would have to observe a change in the regular reflection of light to a nonregular even under conditions of normal propagation. A similar phenomenon is observed in weak mixtures (see Fig. VI), in which the transverse pulsations are directly observable on the head-on photograph. In proportion to the transition from overcompression the size of the inhomogeneities is increased up to a value which corresponds to normal detonation.

Since the transverse pulsations on the detonation front in liquid explosives are always generated in an overcompressed regime, it is obvious that the application of Shchelkin's theory [90] on the mechanism of the formation of pulsations from a one-dimensional

stationary Zel'dovich complex is in this case impossible, at least without additional substantiation. The formation of a pulsating zone in a nonstationary process (the emergence of a wave from over-compression) leads to the conclusion that the analysis of the problem should be based on experiments on the observation of the nonstationary interaction of a flat shock wave with the ignition zone, a particular instance of which is the occurrence of shock initiation of detonation.

The basic questions in examining the mechanism of detonation of liquid explosives are the following:

1. What kind of mechanism exist for the formation of the pulsating zone?
2. Does there exist in homogeneous condensed media a stationary detonation wave with a smooth shock front?
3. Which processes in the pulsating zone accomplish complete heat liberation?
4. To what do the pulsations lead: to an increase in the total time of heat liberation on the front or to its decrease?
5. Do the pulsations on the detonation front amount to a "thin structure" of a one-dimensional detonation complex?
6. Which phenomena in the pulsating front determine the nonstationary restructuring of the wave (emergence from over-compression, spherical detonation etc)?
7. What is the nature of the limits of propagation of a pulsating detonation wave?

§ 1. The Formation of Three-Dimensional Detonation Configurations Behind a Plane Shock Wave

The picture of the formation of detonation in liquid explosives during shock initiation has an unusual character, if as the initiating explosive we take a mixture with a low heat content (nitromethane, strongly diluted acetone). In this case in setting up the experiment, shown in Fig. 9, as usual (see Fig. 10), the detonation of shock-compressed substance (Fig. VIII) begins in the central region of the charge. This detonation is propagated to the peripheral segments of the shock wave, in which self-ignition has undergone separation. In a head-on photo scan this detonation is recorded in the form of a narrow band of weak luminescence. The detonation conversion in an unperturbed liquid takes place in a local region of ignition on the shock front, recording the form of a narrow, relatively bright illuminated band 3.

The totality of the initiating shock wave, the transverse detonation wave and the segment of the local inflammation on the shock front close to the transverse detonation comprises the three-dimensional detonation configuration. A cross section of such a configuration is depicted diagrammatically in Fig. 23.

A similar picture is observed, if instead of the emergence of detonation of the compressed substance as a result of self-ignition this detonation is caused artificially using a miniature initiator, placed on the interface. A photo scan of the process in such an experiment is given in Fig. IX. The layout of the experiment with an artificial initiator in individual cases is preferable, since it insures better repeatability of the experiments and allows a pressure reduction in the shock wave below the excitation threshold, so that self-ignition is not a hindrance to the observations. The region of bright luminescence 4 has a "fine structure," which is clearly destroyed in certain experiments (Fig. IXb), this region consists of a series of finer configurations, recorded in the form of narrow bright lines, situated one behind the

other. In proportion to the distance away from the point of intersection of the transverse wave and the shock wave the distance between neighboring configurations, which compose the "fine structure," increases. The regularity of the succession of these individual configurations one behind the other frequently breaks down as a result of the occurrence of microconfigurations, which follow in the opposite direction.



Fig. 23. Diagram of the propagation of three-dimensional detonation configurations. 1 - initiating shock wave; 2 - detonation of a shock-compressed mixture; 3 - segment of inflammation on the shock front; 4 - re-formed shock wave without inflammation; 5 - detonation products.

The characteristic size of the inhomogeneities in region 4 is less than with normal detonation of the same mixture (see Fig. 27). Hence it follows that this section of the three-dimensional detonation complex is overcompressed. It is apparent that over-compression in region 4 is created by the pressure in the detonation products of the precompressed liquid.

Let us turn once again to Fig. 23. Behind shock wave 4 inflammation is absent, and its front is separated from the detonation products. Since no heat liberation occurs in this region, the pressure behind this shock wave approaches the initial pressure of the initiating shock wave, which is fixed by the parameters of the active charge. In the course of the induction period a new adiabatic flash may take place in this region, leading to the formation of a new triple configuration, extended following the first one. With ideally selected conditions the picture of the detonation transformation should look like a "fir tree" on the photo scan (Fig. 24). Under actual conditions, however, the

regularity of formation of the configuration is greatly distorted. A slight variation in the amplitude of the initiating shock wave leads to a multiplication of the configurations on the surface of the shock front, or to their disappearance altogether.

With artificial excitation of several configurations using miniature initiators it is possible to observe the character of their interaction during collision. Figure X shows how the formed triple configurations can pass through one another without noticeable distortion or, on the other hand, disappear during collision. The interaction scheme in the first case is shown in Fig. 25. The phenomenon of the formation of triple-shock configurations under the effect of a smooth shock wave, undoubtedly, must have a direct relationship to the nature of the transverse pulsations on the front of the stationary detonation. The problem consist of deriving from the observations of large-scale configurations, having a fine structure, a model of the elementary triple configuration, using which it is possible to construct a scheme of the pulsating front of a stationary detonation wave, and also of explaining all the details of the model experiments.



Fig. 24. Suggested form of the photo scan of model experiments under idealized conditions.

Observation of the model configurations allows us to assume that the elementary triple configurations have the same basic signs, namely: the presence of an overcompressed detonation wave, recorded on the photo scan as a clear line of luminescence, the presence of a transverse detonation wave and, finally, the existence of an area of separation of the front of the shock wave from the detonation products. Figure 26 shows an approximate scheme of the

triple configuration, which in simplified form repeats the scheme of the head of spinning detonation [91]. In the compressed explosives the transverse detonation front is propagated. The products of its detonation, which have great pressure, as a result of lateral expansion initiate the clearly luminescent overcompressed detonation front in the undisturbed explosive 2.

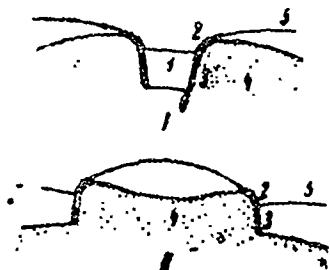


Fig. 25. Schematic depiction of the sequence of phenomena in the collision of triple configurations. I - moment before collision; II - after collision; 1 - initiating shock wave; 2 - overcompressed segment of the detonation complex; 3 - transverse detonation of shock-compressed explosive; 4 - region of detonation products; 5 - shock waves without inflammation; 6 - surface of the boundary of the active charge.

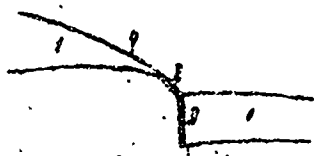


Fig. 26. Scheme of the triple configuration. 1 - areas without ignition; 2 - segment of overcompressed detonation; 3 - detonation of shock-compressed explosive; 4 - site of separation of ignition behind the shock front.

In the model of elementary triple configuration we can, without loss for the ideal aspect of the problem, assume one-dimensionality of the zone of chemical reaction in the overcompressed segment of the configuration. This problem will be analyzed in more detail later. In proportion to the distance away from the triple point the pressure in the area of overcompression as a result of the lateral expansion of the detonation products of the compressed substance quickly falls. As a result, the delay in the ignition in the region of the zone of chemical reaction of overcompressed detonation very rapidly increases. At a certain distance from the triple point the separation of ignition takes place behind the oblique detonated wave. This leads to the separation of the front of the shock wave from the detonation products, and the pressure in

it asymptotically approach the pressure in the initial initiating shock wave, which is fixed by the parameters of the active charge.

It should be noted that ignition separation at point 4 (see Fig. 26), taking place during compensation of chemical self-heating of the substance by the cooling as a result of its adiabatic expansion, has certain peculiarities in comparison with the separation behind the initiating shock wave. In this case the separation is accompanied by the decay of the double discontinuity (the front of the shock wave - the plane of self-ignition), corresponding to the overcompressed one-dimensional detonation complex. Qualitative considerations on the dispersing one-dimensional double discontinuities are expounded in works [41, 90, 92], although the case of separation of ignition is not examined in them. It should be noted that the transverse detonation wave is also one-dimensional. This follows directly from observation of the regular reflection of light from the front of detonation of a shock-compressed mixture of nitromethane with acetone in a 75:25 ratio.

Special experiments with weak artificial initiators, which were incapable of causing detonation of a shock-compressed substance, showed that another type of configuration is also possible, differing from that described above by the fact that instead of a detonation front in the compressed explosive a shock front is propagated. Inflammation in such a configuration proceeds only in the region of Section 2 (see Fig. 26). These configurations are distinguished by their quick attenuation after formation.

§ 2. A Model of a Pulsating Detonation Wave

The above suggested model of triple configuration qualitatively coincides with the model of transverse pulsations on the detonation front in gaseous mixtures [91]. It should be noted that in analyzing the nature of the transverse pulsations on the front in gaseous detonation special attention was concentrated on the examination of the scheme of the flows in the vicinity of the

triple point, i.e., in the head of the configuration. Calculation, as well as a detailed observation of the flows in this region for liquid explosives are inadmissible. However, as well as clear from what follows, a detailed investigation of the structure of the head of the configuration is not necessary, since the basic properties of the detonation wave are determined by the conditions of ignition in region 1 (see Fig. 26). From the problems of the structure of the flows in the region of the triple point there is only one principle problem - whether the transverse wave is a detonation wave?

For the region of configuration 1 of greatest significance is the question of whether the parameters of this shock wave correspond to the one-dimensional Zel'dovich complex, as was suggested in the model for spinning detonation [23, 90]. Let us examine this question, proceeding from the suggested model of triple configuration. Behind the front of the shock wave after the region of separation of the shock front from the products of detonation there is no continuous ignition, characteristic for a one-dimensional detonation complex. Consequently, the pressure jump ("the chemical peak"), created by the continuous ignition behind the shock front in this region, is also absent. The parameters of the shock wave are determined by the pressure in the adjoining detonation products, which play the role of a "plunger." Since there is no pressure jump on the interface of the detonation products and the shock-compressed explosive, the formation of transverse perturbations according to the theory given in work [90] cannot take place.

The emergence of new configurations should take place as a result of the adiabatic thermal explosion in the vicinity of the interface of the shock-compressed explosive and detonation products. Hence the transverse size of the "inhomogeneities," which is determined by the products of the rate of distribution of the configurations for the time of delay of the adiabatic flash has no definite connection with the width, corresponding to the model of the one-dimensional zone of chemical reaction.

The transfer of the model of triple configurations to the detonation front requires certain additional considerations. The recording of the pulsating front in the form of a grid of clearly illuminated lines (see Fig. VI) testifies to the fact that self-ignition in the zone of chemical reaction of a stationary detonation wave does not occur on the entire surface of the detonation front. In the regions between the illuminated lines there is no continuous inflammation behind the leading shock front. This substance is burned by the transverse triple configurations, the overcompressed segments of which also produce luminescence in the form of a bright line.

The sizes of the inhomogeneities on the front of the stationary wave, which can be observed in the experiments (Fig. 27), are not large. However, in individual photo scans one can observe, among the clear lines, narrow bands with weaker luminescence corresponding to a transverse wave. This gives us the basis for assuming that the configurations on the detonation front correspond to a model with a reaction transverse wave. Conversely (with a transverse wave without reaction), one is at a loss to explain in what manner on the pulsating detonation front total heat liberation can exist.



Fig. 27. Dependence of the size of the inhomogeneities on the front on the volumetric concentration of acetone q in a mixture with nitromethane. Conditions of conducting the experiments: width of the steel shells was 3 mm, $d = 62$ mm, $T_0 = 8^\circ\text{C}$.

The construction of a model of the front using configurations of the first type leads to a structure of the chemical reaction zone, which qualitatively satisfies the experimental observations of gaseous detonation [91, 93]. However, the question of how the kinetics of heat liberation in Section 1 (see Fig. 26) of triple configuration, which we will call "weak," determines the basic properties of the detonation wave, remains open.

The self-sustaining regime of propagation of detonation with configurations of the first type may be accomplished in several ways. The simplest model of the detonation mechanism, which differs most from the one-dimensional theory, consist in the assumption of a total analogy of the phenomena during shock initiation and on the front of the stationary wave. We assume, just as before, that the detonation products play the role of a "plunger," determining the pressure in the weak segments of the triple configurations. The delay in ignition in the "weak" segments is determined by the pressure in the adjoining detonation products and, in turn, assigns the characteristic size of the triple configurations.

We can assume that on the front of the stationary detonation wave there occurs a continuous shock initiation of triple configurations because of the series of adiabatic flashes in the weak segments on the wave front. In this case we cannot avoid the assertion that the triple configurations are not stationary. After formation they must attenuate during the course of the travel time between collisions. A different assumption on the mechanism of the pulsating method of propagation of detonation is the fact that the configurations, formed during the transfer of the wave to a stationary regime, are maintained during collision as a result of their penetration through one another.

The characteristic size of the configurations unequivocally is determined by the delay of the adiabatic flash in the weak segments. The "regulation" of the size takes place in the following way. If because of some random reasons the distance between the configurations is increased greater than the normal dimension, the "lifetime" of the substance in the weak segments will exceed the delay in self-ignition in this region, which will also occur, having formed a new configuration. It is obvious that in "instantaneous" photo of the front structure does not allow us to establish just which mechanism insures a self-sustaining pulsating detonation, since the structure of the front in both instances should have an identical form.

A greater degree of determinacy may be introduced to this problem by observation of the pulsating detonation wave under nonstationary conditions, which will be examined below. For the present we can be limited by the assumption that the mechanism of maintenance of a pulsating zone is a combination mechanism.

Since we are resting on the analogy of the process of propagation of detonation with phenomena during shock initiation, we can assume that in the weak segments of the configurations under nonstationary regimes of detonation the phenomenon of ignition separation can be observed. In this case the above examined mechanism of the formation of new configurations will be "turned off." As was already noted, a separation in a region of an over-compressed oblique detonation wave occurs according to a somewhat special scheme: by the dissociation of the double discontinuity. The reason for it is the expansion of the detonation products, which have a limited volume, behind the transverse wave. In the region of weak segments of configurations 1 (see Fig. 26), if the charge were of infinite dimensions, separation phenomena would be impossible, since the continuous replenishment of configurations which disappear for some reasons would be insured.

§ 3. Separation Phenomena in Overcompressed and Spherical Detonation

Separation phenomena in weak sections of a pulsating front of detonation should be observed, if the rarefaction wave, entering into them from the side of the detonation products, compensates for the chemical self-heating of the medium. The rate of fall of the parameters behind the front of the shock wave in the "weak" sections of configurations for nonstationary regimes should be determined by the time of dissipation of the detonation products, which is determined by the dimensions of the charge.

Intense rarefaction in the weak sections may be created during excitation of detonation in a lean mixture by a short powerful charge. In this case the wave quickly passes from overcompression, and the rate of fall of the parameters in the weak sections on the front is especially large. Figure XI shows a photo scan of the process of initiation of detonation in a mixture of nitromethane with acetone in a ratio of 65:35 by a short powerful charge made from hexogene (a charge diameter of 100 mm, a height of 20 mm) according to the scheme shown in Fig. 26. It was discovered that in proportion to the transfer from overcompression of detonation the size of the inhomogeneities in its front quickly increase. Therefore almost simultaneously along the entire cross section of the charge detonation ignition disappears, and detonation ceases. The increase in the size of the inhomogeneities during the passage of the wave from overcompression testifies to the fact that the pulsating zone is capable of quickly restructuring itself according to the change in the parameters of the wave.

The enlargement of the inhomogeneities is possible only if the "excess" inhomogeneities disappear in proportion to the pressure drop in the detonation products. They can disappear for various reasons. For example, during collision or by the merging of neighboring configurations, propagated to one side, because of a random difference in speeds. They can also attenuate right up to collision.

Thus, the triple-shock configurations on the front are incapable of independent existence for a prolonged time period. Hence it follows on the front of pulsating detonation continuous replenishment of the configurations as a result of adiabatic flashes has to play an important role. In proportion to the transfer from overcompression at a certain moment in time in the weak sections conditions of ignition separation are achieved. New configurations are not formed, and the "old" continue to burn the substance for a while. Their quantity quickly diminishes and, finally, they attenuate completely. Detonation ceases.



Fig. 28.

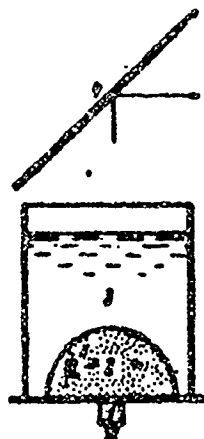


Fig. 29.

Fig. 28. Diagram of the experiment for observing the phenomenon of separation of detonation during the rapid passage of the wave from overcompression. 1 - explosive "lens"; 2 - active charge made up of hexogene (density of 1.78 g/cm^3); 3 - container with liquid explosive; 4 - mirror.

Fig. 29. Diagram of the experiments for exciting spherical detonation. 1 - booster charge; 2 - active charge made from a mixture of trotyl with hexogene with a density of 1.68 g/cm^3 ; 3 - container with liquid explosive; 4 - mirror.

A similar phenomenon is observed during the perturbation of detonation by a semispherical charge (Fig 29). With spherical detonation even in a quasi-stationary regime of its propagation separation conditions in weak sections of the front can be achieved because of the divergence of the flow behind the front of the convex shock wave. Figure XII presents a photo scan of the process of propagation of semispherical detonation, in which the phenomenon of separation of ignition on the front with the subsequent dissociation of detonation is also observable. In this experiment the initiating charge is also sufficiently powerful, and the detonation on the initial segments is overcompressed. With a small radius

of curvature of the front of the wave the conditions for separation, with a fixed pressure in the detonation products, are especially favorable. Therefore, it is impossible to create spherical detonation, which, not being overcompressed at the initial moment, would be capable of then undergoing separation.

The parameters which determine the achievement of separation effect in spherical detonation for a liquid explosive with fixed kinetic properties are: the power of the active charge, its diameter and the heat content of the investigated mixture. With variations in these parameters we succeeded in observing the following interesting phenomenon. With fixed parameters of the active charge, in proportion to the enrichment of the mixture, the moment of the onset of separation of detonation of the mixture moves further and further away from the start of shock loading. Correspondingly, the radius of the detonation wave in the mixture, at which separation proceeds, increases more and more. Finally, in a mixture of a certain concentration spherical detonation disperses with a constant size of the inhomogeneities on the front. A significant peculiarity of the transition process consist in the sudden transformation of the spherical detonation, propagating in a normal regime, wherein the size of the inhomogeneities in the stationary wave are less than it was immediately before the formation of the stationary regime, i.e., the size of the inhomogeneities passes through a maximum (Fig. XIII). These facts are fully explainable on the basis of the assumed model of the front.

The constancy of the size of the inhomogeneities on the front of a spherical detonation, propagating in a normal regime, despite the continuously growing surface of the detonation front, is explainable very simply. The pressure in the weak sections of the front is determined by the pressure in the adjoining detonation products, which is constant in a stationary wave. This pressure unambiguously determines the delay in the adiabatic ignition in the weak sections and, consequently, the distance between the neighboring configurations. With an increase in the distance

between the configurations on the front of a spherical detonation greater than the size thus assigned there takes place between them an additional adiabatic flash, which forms a new configuration. This mechanism also maintains the average size of the inhomogeneities on the front constant.

The extension of the onset of separation in relatively enriched mixtures is explained by the fact that for one and the same active charge the degree of overcompression in them is less, and the process of transfer from overcompression is smoother.

The observable fact of the sudden formation of a normal spherical detonation can be explained in the following way. In proportion to the transition of spherical detonation from overcompression at some moment in time in the weak sections of the front separation took place. However, the detonation conversion on the front was continued for some time by the maintained configurations, which gradually brought out of order, while those remaining as a result of the increase in the "length of travel" were enlarged. As a result of this process, the volume of the products of spherical detonation continue to increase, and the radius of the wave continue to grow. The divergence in the flow in weak sections of the front continued to reduce, since at a certain moment the separation conditions for the adiabatic ignition in them are overcome. From this moment the mechanism of the formation of new configurations "is switched on" and detonation disperses with a constant size of the inhomogeneities on the front. Naturally, this size is less than the size of the pulsations on the front of the detonation wave attenuating before this. Thus, experimental observation of the nonstationary restructuring of the wave is well described by the proposed model of the pulsating front and, in turn, gives additional information for its perfection.

As follows from the classical proof of the selection rule, in an overcompressed regime the rarefaction wave from the side of the detonation products penetrates the zone of chemical reaction

and causes an attenuation of the amplitude of the front of the detonation wave. As a result, the parameters of the detonation wave fall to values which correspond to the Chapman-Jouguet tangency rule. Nothing can be said about the possibility of the separation effect during such a transition and of the "jump" of the detonation through a normal regime right up to total attenuation. This is natural, since in the classical theory the detonation front is identified with the separation surface of the initial explosive and of the detonation product.

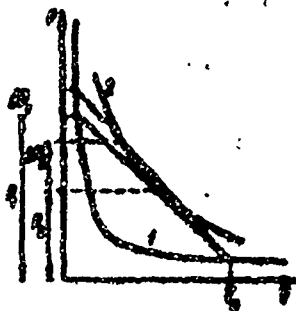


Fig. 30. Explaining the effect of over-compression on the parameters of the shock wave on the detonation front in a one-dimensional model and in a pulsating model. 1 - shock adiabat curve of a liquid explosive; 2 - detonation adiabat curve; P_2 - pressure in the products of normal detonation; ΔP_2 - pressure jump in the weak sections during overcompression; P_1 - pressure on the shock front of one-dimensional detonation in a normal regime of its propagation; ΔP_1 - pressure jump on the shock front of one-dimensional detonation during overcompression; V_0 - initial specific volume of the liquid explosive.

It is obvious that the model of the detonation wave with a one-dimensional zone of chemical reaction, in which the induction period occupies the main time, is also capable of separation phenomena. However, one should assume that the influence of the rarefaction wave from behind on the pulsating zone must be significantly stronger than on a one-dimensional zone. Qualitatively these considerations can be illustrated with graphs (Fig. 30). During the transition from overcompression for a one-dimensional wave model the relative drop in the parameters on the detonation shock front will correspond to $\Delta P_1/P_1$. In a pulsating detonation the kinetic properties of the chemical reaction zone are determined by the weak sections of the triple configurations, the pressure in the weak sections is equal to the pressure in the detonation products.

corresponding to the detonation adiabatic curve. The effect of the transition from overcompression on the weak segments of the pulsating zone will be an incomparably stronger $\Delta P_2/P_2$ than on the front of one-dimensional detonation.

§ 4. Comparison of Pulsating and One-Dimensional Models of a Detonation Front

In conformance with the one-dimensional theory of Zel'dovich a smooth shock front of a detonation wave has a speed equal to that of the detonation. The heat liberation taking place behind this wave leads to an increase in the flow velocity behind the front, and also to a reduction in the pressure and density in the medium. The dependence of the flow parameters on time is unambiguously determined by the kinetics of the heat liberation in the chemical reaction zone. If we exclude time from the corresponding equations, then the flow velocity, density and pressure are interrelated elementary corelationships of the conditions of conservation on the jump.

Experiments to uncover the one-dimensional chemical reaction zone on the front of a gaseous detonation were most frequently reduced to attempts at recording the "chemical peak" on the detonation front, i.e., discovering the region of increased pressures [94]. The clarification of the region of increased density was also carried out by the method of absorption of soft X-rays [95]. The discovery of the "chemical peak" in detonation of condensed explosives is based on the measurement of the increased speed of the substance on the front of the wave by an electromagnetic method or of the increased pressure by the split-off method [71, 96].

It should be noted that the pressure, density and speed of the substance in the chemical reaction zone, which has a nonunivariate structure, are interrelated by simple relationships only if the characteristic dimensions of the transverse perturbations are significantly less than the total width of the chemical reaction

zone. In this case averaging of the parameters of the flow is possible in the planes parallel to the detonation front. Heat liberation in this case occurs in the first approximation along Mikhel'son's straight line, and the measurements of one flow parameter behind the front, at a known detonation rate, determines the two remaining ones. If the nonhomogeneous zone is not reduced to a "fine" structure of the one-dimensional model of the wave front, the interdependence of the flow parameters becomes indeterminant, and information on the medium's pressure, density and speed formally averaged in the planes parallel to the front should be obtained by independent methods.

Returning to the problem of comparing a one-dimensional and a pulsating zone, one can formulate this in the following manner. The classical theory views the front of a detonation wave in the first approximation as a surface of discontinuity of the initial explosive and of the detonation products. The one-dimensional detonation complex of Zel'dovich is the "second" approximation. Are the pulsations in the detonation front of liquid explosives the "third" approximation, as, for example, Shchelkin suggests for gaseous detonation [90]?

Information on the pressure in the chemical reaction zone in liquid explosives is most conveniently obtained using electromagnetic apparatus. The split-off method, in which metal grids are used, can give unreliable data, since with the reflection of weak segments of the pulsating zone from the metal premature ignition can take place in them. The application of electromagnetic methods also requires appropriate experimental equipment, since a metal sensor is used in it.

Before going on to a description of the experimental equipment, let us consider whether there should exist a chemical peak in the suggested model of pulsating detonation. In the weak sections of the wave the pressure in the shock-compressed explosive is close to the pressure in the adjoining detonation products, but the speed of

the shock wave in the sections is less than the detonation rate by a certain value. Therefore, the pressure and the density in these regions of the front must be less than in the front of a one-dimensional wave. In the "heads" of the configurations the zone of chemical reaction both in the overcompressed regions, as well as behind the transverse wave, is very narrow and inaccessible for recording by the electromagnetic method. The region of detonation products of precompressed substance behind the transverse wave must have very high pressures, according to approximate estimates more than twice exceeding the pressure in the normal detonation products. Thus, within the limits of one three-shock configuration the pressure varies by two times, while the level of chemical conversion varies from total heat liberation in the head of the configuration to practically total absence of the reaction in the weak sections.

If we formally average the pressure in the chemical reaction zone, a region of elevated pressures must exist on the pulsating detonation front. This pressure peak is actually recorded experimentally. The sensor made of thin foil (0.03 mm), which does not cause ignition in the shock wave as a result of the very brief time of interaction with it, is placed on the interface with the inert medium, which has dynamic properties close to the mixture, for example, paraffin (Fig. 31). The oscillogram of such an experiment bears witness to the presence of a region of elevated pressures and velocities on the pulsating detonation front (Fig. 32). The time of existence of the elevated pressures as a result of the difference in the dynamic rigidities of the detonation products of the explosives and of the paraffin cannot be obtained from this oscillogram. This is determined in other experiments, when a thin electromagnetic sensor is placed directly in the explosive itself. In this case the oscillogram is qualitatively similar to that shown in Fig. 32.

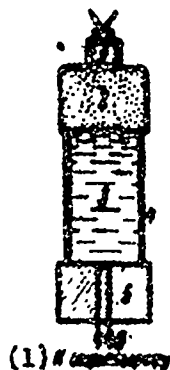


Fig. 31. Diagram of the experiment for observing the pressure peak on the detonation front in a liquid explosive. 1 - initiator; 2 - explosive lens; 3 - liquid explosive; 4 - shell; 5 - paraffin block; 6 - electromagnetic sensor.

KEY: (1) To the oscillography.



Fig. 32. Oscillogram of the rate of travel of the interface: mixture of nitromethane and acetone with a ratio of 75:25 - paraffin.

The time of existence of the elevated speeds Δt for a mixture of nitromethane with acetone in a volumetric ratio of 75:25 is 0.4 μ s. The measured time Δt allows us in turn to calculate the width of the zone of elevated pressures $\Delta t (D - \bar{u})$, where D is the detonation rate, and \bar{u} is the average rate in the investigated region. For a mixture of nitromethane with acetone of 75:25 D is equal to 5.75 km/s, \bar{u} is equal to 1.77 km/s, u in a Chapman-Jouguet plane (the end of the region of elevated speeds) is equal to 1.51 km/s and the pressure in this plane is 90,000 atm. Hence for the unknown width we get 1.6 mm.

The transverse dimension of the inhomogeneities on the detonation front in the same mixture, determined from end photo

scanning, is 1.5 mm, i.e., it turns out that the width of the zone of elevated pressures is approximately equal to the size of the transverse pulsations on the front. This conclusion allows us to continue the comparison of one-dimensional and pulsating zones.

In the proposed model of a pulsating front the size of the configurations or, in another way, the transverse dimension of the inhomogeneities on the front is determined by the ignition delay in the weak sections. Hence it follows that the total width of the pulsating zone is determined by the heat liberation conditions in the weak sections on the wave front. Since the speed of the shock wave in the weak sections is less than the rate of detonation, and consequently, the delay time of the ignition in the weak sections is greater than behind the shock wave, the one-dimensional reaction zone, propagating at the detonation rate, must be significantly less than the pulsating zone.

An experimental comparison of a one-dimensional and pulsating zone can be made, using data, obtained during shock initiation, on the delay times of the formation of detonation of a compressed substance behind a flat shock wave. In measuring this dependence (Fig. 33) special care was taken to eliminate the effect of the material of the boundary and of the quality of the finishing of its surface on the delay value.

The dependence of the delay times on the pressure can be used as a suitable indicator for determining the pressure in the weak sections on the front. An estimate of the delay of the emergence of new configurations on the front can be made, after equating it to the average time of travel of the configurations between collisions. This time (0.2 μ s) corresponds to a significant portion of the total time of existence of the elevated pressures on the front of a detonation wave (0.4 μ s). The difference in the named values is connected with the time of attenuation of the gas

dynamic pulsations in the detonation products. A pressure of 88,000 atm corresponds to a delay of 0.2 μ s. The pressure behind the shock wave, having a detonation rate for this mixture, is 130,000 atm [62], while the pressure in the detonation products is 90,000 atm. Thus, the developed model of the front of the detonation wave receives good confirmation.

The rate of fall of the parameters in time in the weak sections due to their convexity can be somewhat greater than in the initiating shock wave. Therefore, the actual pressure in the configurations can be somewhat greater than the estimated.

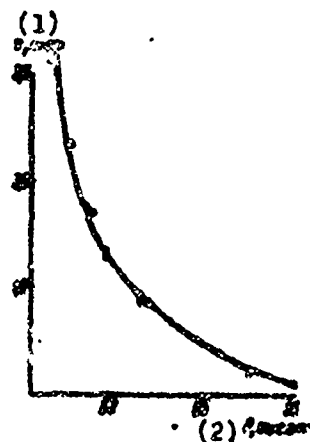


Fig. 33. Dependence of the delay of the formation of detonation of a compressed explosive behind the shock wave (τ) on the pressure on its front (P) where a mixture of nitromethane with acetone in a ratio of 75:25.

KEY: (1) τ , μ s; (2) P , thousands of atm.

If we extrapolate this same dependence to the pressure on the front of one-dimensional detonation, having assumed that the basic reaction time in the zone determines the induction period, then this reaction time must be extremely small. Soloukhin [97] also arrived at the conclusion that the pulsating zone increases abruptly the time of the heat liberation on the detonation front relative to a one-dimensional model, on the basis of experiments in gaseous detonation.

The conclusion arrived at contradicts the concept that a pulsating regime of chemical reaction occurrence on the detonation front corresponds to increased "stability" [98] of this method of propagation of the detonation wave as a result of the increase in

efficiency of the shock heating in a rough shock front. In works [23, 90, 91] it is suggested that a gas, compressed by a flat shock wave, reacts relatively slowly, and therefore the emergence on the front of the shock wave of oblique fractures accelerates heat liberation in the detonation front. Precisely for this reason it is assumed that the most clearly expressed none-dimensional detonation in gaseous mixtures - spin - is always observed on the detonation limits and is the "last possibility" for its propagation.

Let us examine the reasons for the emergence of pulsating regimes. Ignition behind the shock wave at considerable values of activation energy and correspondingly low initial rate of chemical reaction has a particular tendency toward the separation effect. In the pulsating zone of detonation forming as a result of this there occurs as if a separation of the functions of ignition and burning between the "weak" sections of the front and the "heads" of the triple configurations.

The weak sections, in which there is no continuous self-ignition and which, as a result, possess a speed less than the speed of the detonation, determine the kinetic properties of the wave and "control" the distance between the neighboring configurations. The "heads" of the configurations accomplish total heat liberation on the pulsating detonation front, burning the fresher substance in the oblique fractures, and in the transverse detonation - the substance behind the shock front in the weak sections.

The oblique fractures in the "head" of the configurations shorten the time of the chemical reaction behind the shock front relative to the one-dimensional model. In a complex of oblique overcompressed and transverse detonation waves the rate of heat liberation generally approaches the maximum possible. From this, particularly, it follows that collisions of configurations cannot essentially increase the reaction rate at the site of collision, as is suggested in work [90]. Moreover, these collisions can lead, on

the other hand, to attenuation of the configurations (Fig. Xb). Thus, the kinetics of the reaction in the "head" of the configurations in no way determines the average rate of heat liberation on the detonation front, which is determined by the time of their travel between collisions.

The discussion undertaken permits us to explain certain experimental results in a gaseous detonation, which were observed by many authors, but which did not find satisfactory explanation. These experiments are described in detail in the book by Sokolik [99], and are also cited in the article by Zel'dovich [39].

If ignition is observed behind a flat shock wave in mixtures of hydrogen and oxygen, as well as in air-propane mixtures, one can determine the wave parameters, at which the ignition behind the front proceeds with a disappearingly small delay, which is characteristic for detonation ignition. It happens that the speed of such a shock wave is significantly less than the speed of normal detonation in this mixture. At the same time the pressure in this shock wave is very close to that in the detonation products of this mixture. Within the framework of Zel'dovich's one-dimensional theory of a detonation complex with a separated shock front and a zone of ignition these results were not clarified, which gave Sokolik the basis for attempting to construct a one-dimensional detonation model, in which the "chemical peak" would not be an unavoidable consequence. In his opinion, this is possible, if the relaxation processes in the shock front have speeds close to the speed of total heat liberation.

Another mechanism of total combining of the zones of dynamic compression and reaction and, correspondingly, of the absence of a pressure and density peak on the front is Hirshfelder's model [100], in which the transfer processes play a significant role.

A completely different explanation can be offered on the basis of the developed model of a pulsating front. Evidently, in the studied mixtures [7, 101, 102] the front of a normal detonation was pulsating, and the weak sections of the triple configurations having a pressure close to that in the detonation products, determined the kinetics of the heat liberation on the front. Therefore, the characteristic times of ignition on the pulsating front must coincide approximately with the delay time of ignition behind the smooth shock wave, having a speed less than the detonation rate, while the pressure must be close to that in the detonation products, as is also observed in these experiments. A complete analogy of these experiments with the results described above for liquid explosives is apparent.

§ 5. Limits of Propagation of Detonation with a Pulsating Front in Metal Tubes

The analogy in the processes of propagation of detonation in gaseous and condensed homogeneous systems becomes less apparent with the consideration of phenomena on the limits of propagation of a wave.

For gaseous systems the walls of a glass or metal tube do not manage to get noticeably deformed in the process of detonation propagation and in the theory of the limits can be viewed as absolutely rigid. For the detonation of condensed explosives absolutely rigid walls do not exist. Perhaps precisely because of this the phenomenon of spinning detonation is not observed on the boundary of detonation of liquid explosives. Moreover, under propagation conditions close to the limit, the phenomena in the wave possess considerable similarity. In the transition to the limit both in liquid explosives, as well as in gases, the detonation rate remains practically unchanged, although the size of the pulsations on the front increases noticeable here (Fig. 34). If, however, in gaseous detonation in proportion to the approach to the limit the size of the triple configuration may reach in

succession a value of the tube diameter (the case of one-head spin), then in liquid explosives detonation will completely attenuate, when on the surface of the detonation front there are still hundreds of triple configurations.



Fig. 34. Dependence of the size of the inhomogeneities on the detonation front in a mixture of nitromethane with acetone 75:25 on the diameter of the steel shell ($T_0 = 8^\circ\text{C}$).

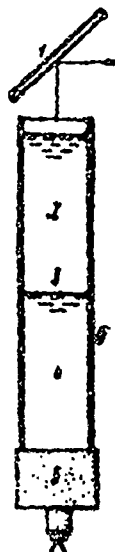


Fig. 35. Diagram of the experiment for by-passing detonation from a rich mixture to a leaner one. 1 - mirror; 2 - mixture of nitromethane with acetone in a ratio of 70:30; 3 - polyethylene film; 4 - mixture of nitromethane with acetone in a ratio of 75:25; 5 - explosive lens; 6 - metal shell.

The cessation of detonation is viewed as the sudden cessation of ignition on the detonation front almost simultaneously across the tube's cross section. The observation of attenuation of detonation in metal tubes can be done when by-passing detonation, propagated under stationary conditions, into a leaner mixture, for which the given diameter of the tube is less than limiting (Fig. 35). Such a formulation of the experiment, for example, is widely practiced in gaseous detonation when finding the concentration limits [23]. During the transfer from the lower tube to the upper detonation attenuates for a certain time in the entire cross section of the charge, across the upper tube passing through a distance, not exceeding its diameter (Fig. XIV).

Overcompression during the transfer of detonation to a mixture with a somewhat lesser heat content is small and must disappear very rapidly right up to the attenuation of detonation. The observable effect of the disappearance of the detonation ignition, apparently, also determines the limits of propagation of detonation in the metal tubes. It should be emphasized that such a method of attenuation of pulsating detonation is characteristic only for a metal shell.

If the detonation is propagated through the liquid explosive in the shell with a relatively low density (paraffin, plexiglas), then the propagation limits set in at a much greater diameter than for a metal shell. The surface of the detonation front in this case undergoes periodic reductions under the effect of the rarefaction waves, which enter the zone from the side of the deformed shell. With a critical diameter the amplitude of the pulsations of the surface of the detonation front are such that the surface of the detonation front is totally reduced and detonation becomes impossible. In a weak shell close to the limits of propagation the dependence of the size of the inhomogeneities on the front on the value of the diameter is still not clear. For example, for a 75:25 mixture of nitromethane with acetone the critical diameter in a weak shell is greater than 200 mm, while the size of the inhomogeneities vary only with steel tube diameters of less than 40-70 mm. Therefore, only in a weak shell is the mechanism of the propagation limits determined by the specific phenomenon of the pulsations of the surface of the front, about which we will speak in more detail in the next chapter.

Let us turn to the appearance of attenuation of a wave in a "rigid" shell, in which the effects of the shortening of the surface of the front of a lateral rarefaction wave is a rare exception and can occur only under the effect of random causes. Since for a gaseous detonation the theory of the limits of propagation amounts to finding the propagation limits of a one-head spin [90, 91], for the theory of the limits of pulsating detonation in a rigid shell in liquid explosives other concepts are necessary.

First, attempts should be made to explain the limits on the basis of the one-dimensional theory of propagation limits of detonation in tubes of limited diameter [23], which in gaseous detonation has found no application. In this theory an essential role is played by the factor of losses due to thermal conductivity and friction of the wave against the tube walls. Losses must lead to a reduction in the speed of detonation and to a corresponding increase in the time of the chemical reaction on the front with the reduction in the diameter of the tube. In particular, for detonation on the limit in gaseous mixtures formula $\Delta D = t_p D^2/d$ is suggested [23], where D is the detonation rate, t_p is the reaction time on the front, d is the tube diameter, ΔD is the decrease in the speed with the approach to the limit.

On the basis of the presented formula let us try to make an estimate of the reduction in the detonation rate on the limit in a liquid explosive. Let us take for an example a mixture of nitromethane with acetone in a ratio of 75:25; t_p for this mixture is 0.4 μ s, D equals 5.75 km/s and the limiting diameter of the tube is 30 mm. Hence one should anticipate a reduction in the detonation rate at the limit of approximately 6-7%. Careful measurements of the detonation rate at the limit with a change in the diameter of the tube right up to the limit did not permit us to discover any noticeable changes in the rate, although the measurement error amounted to less than 1%.

Hence it could be concluded that heat losses and friction against the walls do not determine the limits of propagation of detonation in liquid explosives.

Since the speed of heat transfer in a condensed medium is small, and the diameter of the tube increases the width of the zone of heat liberation on the front by more than one order, it is actually difficult to expect a drop in the parameters of the wave as a result of the cooling of the medium by the shell. However, in the theory of one-dimensional limits [23] it is pointed out that the

weakening of the flanks of the wave on the wall can quickly affect the state of the medium in the central regions of detonation as a result of the rarefaction waves. In condensed systems, if even the factor of thermal and mechanical losses is insignificant, the effect of compressibility and expansion of the shell can replace them. Hence qualitative conclusions of the one-dimensional theory should be maintained. In this case a criterion of the approach to the limits must, as before, be a noticeable reduction in the detonation rate relative to the rate in the same mixture with large charge diameters. This reduction in the reduction rate corresponds to a formal reduction in the heat liberation behind the wave as a result of heat losses in the lateral rarefaction wave.

As was already noted, the experiment does not confirm the assumption of a noticeable drop in the rate of detonation on the limit, although the size of the inhomogeneities on the front increases here somewhat. The zone of heat liberation on the detonation front with limiting conditions of propagation remains as before an order less than the charge diameter. Such rigid conditions of the possibility of detonation propagation force us to look for other reasons for the nature of the limits of propagation of a pulsating detonation wave.

It should be noted that the very process of detonation attenuation, actually accompanied by a drop in the parameters on the wave front, does not require a necessity of introducing a loss factor, even if in the form of a rarefaction wave from the lateral wall. In this nonstationary process the size of the inhomogeneities is enlarged, the zone of heat liberation increases, the detonation process spreads apart and, consequently, there is no total heat liberation. The dispersion of the wave is accompanied by the penetration of rarefaction waves from the detonation products into the pulsating zone, as a result of which there occurs the separation of ignition in the weak sections of the configurations and a progressive reduction in the parameters of a nonstationary wave. All these processes are interconnected.

Significantly more complex is the problem, due to what does the transition to such a nonstationary regime occur. Turning again to the model of a pulsating front, one may note that the criterion of the ability of detonation to a self-sustaining regime of propagation is the possibility of continuous adiabatic ignition in the weak sections of the configurations, which fix the dimensions of the heat liberation zone. If for any reason in the weak sections of the configurations separation of ignition occurs, detonation will transfer to a nonstationary regime and may attenuate, for example, during the rapid transition of a wave from overcompression or in spherical detonation. A similar effect can also arise as a result of the lateral rarefaction wave, which actually, as will be shown in the next chapter, is observed during the propagation of detonation in a weak shell or during the transition of detonation from a wide tube into a volume. Characteristic for the attenuation of a wave under the effect of a lateral rarefaction wave is the subsequent disappearance of the configurations in the lateral rarefaction wave, which is recorded in the form of a distinctive wave of the disappearance of luminescence of the detonation front, propagated into the central portions of the wave at a certain speed.

With the attenuation of detonation in a rigid shell of any perturbations from it on the configurations "grid," which is very sensitive to external influences, is not observed. It remains to allow that the transition to a nonstationary regime from a normal one is possible as a result of the assumption, paradoxical at first glance, concerning the emergence, in a normal regime of detonation propagation, of a rarefaction wave from the region of detonation products into the zone of heat liberation. One can come to such a conclusion from examination of the model of the configuration on the front, presented in Fig. 26.

The pressure in the weak sections is close to the pressure in the detonation products, and the total width of the zone of heat liberation, in succession, is close to the dimensions of the triple configurations. It follows from this that the detonation products

play the role of a plunger for weak sections of the configurations. Therefore, the weak sections are "transparent" for a rarefaction wave from the detonation products. It is possible to show that this conclusion does not contradict the fulfillment of the Chapman-Jouguet condition and is a consequence of the peculiarities of rarefaction waves in a turbulent flow.

Let us postulate that the rarefaction wave from the detonation products always enters the front through the weak sections of the configurations. The profile of the rarefaction waves is determined by the volume of the expanding detonation products. It follows from this that in a given mixture the steepness of the pressure drop in the zone of rarefaction will be determined by the length of the traveled detonation path, if the diameter of the charge is large. If the diameter is small, after establishing detonation the steepness of the rarefaction wave will be determined by the charge diameter, the detonation products of which expand in a radial direction.

With a sufficiently small diameter of the charge the rarefaction wave, entering the turbulent zone, may cause separation of ignition in the weak sections and bring the wave to a nonstationary attenuation regime. With a diameter somewhat greater than limiting, the rarefaction wave causes additional attenuation of the weak sections, as a result of which delays in the ignition in them exceed the values which correspond to a large charge diameter. This also leads to a certain enlargement of the inhomogeneities close to the propagation limits. Since, however, ignition separation in the weak sections close to the limit is overcome, detonation propagates in a stationary regime with total heat liberation and with practically the same detonation rate, which must exist in a wide tube.

Thus, the detonation propagation criterion in a metal tube may be determined as the condition of overcoming the separation of ignition in the zone as a result of the rarefaction wave from a limited volume of detonation products. It remains to give this criterion quantitative characteristics.

The concept of the threshold of ignition initiation behind a flat shock wave was described above in detail. It was shown that this concept is relative, and that the value of the threshold depends on the charge size. Notably, for a given mixture the amplitude of the shock wave, capable of causing ignition, is reduced with the increase in the size of the active charge. The dependence of the limiting dimensions of the active charge on the limiting amplitude of the shock wave is very strong, since in the first approximation the amplitude fixes the shock heating of the medium and, consequently, the initial rate of the chemical reaction through Arrhenius' exponent. The limiting dimensions of the active charge are found from the conditions of compensation of the rarefaction wave of the chemical self-heating of the medium, and a noticeable decrease in the initiation threshold can be achieved only with a very strong increase in the active charge dimensions.

In our analysis of the processes of heat liberation in the pulsating zone an analogy of the phenomenon with shock initiation is assumed, since the products of normal detonation are viewed as a "plunger," creating ignition in the weak sections. The initial pressure, created by this "plunger," is unambiguously determined by the heat content of the selected mixture. Thus, an independent parameter in the problem of finding the conditions of ignition in the weak sections of the configurations is only the linear dimensions of the charge. If these dimensions are sufficiently large, the possibility of ignition separation in the weak sections is overcome, and detonation has the possibility of steadily propagating. In particular, the tube diameter found in the experiments on shock initiation determines the limiting diameter of propagation of detonation of the selected mixture.

Taking into consideration the similarity of the phenomenon with shock initiation, one should expect a sharp increase in the limiting diameter with the leaning of the mixture, when the pressure in the detonation products is reduced. If in a mixture of nitro-methane with acetone in a ratio of 75:25 detonation is propagated

with tube diameters exceeding 30 mm, then for a mixture of 70:30 in tube diameters actually existing in the experiment (up to 200 mm) steady-state detonation cannot be effected. These regularities, naturally, become possible only because the reaction-kinetic properties of the mixture change little with the variation in the heat content. Considering the analogy of the phenomena of the propagation limit and the initiation threshold, one should expect that, since in both instances the diameters of the charges vary insignificantly, then the initiation threshold should coincide approximately with the pressure in the detonation products of the mixture, which is still capable of steady-state propagation under these conditions. In our experiments such a mixture was one with nitromethane and acetone in a ratio of 72:28. The pressure in its detonation products is about 85,000 atm. The initiation threshold, practically speaking, is about 80,000 atm for all mixtures.

From the described analogy it follows that the limits of stable propagation of detonations in any mixture can be found from experiments on shock initiation. For this, it is essential to select the amplitude of the shock wave, equal to the calculated pressure in the detonation products of the selected mixture, and, by varying the dimensions of the active charge, achieve ignition behind the initiating shock wave. The discovered active charge size is approximately equal to the limiting diameter of the tube, in which detonation in the selected mixture will propagate steadily. Using a spherical active charge during shock initiation, in a similar way one can find the limiting diameter for spherical detonation also.

If the diameter of the active charge is very large, the steepness of the rarefaction wave in the products will be determined by the length of the charge. Therefore, limits of propagation with respect to the charge length must exist. Such an assumption makes somewhat indeterminate the treatment of separation phenomena during the transition of a detonation wave from overcompression during initiation by a short powerful charge. This phenomenon was explained

above as the result of a drop in the parameters on the wave front during transition from overcompression. However, one can also allow that up to the moment of separation detonation was already leaving the overcompression mode, but the length of the region of detonation products behind it was less than the critical dimensions, and therefore the attenuation of detonation occurred. It is apparent that the nature of the separation of ignition in the zone remains the same in both instances.

§ 6. Detonation Waves with a Smooth Front

As was already noted, with the enrichment of mixtures of nitromethane with acetone, of nitroglycerin with methanol and others the size of the pulsations on the detonation front is sharply reduced. The resolvent power of head-on photo scanning is rather low and does not permit recording inhomogeneities of the front of less than 1 mm. Therefore, in undiluted liquid explosives using head-on photo scanning one cannot manage to establish whether or not the front remains pulsating. Significantly better resolution ($5 \cdot 10^{-3}$ mm) is obtained by the method of light reflection, suggested by Zel'dovich, Kormer et al. [68]. This method permits one to detect the presence of small pulsations on the front and to answer the question as to whether liquid explosives exist with a smooth detonation front.

The assumption of the existence of triple configurations with a size less than $5 \cdot 10^{-3}$ mm, to which "lifetimes" of configurations on the order of 10^{-9} s must correspond, is not realistic. This conclusion follows from consideration of the detail structure of the pulsating front and is discussed in detail below. It contradicts to a certain degree the conclusions of work [103], in which the presence of extremely small triple configurations is allowed in contrast to the first work of the same authors [68]. The reflection of light from a detonation wave is connected with the presence of a significant density jump on the shock front of detonation of a condensed explosive. The nonuniformity of the density jump on the

pulsating surface of the detonation front and the "hilliness" of this surface complicate the formulation of the experiment for light reflection from a pulsating wave. One of the difficulties consist in the fact that the light reflection from such a rough surface is irregular, and consequently, the intensity of the reflected light may be significantly less than for a smooth wave. Another difficulty consist in the impossibility of quantitative estimates of the density of the shock-compressed substance on the front according to the coefficient of light reflection. In particular, there is no basis for assuming that the integral coefficient of light reflection from the pulsating front must coincide with the coefficient of reflection of a smooth wave, having the same velocity, as is suggested in work [103].

In recording the light reflection of an extraneous source from the front it is essential that the reflected signal in order of magnitude be close to the intensity of the detonation luminescence itself. However, the most powerful (explosive) light sources have limited intensity of illumination in the visible range in connection with "saturation" of the radiative power of the heated body (in the present case of a shock wave in argon) at very high temperatures ($\sim 40,000^\circ\text{K}$) in conformance with Planck's formula. Another limitation of the intensity of the source is the effect of screening of radiation of the shock wave as a result of heating by this radiation of the gas before the front [80].

It is possible to achieve an increase in the intensity of the light, reflected from the pulsating front, by observing several additional conditions when setting up the experiment. If the surface of the front is slightly hilly, then the diagram of irregular reflection of light from it must be relatively narrow, i.e., such a surface is essentially different from a surface which isotropically scatters light, and satisfies Lambert's law. Therefore, in the experiment one can obtain a maximum reflected signal with a given source brightness, if the angular dimensions of this source exceed the opening of the reflection diagram of the rough surface. In

this case one can, in principle, also determine directly the integral coefficient of reflection, about which we spoke above.



Fig. 36. Layout of the experiment for observing the form of the surface of a detonation front from the illumination of the clearance.
1 - mirror; 2 - air gap between liquid explosive and glass 0.1 mm; 3 - steel tube; 4 - lean mixture of nitromethane with acetone; 5 - explosive lens; 6 - initiating charge.

It is possible, using the scheme depicted in Fig. 36, to experimentally estimate the degree of roughness of the pulsating surface in mixtures, where the pulsations are observed directly on the photoregister. With such a formulation one can observe the subsequent illumination of the thin air gap above the surface of the mixture of the nitromethane with acetone in proportion to the removal of the hilly surface of the detonation wave in it. The aperture photo scan shown in Fig. XV corresponds as if to a three-dimensional "impression" of the surface of the detonation front, allowing us to observe its shape. The clarity of the flash of the air gap is much stronger than the luminescence of the wave itself, and it is not an interference for the observations. In examining the photograph one should consider that the relationship of the time scan and of the coefficient of reduction of the image is such that the true concavity of the front is two times less than the unevenness of the lines of this chronogram. This explicit experiment allows us to be convinced that the surface of the pulsating front is slightly hilly with a small relationship of the height of the pulsations to their transverse dimension (~ 0.1).

One can assume that the shape of the configurations vary little with the change in their linear dimensions. A similar conclusion is also drawn for the case of gaseous detonation [90, 91].

Experiments were conducted [69] according to the scheme, presented in Fig. 37. For the observation of the light reflection from a clearly "mirror" shock wave water was used. Figure 38 presents a photo scan of the experiments with glyceride alcohol nitrate ($D = 6.7$ km/s), bearing witness to the roughness of the front of normal detonation in it, since the image edges of the source diaphragm in the form of a slit are blurred. A similar picture is observed in nitromethane.

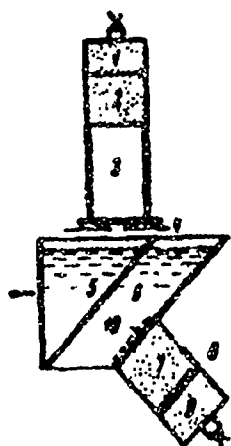


Fig. 37. Layout of the experiment for observation of the reflection of light from detonation waves in liquid explosives. 1 - explosive lens; 2 - charge of hexogene; 3 - transparent box with argon; 4 - diaphragm in the form of a slit with a width of 20 mm; 5 - water; 6 - liquid explosive; 7 - initiating charge; 8 - plexiglas baffle; 9 - explosive lens; 10 - detonation front.

Similar experiments were also conducted for detonation waves in a regime of overcompression [69]. It was discovered that with a sufficient degree of overcompression the detonation wave is smooth (nitromethane, a stoichiometric mixture of nitric acid with dichloroethane). In proportion to the transition from overcompression the detonation front becomes rough. In similar experiments with a mixture of nitromethane and acetone the smoothness of the front was not achieved, apparently, as a result of the inadequacy of overcompression. In experiments with a stoichiometric mixture of nitric acid and dichloroethane the front, on the other hand, becomes

smooth with relatively low overcompression. During overcompression, simultaneously with the mirror reflection the dispersion of light is also observed. It can be assumed that the dispersion of light occurs behind the shock front of detonation, in the zone of heat liberation. Another assumption consist in the fact that during overcompression the surface of the detonation front is divided into separate sections with a smooth and a pulsating front. Such a phenomenon is completely possible on the boundary of instability on the smooth front.



Fig. 38. Photo scan of light reflection in gloricide alcohol nitrate. 1, 2 - image of an illuminated diaphragm on the surfaces of separation: water - glass baffle, liquid explosive - glass bottom; 3 - flash of the air gap between the active charge and the bottom of the box; 4 - luminescence of the detonation front; 5 - photo scan during "depiction" of the diaphragm on the surface of the detonation wave; 6 - image of the diaphragm on the surface of the shock wave in water; 7 - luminescence of the detonation products of the active charge through a transparent bottom; 8 - luminescence of air during dispersion of the detonation products of a liquid explosive with a free surface.

In subsequent experiments liquid explosives were discovered, in which the front of normal detonation is smooth: nitroglycerin, dinitroglycerin, tetranitromethane ($D = 6.4$ km/s) and a mixture of nitromethane with benzene in a ratio of 87:13 ($D = 7.0$ km/s).

Figure 39 shows a photo scan of the experiment with light reflection from detonation with the smooth front. One should note that the mirror reflection of light from the front of normal detonation is not accompanied by the simultaneous scattering of light, as takes place during the overcompression of nitromethane and of a stoichiometric mixture of nitric acid with dichloroethane. All systems which detonate with a smooth front are characterized by the fact that with their dilution with a solution which reduces their heat content, the front in them becomes unstable. For example, in a mixture of nitroglycerin with methanol in a ratio of 36:64 the triple configurations on the front are directly observable on the photoregister. With the dilution of tetranitromethane with benzene up to a ratio of 40:60 ($D = 5.35$ km/s) the light reflection from the front also becomes irregular.

In this way, it can be concluded that there exist a class of homogeneous condensed systems, in which detonation is propagated according to a mechanism, corresponding to the one-dimensional theory of Zel'dovich. It is interesting to discover a zone of increased pressures on the front of one-dimensional detonation in a liquid explosive. However, in the majority of the observed smooth detonation waves the reaction time on the front is low and is not recorded by an electromagnetic procedure, the resolving power of which is $\sim 10^{-7}$ s. An exception is tetranitromethane. A mass velocity profile recording obtained for it (Fig. 40) showed that on the front of a smooth wave there exist a pressure peak, corresponding to the "chemical peak," predicted by Zel'dovich's one-dimensional theory. It is characteristic, however, that the "chemical peak" does not have a clearly expressed induction period (the width of the zone of the chemical reaction is approximately equal to 2 mm, to which the time of existence of the substance in it corresponds, ~ 0.5 μ s).

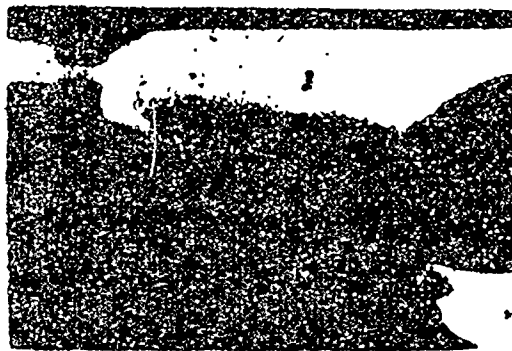


Fig. 39. Photo scan of light reflection in a mixture of tetranitromethane and benzene in a ratio of 87:13. 1 - mirror reflection on the detonation front; 2 - mirror image of a diaphragm in a shock wave in water; 3 - illumination of the detonation of the mixture.

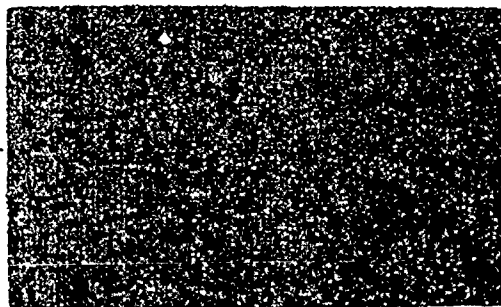


Fig. 40. Oscillogram of the mass velocity behind the front of one-dimensional detonation in tetranitromethane.

For other systems with a smooth front the width of the zone of heat liberation cannot be directly registered; it can be estimated only obliquely. It is known that in metal tubes the detonation of nitroglycerin does not propagate, if the diameter of this tube is less than 1 mm. For dinitroglycerin the corresponding critical diameter is 4 mm. Not one of the existing theories of the critical diameter postulates that the zone of heat liberation on the front of detonation of these explosives is less than 0.1 mm, while the

characteristic time of this heat liberation is correspondingly less than 10^{-8} s. If the detonation front in these explosives were pulsating, the size of the pulsations would be of the order of dimensions of this zone, i.e., 0.1 mm, which is significantly greater than the minimum dimensions of the inhomogeneities on the front, resolved by the method of light reflection. From this follows the validity of the conclusion of the smoothness of these detonation waves from the observance of the mirror reflection of light on them.

In our discussions the assumption is tacitly maintained that the pulsating zone corresponds to the rough surface of the detonation front, with all the criteria described above characteristic for it. In fact it is completely probable that between the class of homogeneous explosives, the detonation of which has a one-dimensional zone, and systems, in which the pulsating character of the detonation front is clearly expressed, there can exist systems with intermediate properties, in which nonstationary processes corresponding to unstable self-ignition can be manifested. It is obvious, however, that if these processes are not accompanied by a complex of separation effects, leading to the hydrodynamic restructuring of the front of the detonation wave, such detonation will in its properties approach the detonation with a smooth front. In this case the nonstationary processes in the zone can actually be classified as a "fine structure" of a one-dimensional front.

§ 7. The Limit of Stability of a Smooth Detonation Front and the Mechanism of Formation of a Pulsating Zone

The theoretical consideration of the instability of a model of a one-dimensional stationary complex, having the same detonation rate [40, 41, 43, 44], became traditional in evaluating the conditions for the existence of a smooth or pulsating detonation wave in gases. As follows from work [45], in which such an investigation was conducted in the most general form, an analogous approach is, in principle, applicable also to liquid explosives.

However, in the latter case it is practically impossible to solve the given problem to the end, since for this exhaustive data are necessary on the chemical kinetics under conditions of detonation and on the equation of state of not only the initial explosive and of the final products, but also of all the intermediate substances. We do not have such data available to us at present.

In principle, the problem of instability of a smooth complex can be simplified using certain additional initial assumptions. For example, in works [40, 41] this complex is examined in the form of a double separation (the shock front and the front of combustion are situated a certain distance from one another). However, for practical application of these works it is first of all necessary to be convinced of the fact that the induction t_{ind} is actually the greater part of the total reaction time. Conversely, the criteria of instability, introduced in these works, turn out to be basically inapplicable.

A simple example shows how far such apprehensions are justified for the detonation of homogeneous condensed explosives. Let us assume that we are attempting to evaluate the stability of a detonation front of a shock-compressed explosive with shock initiation of the detonation in nitromethane or of a mixture of it with acetone. It is impossible, for example, to evaluate the stability of a transverse detonation wave in the pulsating zone. Even if as a result of laborious calculations Shchelkin's criterion is determined, its application will be incorrect for the following reasons. Since the initial density of the medium as a result of the precompression by the shock wave is great, the basic part of the liberated chemical energy can transfer to the elastic part of the energy of the detonation products [24]. It is precisely because of this that the luminescence of the detonation of the compressed substance is significantly weaker than the luminescence of ordinary detonation. Hence it follows that the temperature on the shock front of this detonation and the temperature of its products are close to one another. As a result, the heat liberation

in the reaction zone proceeds almost under isothermic conditions, and the reaction is not self-accelerated. The pressure profile in this zone must be triangular.

It should be noted that the achievement of a triangular profile for the pressure in the zone may also occur under ordinary kinetics of heat liberation behind the shock front. The temperature in the detonation front is sufficiently high, so as to anticipate the effect of burnout of the substance in the initial stages of the process of heat liberation, as a result of which self-acceleration of the process must attenuate, as follows from the theory of a degenerated adiabatic thermal explosion [75]. The clear illustration of such a possibility is the calculation of the pressure profile in the zone of a one-dimensional detonation wave in a gas, introduced in the book of Zel'dovich and Kompaneys [23]. The pressure profile with pressures, temperatures and activation energy usual for detonation in gases proves to be triangular. The profile approaches the rectilinear with a significant increase in the activation energy.

The cited examples show that empirically based data must lie at the basis of the assumptions, which simplify the theoretical problem of the stability of a detonation front. The experimental discovery of a smooth and pulsating front in liquid explosives along with other results indicated above, apparently, can give us a basis for formulating appropriate assumptions. Moreover, we hope that further accumulations of experimental data will allow us to strictly justify the below-expounded qualitative representations on the nature of a pulsating detonation front. Let us note that with the aid of these concepts it is possible to explain all the known pertinent facts.

Attention is first directed to the fact that the pressure profile in the detonation front is in all instances, when it lends itself to observation, triangular. Can we not conclude from this that the detonation front with a triangular profile is basically unstable? Apparently, we can.

Actually, we will, as usual, assume that the reaction behind the shock front proceeds according to the law of an adiabatic thermal explosion. According to the corresponding theory [75], the character of the heat liberation in the reaction zone is determined by two parameters:

$$\gamma = \frac{E T_0}{R Q} \text{ and } \beta = \frac{R T_0}{E}.$$

where E is the activation energy; c is the specific heat; Q is the specific heat liberation; T_0 is the initial temperature of the shock heating. The first of these parameters with a reduction leads to a rise in the acceleration of the reaction as a result of the chemical self-heating of the medium, while a decrease on the second parameter increases the dependency of the reaction rate on the temperature.

Under conditions of detonation parameters β and γ are not independent, this is connected with the fact that with a given equation of state of the medium the temperature of the shock heating T_0 is determined by the detonation rate, which is in turn fixed by the value of the heat content. Simple estimates show that all other conditions being equal an increase in Q leads to an increase in β and γ . Overcompression of the detonation wave leads to an analogous increase in the parameters.

It follows from the theory that a rectangular pressure profile of a smooth detonation front should be observed only when $\gamma \ll 1$ and $\beta \ll 1$. Conversely, there is no clearly expressed induction period behind the shock front, and the pressure profile is triangular. However, in accordance with the physical concepts of the parameters β and γ , the imposed condition denotes a strong dependence of the reaction rate and its self-acceleration on the temperature, and consequently, on the gas dynamic parameters of the flow, which in turn are determined by the process of heat liberation. It is not difficult to see that with sufficiently small values of β and γ such an interdependence of the parameters of the flow and of the

reaction led to instability of the smooth detonation front. Conversely, with large values of β and γ , when the pressure profile at the detonation front is triangular, a smooth front should be stable. Thus, the supposition of instability of the detonation front with a rectangular pressure profile is completely natural, and apparently, may be justified by developing the expounded qualitative considerations.

To determine the conditions for the existence of a smooth and pulsating detonation one may proceed from the other side. Namely, in contrast to the classical formulation of the problem [40-45], one may study the problem of the stable existence of a pulsating detonation front. The limit of the existence of a pulsating zone will also correspond to the possibility of the existence of a one-dimensional detonation wave. Actually, if we succeed in showing that in a system with fixed properties a pulsating zone cannot exist, then in this system a one-dimensional detonation model will be stable.

In order to determine under what conditions pulsating detonation should transfer to one-dimensional, let us turn to Fig. 26. It is obvious that a limit of the pulsating zone will begin, if in the weak sections of the triple configurations the conditions of heat liberation approach the "degenerated." More precisely, if behind the shock wave, which has a speed equal to the speed of the front of the weak section, which is lower than the detonation speed, ignition occurs immediately behind the front without an induction period. Actually, the separation effect in the head of the configurations appears as a result of the fact that, in proportion to the distance away from the triple point behind the shock front, mutual compensation of the self-heating of the substance and of the adiabatic cooling sets in. This leads to an infinite rise in the induction period and to the dissociation of the double separation: the front of the shock wave - the ignition surface. With degenerated kinetics such a dissociation is impossible, since an intensive reaction begins immediately behind the shock front. Consequently,

in this case the conditions for a transverse detonation wave are absent, it simply has nothing to burn. Hence it is clear that with degenerated kinetics the detonation front must be one-dimensional.

Returning once again to the proof of the correctness of the method of light reflection, one may note that the achievement of conditions of degeneration will occur earlier than the dimension of the configurations becomes equal to $5 \cdot 10^{-3}$ mm, while their lifetime is 10^{-9} s. Actually, as follows from Fig. 26, the triple configuration is a complex three-stage set. The characteristic dimensions of the chemical reaction zone in the region of the overcompressed section are one or two orders less than the dimensions of the entire configuration. Apparently, the conditions of heat liberation in the overcompressed section even in relatively lean mixtures are close to degeneration, and it is smooth. With the total "lifetime" of the entire configuration of 10^{-9} s the time of the heat liberation in the overcompressed section should be 10^{-10} - 10^{-11} s. It is further necessary to postulate that at a certain distance from the triple point with such times there appears an induction period, which occupies the greater part of the total time of heat liberation and forms a double nonstationary separation. There is no doubt that the presence of a clearly expressed induction period and heat liberation for 10^{-10} s for a complex organic substance is a totally improbable supposition. With such reaction times it is difficult generally to speak of the temperature of the medium and it is inadmissible to assume the presence of an induction period with a strong dependence of its value on the initial temperature.

In light of what has been said it is easy to explain all the experimental facts. Actually, parameters β and γ grow with the decrease in the activation energy and with the rise in the heat content, since T_0 increases sharply together with Q . Therefore, smooth detonation waves are more probable for liquid explosives with large Q . They should also take place with sufficient over-compression relative to weak mixtures (due to the rise in T_0).

A reduction in the value of the activation energy should also lead to smoothness of the front. The last instance, corresponds, for example, to additives to a liquid explosive of substances which accelerates reaction.

It was shown above that a detonation wave in liquid explosives during initiation by a shock wave is always formed in an over-compressed regime, from which it quickly transfers in proportion to the dissipation of the detonation products behind the "second" wave. Overcompression at the initial moment is very great, the pressure of the detonation products reaches almost a doubled value relative to the pressure of the normal detonation products. One can assume that an overcompressed detonation wave is smooth in all liquid explosives at the initial moment.

If in the given substance normal detonation is smooth, with a degenerated character of the heat liberation in the zone, then the overcompressed detonation wave will transfer to normal without any kind of separation effects. But if normal detonation is pulsating in the given explosive, then at a certain stage of its transition from overcompression in the reaction zone of an initially smooth detonation front an induction period will appear. Since the transition from overcompression occurs rapidly, behind the shock front separation must begin. Following this separation in the ideal case one might imagine such detonation propagation conditions, under which only longitudinal pulsations take place, that is, a detonation front is initiated, transfers from overcompression, is separated, is again initiated etc. Separation finally takes place not simultaneously along the entire front, and as a result of this the usual regime of pulsating detonations is established.

It should be noted that the problem of the boundaries of existence of a smooth or rough detonation front may prove to be significantly more complex, if the given explosive has not one, but two stable detonation regimes - pulsating and smooth. In this case the actually existing regime is determined by the mechanism

of detonation initiation and in conformance with what was said above in an ordinary shock initiation a pulsating regime exist.

In conclusion let us note that the described qualitative concepts are not as intimately related with the thermal nature of the development of the reaction, as appears from first glance. Actually, if we suppose that the reaction develops according to some other mechanism (for example, a chain mechanism), but the dependence of its speed and self-acceleration on the flow parameters has an analogous character, then presented qualitative picture of the formation of the inhomogeneities is essentially unchanged.

CHAPTER IV

THE MECHANISM OF PROPAGATION OF DETONATION IN SOLID EXPLOSIVES

The possibility of the transference of the stationary one-dimensional Zel'dovich complex to detonation of solid porous explosives is not obvious. In the first place, it is unclear whether in every case a shock heating of the explosive is adequate to ensure rapid occurrence of the chemical reaction. Secondly, on the strength of the physical inhomogeneity of porous explosives the detonation wave front in them is not one-dimensional. Doubts on the possibilities of the shock mechanism have forced investigators to advance other ideas on the mechanism of the detonation conversion of solid explosives. The most popular conceptions are those concerning "explosive combustion," according to which the particles of an explosive in a detonation wave at first ignite along the surface and then burn up [5, 104-108].

At the start of his investigations Apin [106] expressed the assumption that the products of the explosion lead to detonation, i.e., that the speed of the stream of explosion products is also the detonation propagation rate. In essence, this is another model of a detonation wave, different from the hydrodynamic model.

At the time when the cited ideas were advanced, direct experimental data were lacking. Therefore, an explanation of the individual experimental facts on the basis of these or other

concepts were viewed as proof of their validity. For example, from the position of explosion combustion it is easy to explain the increase in the critical diameter with the rise in the initial size of the particle of the explosive. According to the model of explosive combustion the reaction time $\tau \propto \delta/u_p$, where δ is the initial particle size, and u_p is the combustion rate under detonation pressure. Using the relationship of the reaction time with the critical diameter according to Khariton's formula $d_{kp} \sim 2c\tau$ [72], where c is the speed of sound in the reaction zone, the adherence of the theory of explosive combustion asserted that an increase in the critical diameter with a rise in δ was connected with an increase in the reaction.

Within the past ten years experimental methods were developed, which have allowed us to directly determine both the detonation parameters (mass velocity, pressure), as well as the chemical reaction time. The study of the effect of various factors (porosity of the explosive, size of the grain, diameter of the charge, etc.) on the reaction time gives us a basis for a more detailed analysis of the mechanism of detonation conversion of solid explosives.

§ 1. Experimental Observation of the Chemical Peak in Solid Explosives

Measurement of the mass velocity $u(t)$ behind the front of a detonation wave allows us to draw a number of conclusions concerning the mechanism of the detonation conversion of the explosive. The chemical peak in the detonation wave of a condensed explosive (cast composition "B": trotyl - 36%, hexogen - 63%, wax - 1%) was first experimentally discovered by Daff and Houston [96]. Later, for trotyl the dependence of the width of the chemical peak on the charge density was investigated [109]. In these works to determine the profile $u(t)$ behind the detonation wave front the so-called "split-off method" was used [71]. The

essence of this consists in experimentally determining the profile of the shock wave in an inert medium (as a rule, a metal), which is in contact with the detonating charge of the explosive. The profile of the shock wave in the metal is revealed by means of the determination of the dependence of the rate of travel of the free surface W on the thickness of the plate l (Fig. 41). Here it is assumed that the dependence at $W(l)$ qualitatively reproduces the profile $u(t)$ (or the pressure profile) of the detonation wave falling on the plate.

If on the detonation wave front there exists a region of elevated pressure (chemical peak), for example sections AB (Fig. 42), then also on the dependence of $W(l)$ in the region of sufficiently thin plates there should be a section of elevated velocities, for example section A'B' (Fig. 43). From the value of l_1 , which corresponds to the point of breakoff of the dependence $W(l)$ and to the parameters of the shock wave in the metal, we calculate the width of the zone a and the time of the chemical reaction τ , as well as the pressure P_1 and the mass velocity u_1 of the detonation products at the Chapman-Jouguet point.



Fig. 41.

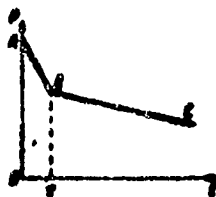


Fig. 42.

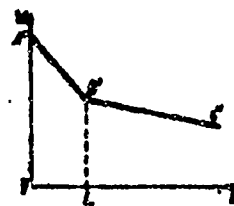


Fig. 43.

Fig. 41. Assemblage of the charge for experiments on determining the rate of travel of the free surface of metal plates W . 1 - explosive; 2 - plane detonation front; 3 - metal plate.

Fig. 42. Overall view of the pressure profile in a detonation wave according to the modern theory of detonation. OA - shock front; AB - chemical reaction zone (chemical peak); BC - region of isentropic escape of the detonation products; B - Chapman-Jouguet point.

Fig. 43. Assumed dependence of the rate of travel of the free surface of metal plates on their thickness. A'B' - region of influence of the chemical peak; B'C' - region of influence of the isentropic rarefaction wave.

Later, the chemical peak in a detonation wave of condensed explosives was successfully recorded by the electromagnetic method [110]. This method, suggested by Zavoytskiy, allows us to track directly the velocity of the mass flow behind the front of a shock or detonation wave. The concept of this is depicted in brief in work [71]. Methods of the experimental determination of the parameters of detonation are viewed in more detail in work [111]. Figure 44 shows typical examples of oscillograms of $u(t)$ on an explosive-paraffin interface and in paraffin at a significant distance from the interface of the explosive. In an inert medium one observes a sharp rise in u in the front of the shock wave, in then a smooth drop. But if the sensor of the mass velocity is placed on the explosive-inert material interface, then a peak on the leading edge is clearly visible on the recording of $u(t)$. The peak behind the front of the detonation wave is also observed with the direct placement of the sensor in the explosive, if the time of the steep slope of the front of the oscillograms is less than the time of existence of the chemical peak τ . As numerous experiments have shown, the presence of the chemical peak of the mass velocity is characteristic for normal detonation regimes of cast, pressed and compact charges of solid explosives, significantly differing both in the heat of explosion, as well as in the pressures of detonation (pentrite, tetryl, hexogen, trotyl, ammonium nitrate and so forth). As an example Fig. 45 shows oscillograms of the recordings of $u(t)$ behind a detonation wave front for several explosives.



Fig. 44. Typical recordings of $u(t)$ by the electromagnetic method behind the front of a detonation and of a shock wave. The sensor is placed on the trotyl-paraffin interface a) and in paraffin at a distance of 10 mm from the interface b); time markers follow every $2 \mu s$; charged density of the trotyl is 0.8 g/cm^3 .

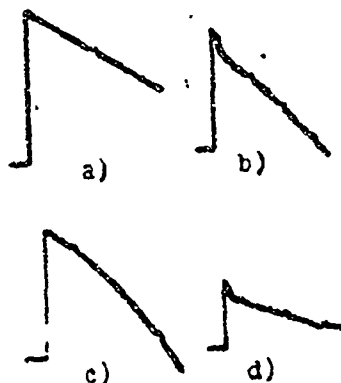


Fig. 45. Typical oscillograms of the mass velocity for detonation waves in charges of explosives of various initial density ρ_0 . a) trotyl, $\rho_0 = 1.59 \text{ g/cm}^3$; b) trotyl, 0.7; c) tetryl, 1.67; d) tetryl, 0.9 g/cm^3 .

With high densities in pressed charges of powerful explosives (pentrite, hexogen, tetryl, trotyl) the mass velocity peak is not resolved by the electromagnetic method, since the time of its existence is less than the oscillograph's resolution time. We use an oscillograph with a resolution time of $\sim 0.1 \text{ } \mu\text{s}$. Besides this, the time of the steep slope of the leading edge of the oscillogram depends on the inertia of the sensor and on the curvature of the wave front. The sensor's inertia exerts the greatest influence on this time, as experiments with sensors made from various materials and with various thicknesses have shown. The dependence of the time of the steep slope on the width of an aluminum sensor, obtained during measurement of $u(t)$ behind a flat shock wave in paraffin, is characterized by the following data:

width of the sensor, mm	1.0	0.35	0.16	0.1
time of the steep slope, μs	0.45	0.12	0.1	0.1

As can be seen, good results can be obtained by using sensors made from aluminum foil with a thickness of 0.1-0.2 mm. The use of sensors with a lesser thickness is not always advisable, since they often tear and do not produce satisfactory recordings.

In accordance with the conclusions of the contemporary hydrodynamic theory the deflection on the $u(t)$ dependence should be viewed as the Chapman-Jouguet point. At this point, independent of whether the shock front of the detonation wave is smooth or not, according to the phenomenological theory expounded above, the condition of tangency is fulfilled in the overwhelming majority of cases.

A check for the fulfillment of the Chapman-Jouguet selection principle can be made experimentally, if an overcompressed detonation wave is created and if its propagation is tracked. If the detonation wave in a self-sustaining regime would be inadequate, then at a certain stage of its formation from an overcompressed wave the formation of a two-wave flow configuration would have to be observed (see Fig. 8b). The recording of the profile of the mass velocity using the electromagnetic method with such a formulation of the experiment in nitromethane and trotyl (initial density of 0.75 g/cm^3) does not detect the suggested two-wave configuration in the entire region of the transition to normal mode. In experiments of this type overcompression was accomplished by the detonation of a trotyl charge with an initial density of 1.59 g/cm^3 of the same diameter as in the main charge (60 mm).

Other evidence for the presence of a supersonic flow of the products behind the front of detonation waves, the propagation of which would occur in an insufficiently compressed regime, should have been the region of constant dynamic parameters. This region would be directly behind the detonation front and would be inaccessible for rarefaction waves. Such a region with the use of a flow profile by the electromagnetic method behind the front of self-propagated detonation wave in a wide class of explosives was also not detected.

For ideal detonation ($L \gg a$, $d \gg a$, where a , L and d correspond to the width of the zone of chemical reaction, the length and the diameter of the charge. The profile of the mass velocity within the limits of the chemical peaks is determined by the kinetics of the chemical reactions, and also by the kinetics of the dissipative processes of attenuation of the pulsation. Conversely, in a rarefaction wave a drop in the mass velocity must first be nonstationary and depending on L , while with sufficiently large L it must become stationary and depend on d . The latter is connected with the fact that the dispersion of the product, which on the axis of the charge is one-dimensional at first, eventually becomes basically three-dimensional. For an example, Figs. 46 and 47 show the dependences of $u(t)$, obtained by the electromagnetic method in charges of tetryl and trotyl of various dimensions. In these experiments the width of the reaction zone was not resolved. From the graphs it is clear that, beginning with $L \geq (2.5-3) d$, the profile of the mass velocity becomes stationary for every detonation wave. Since the initial value of the mass velocity in all the curves is one and the same, it can be transferred to the Chapman-Jouguet point.

A comparison of the data obtained by the electromagnetic method with the results of the split-off method for composition "B" [96] and trotyl [109] showed their strong distinction. Thus, for cast composition "B" $\tau_1 = 0.32 \mu s$, while according to the split-off method $\tau_{\text{split}} = 0.027 \mu s$. An analysis of the possible errors of both methods led to the conclusion that the deviation in the dependence of $W(l)$ when $l_1 = 1 \text{ mm}$, obtained in cast composition "B," does not correspond to the actual position of the Chapman-Jouguet point. The second deviation when $l = 4-5 \text{ mm}$ corresponds to it. Daff and Houston did not detect a second breakoff due to the insufficient width of the plates used by them, which can be seen from a comparison of their data with the dependence $W(l)$, obtained on thicker plates by Deal [112] (Fig. 48). The dimensions of the charges in comparable experiments were approximately identical. There is an insignificant difference

in the composition and the density of the charges. Therefore the parameters of detonation, obtained in work [96] for cast composition "B" with $\rho_0 = 1.67 \text{ g/cm}^3$, were recalculated for the density of $\rho_0 = 1.71 \text{ g/cm}^3$, at which the measurements in work [112] were conducted.

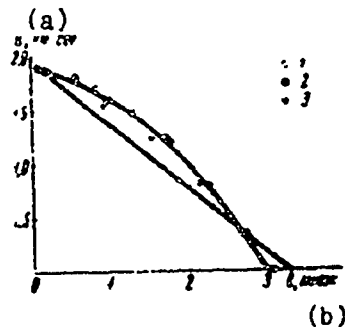


Fig. 46. Dependence of the mass velocity on the time behind the detonation wave front in tetryl with various values of L/d . Straight line - $L/d = 2$; 1 - $L/d = 3$; 2 - $L/d = 4$; 3 - $L/d = 6$. KEY: (a) u , km/s; (b) t , μs .

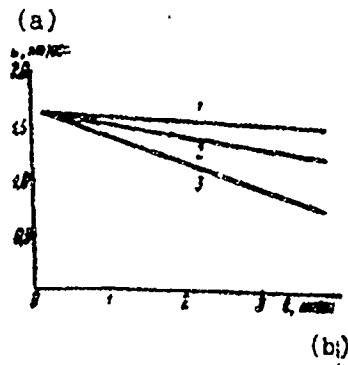


Fig. 47. Dependence of the mass velocity on the time behind the detonation wave front in trotyl with various values of L/d . 1 - $L/d = 2.5$ ($d = 100 \text{ mm}$); 2 - $L/d = 2.25$; 5.75; 9.75 (60 mm); 3 - $L/d = 2.5$ (40 mm). KEY: (a) u , km/s; (b) t , μs .

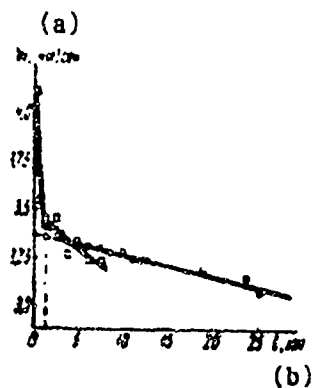


Fig. 48. Dependence of the speed of the free surface of the plate on its width according to the data of Daff and Houston (square points) and of Deal (round points). KEY: (a) W , km/s; (b) L , mm.

The calculation of the mass velocity u and the width of the zone of chemical reaction a from the point of the second deviation gives values ($u = 1.98$ km/s, $a = 1.2$ mm), which coincide within the limits of accuracy of experiment with the data of the electromagnetic method ($u = 1.94$ km/s, $a = 1.75$ mm) [110].

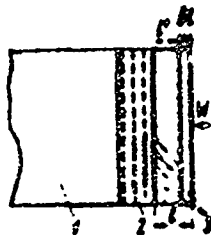


Fig. 49. Assembly scheme of the experiment with artificial split off. 1 - Explosive; 2 - paraffin substrate with a thickness of 10 mm; 3 - aluminum unit; W - weight of travel of the free surface.

For the bend in the $W(l)$ dependence experimenters recently obtained $\rho_0 = 1.63$ g/cm³ in work [113] for pressed trotyl. In conformance with this dependence the author divided the pressure profile in the detonation wave into three zones: 1) the reaction zone - from the shock front up to the first deflection when $l_1 = 1$ mm, 2) the dissipation zone - from the first up to the second deflection and 3) the zone of the slow pressure drop, following the second deflection. The first deflection is put into conformance with the Chapman-Jouguet point, proceeding from the results of Daff and Houston. However, an analysis of the causes of the appearance of two deflections on the $W(l)$ dependence, obtained on the cast composition "B" and pressed trotyl, lead to the conclusion that the deflection when $l \approx 1$ mm is a consequence of the phenomenon of split off.

The distortion of the $W(l)$ dependence as a result of the phenomenon of split off is clearly visible from the following data. On the final basis (1-2 mm) the rate of travel of the free surface W of the aluminum unit having a thickness of 8 mm was measured. The shock wave was created by the detonation of a charge of trotyl $\rho_0 = 1.44$ g/cm³. Between the charge and the

aluminum unit a plate made from paraffin 10 mm thick was placed (Fig. 49). The pressure peak, corresponding to the zone of chemical reaction, completely attenuates in the paraffin, and in the aluminum a shock wave of approximately triangular profile is propagated. If the aluminum unit is assembled from two parts l' and δl of different widths, preserving, however, a mutual thickness $l = l' + \delta l = 8$ mm, then it turns out that W depends on δl . From the results of the experiment (Fig. 50) it is clear that with an increase in δl right up to a certain value $\delta l_0 = 1$ mm W changes and only when $\delta l > \delta l_0$ remains constant and equal to the corresponding value for a continuous plate $l = 8$ mm.

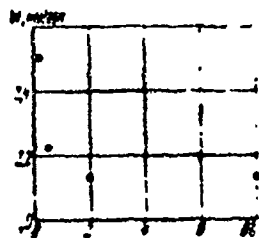


Fig. 50. Speed of the free surface W as a function of δl (artificial split off).

[$\text{км/сек} = \text{km/s}$]

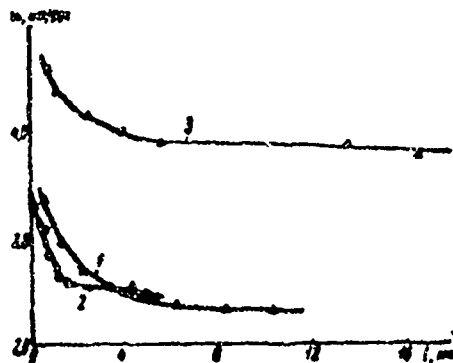


Fig. 51. Dependence of $W(l)$, obtained during detonation of charges of trotyl (1 and 2) and of alloy TG 50/50 (3).

[$\text{км/сек} = \text{km/s}$]

The only possible explanation of the detected dependence consists in the fact that during the passage of the shock wave to the free surface of the unit a plate with thickness $\delta l_0 \approx 1$ mm is split off. This thickness depends on the pressure profile in the shock wave and the dynamic tensile strength of the material of the plate. In the examined experiments the plates with thickness $\delta l < \delta l_0$ fly off completely, and the dependence $W(\delta l)$ is a consequence of averaging of the impulse of part of the shock wave on the plate of given thickness. When $\delta l > \delta l_0$ the split-off plate flies off, and therefore W is constant. Analogous experiments were conducted with continuous plates ($l = 8$ mm), in which the split-off plates were collected in water. Their thickness turned out to be close to 1 mm.

The examined phenomenon, apparently, takes place for the split off method and in determining the pressure profile behind the front of a detonation wave. We conducted a number of measurements using the method of artificial split off, when to determine the dependence $W(l)$ two plates were employed. The thickness δl was constant here and certainly less than the thickness of the natural split off plate. The results of such experiments with charges of trotyl ($\rho_0 = 1.59$ g/cm³) with a diameter of 40 mm are shown in Fig. 51 (curve 1). In these experiments plates made from aluminum with $\delta l = 0.3$ mm were employed. For comparison there (curve 2) the results of the experiments with the continuous blades are shown. It is clear that on curve $W(l)$, obtained from the experiment on plates without official split off, there is no deflection when $l \approx 1$ mm. One split off when $l \approx 4$ mm is observed also on curve $W(l)$, obtained in cast charges of trytol-hexogen 50/50 ($\rho_0 = 1.68$ g/cm³) with a diameter of 60 mm (curve 3). When this dependence was obtained, plates made from magnesium with $\delta l = 0.5$ mm were used. Calculation of the parameters and of the width of the chemical reaction zone from the point of deflection on curve $W(l)$, obtained for samples with artificial split off, produce values which coincide with the limits of accuracy of experiment with the data of the electromagnetic method.

It should be noted that, besides the examined effect in determining τ from the method of split off even with artificially calculated plates, a strong understating of the result is possible due to the effect of the shock wave reflected from the plate. This influence depends on the relationship of the dynamic rigidities of the explosive and the material of the plate, and also of the character of dependence $\tau(P)$. The coincidence of the values of time of chemical reaction, mass velocity and pressure, determined by the split off method with a calculated plate, with the corresponding values, measured by the electromagnetic method for alloys of trotyl with hexogen and pressed trotyl ($\rho_0 = 1.59 \text{ g/cm}^3$), bears witness to the fact that in the given case the effect of the reflected waves is small. Evidently, the effect of a reflected shock wave on measurements by the split off method will be significant in experiments with charges of compact density [114].

The ratio of the mass velocity on the shock front to its value at the Chapman-Jouguet point u_ϕ/u_1 for various explosives fluctuates within a range of 1.3-1.6. An estimate of this ratio from experimental adiabatic shock curves existing for certain explosives gives a value of $u_\phi/u_1 \approx 1.5$ [115, 116], which is significantly less than the theoretical value for gases $u_\phi/u_1 = 2.0$ (evidently, this is related with the difference in the equations of state of the initial explosive and of the detonation products).

The presence of a chemical peak is characteristic for a detonation wave and distinguishes it from the transient processes, arising during initiation of detonation by the shock wave or during its attenuation in charges of small diameter ($d < d_{kp}$). As was shown in the analysis of initiation of detonation of solid explosives by a shock wave, in the region of formation of the detonation wave from a shock wave at first the profile $u(t)$ does not have a clearly expressed peak. The latter is manifested

only in those stages of development of a process, when the speed of the front and the other parameters approach detonation values. A similar picture of the transformation of the profile $u(t)$, but in reverse order, is observed in the case of attenuation of detonation in charges when $d < d_{np}$. Figure 52 shows, by way of example, oscillograms of $u(t)$ in a detonation wave with various charged diameters. Simultaneous measurement of the mass velocity and the velocity of the front shows that the profile u with a clearly expressed peak on the leading edge corresponds to steady-state detonation (1, 2, 5, 6), but the other profiles refer to an attenuating wave (3, 4, 7, 8). Qualitatively, this means that the mechanism of propagation of normal detonation in charges of various diameters is identical.

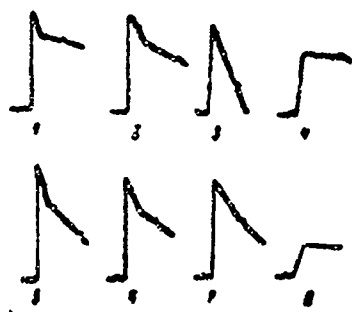


Fig. 52. Examples of oscillograms of the recording of $u(t)$ behind a detonation wave front in charges of trotyl of various diameters. Upper row - cast trotyl ($\rho_0 = 1.63 \text{ g/cm}^3$); d (in mm): 1 - 40; 2 - 20; 3 - 16; 4 - 16. Lower row - trotyl; ($\rho_0 = 1.0 \text{ g/cm}^3$); d (in mm): 5 - 40; 6 - 30; 7 - 22.5; 8 - 22.5.

The presence of a peak for the mass velocity (for pressure) on the front of the detonation wave in cast, pressed and compact charges testifies to the fact that the substance at first is compressed by the shock front, and then reacts. The explosive's compression time turns out to be significantly less than the reaction time. Consequently, in the propagation of detonation in solid explosives a leading role is played by the shock wave, i.e., formerly the detonation process is accomplished according to Zel'dovich's scheme. This gives us the basis for thinking unjustified the criticism of the dynamic theory in Cook's viewpoint, which denies the existence of a chemical peak in the detonation wave [21].

The presence of a clearly expressed chemical peak in the detonation wave front of solid explosives also points out the untenability of the jet mechanism as a model of detonation propagation. If this model existed, the front of the detonation wave would be greatly blurred [117]. From the model of detonation propagation by stream products one should distinguish between the mechanism of "explosive combustion" as a means for the occurrence of the chemical reaction behind the shock front of the detonation wave. This means that there still remains the possibility of conductive ignition and combustion of the particles of the explosive behind the front at the sites of contact with the products or with compressed and heated air. It is also possible that the role of the products amounts to only purely shock action on the explosive.

§ 2. The Effect of the Gas-Permeability of the Medium on the Propagation of Detonation

The propagation of detonation in charges made from nitroglycerine powder NB (the powder density is 1.63 g/cm^3) has been studied. The experiments were distinguished by the configuration and placement of the individual elements making up the charges. In all cases the diameter of the charges were 60 mm, the density - 1.3 g/cm^3 . The charges of the first type consisted of a flatly packed powder rod of NB, placed along the axis of the charge. The diameters of the rods in the rod in the various series of experiments were 2 mm and 5 mm, which is less than the critical diameter for a compact powder NB (8-10 mm [118]). Charges of this type were perforated in their entire length by longitudinal passages, into which the detonation products could penetrate. Charges of the second type were a set of plates made of NB powder, placed normal to the axis of the charge and separated by air gaps. With a plate thickness of 3 and 5 mm (various series of experiments) the air gaps were 0.8 and 1.3 mm, respectively. This ensured the

same average charging density of 1.3 g/cm^3 . In such charges the detonation products of the individual layers make an impact on the explosive layer lying in front of them. Here the contact surface of the detonation products with the substance is sharply reduced. And, finally, as the third type ordinary charges were used with random placement of the powder particles of NB with a transverse size of 2 mm.

Experiments with charges of the first type produced the following results. With the initiation of the explosive lens, separated from the charge by a plate made of Plexiglas 2 mm thick (the plate prevents the penetration of PD of the initiator into the passages), the explosion occurred on the interface. High-speed photography shows that along the axis of the charge the process propagates with intensive luminescence (1, Fig. XVI). At a significant distance from the front of this luminescence, the front of a second process, accompanied by the dispersion of the substance to the sides, propagates. An electromagnetic sensor also records the two mass flows, which are noticeably separated in time (Fig. 53). The setup of this experiment is given in Fig. 54. It is evident that the intensive luminescence of the photograph and the first signal on the oscillogram correspond to the escape of the explosion products through the passages; the dispersion of the substance to the sides and the second intensive signal with the abrupt leading edge on the recording of $u(t)$ refer to a process, which is also properly detonation. In the charges of the first configuration, despite the presence of the products in front of the main wave front, detonation does not propagate steadily, and the speed of its front is reduced in proportion to the distance away from the site of the initiation.

In charges of the second and third types detonation propagates steadily. The basic difference in these versions consists in the fact that in the two last cases the products have no possibility of significantly expanding, they are decelerated with impact against

the layers or powder particles, causing a shock wave in them. The measurement of the front velocity on the thickness of the plate, the mass velocity on the interface of the air and plate and in the plate itself (these speeds are equal) during the detonation of the charges of the second type enabled us to calculate the pressures developed during deceleration of the products on the interface with the plate of the powder and in the plate itself. They proved to be close ($\sim 190,000$ atm). It is apparent also during detonation of actual charges of compact density with random distribution of particles the products at the sites of deceleration create pressures which are practically no different from those average pressures determined in the experiment.



Fig. 53. Oscillogram of the mass velocity in a charge of powder NB with longitudinal passages at a distance of 50 mm from the initiation site. 1 - Weak signal from the flow of products in the channels; 2 - second signal from the detonation front.

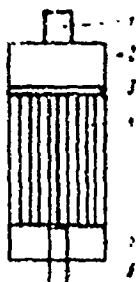


Fig. 54. Layout of the experiment to determine the mass velocity in charges with longitudinal passages. 1 - Explosive booster tablet; 2 - explosive lens; 3 - plate made from Plexiglas with a thickness of 3 mm; 4 - charge made from rods of NB powder; 5 - tablet made from compact NB powder; 6 - sensor for recording the mass velocity.



Fig. 55. Oscillogram of the mass velocity in charges made from rods of NB powder with passages plotted with paraffin.

The role of the pressure in the initiation of the reaction is even more clearly visible from experiments with the same charges of the first and second types, but without air gaps. If the passages in the charges of the first type are filled with paraffin, detonation in them propagates stably and the $u(t)$ profile has the usual form (Fig. 55). The detonation rate in this case coincides with the detonation rate of compact charges of NB powder ($D = 7.6$ km/s). In similar experiments with charges of the second type the detonation rate increased up to 7.2 km/s (instead of $D = 5.7$ km/s in experiments with air gaps), but remained less than the detonation rate of compact charges. The transmission of detonation from layer to layer is accomplished here by the shock wave, contact of the explosive with the products is eliminated, and the detonation process proceeds more intensively.

Thus, from the cited data it follows that the products of the explosion are primarily an instrument for the creation of a shock wave and for initiation as a result of shock heating of the chemical reaction. The pressure created during deceleration of the products against the barrier depends on the degree of their expansion. Under certain conditions in charges with axial passages, which are periodically covered by layers of explosives, it is possible to have an average propagation rate of the front greater than for a compact charge of the given explosive [119]. Initiation of the reaction is accomplished here basically as a result of the shock activity of the products. In actual charges of porous explosives the surface of contact of the products and of the heated air with the substance in the reaction zone may turn out to be much greater and conductive heat exchange will become significant. For further analysis of these problems it is essential to clarify the influence of various factors directly on the time of the chemical reaction in the detonation wave.

§ 3. Effect of the Structure and of the Charged Diameter on the Detonation Parameter

Influence of the charge density

In the experiments regular explosives of the following grain sizes were used: trotyl ~ 0.12 mm, hexogen ~ 0.1 mm, tetryl ~ 0.25 mm, stabilised pentrite ~ 0.45 mm, dina ~ 0.7 mm. The grain size in the pressed charges of the same explosives were not checked. Cast charges of trotyl and of trotyl with hexogen (TG) were obtained from melting with careful stirring. The pour off had a fine-crystal structure. The diameter of the cast charges was 60 mm, that of the others - 40 mm. Initiation was done using a booster tablet made of TG 50/50 with a weight of 10 g and an explosive lens, forming a flat front. Experiments with charges of various lengths (L) showed that with a ratio of $L/d \geq 2-2.5$ the parameters of the detonated wave and the reaction time on its front do not depend on the length of the charge. Therefore, in the majority of the experiments the charge length was not less than 2.5 times greater than its diameter.

The mass velocity u_1 and the chemical reaction time τ_1 were determined from the point of break off of the $u(t)$ profile. From the values of D , u_1 and τ_1 the other parameters at the Chapman-Jouguet point were calculated: the pressure $P_1 = \rho_0 u_1 D$, the density of the products $\rho_1 = \rho_0 D / (D - u_1)$, the polytropy factor of the explosion products $n = D / u_1 - 1$, the width of the zone of chemical reaction $a = (D - \bar{u}) \tau_1$. The polytropy factor relates the pressure P and the density of the detonation products (ρD) in the environment of the Chapman-Jouguet point: $P = A\rho^n$. The average value of the mass velocity in the zone of reaction was taken as equal to $\bar{u} = (1.25-1.3) u_1$, since for the majority of solid explosives the value of the mass velocity on the shock front is $(1.5-1.6) u_1$. The accuracy of determining $\Delta u/u$ is approximately equal to 3%, while $\Delta \tau_1/\tau_1 \sim 10-15\%$. Experimental

data are shown in Table 1. For charges of trotyl with an initial density of $\rho_0 = 1.59 \text{ g/cm}^3$ u_1 and a were obtained by the split-off method with artificial split off.

From the presented data it follows that for all the investigated explosives the detonation parameters (D , u_1 , P_1 , ρ_1) increase with a rise in initial density. The pressure in the detonation products grows with the increase in ρ_0 as a result of the rise in both D , as well as in u_1 and reaches $\sim 300,000 \text{ atm}$ in powerful explosives. Values of the polytropy index n for the investigated explosives differ somewhat from one another with identical pressures, which apparently is connected with a difference in the composition of the PD. For all explosives an increase in ρ_0 the polytropy index at first rises, and then becomes constant or even falls somewhat. But in general under great pressures ($150,000$ – $300,000 \text{ atm}$) the values of n are close to three. For all the studied explosives with an increase in pressure in the detonation wave the time and the width of the zone of chemical reaction are decreased.

Attention is drawn to the significant influence of the initial structure of the explosive on the reaction time. In cast TNT explosives in comparison with pressed the reaction time in the detonation zone is clearly greater. The effect of the initial structure of the explosive on the reaction time in the detonation wave should be especially noticeable, if experiments are conducted on charges of various diameters, when the initial structure (the size of the particles) influences the parameters of detonation (D , P and so forth).

Table 1. Dependence of the detonation parameters and the chemical reaction time on the density of the charge of solid explosives.

Р-с. ступ	D, км/сек	Взрывное	P _с , тыс. атм	Р-с. ступ	В	Взрывное	В, мкс
(1) Тротил							
1.50	6.91	1.01	973.0	2.02	3.3	0.2	0.97
1.63	6.90	1.04	942.0	1.80	3.3	0.2	1.0
1.75	6.50	1.06	923.3	1.77	3.29	0.22	1.25
1.90	5.0	1.32	63.0	1.35	3.20	0.47	1.23
0.90	4.24	1.06	23.4	1.09	3.12	0.86	2.33
(2) Ливей TNT							
1.02	6.94	1.02	923.2	2.11	2.3	0.23	1.27
(3) Гексорол							
1.72	8.65	2.12	203.5	2.29	3.0	<0.1	<0.7
1.60	8.13	2.0	200.0	2.12	3.05	<0.2	<1.0
1.46	7.00	1.86	206.0	1.93	3.05	<0.2	<1.0
1.44	7.53	1.90	195.2	1.89	3.06	0.2	1.0
1.39	7.0	1.82	194.0	1.75	3.06	0.24	1.12
1.30	6.14	1.76	180.0	1.54	2.92	0.28	1.20
0.62	5.00	1.72	96.5	1.35	2.87	0.60	1.43
0.70	4.56	1.45	47.2	1.02	2.20	0.85	1.53
0.26	4.05	1.23	21.5	0.85	1.92	0.70	1.57
(4) Прессованный ТГ 36/64							
1.44	7.53	1.20	257.5	2.24	3.0	<0.1	<0.5
1.40	6.93	1.66	100.0	1.84	3.17	0.2	1.6
0.33-0.9	5.40	1.39	67.0	1.17	2.91	0.5	2.16
(5) Литой ТГ 36/64							
1.71	8.0	1.94	206.0	2.26	3.13	0.22	1.76
(6) Литой ТГ 50/50							
1.63	7.63	1.83	215.0	2.25	2.84	0.25	1.33
(7) Тетрил							
1.05	7.50	1.57	235.6	2.24	3.0	<0.1	<0.6
1.70	6.03	1.54	140.0	1.77	3.20	0.21	0.96
0.9-0.85	5.26	1.34	64.6	1.20	2.0	0.41	1.43
(8) Стабилизированный ТЭН							
1.04	8.10	1.63	266	2.14	3.02	<0.1	<0.5
1.51	7.42	1.67	157	1.95	3.44	0.16	0.84
0.16	5.9	1.29	64.5	1.25	3.14	0.33	1.53
(9) Дина							
1.04	7.00	2.06	253	2.23	2.76	<0.1	<0.6
1.50	7.00	1.64	155.1	1.75	3.26	0.21	1.02
0.06	5.06	1.20	65.1	1.20	3.05	0.34	1.64

KEY: (1) Trotyl; (2) Cast TNT; (3) Hexogen;
 (4) Pressed TG 36/64; (5) Cast TG 36/64;
 (6) Cast TG 50/50; (7) Tetryl; (8) Stabilized
 pentrite; (9) Dina.

[г/см³ = г/см³; км/сек = км/с; тыс. атм =
 = thousands of atm; мксек = μs]

Effect of the diameter of the charge
and of the size of the initial
particles on the parameters
and reaction time in the
detonation wave

The majority of experiments were conducted with charges of cast trotyl of two types of castings and with charges of trotyl, NB powder, hexogen and compact-density ammonium nitrate. The trotyl castings of the first type were obtained by cooling the melt with continuous stirring. They had a homogeneous fine-crystalline structure throughout the entire cross section of the charge. The density of such castings, determined by analytic suspension in water, amounted to 1.62 g/cm^3 . Castings of the second type were manufactured similarly, but the melt was cooled without stirring. As a result castings were obtained with large crystals, extending from the periphery to the center, and their density was 1.6 g/cm^3 on the average. Charges of NB powder were manufactured from particles of spherical form with a specific weight of 1.63 g/cm^3 . The particle size of the compact-density charges was determined by sifting through analytic sieves and a composition close to monodispersed was selected.

In all the experiments a powerful initiator was used, and the parameters were determined under steady-state detonation conditions. The length of the charges under conditions close to critical was $(10-12)d$. Values of u_1 , τ_1 and other parameters were calculated from the point of deflection of the profile $u = u(t)$, just as in the case of ideal detonation regimes. The calculation of other parameters was made using the laws of conservation for a one-dimensional flow, i.e., expansion of the tube of the flow due to the curvature of the wave was disregarded. The error here is apparently insignificant, since τ_1 are small, and measurements are made on the axis of the charge. Table 2 shows experimental values of the parameters of detonation of a number of explosives in charges of various diameters and with various initial structures.

Table 2. The dependence of the parameters of detonation on the diameter of the charge and the grain size.

d, mm	$D, \text{m/sec}$	$\rho, \text{g/cm}^3$	$P, \text{atm/cm}^2$	$q, \text{J/cm}^2$	n	T, mm	σ, mm
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(1) Литей тротил первого типа станок. $\rho = 1,65 \text{ g/cm}^3$

80	6,86	1,63	163,3	3,11	2,3	0,36	1,37
60	6,86	1,60	160,1	2,90	2,34	0,33	1,33
50	6,80	1,52	160,5	2,78	2,53	0,30	1,47
35	6,86	1,23	160,7	2,88	6,9	0,34	1,37
25	6,75	1,31	143,2	2,91	6,15	0,30	1,34
20	6,64	1,54	133,3	1,90	6,25	0,34	1,71
16	6,53	1,20	126,7	1,96	6,43	0,23	1,94
16*	6,36	1,1	113,3	1,95	6,70	0,36	1,77

(2) Литей тротил второго типа станок. $\rho = 1,65 \text{ g/cm}^3$

80	6,86	1,60	173,5	2,10	3,20	0,30	1,63
60	6,74	1,60	150,9	2,16	3,52	0,245	1,54
35	6,70	1,43	133,3	2,03	3,66	0,31	1,30
20	6,57	1,30	140,8	2,06	3,50	0,36	1,85
27,5*	6,50	1,20	112,0	1,95	6,15	0,35	1,67

(3) Тротил мелочный, $\rho = 1,10 \text{ g/cm}^3$, $\delta = 0,1 \text{ mm}$

120	5,13	—	—	—	—	—	—
100	5,10	1,54	78,5	1,43	2,31	0,43	1,23
80	5,16	1,50	78,6	1,42	2,30	0,62	1,26
60	5,16	1,53	78,6	1,43	2,31	0,66	1,65
40	5,0	1,32	68,0	1,35	2,73	0,47	1,88

(4) Тротил чешуированный, $\rho = 1,10 \text{ g/cm}^3$, $\delta = 0,5 \text{ mm}$

120	5,14	1,50	78,3	1,42	2,30	0,51	1,63
80	5,0	1,44	72,0	1,44	2,17	0,52	1,68
60	4,80	1,60	67,2	1,41	2,43	0,54	1,71
40	4,50	1,27	57,2	1,39	2,54	0,57	1,68

(5) Тротил 64%, $\rho = 0,95 \text{ g/cm}^3$, $\delta = 0,5$ и 16%, $\delta = 0,1 \text{ mm}$

80	5,0	1,31	82,2	1,29	2,84	0,56	1,91
50	4,93	1,30	81,4	1,30	2,79	0,55	1,70
40	4,14	1,27	57,2	1,25	2,86	0,54	1,85
20	4,14	1,30	55,2	1,28	3,03	0,70	2,20
27,5	4,53	1,18	50,8	1,28	2,94	0,74	2,25
25	4,13	1,0	44,3	1,23	3,02	0,85	2,53
22,5*	4,10	1,00	39,9	1,25	3,10	0,90	2,58

(6) * Критический диаметр тротила.

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Table 2 (Continued).

δ , cm	P_0 , g/cm ²	η_0 , g/cm ²	P_0 , g/cm ²	P_0 , g/cm ²	α	η_0 , g/cm ²	α
(7) Порох НВ, $\rho_0 = 1,60$ g/cm ³ , $\delta = 0,25$ мм							
60	5,30	1,00	76,6	1,63	2,51	1,64	3,22
40	5,93	1,24	64,3	1,24	2,92	1,21	3,72
20	6,95	1,0	46,6	1,27	3,66	1,20	3,90
(8) Порох НВ, $\rho_0 = 1,10$ g/cm ³ , $\delta = 0,43$ мм							
60	5,68	1,70	52,6	1,63	2,30	1,04	3,26
40	5,64	1,65	40,7	1,64	2,29	1,06	3,39
20	5,90	1,42	72,4	1,62	2,56	1,09	3,46
40	4,56	1,16	53,0	1,56	2,83	1,22	3,66
20	4,21	1,00	43,1	1,39	3,26	1,41	3,88
(9) Порох НВ, $\rho_0 = 1,10$ g/cm ³ , $\delta = 2,0$ мм							
60	4,72	1,66	68,5	1,44	2,29	1,46	3,12
40	4,21	1,26	55,2	1,42	2,35	1,31	3,17
20	3,82	0,96	34,5	1,39	2,69	1,70	3,27
40	—	—	—	—	—	—	—
(10) Порох НВ/Н ₂ O, 76/24, $\rho_0 = 1,31$ g/cm ³ , $\delta = 0,43$ мм							
100	6,03	1,10	93,5	1,63	4,1	1,16	5,22
40	6,03	1,18	93,5	1,63	4,1	1,16	5,22
60	—	—	—	—	—	—	—
(11) Порох НВ, $\rho_0 = 1,60$ g/cm ³ , $\delta = 0,63$ мм							
60	5,40	1,60	56,5	1,42	2,36	1,0	3,32
(12) Гексоген, $\rho_0 = 1,60$ g/cm ³ , $\delta = 1,8$ мм							
40	6,00	1,58	95,0	1,36	2,60	0,67	2,50
30	5,60	1,45	84,5	1,33	3,0	0,75	2,80
22	5,14	1,16	59,8	1,29	3,62	0,60	2,90
18	3,03	0,66	64,5	1,21	4,72	0,92	3,16
(13) Гексоген, $\rho_0 = 1,60$ g/cm ³ , $\delta = 0,15$ мм							
40	6,0	1,63	99,0	1,36	2,64	0,67	2,62
(14) Гексоген, $\rho_0 = 1,60$ g/cm ³ , $\delta = 0,43$ мм							
60	6,66	1,60	97,0	1,33	2,76	0,69	2,74
(15) Гексоген/Н ₂ O 3:1, $\rho_0 = 1,35$ g/cm ³ , $\delta = 0,63$ мм							
40	6,45	1,50	121,0	1,76	3,3	0,72	3,24
(16) Гексоген микрокристалл, $\rho_0 = 1,60$ g/cm ³ , $\delta = 1,3$ мм							
30	6,06	1,66	96,5	1,31	3,20	0,65	1,63
(17) — Данных нет.							
(18) — Данных нет, $P_0 \leq 3$ мм рт. ст.							

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Table 2 (Continued).

d, mm	ρ_0 , g/cm ³	δ , mm	P_0 , atm	P_0 , atm	α	ρ_0 , g/cm ³	d, mm
(19) ZhV Salt peter, $\rho_0 = 0.90$ g/cm ³ , $\delta \leq 0.2$ mm							
130	2.32	0.2	25.14	1.25	2.15	2.25	4.07
140	2.47	0.25	25.25	1.25	2.25	2.30	4.12
150	2.35	0.25	24.30	1.25	2.07	2.40	5.08
160	2.20	0.25	23.4	1.25	2.05	2.5	4.79
75	2.43	0.15	29.5	1.25	2.07	2.0	4.27
70	2.9	0.45	5.24	1.15	2.15	2.15	5.34
65	1.55	0.45	7.9	1.05	2.00	4.5	5.55
60*	1.75	0.25	5.55	1.12	4.05	5.5	7.05

KEY: (1) Cast trotyl - first type of pour off, $\rho_0 = 1.62$ g/cm³; (2) Cast trotyl - second type of pour off, $\rho_0 = 1.60$ g/cm³; (3) Ground trotyl, $\rho_0 = 1.00$ g/cm³, $\delta = 0.1$ mm; (4) "Scaled" trotyl, $\rho_0 = 1.00$ g/cm³, $\delta = 0.5$ mm; (5) Trotyl 84%, $\rho_0 = 0.95$ g/cm³, $\delta = 0.5$ and 16%, $\delta = 0.1$ mm; (6) Critical diameter of the charges; (7) NB powder, $\rho_0 = 1.00$ g/cm³, $\delta = 0.26$ mm; (8) NB powder, $\rho_0 = 1.00$ g/cm³, $\delta = 0.23$ mm; (9) NB powder, $\rho_0 = 1.00$ g/cm³, $\delta = 2.0$ mm; (10) NB/H₂O powder, 76/24, $\rho_0 = 1.31$ g/cm³, $\delta = 0.43$ mm; (11) NB powder, $\rho_0 = 1.00$ g/cm³, $\delta = 0.43$ mm***; (12) Hexogen, $\rho_0 = 1.00$ g/cm³, $\delta = 1.8$ mm; (13) Hexogen, $\rho_0 = 1.00$ g/cm³, $\delta = 0.15$ mm; (14) Hexogen, $\rho_0 = 1.00$ g/cm³, $\delta = 0.45$ mm; (15) Hexogen/H₂O, 72/28, $\rho_0 = 1.35$ g/cm³, $\delta = 0.45$ mm; (16) Microporous hexogen, $\rho_0 = 1.00$ g/cm³, $\delta = 1.3$ mm; (17) Detonation attenuates; (18) Air was pumped out, $P_0 \leq 1$ mm Hg.; (19) ZhV Salt peter, $\rho_0 = 0.90$ g/cm³, $\delta \leq 0.2$ mm.

[km/cm = km/s; тыс. атм = thousands of atm; g/cm³ = g/cm³,
мксек = μ s]

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Let us examine first of all the dependence of the parameters and the width of the chemical reaction zone on the charged diameter. For all the investigated explosives D , u_1 , P_1 , and ρ_1 decrease with a decrease in the diameter of the charge. The index of polytropy of the explosion products increases noticeably with small diameters of the charge, despite the fact that the pressure is reduced. This is apparently connected with incomplete chemical reaction and to a "worsening" of the composition of the detonation products. Here two cases can be realized. It is possible for the explosive to decompose right up to the composition determined by the conditions of equilibrium with given P and T . The other variant consists in the fact that part of the explosive will not manage to appreciably react to the point of deflection of $u(t)$, but will decompose later in a rarefaction wave or will not react at all as a result of the rapid drop in pressure and temperature during dispersion.

Along with the reduction in pressure the time and the width of the chemical reaction zone increase with a reduction in the charge diameter. Such a dependence of the detonation parameters and of the width of the chemical reaction zone on the charge diameter is direct experimental confirmation of the basic concept of Khariton's principle of detonation capability [72], according to which the possibility of detonation propagation in charges of finite diameter depends on the ratio of the speeds of the energy liberation as a result of chemical reaction and energy losses due to lateral expansion, which increase with a reduction in the charge diameter. This leads to a reduction in the parameters on the shock front and to an increase in τ_1 . As can be seen from the data of Table 2, the quantitative relationship of Khariton $R_{kp} = d_{kp}/2 = ct = a_{kp}$ is not fulfilled (c is the speed of sound in PD, a_{kp} is the width of the chemical reaction zone under critical detonation conditions). Detonation ceases with charge diameters, which significantly exceed the reaction zone size. The critical reaction zone for the investigated explosives is equal to approximately $(0.1-0.2) R_{kp}$.

Let us turn to the dependence of P_1 and a on the diameter for charges of cast trotyl of the first and second types of pour offs (see Table 2). Identical values of P_1 (consequently c) and a are achieved with different diameters. Despite the fact that d_{kp} of the charges of both types of pour offs differ by 1.7 times, τ_{kp} and a_{kp} are equal within the limits of accuracy of experiment. Consequently, the relative estimate of τ with respect to the critical diameters $\tau_1/\tau_2 = d_{1kp}/d_{2kp}$ are also not confirmed. The critical diameter is determined, obviously, by a whole list of factors, which are not taken into consideration by these simple approximate relationships. Let us recall, for example, that for the initiation of detonation of one and the same explosive of different physical structure different initial impulses are required. Thus, according to the data of [108] with the initiation of detonation in normally cooled cast trotyl a portion of tetryl of 15 grams is required, in slowly cooled - 26 grams, and for very slowly cooled - 144 grams. In our conditions trotyl of the first type of pour offs detonated from a tablet made from TG with a weight of 10 grams, while trotyl of the second type of pour offs from such an initiator did not detonate.

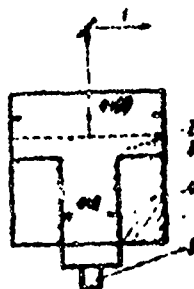


Fig. 56. Scheme of the experiment for photographing the front of a detonation wave during its passage from the charge in a steel shell into a volume. 1 - mirror; 2 - basic explosive charge; 3 - cardboard shell, 4 - steel shell; 5 - initiating charge.

To clarify the nature of the critical diameter of solid explosives it may be interesting to note the results of experiments on the passage of detonation of trotyl charges in a steel shell into the trotyl volume. The layout of these experiments is shown in Fig. 56. The charges had identical density ($\sim 10 \text{ g/cm}^3$) and

identical detonation parameters, but differed in grain size (0.7 and 2.3 mm). With the aid of a high speed photorecorder a shortening of the unperturbed region of the front of the wave under the effect of lateral rarefaction waves at various distances from the site of transition of detonation from the tube into the volume was observed. It turned out that the front of the wave is shortened more quickly, where the initial size of the explosive particles is greater. In the case of the NB powder, as can be seen from Table 2, a change in the initial grain size affects not only the value d_{np} , but also the critical parameters (D , u_1 , P_1), which are so much the lower, the greater is δ . The reaction time close to d_{np} are also different. It follows from this that it is impossible to determine τ_1 unambiguously only from value d_{np} .

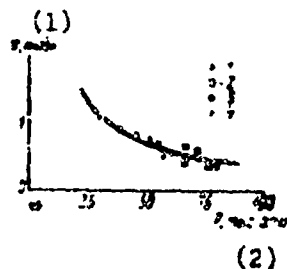


Fig. 57. Dependence of the chemical reaction time on the pressure, obtained in trotyl charges with various grain sizes (δ , in mm) with one and the same density. 1 - $\delta = 0.1-0.5$; 2 - 0.1; 3 - 2.3; 4 - 0.5. KEY: (1) τ , μs ; (2) P , thousands of atm.

From the viewpoint of the mechanism of the detonation conversion of the substance it is important to analyze the dependence of τ on the initial size of the particles in charges of compact density. If on the detonation wave front particles of explosives are burned from the surface by detonation products or by the gas heated during shock compression in the pores and burn in parallel layers, then the reaction time must be directly proportional to the initial particle size with identical pressures. However, a great difference in the initial dimensions of the particles (of 5-10 times) does not lead to such a difference in τ with identical pressures. The reaction times do not depend on the initial particle size of the explosives (NB powder, hexogen) or

they differ slightly (trotyl). Figure 57 shows the dependence of $\tau_1(P_1)$ for trotyl, obtained in charges with various initial particle sizes.

The independence of τ_1 from δ under identical pressures, shown in the example for NE powder, hexogen and trotyl, contradicts the concepts of the mechanism of the detonation conversion of a substance by means of explosive combustion of the initial particles of the explosive, accomplished as a result of their ignition by the combustion products of detonation by hot gas in the pores, or else as a result of the heating of the explosive itself at the sites of initial contact of the particles. These concepts may in some measure be consistent with the experiment, if we assume that the particles of the explosive in the front of the wave are crumbled to extremely small sizes, which with an identical amplitude of the shock wave are, practically speaking, independent of the initial size of the particles. However, then it is completely clear that it is not valid to connect τ_1 with the initial size of the particles. Consequently, the basic argument in favor of the mechanism of explosive combustion - the dependence of d_{np} on the initial particle size - also loses its force.

Crumbling of the particles in the shock wave

The behavior of the particles of the explosives in the front of the detonation itself is difficult to study, since the entire process of compression and conversion of the initial substance into the product lasts only fractions of a microsecond. Therefore, if only to obtain qualitative data it is important to find a study method, preserving, if possible, the specific conditions, which take place in actual detonation. With this purpose in mind, a procedure was developed to maintain samples of porous explosives after the shock loading up to 1500-2000 atm [120]. The layout of the experiment can be seen in Fig. 58. The presence

of a paraffin plate between a steel disk and the studied sample facilitated the determination of the parameters of the shock wave, entering into the sample, and excluded the possible influence on it of the elastic wave in the steel. The studied samples were enclosed in a glass or steel shell and put into a container with water, which ensured favorable preservation conditions. The active charge and the elements of the structure were selected in such a way, that the steel boundary was not penetrated and so that there was no contact of the studied sample with the PD.

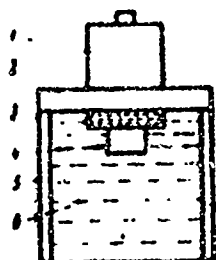


Fig. 58. Layout of the experiment for preserving the substance. 1 - Explosive charge; 2 - steel boundary; 3 - paraffin plate; 4 - studied sample; 5 - container; 6 - water.

Different variants of setting up the experiments were developed and used, in which with an identical wave amplitude the duration of its effect was measured and in which the air was pumped from the samples up to $P_0 \leq 1$ mm Hg. In the majority of the experiments, except for those indicated specially, the time of action of the shock wave was 15-30 μ s. The amplitude of the shock wave was not directly measured in the studied samples. It's measurements in paraffin produced 1700 atm.

Small differences in the initial densities of the paraffin and the studied explosives permit us to assume that the pressures in the latter were approximately the same as in paraffin, i.e., 1500-2000 atm.

The samples preserved after compression of the shock wave were studied under the microscope in order to clarify the destruction

of the initial structure of the particles and a granulometric analysis of them was made. The particles were, as a rule, large conglomerates, easily destroyed under a load of $\sim 1 \text{ kgf/cm}^2$. The breakdown of such conglomerates into particles was made using an ultrasonic disperser UZDN-1 in water. A similar treatment using ultrasonics of the initial substance, not subjected to shock action, for a significantly greater time period does not destroy the particles. After drying and separation the relative quantity n/n_Σ and the weight percent P/P_Σ of particles of given size were determined (n_Σ and P_Σ are the total number of particles at the weight of the analyzed sample, respectively).

To develop a procedure and to clarify certain general regularities of the behavior of particles of solid substance in the front of the shock wave the first experiments were conducted with samples of an inert substance at polystyrene (the natural density of polystyrene is 1.1 g/cm^3). In the initial state the polystyrene particles are completely transparent, and it is easy to observe in them the emergence of defects and crumbling after shock action. In individual granule of polystyrene with an initial cross-sectional diameter $\delta = 3-5 \text{ mm}$ is converted into a crumbled and caked conglomerate, flattened across the direction of propagation of the shock wave. A porous sample of compact density ($\sim 0.7 \text{ g/cm}^3$) of these same particles crumbles even more intensively. But if the cavities in this sample are filled with water, the particles keep their initial shape, but lose the transparency and turn out to be penetrated cracks.

The influence of the shock wave on the following explosives was further investigated: trotyl, hexogen, powder NB, ammonium nitrate. Porous samples of trotyl (a density of $\sim 1.0 \text{ g/cm}^3$) were prepared from particles of "scaled" substance with a diameter of $\delta = 0.4$ to 1.0 mm . During prolonged activity of the shock wave ($\sim 15-20 \text{ ms}$) the particles crumble, are pressed and form a single conglomerate. At individual sites of the conglomerate scorched dark spots are visible. They are disseminated into the mass of the substance

which was not touched by the composition. A reduction in the time of the effect of the shock wave of up to 3-5 μ s does not change the granulometric composition of the crumbled substance, but has a significant effect on the degree of scorching of the conglomerate. In this case in a crumbled and caked sample there can be seen only a nuclei center of the reaction with a size of ~ 0.01 μ m with a concentration of 5-10 per 1 cm^3 .

Samples of hexogen (density of ~ 1.0 g/cm^3), composed from monocrystalline particles ($\delta = 0.4-1.0$ mm), were managed to be preserved only in the experiments with air removal up to $P_0 \leq 1$ mm Hg. The samples with air burst, which was recorded from the destruction of the shell. It is difficult to judge the character of the explosion from these experiments. Preserved samples were conglomerates of crumbled and caked particles without noticeable traces of decomposition.

Samples of ballistite powder NB had an initial density of ~ 1.0 g/cm^3 and were manufactured from spherical particles $\delta = 0.37-0.5$ mm. After the action of the shock wave the samples did not crumble and did not cake, and a few particles only lost their spherical shape.

In investigating granulated ammonium nitrate with an initial density of ~ 1.0 g/cm^3 , $\delta = 0.4-1.0$ mm a steel cylinder was filled not with water, but with batting, so as not to dissolve the preserved sample. For the same reason treatment of the latter by ultrasonics was also made not in water, but in methyl alcohol. The preserved samples were crumbled and caked conglomerates without noticeable traces of decomposition.

Results of the granulometric analysis of the preserved samples for various substances are shown in Table 3 and in Figs. 59-61. For hexogen data, obtained during the action of shock waves of various intensity on the sample, are presented. A different intensity of the shock wave was obtained by varying the thickness

of the metal boundary. The parameters of the shock wave were not measured. A noticeable reduction in its amplitude could be qualitatively measured from the reduction in the deformation of the boundary.

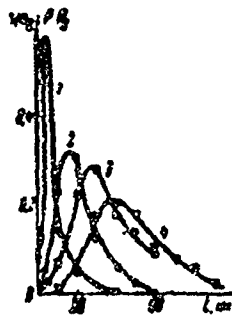


Fig. 59. Results of granulometric analysis of the preserved samples of hexogen. Quantitative (1) and gravimetric (3) distribution of particles when $P = 1500-2000$ atm; quantitative (2) and gravimetric (4) distribution of particles when $P < 1500$ atm.

[$m_k = \mu$]

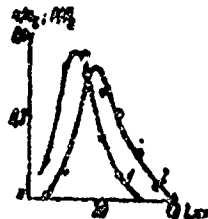


Fig. 60. Results of granulometric analysis of the preserved samples of ammonium nitrate. 1 - Quantitative distribution of particles; 2 - gravimetric.

[$m_k = \mu$]

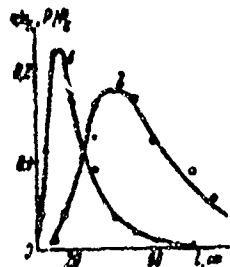


Fig. 61. Results of granulometric analysis of the preserved samples of trotyl. 1 - Quantitative distribution of particles; 2 - gravimetric.

[$m_k = \mu$]

From the presented data it is clear that even with a low (in comparison with the detonation) amplitude of the shock wave there occurs a strong change in the initial structure of porous samples of various substances. If in the case of polystyrene even around 60% (by weight) of the particles do not crumble,

then more than 90% of the mass of preserved particles of hexogen, trotyl and ammonium nitrate comprise particles, the size of which is approximately one order less than the initial size. A maximum of the gravimetric distribution corresponds in these cases approximately to an identical final size of the particles ($\sim 15-40 \mu$). The results of the quantitative and gravimetric distribution of particles of hexogen of the studied size, obtained with various amplitudes of the shock wave, allow us to draw the qualitative conclusion, that the degree of crumbling under the investigation conditions depends on the amplitude of the shock wave acting on the sample. With an increase in the pressure the weight percentage of fine particles increases and the distribution maximum shifts to the side of a decrease in their final size.

Table 3. Granulometric analysis of the crumbling of particles of polystyrene in a shock wave.

(1) Параметры	(2) Результаты анализа				
(3) Полистирол, $\delta_0 = 1,1-1,5$ мм					
l , мм	0,1	0,1-0,2	0,2-0,4	0,4-1,0	1,0-1,5
n/n_0	0,83	0,13	0,03	0,01	0,004
P/P_0	0,01%	0,04	0,07	0,24	0,64
(4) Полистирол, $\delta_0 = 3,5-5,0$ мм					
l , мм	0,4	0,4-1,0	1,0-1,5	1,5-3,0	3,0-5,0
n/n_0	0,95	0,03	0,01	0,007	0,003
P/P_0	0,03	0,34	0,66	0,32	0,18

KEY: (1) Parameters; (2) Results of the analysis; (3) Polystyrene, $\delta_0 = 1.1-1.5$ mm; (4) Polystyrene, $\delta_0 = 3.5-5.0$ mm.

The discovered change in the initial structure of the explosive is a result of the integral action on the sample of several factors, of which we should note primarily the shock compression in the front and the subsequent action of the high pressure in the rarefaction wave. It is necessary to explain which of these factors is decisive, since under detonation

conditions what is important is only what occurs with the substance on the shock front and for times, not exceeding the reaction time ($\tau_1 \leq 1.0 \mu s$).

The obtained results permit us to assume that the crumbling and pressing of the samples occurs basically in the front of the shock wave. This is borne out by experiments with polystyrene and trotyl. Thus, porous samples of polystyrene are intensively crumbled, while in water-filled samples the particles do not lose their initial shape with an approximately identical duration of the phase of compression and expansion. The difference in these two variants, apparently, is in the possibility of shifts of the substance in the very front of the shock wave in the case of porous samples. The filling of the cavities with water made the sample continuous and thus reduced the possibility of relative shifts. The shock wave amplitude increased as a result of the increase in the initial density of the sample, while the degree of crumbling fell sharply.

Experiments with samples of porous trotyl showed that the change in the length of the shock wave does not effect the final distribution of particles with respect to the dimensions, but does strongly effect the degree of scorching of the conglomerates. It follows from this that burning arises and is developed for times, significantly greater than the compression time on the front of the shock wave, while crumbling and the formation of conglomerates proceeds in the very front of the shock wave. The fact that the pumping of air from the trotyl and hexogen samples to pressures of $P_0 \leq 1 \text{ mm Hg.}$ in the first instance eliminates the appearance of scorched conglomerates, and in the second - the explosion of the samples during the experiment allows us to assume that the heating of the compressed air is the basic source of the initiation of combustion. A minimum estimate of the heating of the air can be obtained by assuming that it is compressed adiabatically up to the pressure in the shock wave.

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For $P = 2000$ atm such an estimate produces $T \approx 1000^\circ\text{K}$ [55]. It is apparent that at such temperatures and with the duration of the action of the shock wave of 10^{-6} sec the air in the pores is capable of igniting the mentioned explosive.

Along with the combustion as a result of the warming of the air in the trotyl, reaction products of fine black dots are observed. Their appearance is connected with the presence of air in the pores and the action of the shock wave. Apparently, a reason for the appearance of products of initiation of reaction is the plastic deformation of the explosive during packing in the front of the shock wave. Such facts were observed by Sukhikh and Khariton in samples of trotyl during their sufficiently rapid deformation in tests using a pile driver [12]. At the present time it is widely acknowledged that in solid explosives the excitation of the explosive with mechanical action proceeds as a result of inelastic deformation [12], but the effect of air in our case is also obvious. Therefore the problem arises, to what degree can the obtained data on the crumbling of the substance and the initiation of reaction by air heated during compression and as a result of plastic deformation be transferred to the case of normal detonation?

Since in the front of normal detonation the pressure is one order or more higher than that in the examined case, crumbling and plastic deformations will not take place there to a lesser degree. With respect to the igniting role of the air (or of the reaction) a definite conclusion cannot be drawn. The fact is that under the examined conditions the initiating role of the air and the decomposition of a noticeable portion of the explosive by means of burning occur for time periods which exceed by one or two orders the times characteristic of detonation (see Table 1). On the other hand, under high dynamic pressures the rate of combustion may increase significantly independent of how it arose (the ignition by detonation products, by heated air, or as a result of the warming of the explosive itself at individual centers).

Effect of filling with water on the reaction time in a detonation wave

The possibility of ignition of the explosive by heated air or by reaction products in the front of a detonation wave can be established from the following experiments. If the initiation of the reaction in a detonation wave is caused by the igniting effect of heated gases or streams of reaction products, then filling the pores in the charges of explosives with water should effect the magnitude of the reaction time in the detonation wave. In experiments, however, this is not detected. As was noted above, independent of the size of the initial particles of explosives all the experimental points lie on one curve $\tau = \tau(P)$. On this same curve also lie the points obtained in water-filled charges (Fig. 62).

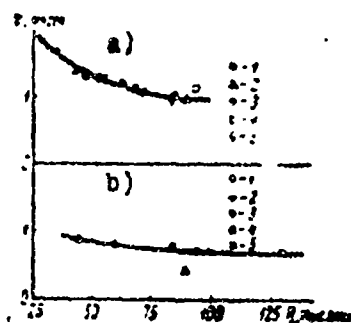


Fig. 62. Dependence of the reaction time on the pressure in the detonation wave of charges of NB powder a) and hexogen b) of different structures. a) 1 - $\delta = 0.26$; 2 - 0.43; 3 - 2.00; 4 - with water; 5 - vacuum up to $P_0 = 1$ mm Hg; b) 1 - $\delta = 0.15$; 2 - 0.45; 3 - 1.80; 4 - micro-porous; 5 - with water. [мксек = μ s; тыс.атм = thousands of atm]

By analogy with the experiment on crumbling, where air removal down to pressures of less than 1 mm Hg. significantly effected the emergence and development of the explosion, experiments were conducted on determining the reaction time in the detonation wave with vacuum-treated charges of NB powder. The parameters and time of reaction also did not change (see Fig. 62). Thus, the obtained results mean that the ignition of the particles of the explosive by the heated gas in the pores and by the detonation products is absent.

The totality of the experimental material presented permits us to assert that during detonation of both compact as well as porous solid explosives the chemical reaction is initiated as a result of the heating of the explosive itself under the action of the shock wave. This conclusion is confirmed by estimates of the temperature of the shock compression, obtained by the basis of a study of shock compressibility of explosives in compact and porous states.

§ 4. Shock Compressibility and Heating of Solid Explosives

Various experimental data [71, 80, 122, 123] are currently in wide usage, along with the concepts of the theory of a solid body, to describe the thermal dynamic properties of condensed substances under high dynamic pressures.

Zel'dovich [80] suggested the use of curves of dynamic compressibility of a substance with various initial densities to obtain information on the thermodynamic parameters under high pressures. The collection of such data for solid explosives is impeded by the fact that they quickly decompose under the action of even relatively weak shock waves. The existing experimental data on shock compressibility of solid explosives are limited only to several substances with a density close to a monocrystal [115, 116]. Definite successes have been achieved in works [124, 125], where formulas were suggested for calculating the shock adiabatic curves of various substances, including liquid and compact solid explosives, from the known values of the speed of sound in the normal state.

With respect to porous explosives only the first attempts have been made [126, 127]. In the process of compression of a porous explosive in the front of the shock wave there may occur the partial chemical decomposition or phase transformation and the state obtained after compression will be classified as a mixture of the initial substance and of the second phase. All this

imposes increased requirements on the experimental technology and treatment of the obtained results.

For high accuracy and the avoidance of possible errors the experimental determination of the shock compressibility of porous explosives is most conveniently made by the simultaneous measurement of the mass velocity (u_0) on the interface of the inert boundary - studied explosive and of the velocity of the front (D) on a finite measurement base under conditions of action of the shock wave of rectangular profile [128]. The scheme of the experiment is shown in Fig. 63. The width of the air gap and the thickness of the paraffin plate between the charge of the explosive and the studied sample were selected in such a way that a rectangular-profile shock wave acts on the sample.

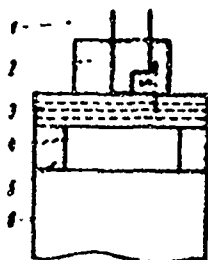


Fig. 63. Layout of the experiment for determining the shock compressibility of an explosive by the electromagnetic method. 1 - Detector; 2 - studied sample; 3 - paraffin boundary; 4 - air gap; 5 - ring; 6 - charge; S - shock wave velocity measurement base.

A study was made of the shock compressibility of porous samples of NB powder ($\rho_0 = 1.0 \text{ g/cm}^3$), manufactured from spherical particles of two sizes - 0.43 and 2.0 mm, and of hexogen of the same density from monocrystalline particles 0.5-1.0 mm, and the shock adiabatic curve of compact powder NB was also obtained. For an example, Fig. 64 shows typical oscillograms of the recording of the profile $u(t)$ on the interface of the paraffin - inert substance (NaCl) and of paraffin - studied explosives (NB powder). Under comparatively low pressures ($\sim 10,000 \text{ atm}$) recordings of $u(t)$ do not basically differ. This means that the explosive behaves inertly, and there is no noticeable decomposition of it during the experiment.

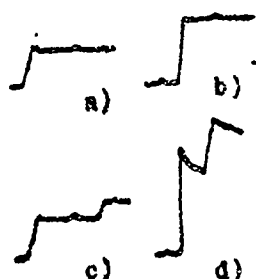


Fig. 64. Recordings of $u(t)$ on the interface of paraffin with NaCl and NB powder. a - NaCl, $P \sim 10,000$ atm; b - NaCl, $P \sim 50,000$ atm; c - NB powder, $P \sim 10,000$ atm; d - NB powder, $P \sim 50,000$ atm. The time scale - $2 \mu s$. Second sharp rise in the recordings of $u(t)$ corresponds to the moment of passage of the measurement base by the wave front.

Under higher pressures (for NB powder $\sim 50,000$ atm) the decomposition of the explosive leads to a sharp drop in u immediately behind the front of the shock wave. In connection with this the question arises, what value is u to take on the oscillogram for the value of the mass velocity on the interface of u_0 .

Values of u_0 were always obtained by the extrapolation of the recording of $u(t)$ to $t = 0$ (the moment of the start of movement of the detector). Obviously, under these amplitudes of the shock wave, where the profile $u(t)$ is rectangular, at least during the passage of the base of measurement (S, Fig. 63) such an extrapolation does not introduce additional error, and the obtained values of D and u_0 correspond to one and the same date. But in cases where in the recordings of $u(t)$ a peak appears, the extrapolation to $t = 0$ makes it possible to avoid errors connected with the effect of decomposition of the explosive.

The point with maximum u value, strictly speaking, should not be considered to be a point on the shock adiabatic curve of the explosive, since for the time of the steep slope of the leading edge of the oscillograms a noticeable portion of the explosive might already have reacted. Since the sharp drop in u behind the rectangular wave is caused by the occurrence of the chemical reaction, the extrapolation of the dependence $u(t)$ to $t = 0$ gives the point on the shock adiabatic curve of a compressed, but not of a reacted explosive. Naturally, such a systematic overstatement

of values of u_0 is possible, but the difference from the maximum registered value of the mass velocity will not exceed, as the rule, 10%. In the case where compact samples are used, such an extrapolation is more justified, since the steep slope of the leading edge of the oscillograms is determined totally by the inertness of the detector.

Another important moment in the determination of shock adiabatic curves is the acceleration of the front of the wave on the measuring base in those cases, when there arises in the explosive a noticeable exothermic reaction. Possible errors as a result of this may be eliminated by two means. One of these consists in measuring D at various distances from the interface of the inert boundary and explosive and in the extrapolation of the obtained dependence to the zero distance. Measurements of D on various bases under our conditions showed that, in practice, on $S = 3$ mm D does not differ within the limits of accuracy of the experiment ($\sim 5\%$) from the values of D_0 on the interface, obtained by the mentioned extrapolation. Therefore, in the majority of the experiments for value of the velocity of the wave front in the investigated explosive on the interface values of D were taken, obtained by measurement on a base of 3 mm. Moreover, the calculation of D_0 was conducted by the method of reflection [71] according to the known value of u_0 on the interface of the paraffin and explosive. The accuracy of determining D_0 in this manner is significantly lower than with direct measurement. Within the limits of this accuracy ($\sim 10\%$) the calculated and measured values of D coincide in the entire investigated range of pressures.

Values of D and u were obtained by averaging the results of 3-5 measurements. The deviation of values of individual measurements from the average value did not exceed 5%. The greatest values of D and u correspond to the parameters of the shock front of ideal detonation. At coordinates $D - u$ experimental data for

(Fig. 65) and hexogen (Fig. 66) can be described by straight lines. For porous samples of powder independent of the initial dimensions of the particles all the experimental points are described by one analytic dependence: $D = (0.58 + 1.68 u)$ km/s. The shock adiabatic curve of compact powder NB has the form: $D = (1.70 + 1.85 u)$ km/s. This is close to the shock adiabatic curve of powder N, shown in work [17] $D = (1.76 + 1.86 u)$ km/s. The shock adiabatic curve of porous hexogen is described at coordinates $D - u$ by the formula $D = (0.4 + 2.04 u)$ km/s.

A linear dependence between D and u can be observed, as witnessed by the fact that in the front of the shock wave no phase transformations occur [129]. Using analytic expressions of the shock adiabatic curve at coordinates $(D - u)$, it is easy to construct them at coordinates $(P - V)$ (Figs. 67 and 68). At these coordinates the shock adiabatic curves of the porous samples are situated higher than the shock adiabatic curves of the compact samples, as must be for a substance with normal thermodynamic properties (the coefficient of thermal expansion $\alpha > 0$, the Grüneisen coefficient $\Gamma > 0$) with equilibrium behind the shock wave front. On the other hand, in experiments on the isothermic compressibility of NB powder [130] it was found that $\alpha < 0$. A negative coefficient of thermal expansion is also obtained from a comparison of the curve of shock and isothermic ($T = 18^\circ\text{C}$) compression of compact powder (curves 2 and 3 in Fig. 67), since with identical pressures shock compression proves to be greater than isothermic. This conclusion, however, is contradicted by the mutual position of the shock adiabatic curves of compact and porous powder. If α had been negative during shock compression, then curve 1 would have been situated lower than curve 2. The cause of such a contradiction is apparently cut out in the course of the isotherms. In work [130] there was expressed the assumption of the possible change in the thermodynamic properties of the studied system as a result of the change in the interaction of its components. Possibly, during static isothermic compression higher than certain values of P there occurs a separation of

phases and the volume of the system increases, which formerly leads to a reduction in α . As a result of this the obtained isotherms (curves 3 and 4, Fig. 67) are steeper than should occur in the absence of the cited interaction of the components. During shock loading the phase separation, apparently, does not occur, and the compressibility of the substance, existing in a certain metastable state, is fixed.

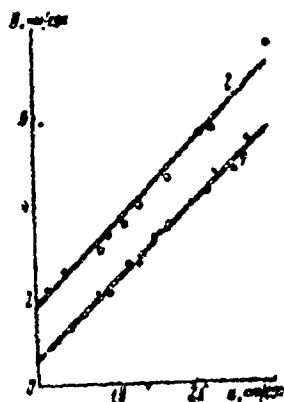


Fig. 65. Shock adiabatic curves of porous (1) and compact (2) powder NB. Grain size: \circ - 0.43 mm; and + - 2.0 mm.

[$\text{cm/sec} = \text{km/s}$].

Fig. 66. Shock adiabatic curves of porous (1) and compact (2) hexogen.

[$\text{cm/sec} = \text{km/s}$]

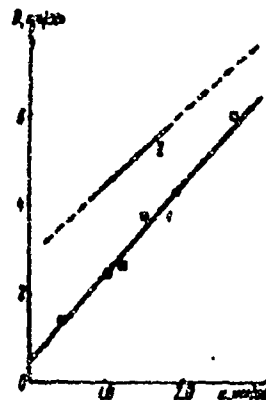




Fig. 67. Shock adiabatic curves of porous (1) and compact (2) samples of NB powder and isotherms of compact NB powder at a temperature of 18°C (3) and 92°C (4) [130].

[$\tau_{\text{thc.atm}}$ = thous. of atm.; cm^3/g = cm^3/g]

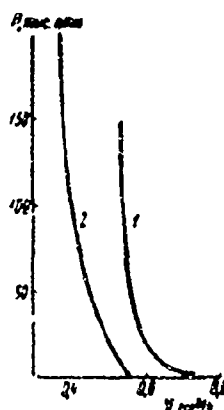


Fig. 68. Shock adiabatic curves of porous (1) and compact (2) hexogen.

[$\tau_{\text{thc.atm}}$ = thous. of atm.; cm^3/g = cm^3/g]

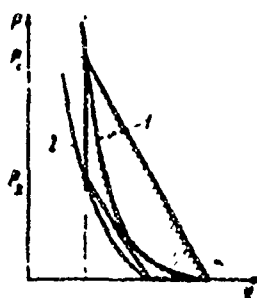


Fig. 69. Shock adiabatic curves of porous (1) and compact (2) substances. Shaded area - conversion of energy in the porous sample in comparison with the compact.

An increase in pressure and energy in the porous samples in comparison with the compact during compression up to an identical volume is explained by the rise in the heat components of the pressure and energy (Fig. 69) [80]. On the strength of this, the Grüneisen coefficient is found

$$\Gamma_v = \frac{V(P_2 - P_1)}{E_2 - E_1}.$$

Table 4 presents the values of the specific volumes, pressures, specific internal energy E and the coefficient Γ for compact and porous samples of powder and hexogen.

With the use of a value of the Grüneisen coefficient of 1.5 obtained for NB powder a calculation was made for the temperature of the shock heating according to the scheme, suggested in work [63] and perfected later in [131]. Calculation of the temperature on the shock front of a detonation wave with an amplitude of 150,000 atm for porous NB powder gives 1500°K, and for compact powder ($P = 350,000$ atm) - 2000°K. In the calculations the increase in the specific heat was taken into account (~ 0.3 cal/g \times \times deg under normal conditions) with an increase in the temperature within the 1000-2000°K range by approximately 2.5 times [132].

Table 4. Values of the Grüneisen coefficient for NB powder and hexogen.

(1) Substance	V , cm ³ /g	P_1 , thous. atm	P_2 , thous. atm	E_1 , 10 ³ , dm ³ /g	E_2 , 10 ³ , dm ³ /g	Γ
(2) Powder HB	0.45	100	20	23.2	1.9	1.45
	0.29	14	24	26.0	1.2	1.45
	0.22	42	14	29.1	0.7	1.16
(3) Hexogen	0.26	25	0	12.22	0	2.22

KEY: (1) Substance; (2) NB powder; (3) Hexogen.

[cm³/g = cm³/g; thous. atm = thous. of atm.;
dm³/g = J/g]

For porous samples of hexogen we limited ourselves to the minimum estimate of the heating, taking the difference between the total increment of specific internal energy of porous and compact substance for the increments of the heat fraction of internal energy of the porous sample. It is obvious that such an estimate is understated, since it does not take into account the increment of the thermal energy in the shock-compressed compact substance. However, in this case also with a pressure on the shock front of the detonation wave of $\sim 150,000$ atm (the estimates produced $T = 1100^\circ\text{K}$) (an increase in the specific heat with a rise at the temperature was calculated and the average specific heat was taken as equal to ~ 0.6 cal/g-deg [132]). Thus, solid explosives (just as liquid) during shock compression up to pressures of 100,000 atm and higher, undergo significant heating.

§ 5. On The Mechanism of Detonation Of Solid Explosives

As was pointed out above, a normal detonation regime for all the investigated solid explosives (cast, pressed, powder) is characterized by the presence of the chemical peak. The width of the shock front of a detonation wave is significantly less than the overall time of the chemical reaction, i.e., in the process of compression the explosive is almost not decomposed. The detonation process is managed by the shock wave. In the mechanism of initiation of the reaction in the front of the detonation wave the ignition of the explosive by the hot products and by the gases heated in the pores plays no noticeable role. The shock wave crushes, and heats the explosive itself to high temperatures. For typical porous explosives under the pressures of detonation of $\sim 100,000$ atm average temperatures of the shock compression of 1000-1500°K are totally attainable.

Are such temperatures adequate to ensure the decomposition of the explosive for the reaction times characteristic for detonation? If the kinetics of the decomposition of the explosive

under detonation conditions were known, an answer to this question might be obtained by direct calculation of the temperature through the reaction time known from experimentation. Since there are no such data on the kinetics, obviously, it is most reasonable to use the concepts of a normal adiabatic explosion for such a calculation. However, the experimental data contradict such a representation of the decomposition of solid explosives in detonation waves. As was pointed out above, a noticeable induction period behind the front of the detonation wave of solid explosives is not observed. Nonetheless, the ideas of a normal adiabatic thermal explosion can be employed, if we assume that the chemical decomposition of the solid explosives in the detonation wave exists in the form of successive normal adiabatic explosions at the centers. They arise in the shock front of a detonation wave as the result of heterogeneous heating during compression.

The successive flashes of the hot centers easily explain in approximation the triangular pressure profile in the zone of chemical reaction of the detonation wave. It follows from these considerations that the total time of reaction is determined by the time of delay in the normal adiabatic explosion of the coldest centers.

For the majority of powerful solid explosives (see Tables 1 and 2) the chemical reaction time for detonation varies from tenths of a microsecond up to one microsecond. Calculation using kinetic constants for $\tau_1 = 0.2$ and $\tau_1 = 1.0 \mu s$, for example, in NB powder produce temperature values of 1160 and 1270°K, respectively [120, 133]. Close temperatures are also required for other powerful explosives. Temperatures of such an order, as can be seen from the above cited data, are achieved in the front of a detonation wave of both compact and of porous explosives.

The introduced calculations show that the temperatures achieved during compression of solid explosives by shock waves with an amplitude close to the pressures on the shock front of the detonation wave are sufficiently high, so as to explain the total time of the chemical decomposition of the explosive as a result of a normal adiabatic thermal explosion. Therefore, there is no basis in the solution of the problem on the mechanism of the detonation conversion of solid explosives (of both compact and of porous) of disregarding the shock heating of the substance itself.

The actual process of decomposition of porous explosives in a detonation wave has not been clarified to the end, and it is not reducible to a simple model of focal, normal thermal explosions. Actually, in the latter case the dependence $\tau_1(P)$ should also be strong, which is not observed in the experiment. This concept is contradicted also by the equality of the reaction in porous and in water-saturated explosives. Obviously, the temperature of the explosive on the shock front of the detonation wave of the charges is different (this follows from the data on the compressibility of compact and of porous NB powder), while the reaction times with identical pressure turn out to be equal. These experimental facts have still not received an unambiguous explanation.

However, we have not excluded the fact that melting occurs in the front of the detonation waves of certain porous explosives. In this case decomposition of the explosive proceeds in the form of a degenerated explosion of an almost homogeneous medium and the dependence $\tau(P)$ will also be weak. Finally, the degeneracy may be caused by the low rates of occurrence of the final stages of the decomposition process, which also leads to a weak $\tau(P)$ dependence.

Whatever the reasons might be for the weak dependence of $\tau(P)$ in solid explosives, apparently, connected with this is the possibility of the existence in them of stable detonation regimes with parameters considerably lower than ideal in a certain range of measurement of the charge diameters. Because of the weak dependence of $\tau(P)$ a noticeable decrease in the amplitude of the detonation wave with certain charge diameters leads to a slight rise in τ , and the breakdown of the reaction does not proceed. Together with the decrease in the wave amplitude the intensity of the expansion also falls, and the process is propagated stably as before.

In conclusion, let us note that in principle detonation waves in solid explosives without a sharply defined chemical peak are possible. This may be during detonation of sufficiently sensitive porous explosives, if the decomposition, having begun at the centers, terminates during compression. Such a case is possible for an explosive, the critical temperature of the centers of which is close to or less than the melting temperature [121]. The chemical peak may, in practice, also be absent in strongly porous systems in the case where the process of propagation of detonation will exist as streams of PD.

CHAPTER V

LIMITS OF THE PROPAGATION OF DETONATION IN CONDENSED EXPLOSIVES

The smallest diameter of the charge of an explosive, with which the propagation of self-sustaining detonation is still possible, called the critical diameter d_{kp} . The existence of such a diameter cannot be explained within the framework of the classical detonation theory, since a finite width of the reaction zone in this theory is not taken into consideration, and the processes which occur behind its limits cannot transmit perturbations, which overtake the detonation front in the case of $d < d_{kp}$. Therefore, concepts of the limits of propagation of detonation might be developed only if the appearance of a detonation theory which takes into consideration a finite time of the chemical reaction in the front of the detonation wave.

Levartov [72, 134] was the first to mark out the proper path for an understanding of the nature of d_{kp} . According to his ideas, with a reduction in the charge diameter there is an increase in the dispersion of the reacting explosive to the sides and a corresponding loss of energy, which, in the opposite case, would go for the maintenance of the detonation front. At a certain finite diameter, which is also the critical diameter, the equilibrium between the heat receipt and the energy losses is first destroyed, i.e., detonation cannot propagate.

According to Khariton, any substance capable of an exothermic reaction with constants P and V can detonate, if we take a sufficiently large diameter. In other words, the difference between the explosive and the remaining exothermically reacting substances is not basic. It consists in the fact that the critical diameter of the first lies within the limits of the charge sizes used in practice, while in the second, on the other hand, it is very large.

Taking into consideration the fact that the dispersion of the reacting medium is nothing different than its expansion in a rarefaction wave, and the structure of the latter is determined chiefly by the speed of sound c , Khariton gave a formula for estimating d_{kp} :

$$d_{kp} \approx 2c\tau,$$

where τ is the reaction time, characteristic for the detonation.

These ideas, which received propagation under the name of "Khariton's principle," were the first to enable us to connect the reaction time during detonation with the external characteristic of the given process. This, to a significant degree, stimulated the development of experimental works to determine the reaction time under conditions of detonation and, in general, on the study of detonation close to the limit of its propagation [59, 135-138]. The accumulated factual material not only confirmed the validity of the advanced qualitative ideas on the nature of d_{kp} , but also, to a significant degree, advanced our understanding of detonation as a physical-chemical process.

The development of the theory in this direction lagged far behind the experimental investigations. The undertaken attempts at constructing a theory of nonideal detonation and of the critical diameter [21, 108, 139-144] rests on the extremely simplified

schemes of flows and in essence have introduced nothing new in comparison with Khariton's principle. Up to the present time a strict theory of detonation limits for condensed explosives has still not been created.

In the cited theoretical works it is assumed that c and τ in Khariton's formula are the average speed of sound and the reaction time within the limits of the detonation front, respectively. Moreover, Khariton, and following him also the authors of other of the above-mentioned theoretical investigations tacitly assume that only a stationary detonation front can be self-sustaining.

This supposition, correct for solid (nonhomogeneous) explosives, is not fulfilled in many instances of detonation of liquid explosives. It turned out that a detonation front may be separated from the boundaries of the charge and again returned to them. Such a "nonstationary" detonation front may propagate as long as it wants, and its critical diameter is connected not with the time of reaction at the front, but with the processes leading to its restoration of the area along the entire cross section of the charge. In the future, for the sake of brevity, any theory resting on the assumption of a stationary front we shall call stationary in contrast to the ensuing nonstationary theory of a detonation front with a pulsating area.

Examined below are the fundamentals of the formulation of the problem, from which, in our opinion, there must follow the ensuing strict stationary theory of d_{kp} , and also on the basis of the experimental data fundamental physical principles, which henceforth must be set up as the basis of the nonstationary theory of d_{kp} , are clarified. Here we will be speaking mainly of d_{kp} in charges of explosives without a shell (or in a very weak shell).

§ 1. The Propagation of Detonation in Charges of Finite Diameter

The Motion Equation

The flow of a continuous medium during the detonation of a charge of finite diameter is described by three-dimensional equations of motion:

$$\frac{\partial \rho}{\partial t} + \nabla \rho \mathbf{u} = 0, \quad (36)$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\nabla \rho \mathbf{u}) \mathbf{u} + \nabla P = 0, \quad (37)$$

$$\frac{\partial}{\partial t} \rho \left(E + \frac{u^2}{2} \right) + \nabla \left[\rho \mathbf{u} \left(E + \frac{P}{\rho} + \frac{u^2}{2} \right) \right] = 0, \quad (38)$$

where ρ is the density of the medium; \mathbf{u} is the vector of the flow velocity; P is the pressure; E is the specific internal energy; ∇ is the vectorial operator:

$$\nabla = i \frac{\partial}{\partial x} + j \frac{\partial}{\partial y} + k \frac{\partial}{\partial z}$$

(i, j, k are unit vectors, directed along Cartesian coordinate axes).

It can be pointed out that in the case of a rough detonation front equations (36)-(38) do not change their form, if the flow of the reacting medium is isotropic-turbulent. In this case to obtain the appropriate averaged equations of motion (36)-(38) it is sufficient to set up in place of ρ and \mathbf{u} their average values, and in place of P and E - the corresponding formal values. Therefore, henceforth we shall make no distinction between a laminar and an isotropic-turbulent reaction zone.

The supposition of isotropic turbulence for the case of liquid explosives with a rough front is not carried out on account of the

regular character of the inhomogeneities. On the other hand, in the case of solid explosives on account of the chaotic character of the initial inhomogeneities of the medium the flow in the detonation front must be isotropic-turbulent. Therefore the inclusions of this paragraph are in force only for solid explosives and, of course, for liquid explosives with a smooth detonation front.

Let us apply equations (36)-(38) to an analysis of detonation close to the limit. In a system of coordinates, connected with a stationary detonation front, from the equations of motion the derivatives with respect to time fall out, which enable us to simplify significantly the given equation. Let us introduce into the consideration flow tubes, i.e., imaginary tubes of any cross-sectional shape, the limits of which at each point coincide with the direction of the velocity. Through these limits there are no flows of mass for energy. Consequently, if the cross sectional area of a flow tube is equal to σ , then the total flow of mass to its cross section is equal to $\rho u \sigma$. Therefore, equation (36) transfers to equation

$$\frac{dms}{dt} = 0, \quad (39)$$

where l is the length, measured along the tube of flow.

Having obtained precisely the same expression for the energy flux and using the latter equality for the mass flux, one can transfer to the equality

$$\frac{d}{dt} \left(E + \frac{p}{\gamma} + \frac{u^2}{2} \right) = 0. \quad (40)$$

For the transformation of equation (37) the term in the middle of its left side is transferred to another form:

$$(\nabla \rho u) u = u (\nabla \rho u) + (u \nabla) u = \rho u \frac{du}{dt}.$$

By introducing the unit vector e_v in the direction of the velocity from the preceding expression we obtain the following:

$$u \frac{\partial u}{\partial t} = u e_r \frac{\partial u}{\partial r} + u e_\theta \frac{\partial u}{\partial \theta}.$$

Multiplying equation (37) scalarly by vector e_r and taking into account that $e_r(\partial e_r / \partial t) = 0$, we obtain

$$u \frac{\partial u}{\partial t} + \frac{\partial p}{\partial t} = 0. \quad (41)$$

If we consider the absence of heat exchange ($dE = -PdV$), then as a result of differentiation of (40) we obtain equation (41). Multiplying scalarly equation (37) by vector e_r , directed along the surface $P = \text{const}$, and taking into account $e_r \nabla P = 0$, we find

$$e_r \frac{\partial u}{\partial t} = 0. \quad (42)$$

A Prandtl-Meyer Flow

Let us examine the structure of a flow, which arises at the limit of a detonating charge. We will assume that in front of the zone of reaction a shock front is propagated, the width of which can be disregarded. This assumption can be assumed to be valid for the majority of practically important cases of detonation of solid explosives; in the case of liquid explosives with a smooth detonation front it is so much the more valid. The shock front intersects the free boundary of the charge along a certain line, which is special for the equations of motion. For example, a whole sheaf of surfaces of constant pressure converges to this line, since any particle of the reacting medium, no matter how closely it passes by the special line, must pass through all the pressures from the shock front to the pressure of the medium, surrounding the charge. The flow region, corresponding to the fan of surfaces of constant pressure diverging from the special

line, in the infinitely close vicinity of the cited line is called a Prandtl-Meyer flow [4]. It is necessary to study under what conditions this flow will be stationary.

Let us select the natural coordinate surfaces (Fig. 70). First, as such surfaces one can take planes, passing through the axis of the charge. Let one of these coincide with the plane of the figure. The coordinate, corresponding to the given surfaces, is the angle α , counted off around the axis of the charge. The rotation of the line of flow around the axis of the charge gives another system of coordinate surfaces. Finally, as a third system of coordinate surfaces let us select the surfaces of constant pressure, determined in the region of the Prandtl-Meyer flow by the angle ϕ , which is counted off around the special line from a certain arbitrary surface.

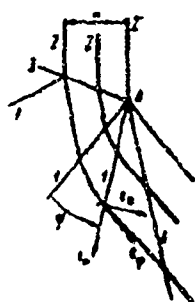


Fig. 70. Selecting a system of natural curvilinear coordinates on the free boundary of the charge. 1 - constant-pressure lines; 2 - lines of flow; boundary of the explosive charge; 3 - shock front.

The increment of the radius-vector dr is in the following manner connected with the change in the curvilinear coordinates

$$dr = H_\alpha e_\alpha d\alpha + H_r e_r dr + H_\phi e_\phi d\phi, \quad (43)$$

where e_α is the unit vector perpendicular to the coordinate plane, and e_r and e_ϕ are the above-determined vectors, directed along the line of flow and along the surfaces of constant pressure, respectively, where

$$e_\alpha \perp e_r \text{ and } e_\alpha \perp e_\phi.$$

Coefficients H_α , H_r and H_ϕ are assumed to be known functions of r and ϕ . They do not depend on α on account of the axial symmetry of the problem.

Applying (43) to the line of flow, we get

$$d\alpha = H_\phi d\phi. \quad (44)$$

Hence equations (39), (41) and (42) can be rewritten in the following form:

$$\frac{\partial p}{\partial \phi} = 0, \quad (45)$$

$$u \frac{\partial u}{\partial \phi} + \frac{\partial p}{\partial \phi} = 0, \quad (46)$$

$$u_r \frac{\partial u}{\partial \phi} = 0. \quad (47)$$

Let us introduce the component velocities: u_ϕ - directed along the normal to the surface of constant pressure and u_r - lying on this surface. The unit vector, normal to the surface of constant pressure, we will designate by e_n .

For the conversion of the first equation (45) one can use the expression ensuing from (43):

$$u = H_\alpha H_r (e_n \cdot e_\phi). \quad (48)$$

In fact, - let us take a tube of flow of rectangular cross section, determined by the increments of coordinates $\Delta\alpha$ and Δr . Then the area of the rectangle, which is cut by the tube of flow on the constant pressure surface, is equal to the product of the length of its sides $H_\alpha \cdot \Delta\alpha$ and $H_r \cdot \Delta r$. Since the surface of constant pressure is not orthogonal to lines of flow, in obtaining expression (48) one should introduce the multiplier $(e_n \cdot e_\phi)$. Thus, for σ the expression $H_\alpha H_r (e_n \cdot e_\phi) \Delta\alpha \Delta r$ is found. Now, taking into consideration the fact that $\Delta\alpha$ and Δr do not depend on ϕ , they can be thrown out, as a result of which expression (48) is also obtained.

Since it is suggested that we subsequently examine the flow in the infinitely small vicinity of the special line, the value H_0 can also be discarded, since in this vicinity $\partial H_0 / \partial r = 0$. The latter follows from the fact that near point A the distance from the axis of the charge in the first approximation does not vary with the change in ϕ .

Until the substitution of expression (48) into the equation it is advisable to determine the derivative of $\partial H_0 / \partial \phi$. For this let us examine the change in the distance R of a certain point of the medium from point A as a function of the angle ϕ . Expression $R d\phi / u_\phi$ is the time, for which the point would describe the angle from ϕ to $\phi + d\phi$. During this time R would increase by the value $dR = u_r (R d\phi / u_\phi)$. Hence it follows that

$$\frac{dR}{d\phi} = R \frac{u_r}{u_\phi}.$$

Differentiating this expression with respect to r, with consideration of the fact that $\partial R / \partial r = H$, and discarding terms which fall out when $R \rightarrow 0$ we find

$$\frac{\partial H_r}{\partial \phi} = H_r \frac{u_r}{u_\phi}. \quad (49)$$

The substitution of (48) and (49) into equation (45) with consideration of equality $u(e_\phi \cdot e_\phi) = u_\phi$ leads to expression

$$\frac{\partial u_\phi}{\partial \phi} + \rho u_r = 0. \quad (50)$$

Equation (46), by the simple substitution of $u^2 = u_\phi^2 + u_r^2$, is reduced to the form

$$\rho u_\phi \frac{\partial u_\phi}{\partial \phi} + \rho u_r \frac{\partial u_r}{\partial \phi} + \frac{\partial \rho}{\partial \phi} = 0. \quad (51)$$

Equation (47) is transformed using equality $\partial u / \partial \eta = 0$, which is valid in the infinitely small vicinity of the special line, when the surfaces of constant pressure can be assumed to be flat. With consideration of equalities $(u_{\eta}) = u_0$ and $(u_{\eta}) = u$, we find the equation

$$\frac{\partial u}{\partial \eta} - u_0 = 0. \quad (52)$$

In the examined infinitely small vicinity any particle passes an infinitely small time. Therefore, its composition and entropy, obtained as a result of the shock compression, can be assumed to be constant and the following relationship can be written:

$$dP = c_3^2 d\rho, \quad (53)$$

where c_3 is the frozen speed of sound.

The multiplication of equation (50) by u_0 and its subtraction from equation (51) using (52) for the introduction of similar terms lead to expression

$$-u_0^2 \frac{\partial \rho}{\partial \eta} + \frac{\partial P}{\partial \eta} = 0.$$

from which after the substitution of relationship (53) the following equality is obtained:

$$(u_0^2 - c_3^2) \frac{\partial \rho}{\partial \eta} = 0. \quad (54)$$

Hence it follows that in the zone of the Prandtl-Meyer flow, where $\partial \rho / \partial \eta \neq 0$,

$$u_0 = c_3. \quad (55)$$

Let us substitute this value into equation (50). Since

$$u_x = u_s = u \sqrt{-V^2 \left(\frac{\partial p}{\partial V} \right)_{s,s}} = \sqrt{- \left(\frac{\partial p}{\partial V} \right)_{s,s}}.$$

then

$$u_x = - \frac{1}{\gamma} \sqrt{- \left(\frac{\partial p}{\partial V} \right)_{s,s}} = - \frac{V}{2\gamma} \left(\frac{\partial p}{\partial V} \right)_{s,s} \frac{\partial V}{\partial x}.$$

Taking into consideration the fact that in ordinary substances

$$\left(\frac{\partial p}{\partial V} \right)_{s,s} > 0$$

and that in the region of the examined flow expansion of the medium takes place, i.e., $(\partial V / \partial x) > 0$. It is not difficult to see that

$$u_x > 0. \quad (56)$$

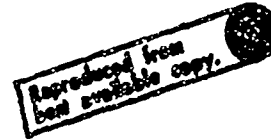
Because of such a sign of u_x perturbations from the special line can propagate across the entire region of the Prandtl-Meyer flow, and to the special line - only from the flow, running into the region of this flow.

It follows from equality (55) that the boundary of the Prandtl-Meyer flow coincides with the Mach line, i.e., the line in the flow, with respect to which the normal component of the velocity is equal to the speed of sound. Hence it follows that the oncoming flow to the boundary of the Prandtl-Meyer flow should not be supersonic, and perturbations from the special line do not penetrate into the region of its flow.

The study of the Prandtl-Meyer flow was conducted on the assumption of stationarity of the flow. However, it can be demonstrated that this assumption is not essential, and it is sufficient to make the less rigorous supposition of a finite value of the derivatives with respect to time in equations (36)-(38). In fact, in the vicinity of the special line, and more

precisely in the region of the Prandtl-Meyer flow all the derivatives with respect to the spatial coordinate tend toward an infinite value. For this reason, it makes no difference whether we discard all the derivatives with respect to time.

Structure of the Flows in the Stationary Detonation Wave



The layout of the basic flow elements with stationary detonation is represented in Fig. 71. So that nonstationary rarefaction waves might not penetrate inside the detonation front, from point A the supersonic flow must exit, i.e., on the boundary of the charge behind the shock wave:

$$u < c_s. \quad (57)$$

As was pointed out above, only in such a flow can the forward boundary of a stationary rarefaction wave and a Prandtl-Meyer flow exist. On the other hand, on the axis of the charge directly behind the shock front there must exist

$$u < c_s. \quad (58)$$

Consequently, the sound surface, on which

$$u = c_s. \quad (59)$$

intersects the shock front. Thus, the region of the subsonic flow, from which perturbations can admittedly enter the front (in Fig. 71 this is shaded), does not reach the free boundaries of the charge, and it is precisely this that ensures steady-state conditions.

When it is said that the flow behind the shock front always exits from it with a subsonic speed, it is understood to mean the components of the flow velocity normal to the shock front. But if



Fig. 71. Simplified scheme of the flows during stationary detonation in a charge of finite diameter.
1 - Mach lines; 2 - boundary of the charge; 3-- shock front; 4 - sound surface.

we transfer to another coordinate system, sliding along the surface of the shock front, then it is not difficult to see that the tangential component of the velocity does not vary with the transition of the medium through jump P. It is always possible to select such a value of the tangential component, with which the total velocity behind the shock front is supersonic. Therefore, to fulfill condition (57) the shock front close to the boundary of the charge must be sloping with respect to the oncoming flow of the initial medium. Hence it follows, in turn, that the amplitude of the shock front on the axis of the charge is greater than on the boundary due to the corresponding difference in normal components of the oncoming flow of the explosive. As a result, the shock front becomes convex in the direction of propagation of detonation, as is also shown in Fig. 71.

In the transition through the convex shock front all the lines of flow, except the axial, undergo fracture and begin to leave the axis of the charge. This conclusion follows from the fact that the normal component of the velocity according to the law of preservation of mass ($\rho u = \rho_0 u_0$) is reduced during the transition through the shock front, while the tangential component remains unchanged.

Hence it is possible to suppose that behind the shock front the flow density j falls downward with respect to the flow:

$$\frac{dj}{dx} < 0. \quad (60)$$

From the fact of the divergence of the lines of flow follows only the reduction of the average flow density throughout the entire cross section and the validity of the inequality (60) on the axis of the charge. Therefore, in the strict theory inequality (60) must be justified.

Let us make two more assumptions for later. We will assume that, first, the derivative $\partial/\partial r$ increases in absolute value with the movement from the axis to the periphery of the charge, and, second, that the pressure falls monotonically along the entire region of the flow behind the shock front, i.e., $\partial P/\partial r < 0$.

Let us determine the relationship between the pressure and the volume in the reacting medium. With the absence of transfer phenomena the following equality is correct

$$\frac{dE}{dt} = -P \frac{dV}{dt}. \quad (61)$$

The left hand side of this expression can be represented in the following form:

$$\frac{dE}{dt} = \left(\frac{\partial E}{\partial P} \right)_{r,s} \frac{dP}{dt} + \left(\frac{\partial E}{\partial r} \right)_{P,s} \frac{dr}{dt} + \left(\frac{\partial E}{\partial s} \right)_{P,r} \frac{ds}{dt}. \quad (62)$$

Using the thermodynamic relationships

$$\begin{aligned} \left(\frac{\partial E}{\partial P} \right)_{r,s} &= T \left(\frac{\partial S}{\partial P} \right)_{r,s} - P = -T \left(\frac{\partial V}{\partial P} \right)_{r,s} \left(\frac{\partial S}{\partial V} \right)_{r,s} - P = \\ &= - \left(\frac{\partial P}{\partial r} \right)_{s,s} \left(\frac{\partial S}{\partial P} \right)_{r,s} - P. \end{aligned}$$

we transform (61) into

$$\frac{dP}{dt} = \left(\frac{\partial P}{\partial r} \right)_{s,s} \frac{dr}{dt} - \left(\frac{\partial E}{\partial r} \right)_{P,s} \frac{dr}{dt} / \left(\frac{\partial E}{\partial P} \right)_{r,s}. \quad (63)$$

With the aid of expression (62) it is not difficult to be convinced that the second term in the right hand side of equality

(63) represents the rate of increase of the pressure during the occurrence of the chemical reaction under conditions of constancy of E and V. For this value let us introduce a special designation:

$$p = - \left(\frac{\partial E}{\partial V} \right)_{P, r} \frac{dV}{dt} / \left(\frac{\partial E}{\partial P} \right)_{V, r} \quad (64)$$

In this expression the numerator is none other than the rate of heat liberation of the chemical reaction with constants P and V.

Since $(\partial E / \partial P)_{V, r} > 0$, from equality (64) it follows that the sign P coincides with the sign of the heat liberation with constants P and V. In the case of an exothermic reaction it must be positive.

Using the expression for the density of the sound flow $j_{3B}^2 = (\partial P / \partial A)_{A, r}$ after the replacement of the differentiation of $u dt = dz$ from (63) and (64) with a variable we obtain

$$j_{3B} \frac{dV}{dt} - \frac{p}{V} + \frac{\partial P}{\partial V} = 0 \quad (65)$$

By the substitution of $u = jV$ into equation (41) we find

$$\frac{dV}{dt} + V \frac{dV}{dt} + \frac{\partial P}{\partial V} = 0 \quad (66)$$

The exclusion of the last two equations of the derivative dV/dt leads to the following basic expression:

$$(j_{3B}^2 - P) \frac{\partial P}{\partial V} = -N \left(P + c_0 \frac{\partial P}{\partial V} \right) \quad (67)$$

The value of P can be assumed to be the characterizing heat income. Then term $c_0 (\partial P / \partial V)$ can be viewed as the characteristic of the heat losses, occurring as a result of the expansion of the reacting medium to the sides. In the absence of the latter, i.e., when $\partial P / \partial V = 0$, the right side of expression (67) is negative. If, as was assumed above, $\partial P / \partial V < 0$, then in the entire region of the flow

$$k > 1.$$

(69)

(Hence it is possible in another way to arrive at a justification for the Chapman-Jouguet selection principle.)

Let us show that in the case of $\partial/\partial t < 0$ the rate of detonation on the axis of the charge is less than the rate of ideal detonation. For this, with the aid of equation (66) we will write the connection between the pressure and the specific volume in the detonation wave:

$$\frac{dp}{dv} = -\rho^2 \frac{dV}{dv}. \quad (69)$$

From the last equality it follows that the point, depicting the state of the reacting medium, shifts not along Mikhel'son's straight line, corresponding to the initial shock compression, but along a certain more smoothly sloping trajectory (Fig. 72), since $dj/dV < 0$. If the shock front were to propagate with the speed of ideal detonation, then Mikhel'son's straight line OA would touch the equilibrium detonation adiabatic curve OCB at point C. In this case the trajectory of the point of the state AB would intersect the detonation adiabatic curve at a certain point B.

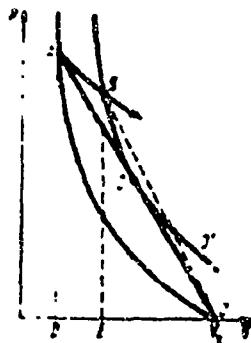


Fig. 72. On the proof of the impossibility of an ideal detonation rate in a charge of finite diameter.

Assuming for the sake of simplicity that $P_0 = 0$, we will determine the specific internal energy of the reacting medium in the state B. In conformance with the equation of the shock adiabatic curve of the initial explosive:

$$E - E_0 = \frac{P}{2}(V_0 - V), \quad (70)$$

The specific internal energy at point A after the deduction of the constant E_0 is equal to area S_1 of triangle OAD. With the transition to point B the specific internal energy is reduced by the value of the work done by the reacting substance, which is equal to area S_2 on the curvilinear trajectory ABED.

Thus, the specific internal energy of the reacting medium in the state B is equal to

$$E_B = E_0 + S_1 - S_2. \quad (71)$$

On the other hand, the specific internal energy of the final reaction products with the same values of P and V in conformance with the equation of the detonation adiabatic curve is equal to

$$E_B = E_0 + S_3. \quad (72)$$

where S_3 is the area of the triangle OBE.

Irrespective of whether the reaction succeeded in going to completion up to the moment of achievement of state B or not, for an exothermic reaction the following must be observed

$$E_B > E_B. \quad (73)$$

Therefore,

$$E_0 - E_B = S_1 - S_2 - S_3 > 0. \quad (74)$$

must exist. However, from Fig. 72 it is immediately clear that the opposite inequality is fulfilled. Consequently, the trajectory of the point of state should not intersect the equilibrium detonation adiabatic curve, and this is possible only in the case where

Mikhel'son's straight line OA will have a smaller slope than that, which corresponds to ideal detonation.

In the same way it is possible to prove the more rigorous assertion, namely that the actual detonation rate cannot exceed the rate of ideal detonation, which corresponds to the intermediate detonation adiabatic curve of the chemical composition, achievable on the intersection of the axis of the charge with the boundary of the region, from which perturbations can enter the front. Actually, the solution of the equations of motion for this region does not change, if we assume that the reaction behind its limits is cut short. In such a case it is possible with accuracy to repeat the preceding discussions, having substituted the equilibrium detonation adiabatic curve for the intermediate detonation adiabatic curve of the composition, achievable on the boundary of this region. Hence follows the qualitative conclusion that the rate of the stationary detonation front D must be reduced with the decrease in the charge diameter d.

The majority of work on nonideal detonation is dedicated precisely to attempts using various simplifying assumptions to obtain a quantitative dependence of $D = D(d)$. From the fundamental expression (67) it follows that on the entire sound surface the essential condition of a stationary detonation propagation is fulfilled:

$$P = -c_s^2 \frac{dP}{dR}, \quad (75)$$

which, being applicable to the line of intersection of the sound surface with the shock front, will play an important role in further discussions.

On the Limit of Propagation of Stationary Detonation in Solid Explosives

Let us designate the smallest diameter of stationary propagation of detonation by d_{cr} . This diameter does not necessarily coincide with d_{gr} . The only thing that can be confirmed is

$$d_{cr} > d_{gr} \quad (76)$$

Let us first examine, expressing ourselves figuratively, the classical region, leading to the existence of a finite diameter d_{cr} , which in one form or another figures in all the works on ideal detonation. This reason is connected with the fact that the rate of the chemical reaction decreases together with the amplitude of the shock front initiating it. Moreover, as was pointed out above, the reaction rate decreases with an increase in the rate of the pressure drop behind the shock front (this is especially apparent in the induction period in the case of the kinetics of heat liberation, answering the law of a normal thermal explosion). Figure 73 represents with continuous lines the suggested dependences of the reaction time τ on the speed of the detonation front, which in some manner is fixed by an exterior source and does not depend on τ . This dependence of τ on D , generally speaking, must vary with the change in the charge diameter, which determines the rate of the fall in the parameters behind the shock front. Therefore, Fig. 73 represents the entire series of given dependences, situated one behind the other and decreasing order of the charge diameter d .

The second series of curves, depicted by dotted lines, represents the dependence of D on τ , when, conversely, τ is fixed by the external source. When $\tau = 0$ detonation, apparently, must be ideal within a charge diameter. Therefore, all the dotted curves, each of which corresponds to one value of d , begin at point D_u , corresponding to the rate of ideal detonation. And in precisely



Fig. 73. Qualitative kinetic curves of $v(D)$ (continuous lines) and $D(v)$ (dotted lines) with different charge diameters.

the same way when $d = \infty$ detonation will be ideal at any τ , and therefore for an infinite diameter the curve will run vertically. With any finite diameter of the charge the corresponding dotted curve must, with an increase in τ , gradually depart from the ideal velocity D_{∞} and asymptotically approach the speed of sound c_0 in the initial explosive. The smaller the charge diameter, the lower the value of τ , at which such a transfer should be accomplished. In contrast to the first series of kinetic curves the lines of the second series are situated one behind the other in order of increasing charge diameters.

The points of intersection of the continuous and dotted kinetic curves for one and the same charge diameter must, obviously, correspond to a self-sustaining detonation regime. From these points one can plot the dependence of $D(d)$ (Fig. 74). There exists a certain (minimal) diameter d_{\min} , at which the continuous and dotted kinetic curves (see Fig. 73) touch one another. With lower d the kinetic curves, in general, do not intersect, and therefore stationary propagation of detonation is impossible.

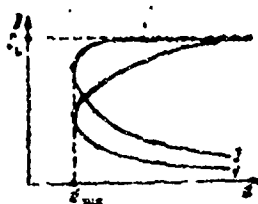


Fig. 74. Dependences of $D(d)$, plotted from points of intersection of the kinetic curves for cases 1 - of a strongly degenerated thermal explosion; 2 - of an almost normal thermal explosion.

The curves shown in Fig. 74 correspond to two different laws of variants of heat liberation in the reaction zone. Curve 1 corresponds to the law of a strongly degenerated thermal explosion, in which the kinetic curves of the first series for various diameters almost coincide with one another, while the kinetic of the second series descend rather mildly slopingly from line D_{μ} to line c_0 . Such behavior of the curves must be characteristic for solid explosives. On the other hand, in the case of the approach of the character of the heat liberation in the reaction zone to the law of the normal thermal explosion the kinetic curves of the first series diverge more and more from one another, and the transition of the kinetic curves of the second series from D_{μ} to c_0 is accomplished more abruptly (approaching a jump), since slight spatial movements of the solid surface on the rear section of the reaction zone lead to great displacements of the given surface relative to the chemical composition. It is not difficult to see that as a result of this change in form of the course of the kinetic curves the dependence $D(d)$ far from d_{\min} is more mildly sloping than in the first case, and in return in the vicinity of d_{\min} it runs, on the other hand, much more crookedly. Such a variation in $D(d)$ (curve 2) must correspond to liquid explosives.

Let us note that the analysis of the dependences of $D = D(d)$ with various laws of heat liberation in the reaction zone permit us to approach from a somewhat different viewpoint the chemical reaction separation mechanism, which determines the limit of propagation of detonation of liquid explosives in rigid tubes.

According to Fig. 74, two rates of stationary detonation correspond to each charge diameter $d > d_{\min}$. The lower branches of the represented curves correspond to a rise in D with a decrease in d . The corresponding regimes, apparently, are unstable, since the individual branches of the detonation front may move out forward. With a charge diameter less than d_{\min} the stationary front cannot propagate independently due to the insufficient heat

liberation in the subsonic reaction zone. Therefore, with these diameters self-sustaining nonstationary detonation regimes are also impossible. In other words, the value of d_{\min} is that absolute threshold, lower than which values of d_{sp} cannot lie, i.e.,

$$d_n > d_{\text{sp}} > d_{\min} \quad (77)$$

If we follow the theoretical works, in which the conditions of stationary propagation of detonation on the axis of the charge were discussed, both inequalities in (77) should be placed with equalities. Let us show that in the general case this is untrue. Let us examine the conditions for detonation propagation on the periphery of the charge, namely on the line of intersection of the shock front with the sound surface. On this line equality (75) should be fulfilled. The value \dot{P} , entering into this equality, characterizes the initial rate of the reaction behind the shock front on the line of its intersection with the sound surface. This value has a very far-removed relationship to the total time of reaction on the axis of the charge, and therefore the destruction of equality (75) may destroy dependence $D(d)$ with values of d , which far exceed d_{\min} . Let us examine two extreme cases, corresponding to equal laws of heat liberation behind the shock front.

Let us first assume that the chemical reaction on the line of intersection of the shock front with the sound surface has an induction period. Here the value of \dot{P} is disregardably small, and the divergence of the flow $\partial u / \partial r$ has, apparently, a finite value with any finite charge diameter. Consequently, equality (75) can be unfulfilled even with infinite charge diameters. In this case stationary detonation would be totally impossible. But if the value \dot{P} has an albeit small, nevertheless a finite value, then with a rise in the diameter in with corresponding decreases in $\partial u / \partial r$ equality (75) can be satisfied when $d \gg d_{\min}$. Thus, if the character of the heat liberation in the reaction zone approaches the law of a normal thermal explosion (as in the case of many

liquid explosives), then depending on the specific circumstances the diameter of the stationary propagation of detonation d_{cr} must have a very great or even an infinite value. The critical detonation diameter here must be found from the nonstationary theory.

Let us now turn to another extreme case, where the heat liberation over the entire reaction zone takes place according to the law of a strongly degenerated thermal explosion. Apparently, all the porous solid explosives satisfy this assumption. In this case d_{cr} is close to d_{min} , which is indicated by the strong dependence of $D(d)$, determined experimentally at the limits of detonation propagation. In fact, from Fig. 74 it is clear that when $d = d_{min}$ the cited curve has a vertical tangent. The critical detonation diameter of solid explosives, apparently, may be described by the stationary theory. It is unclear, however, which factors determine the position of the line of intersection of the sound surface with the shock front with respect to the charge boundary. If we proceed from the fact that the subsonic region of the flow strives to encompass as great an area as possible of the cross section of the charge, then the mentioned line may be set up at a distance from the charge limit, comparable with its initial inhomogeneities.

§ 2. Critical Conditions of Detonation Propagation in Liquid Explosives With a Rough Front

Nonstationary Propagation of a Detonation Front in Charges Without a Shell

A typical representative of liquid explosives with a rough detonation front is nitromethane and its mixtures with an inert solvent (acetone), mixtures of nitroglycerine with a sufficiently large quantity of methyl alcohol, mixtures of nitric acid with dichloroethane and so forth. As was pointed out above, the roughness of the detonation front in liquid explosives testifies

to the fact that behind the shock front, which has a detonation velocity, the kinetics of the heat liberation are close to the law of a normal thermal explosion. It is precisely this circumstance that leads to the impossibility of the propagation of a one-dimensional detonation process. And this leads to instability of the detonation front on the free boundary of the charge.

Experiment shows that during the propagation of detonation in a charge without a shell (more precisely, in a weak shell) from the boundary of the charge every now and then "waves of reaction cessation" propagate, which replace the detonation front with a shock front, and each time the detonation front is reestablished anew along the entire cross section of the charge as a result of the adiabatic flashes of the explosive behind this shock front (Fig. 75). Thus, a rough detonation front is not only micrononstationary due to the existence of the inhomogeneities, but also micrononstationary due to the waves of reaction cessation. Lateral rarefaction waves, arising in the reaction zone, lead to the separation of the adiabatic flash on the level of pressures, existing in the inhomogeneities. New inhomogeneities are therefore not formed, the old ones end their existence on the boundary, and there arises a wave of reaction cessation, which subsequently destroys the oncoming inhomogeneities in its path.

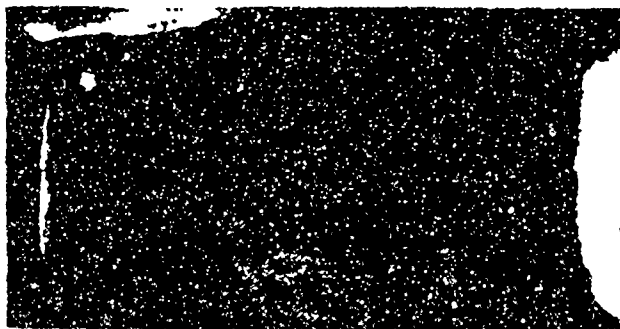
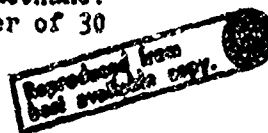


Fig. 75. Head-on scan of the luminescence of the detonation front in nitromethane. A plexiglas shell, charge diameter of 30 mm, length of 100 mm.



But why in the case of a rough detonation front in liquid explosives is a quasi-stationary regime of propagation of the process not established. Apparently, this is connected with the very strong dependence of the reaction rate on the temperature and as a result of this on the pressure in the shock-compressed explosive. As a result of this dependence the size of the inhomogeneities is a strongly diminishing function of the detonation rate. Therefore, in the oblique detonation front, which should have been established on the charge boundary in the case of a quasi-stationary regime, the size of the inhomogeneities would reach gigantic values, due to which the concept of an oblique detonation front would lose all meaning.

Liquid explosives with a rough detonation front do not have diameters of stationary detonation propagation, i.e., with any diameter the detonation will be nonstationary. From this it does not follow that the detonation front has a variable velocity. On the contrary, on the axis of the charge, as experimentation has shown, it always propagates with a constant velocity, which coincides within the limits of accuracy with the velocity of ideal detonation. Nonstationarity of the detonation front is manifested in the fact that the distribution of the parameters on its edges varies all the time. Thus, the theory of a critical diameter in the examined liquid explosives must be nonstationary. For clarification of the basic principles, which should be laid down on the basis of it, let us turn to the experiment on the investigation of the mechanism of attenuation and restoration of the detonation front.

The Transfer of Detonation From a Tube to a Volume

The named mechanism appears in its purest form during the transfer of detonation from a tube with rigid walls into a wide volume, occupied by the explosive. Head-on scanning of this process

is represented in Fig. 76 (a, b). At first the size of the illuminated region is constant and corresponds to the tube diameter d . At moment t_0 of the emergence of the detonation front into the volume its boundaries begin to constrict with constant velocity toward the axis of the charge. This velocity may be determined by measuring the angle ϕ . It turned out that its value v close to the rate of propagation of the inhomogeneities along the surface of the detonation front. At a certain moment t_1 to the side of the axis of the charge there arises a diverging detonation front (points A and A' in Fig. 76), the boundaries of which diverge both in the direction toward the charge axis, as well as to the opposite sides. At a certain moment t_2 the internal boundary of the diverging detonation front overtakes the boundary of the attenuating detonation front, and from this moment only the expansion of the area of the detonation front occurs right up to the moment when the entire cross section of the volume is encompassed.

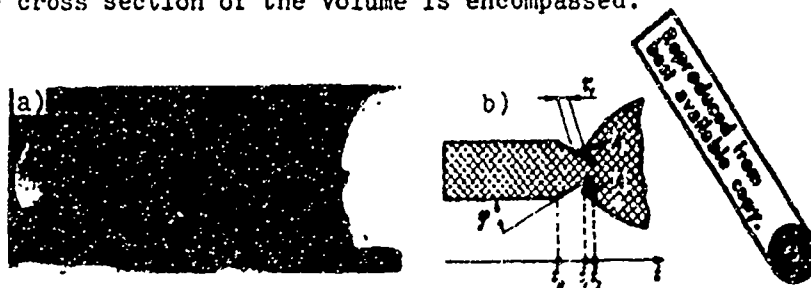


Fig. 76. Head-on scanning of the luminescence of the detonation front in nitromethane during the passage of detonation from the tube into the volume (a) and a diagram of it (b). Tube diameter is 19 mm.

With the reduction in the tube diameter we discover its critical value, below which the transfer of detonation into the volume does not occur. In this case the diverging detonation front is not formed, and the boundaries of the detonation front exiting from the tube with the same constant velocity are confined in the direction to the axis of the charge right up to the total attenuation of detonation. A corresponding head-on scan is represented in Fig. 77.



Fig. 77. Head-on scan of the luminescence of the detonation front in a mixture of nitromethane with acetone (75:25) during the passage of the detonation from the tube into the volume (diameter of the tube is 37 mm).

The critical diameter of the transfer of the detonation from the tube into the volume, as was pointed out, depends neither on the material, nor on the width of the walls of the tube, if only the detonation in the latter propagates stably. It is interesting to note that the cited diameter coincides with good accuracy with the critical diameter of the same explosive, which is determined in the charges, placed into the thin cellophane shell. Such a coincidence points out the generality of the process, which leads to the attenuation of detonation in this and in the other case.

Let us examine the gas dynamic problem of the transfer of detonation from a cylindrical tube into a volume. According to head-on scanning, a diverging detonation wave is formed at a considerable distance from the axis of the charge, which permits us to simplify the problem by the substitution of a cylindrical diagram of the flows by a flat diagram. Such a substitution does not introduce significant distortions into the structure of flows to the side of the axis of the charge, however in calculating the induction time behind the shock wave between a cylindrical and a flat diagram significant distortion may result. Therefore, in an analysis of the processes connected with the kinetics of the heat liberation, we will keep in mind that the examined problem is cylindrical. Figure 78 represents a cross section of a charge

along the plane, drawn through the axis of symmetry. Let us stipulate that the leadoff time runs from the moment of the passage of detonation from the tube into the volume.

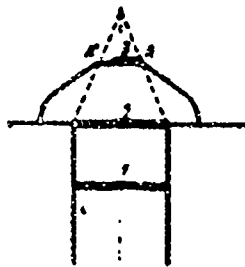


Fig. 78. Diagram of the passage of the detonation front from the tube into the volume.

As experiment shows, the surface of the detonation front in the tube, as well as after its passage into the volume is flat (in the macroscopic sense). This fact, apparently, is explained by the interaction of the inhomogeneities with the wall as with an absolutely rigid barrier, as a result of which valid initiation of the reaction is ensured on the edges of the charge as well. In future discussions this circumstance will be used to a significant degree.

At the moment of passage of the detonation front from the tube in its boundaries the interaction with the rigid shell disappears. Due to the strong dependence of the rate of the reaction on the temperature (in the final analysis, on the pressure) on the boundaries of the front there occurs a separation of the chemical reaction in precisely the same way, as on the free surface of the charge. Thus, the reaction time increases with a jump from the value, which existed in the unlimited detonation front (and is preserved on its sections, which lie close to the axis of the charge, to a certain greater value. Due to the strong dependence of the rate of the reaction on the pressure its separation occurs practically immediately, on the front of the rarefaction wave. Therefore, on the surface of the detonation front a wave of reaction cessation will be propagated with a

constant velocity. Its velocity will be determined by the velocity of the shift of the leading edge of the rarefaction wave along the surface of the front. This value, naturally, is connected with the sound speeds in the shock-compressed explosive and in the products.

Let us examine the flow scheme in the vicinity of the boundary of the attenuating detonation front in approximation, when this front can be assumed to be a separation surface. It is concrete, i.e. $d \gg a$, which will also be assumed in the future. But this assumption allows us to assume that the classical detonation theory is applicable for the movement of the detonation front both in the tube, as well as in the volume. In particular, the products of the explosion leave the detonation front with the speed of sound.

Let us connect the coordinate system with point A (Fig. 79), which is situated on the boundary of the attenuating detonation front. In this coordinate system the oncoming flow of the initial explosive has a velocity D^* . It is parallel to trajectory 3 on the top of the right angle 1-1' (in the given coordinate system this angle moves). The velocity of the flow of products u_1 is the vectorial sum of the velocity of the wave of reaction cessation along the front v and the velocity of the outflow of products from the front, which in conformance with the assumption that $d \gg a$ is none other than the speed of sound c_1 (Chapman-Jouguet principle). Shock front 4, formed as a result of the expansion of the products to the sides and of the expansion of the initial explosive by them, it joins attenuating detonation front 2. As a result of the expansion of the products to the sides the pressure in them must fall. Therefore, in the flow of the products a rarefaction wave 6-6' is established. The flow of products, having avoided the rarefaction wave, becomes parallel to the flow of the explosive behind shock front 4. The pressure on both sides of the interface 5 must be identical. In the future, all the values referring to one of these regions (0), (1), (2), (3), (4) (Fig. 95) will be designated by letters with the corresponding subscripts 0, 1, 2, 3, 4.

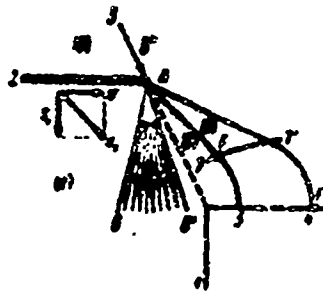


Fig. 79. Structure of the flows in the vicinity of the boundary of the attenuating detonation front.

The flows in region (0) and (1) are determined by the fulfillment of the conditions of the problem, since the rate of detonation D , the rate of movement of the wave of the reaction cessation v and the velocity of the product outflow from the front c_1 are determined by the properties of the selected explosive. All the remaining parameters of the flow may be calculated, if we know the equation of state of the initial explosive or at least its shock adiabat curve, and also the isentrope of the explosion products. Henceforth we shall assume that all the elements of the cited scheme of flows are known; the specific calculation for nitromethane and cast trotyl is shown in work [145].

It is possible to show that u_2 and u_3 are greater than the corresponding speeds of sound c_2 and c_3 . Actually, the normal component of the flow, intersecting the boundary of the Prandtl-Meyer flow, is equal to the speed of sound at the given point in space. Consequently, the total velocity $u_2 > c_2$.

The second inequality $u_3 > c_3$ is proven, on the strength of the physical concept of the speed of the wave of reaction cessation v . Let us submit for the moment that the shock front 4 does not diverge with respect to the detonation front 2. In this case velocity u_3' would have a lower value than it does in fact have. On the other hand, it would be equal to the speed of sound c_3' , corresponding to a pressure not lower than the pressure of the weak sections of the detonation front. In turn, the weak sections have a pressure of not less than that obtained behind the shock

front as a result of the disappearance of the reaction over the entire area, i.e., during the discharging of the reaction products forward along the detonation path. Shock front 4 corresponds to the discharging of the same products to the side and therefore has a lower pressure. Consequently, $c_3 < c_3'$. However, in such a case $u_3 > u_3' = c_3' > c_3$.

From the demonstrated inequalities

$$u_3 > c_3 \quad (78)$$

$$u_3 > c_3 \quad (79)$$

it follows that the examined scheme of flows is correct not only in the small vicinity of point A, but also in a certain finite region of space around this point. The boundary of this region from the aspect of the shock-compressed explosive and the rarefied products is the leading edge of the second rarefaction wave 7-7'. The latter forms because of the same reason, that the products and the compressed explosive must of necessity somewhere be discharged to the pressure of the medium surrounding the detonation charge. The point of intersection F of boundary 7-7' with the separation surface 5 is removed from point A with velocity u_p , which is equal to the lesser of values $u_2 - c_2$ or $u_3 - c_3$. For example, let us assume that $u_2 - c_2 < u_3 - c_3$. This means that the sonic disturbance in the product is communicated with a flow velocity less than the sonic disturbance proceeding in the explosive. In this case point F will shift with a velocity $u_2 - c_2$, while the front of the rarefaction wave in the compressed explosive will form such an angle to the line of separation 5, so as to enable it to interlock with the front of the rarefaction wave, propagating from the products. In other words, in the examined case the rarefaction wave in the products "leads" the rarefaction wave in the compressed explosives. This may lead only to the attenuation of the steepness of its front, but it will not be expressed in its velocity. Thus, point F shifts with the speed of

the leading wave, and therefore $u_p = u_2 - c_2$, i.e., this speed is actually equal to the lesser of the cited velocities.

The Mechanism of Detonation Cessation

The explosive shown in region 3 has the potential of flaring up after the lapse of the induction period τ , which is determined by the conditions behind shock front 4. Thus, τ is that value, to which the reaction time increases after the disappearance of interaction of the detonation front with the wall of the tube.

It is necessary to point out that the induction time τ is related not only with the pressure behind the shock front, but even with the rate of fall of this pressure in each particle of the explosive after its passage through the shock front. In the case of a flat system of flows the fall in the parameters behind shock front 4 right up to the rarefaction wave 7-7' does not take place. However, actually the system of flows is cylindrical, and therefore the flow of the explosive behind the shock front is diverging from the axis of the charge and the pressure in this flow falls in proportion to the distance away from point A. Consequently, induction period τ in this case is greater than it would be in the case of a shock front of the same amplitude, but with constant parameters behind it.

At first deflagration takes place only at that moment t_1 , when the portion of the explosive, which remained in region 3 not less than the induction period, reaches point F. Toward moment t_1 point F will move away from point A by the distance $u_p t_1$, since these points coincided initially. The same path is traversed by a section of the explosive with speed u_3 for time τ :

$$u_p t_1 = u_3 \tau. \quad (80)$$

The flash of the compressed explosives at point F, just as in the initiation of detonation by the shock wave, leads to the formation of detonation in the compressed explosive. It is propagated to all sides, including in the direction of the attenuating detonation front. Overcoming shock front 4, the regenerated detonation leads to the initiation of an ordinary detonation front in the initial explosive, which by its boundaries is based on the detonation in the compressed explosive. Points A and A' on the head-on scan of Fig. 76 also corresponds to this moment precisely.

Because of the fact that the regenerated detonation front (Fig. 80) interlocks its edges with the detonation front, propagating through the compressed explosive, it is overcompressed on the edges, since the pressure behind the detonation front in the compressed explosive is higher than the pressure behind the normal detonation front in the initial explosive. Consequently, the detonation front in the initial explosive on the edges must be even more stable than in the center. The stability of the entire regenerated configuration of the detonation fronts depends mainly on the possibility of stable propagation of detonation through the compressed explosives. In nitromethane, mixtures of it with acetone and melted trotyl detonation in the compressed explosive, as experiment shows, is stably propagated both to the axis of the charge, and in the counterdirection, i.e., also in the region encompassed by the rarefaction wave - below 7-7' (see Fig. 79).

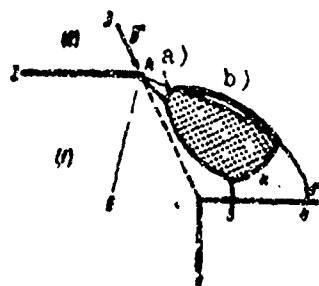


Fig. 80. Diagram of the propagation of a diverging detonation front. a) detonation front in the compressed explosive; b) diverging detonation front.

Let us determine time t_2 , passed from the first deflagration to the moment when detonation of the compressed explosive overtakes the boundary of the attenuating detonation wave, assuming as known the rate of detonation in the compressed explosive D_2 and assuming that this detonation is formulated practically at one point:

$$t_2 = \frac{2d}{D_2 - D_1} \quad (81)$$

In the numerator we have the path, which has to pass the detonation in region (3), and in the denominator - the velocity, with which the detonation overcomes this path. Thus, the attenuation of the detonation front after its exit from the tube into the volume will cease after

$$t = t_1 + t_2 = 2d_1 \left(\frac{1}{D_1} + \frac{1}{D_2 - D_1} \right) \quad (82)$$

After this time the opposite points, lying on the boundary of the attenuating detonation front, will succeed in decreasing to value

$$d_1 = 2d = 2D_1 t \left(\frac{1}{D_1} + \frac{1}{D_2 - D_1} \right) \quad (83)$$

Experiment shows that the critical diameter on the transfer of detonation from the tube to the volume coincides with d_1 . It was found that detonation cannot disperse even in the case where the deflagration of the explosive behind shock front 4 occurs, but the arising detonation in the compressed explosive does not succeed in reaching the boundary of the attenuating detonation front before its disappearance. In this case the flash which was about to arise attenuates. The reason for the behavior of the detonation, apparently, lies in the formation of a rarefaction wave diverging from the axis of the charge, which we shall call the central rarefaction wave. It is formed in moments of total disappearance of the attenuating detonation front. Actually, the latter served as the source, feeding shock front 4 and sustaining

constant pressure in region 3. The disappearance of such a source is equivalent to the emergence of a new rarefaction wave on the charge axis.

The central rarefaction wave encounters detonation from the compressed explosive (if the latter has arisen) and quickly transfers the edge of the diverging detonation front from overcompression. With the rapid removal of overcompression there occurs a separation of the reaction, and the diverging detonation front attenuates. The same thing occurs with the other boundary of the diverging detonation front. If the central rarefaction wave arises earlier than the deflagration of the explosive behind shock front 4, then it may, in general, destroy the possibility of ignition, i.e., deflagration will not occur at all.

If in some manner the central rarefaction wave attenuates, then deflagration and divergence of detonation would have to be observed also after the disappearance on the attenuating detonation front. The central rarefaction wave can be weakened by the replacement of the cylindrical tube by a flat , i.e., having a rectangular cross section, one side of which is considerably larger than the other. In this case the central rarefaction wave will be weaker because the compressed substance after the disappearance of the attenuating detonation front will have to discharge not to all sides of the axis of the charge, but only into two sides from the plane of symmetry. Experiments conducted with flat tubes have shown that the deflagration and expansion of detonation in the volume take place even much later after the disappearance of the attenuating detonation front, where the deflagration can also take place on the plane of symmetry of the charge, i.e., clearly in the region encompassed by the central rarefaction wave.

As was already pointed out, the critical diameter of the transition of detonation from the tube into a volume, designated subsequently as d_1 , coincides approximately with the critical

diameter of the given charge in a weak shell. Such a coincidence is not accidental and is connected with the identical mechanism of formation of the wave of reaction cessation and of the restoration of the detonation wave.

Actually, detonation in the charge of the liquid explosive in a weak shell is accompanied by periodic attenuation of the detonation front after its boundaries have come in contact with the free surface of the charge and after its subsequent restoration as a result of the deflagration and detonation of the compressed explosive (see Fig. 75). Pulsations of the surface of the detonation front, propagating through the charge in a weak cellophane shell, have, however, an irregular character and occur asynchronously from various sides from the axis of the charge.

The difference between d_1 and d_{np} can arise as a result of the fact that in the first case the attenuating detonation front is macroplane, and in the second case it, as a result of several pulsations, becomes convex. Because of this, shock front 4 comprises the smaller angle with the axis of the charge, increases the divergence of the flow from the axis behind this front and increases the induction period. In other words, for this reason $d_{np} > d_1$ must exist. However, the above-cited irregularity of the pulsations of the front may in the second case lead to the opposite result, since the wave of reaction cessation, arising only from one side of the charge, may penetrate further than the axis, without leading to the emergence of a central rarefaction wave. Coincidence between d_1 and d_{np} shows that the given reasons practically balance one another.

Thus, expression (83) can be assumed for the approximate formula for the critical diameter of detonation of the examined liquid explosives. It follows from this formula that the critical diameter is determined not by the reaction time in the detonation wave, but by the greater induction time behind the shock front, adjoining the attenuating detonation front. Therefore



(84)

where a , as always, is the width of the reaction zone. Inequality (84) shows that the rough detonation front on the axis of the charge even in the vicinity of its limit of propagation may be examined from the viewpoint of the theory of ideal detonation. In particular, its speed in conformance with experimentation must be equal to the speed of ideal detonation.

From formula (83) a calculation was made of the ratio d_1/τ for nitromethane, mixtures of it with acetone and melted trotyl [145, 146]. The calculation error, determined mainly by the accuracy of the initial data, is equal to 20%. It was found that values of d_1/τ , calculated and measured from head-on scans during the transition of detonation from a tube to a volume, differ by 19% in the case of nitromethane and 3-8% in the remaining cases. Such a result can be taken as good confirmation of the theory.

It is interesting to note the formal similarity of expression (83) with Khariton's formula, which is found, $d_1/\tau = 2c'$. The value of c' for nitromethane and mixtures of it with acetone is equal to 14 km/s, and with a certain degree of stretching it can be taken as the speed of sound. However, in contrast to Khariton's formula the value of τ in expression (83) represents the reaction time not in the detonation front, but behind the shock front adjoining it.

§ 3. The Nature of the Critical Diameter of Detonation of Liquid Explosives with a One-Dimensional Reaction Zone

Comparison of Liquid Explosives From the Viewpoint of the Structure of the Detonation Front

In the case of a smooth detonation front the process of heat liberation in the reaction zone occurs according to the law of

a degenerated thermal explosion. The highest degree of degeneration from studied liquid explosives is observed in tetranitromethane. Therefore, using it as an example, the most clearly expressed differences are those in the behavior of the detonation front from the just examined case of liquid explosives without a one-dimensional reaction zone. Figure 81 shows in-time scans of the luminescence of the detonation front during the passage of the latter from the tube into the volume for two different diameters of the tube. The detonation attenuation observable with a smaller diameter after its passage into the volume is reminiscent of the corresponding picture for the case of explosives with a rough detonation front, with the exception, however, that the rate of the wave of reaction cessation depends strongly on the tube diameter and is not constant in time.

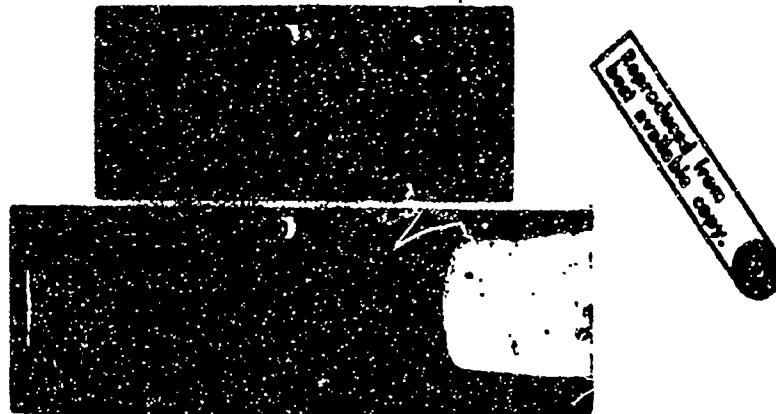


Fig. 81. Head-on scan of the luminescence of the detonation front in tetranitromethane during its passage from the tube into the volume. Tube diameter: a) 15 mm; b) 35 mm.

With a certain tube diameter (16-17 mm) after the transfer of detonation into the volume the area of a front is not yet shortened, but remains constant. Thus, detonation is propagated through the volume, as if it were going through an extension of the tube. Although in this case detonation does not diverge through the volume, it nevertheless does not attenuate, and the corresponding diameter should be assumed to be the critical diameter of the

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transfer of detonation from the tube into the volume. In proportion to the further increase in the diameter the detonation front becomes divergent, as if after leaving the tube it were continuing its movement within the limits of a certain cone, whose opening angle increases together with the tube diameter.

The critical diameter of the transition of detonation from the tube into the volume, as experimentation has shown, coincides with the critical diameter of propagation of detonation in glass tubes. This bears witness, just as before, to the similarity of the processes which determine the critical diameters of the cited forms.

Besides the above-expounded differences, tetranitromethane also possesses properties, which unite it into a single class with liquid explosives with a rough detonation front.

In the study of detonation of liquid explosives with sufficiently large d_{kp} values an interesting phenomenon was discovered, which is not explainable from the viewpoint of the works, mentioned in the beginning of this chapter. It was found that the critical detonation diameter decreased sharply, if the internal wall of the glass or other employed nonmetallic shell was covered with a thin metallic foil. If, as is tacitly assumed in the cited works, the critical diameter coincided with d_{min} , then for a significant decrease in this value a shell would be required, comparable in width with d_{kp} , since a thin shell is not capable of significantly affecting the divergence of the flow. Since d_{kp} is much greater than the width of the foil, then

$$d_{kp} \gg d_{min} \quad (35)$$

Tetranitromethane, in comparison with liquid explosives having a rough detonation front, has an additional peculiarity. In liquid explosives with a rough detonation front the above-cited width of the foil must be of the order of the size of the

inhomogeneities (and, consequently, simultaneously of the width of the reaction zone), which has a simple explanation. An extreme inhomogeneity after its collision with the shell must rest for a sufficient time on the wall, so that the adiabatic flash in it can pass through before the arrival of the rarefaction wave from the outer boundary of the shell. In contrast to the cited liquid explosive the width of the shell made from foil, which substantially reduces the critical diameter of the tetranitromethane (from 16 to 6 mm), is equal to 0.05 mm, which is significantly less than the width of the reaction zone of 2 mm. A tentative explanation of this fact is that the shell must in this case maintain the parameters of the shock compression on the boundary of the charge only, during the initial period of occurrence of the reaction, when the latter has not yet reached sufficient speed.

In all the investigated liquid explosives there was also detected a somewhat different effect of the thin shell, which consists in the following. If during the passage of detonation from the tube into the volume there is established in the latter a continuation of the tube from the thin metallic foil, then even with a tube diameter greater than critical detonation in the volume is propagated only within the limits of the cylinder, limited by the foil. Let us recall that with the absence of the latter the detonation front in tetranitromethane would diverge within the limits of a cone, while in liquid explosives with a nonone-dimensional reaction zone a detonation wave diverging into the entire volume would arise.

It is interesting to note that if the mentioned tube made from foil is shortened and stops within the limits of the volume, then after leaving it the detonation front behaves precisely in the same way as during passage from the rigid tube into the volume. Let us now examine all these phenomena from theoretical positions.

Peculiarities of the Flow Around the Limit of an Attenuating Detonation Front

In constructing the flow scheme for liquid explosives with a nonone-dimensional reaction zone two assumptions are used: that of the practically instantaneous separation of the reaction at the forwardmost edge of the rarefaction wave and that of the initiation of detonation in the compressed explosives within the limits of a very small volume, which, practically speaking, can be assumed to be a point. These assumptions can be fulfilled only for those explosives, in which the kinetics of the heat liberation correspond to the law of a normal thermal explosive.

What will happen with a departure from this law? Obviously, in proportion to its degeneration there will be a breakdown in the geometric rectilinearity of the system of flows, represented in Fig. 80 for the limiting case. Actually, although the forward boundary of the lateral rarefaction wave must, as before, propagate over the area of the detonation front with a constant speed, the line of separation of the chemical reaction will be distant from this boundary by the value, determined by the deepness of the rarefaction wave.

For the transfer from the tube into the volume the latter designates that at the initial moment, i.e., when leaving the tube, the separation line almost coincides with the forward boundary of the rarefaction wave, then the distance between them grows as the rarefaction becomes smoother. Finally, in the vicinity of the axis of the charge as a result of the divergence of the flow the steepness of the rarefaction curve again increases, and the separation line again must approach the leading edge of the disturbance, going along the reaction zone. Thus, the observable variable speed of the boundary of the attenuating detonation front and its dependence on the initial diameter of the tube can be explained naturally. It is sufficient only to assume that this

boundary coincides with the line of separation and to keep in mind that with a rise in the tube diameter the divergence of the flow to the sides of the charge axis decreases and, consequently, the steepness of the rarefaction wave, propagating over the area of the detonation front, also decreases.

Thus, with the deviation of the law of a thermal explosion from normal first of all point A in Fig. 79 is blurred into the region of separation of finite dimensions, depending on the initial diameter of the detonation front (zone A-A' in Fig. 82), since in this region the amplitude of the shock front is weakened, the edges of the latter must fall. In turn this leads to a lower value of the angle between shock front λ and the axis of the charge, i.e., to a reduction in its amplitude and to an increase in the flow divergence from the mentioned axis. Thus, as the region of separation A-A' expands, the conditions of initiation of detonation behind shock front λ must deteriorate.

At a certain stage of degeneration of the law of thermal explosion there is a qualitative abrupt change, connected with the impossibility of the formation of detonation in the compressed explosive behind shock front λ . Apparently, tetranitromethane conforms exactly to the latter inclusion. In this case the critical diameter of the transfer of detonation from the tube into the volume is determined not by the flash of the explosive behind the shock front λ , but by the dependence of the rate of propagation of the separation line to the axis of the charge on the tube diameter. This rate decreases to zero with the increase in the tube diameter and then becomes negative (i.e., directed from the axis of the charge) this permits us to explain the observed coincidence of critical diameters during the transfer of detonation from the tube into the volume and during its propagation in cylindrical charges. At a zero rate of attenuation of the detonation front behind shock front λ supersonic flow of the compressed explosive takes place. In this case the flow within

the limits of the detonation front would not change, if in the cited flow a free charge boundary was found. From this also follows the coincidence of the two forms of critical diameter for tetranitromethane.

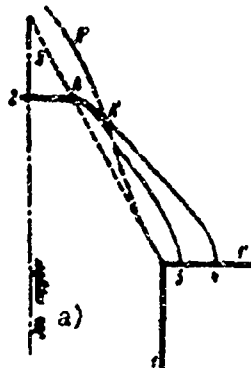


Fig. 82. Diagram of the attenuation of detonation with a one-dimensional zone in a liquid explosive during the passage of the detonation front from a tube into a volume.

KEY: a) Axis of the tube.

From what has been said it follows that the critical diameter of the charge of tetranitromethane without a shell must be described by the stationary theory, i.e.,

$$d_{st} = d_{cr}. \quad (85)$$

It is difficult to confirm this conclusion with direct experimental checking, at least until the mechanism of the effect of a thin shell on the value of the critical diameter is completely clarified. Actually, charges of tetranitromethane, as with any liquid explosive, must have some kind of shell. However, in such a case the reason for stationary propagation of detonation in these charges can be attributed with certain care to the effect of the given shell.

The following experimental fact indirectly bears witness in favor of equality (86). It was found that during the propagation of the detonation front, resting with one edge on the free boundary of the tetranitromethane, no pulsations of the area of the front

were detected, such as occur in a similar situation with liquid explosives with a nonone-dimensional reaction zone. In this respect the detonation of tetranitromethane is similar to the detonation of solid explosives.

Let us examine in more detail the possible reasons for the strong influence of the thin shell on the value of the critical diameter of the detonation of tetranitromethane. As was already mentioned, the presence of such an effect testifies to the great difference between solid explosives and tetranitromethane and places the latter into a single category with other liquid explosives.

The Effect of a Thin Shell

To clarify the role of the thin shell let us construct one of the possible schemes of flow in the vicinity of the charge boundary with the shell (Fig. 83). As is usual, the picture of the flows is examined in a system of coordinates, connected with the detonation front. In order for this picture to be stationary, the flow behind the shock front in the vicinity of point A must be supersonic. In the opposite case, the boundary of the stationary rarefaction wave A'FE could not be established in this flow.

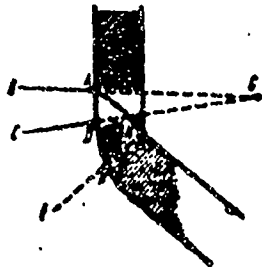


Fig. 83. Approximate diagram of the flows in a stationary detonation wave when there is a thin metal shell.

The flow behind the shock front of detonation AB in the vicinity of point A may turn out to be both supersonic, as well as subsonic. In the first case the structure of the flows in the

reaction zone would basically not differ from that examined earlier for a charge without a shell (see Fig. 71). Just as before, the sonic surface would have to intersect the shock front AB, and the effect of the shell would be exerted only in the region of the supersonic flow of the reacting medium. For this reason the given case probably has no relationship with the effect of the thin shell.

In the second case, i.e., with a subsonic speed of flow of the reacting medium away from point A, the sonic surface CD does not intersect the shock front of detonation. Apparently, in this case we may assume that the shell substitutes itself for the imaginary section of the detonation front AC, which should have maintained approximately the same conditions of stationary propagation of detonation on boundary AD with no shell present.

The preceding assumption allows us to explain the effect of a thin shell by supposing that the imaginary section of the detonation front has such large dimensions, that with no shell present the charge diameter must be increased n times, so that a stationary detonation front can be propagated through the latter. Under such conditions is this possible?

Let us return to the fundamental expression (67). It follows from it that in the region of subsonic flow in the reaction zone the following inequality must exist

$$p > 2 \frac{q}{u}. \quad (87)$$

However, the divergence of the flow $\partial/\partial r$ directly behind the shock front, with the other conditions remaining constant, is apparently a monotonically increasing function of the slope of the latter. Consequently, depending on the kinetics of the heat liberation in the reaction zone at the initial moment after the shock compression inequality (87) imposes greater or lesser limitations on the value

of the slope of the shock front of the detonation. In turn, the slope of the shock front determines the distance from the line of its intersection with the sonic surface up to the axis of the charge, and it is this distance which increases with the decrease in the slope.

Summing up all the foregoing considerations, one can draw the following conclusions. With strongly degenerated heat liberation kinetics, when the value P immediately after shock compression as a large value, the sonic surface and the shock front are quite bent and converge at a large angle toward one another (at the limit of propagation of detonation). Therefore, the size of the imaginary section of the detonation front AD must be small. In other words, the thin shell will not significantly affect the value d_{np} . On the other hand, in proportion to the approach of the heat liberation kinetics to the normal law of a thermal explosion, which primarily consists in the reduction in the initial value P (if the total reaction time is assumed to be constant), the slope of the shock front and of the sonic surface falls, the angle of their intersection is reduced, and the size of the imaginary section of the detonation front AC increases correspondingly.

It is interesting to note that in the experiment a sharp reduction is noted in the slope of the detonation front, including at the limit of its propagation (both in the charge with a shell and in the one without it), during the transition from solid explosives to liquid. Thus, the conclusion about the reduction of the slope of the front as the kinetics of the heat liberation approaches the law of the normal thermal explosion is confirmed experimentally.

Thus, the effect of a thin shell for a smooth detonation front must exist only in the case where the kinetics of the heat liberation in the reaction zone correspond to the law of a weakly degenerated thermal explosion. It should be emphasized once again

that this conclusion is based essentially on the assumption of equivalency of the effect of the shell on the sub-sonic reaction zone and of the effect on the same zone of the degenerated portion of the detonation front (which in the absence of the shell must be replaced by a real section of the front). If this assumption is not justified with sufficient accuracy, then another explanation of the effect of a thin metal shell should be found.

From the diagram of flows shown in Fig. 83 it is clear that not every shell material can lead to its noticeable influence on the value of d_{sp} . For the examined effect a definite relationship between the dynamic properties of the material of the shell and of the studied explosives is necessary. In particular, the shell density must be as large as possible, so that with one and the same shock compression pressure the normal speed of the shock front in the shell will be less than the same speed in the explosive. Consequently, if the conclusions drawn here are more rigorously justified, then one can give a strict experimental confirmation to formula (86) by using the appropriate shell material.

The small slope of the shock front of detonation in the charge of a liquid explosive with a thin metal shell also allows us to easily explain the second of the earlier mentioned effects of a thin shell. Actually, if the space around this charge is filled with the same liquid explosive, then it has no significant effect on the detonation propagation within the confines of the shell, since in the determinant section AD (see Fig. 83) the effect of the thin shell with all other conditions being equal is equivalent to the effect of an infinitely thick shell (information on the thickness of the shell comes to the flow of the explosive only at point F). Thus, the detonation front within the limits of the shell will be flat in contrast to its shape when there is no shell.

Figure 84 gives a diagram of the flows, arising behind the detonation front and in the surrounding explosive. It can be obtained from the diagram of flows in the vicinity of the attenuating detonation front, represented in Fig. 79, if we assume that the speed of the wave of reaction cessation is $v = 0$. In the latter flow system the flow behind shock front 4 is essentially divergent from the charge axis. Because of this each element of the initial explosive after shock compression immediately appears to be under conditions of rapid adiabatic expansion. Under such conditions all liquid explosives may undergo separation of the possibility of ignition, as a result of which the induction period becomes infinite (the surrounding explosive does not detonate, in spite of the increase with time of the dimensions of the region of the compressed explosive). Thus, the second effect of a thin shell is related with the fact that it obstructs the buildup of the edges of the detonation front and does not enable it to propagate to the side.



Fig. 84. Diagram of the flows during detonation propagation within limits, delimited by a thin metal shell.

Let us note that in solid explosives such an effect is apparently impossible because they begin to react immediately on the shock front.

Transfer From the Stationary Theory of d_{kp} to the Nonstationary

Of great interest is the investigation of those liquid explosives, which are between tetranitromethane and nitromethane with respect to the peculiarities of the kinetics of the heat liberation in the reaction zone. As an example of such explosives

we can point out the form of the transfer from the stationary theory of d_{kp} (tetranitromethane) to the nonstationary theory (nitromethane).

Nitroglycerine and dinitroglycerine belong to the cited liquid explosives. These explosives are close to one another in chemical structure and are distinguished by their high power. The strong effect of the thin metal shell on the d_{kp} value can also be observed for them.

Figure 85 shows time scannings of the luminescence of the detonation front in nitroglycerine during its transition from rigid tubes of various diameters into a volume. To increase the image on the film of the photo recorder in these experiments magnifying lenses, placed in front of the charge at a distance of less than the focal length, were used. Such scannings for dinitroglycerine do not differ qualitatively from those represented, if we do not consider the approximately fourfold increase in the critical diameter in the latter case.

The photoscannings shown testify to the significant difference of the picture of the transfer detonation from a tube to a volume both from the case of tetranitromethane (see Fig. 61), as well as from the case of nitromethane (see Figs. 76 and 77). Attention is drawn to the fact that after the passage of detonation into the volume the boundaries of the detonation front reveal special pulsations, which can be explained in the following way.

In nitroglycerine and dinitroglycerine the detonation front is one-dimensional. Therefore, the nature of the detonation attenuation during its passage into the volume and after each pulsation must be the same as in tetranitromethane. At the same time behind the shock front, adjoining the boundary of the attenuating detonation front, the kinetics of the heat liberation corresponds to the law of a normal thermal explosion. Therefore,

just as in nitromethane, in this case behind shock front 4 (see Fig. 79) adiabatic flashes occur and detonation in the compressed explosive is formed.

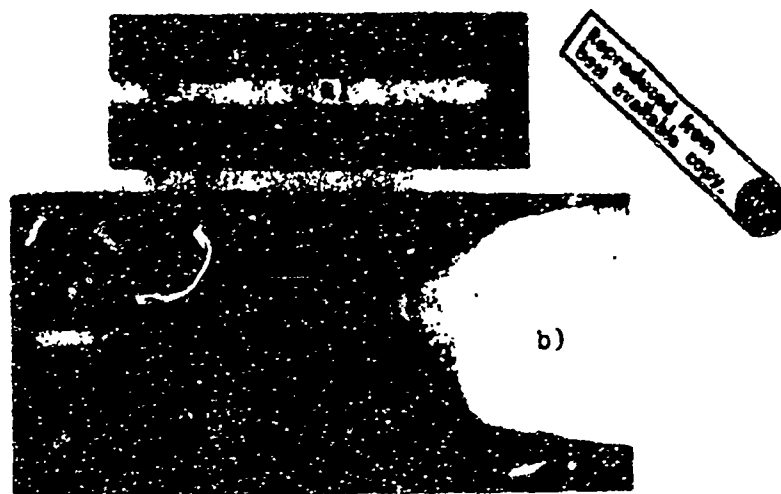


Fig. 85. Head-on scanning of the luminance of the detonation front of nitroglycerine during its passage from a tube into a volume. Tube diameter a) 1.7 mm; b) 2.4 mm.

It would seem that the further development of detonation should take place according to the system, existing in nitromethane. However, instead of propagating to both sides from the site of its emergence, detonation in a compressed explosive proceeds only toward the axis of the charge, and trailing behind it a wave of reaction cessation is propagated. Such detonation behavior, however paradoxically, is related with the small value of the induction period behind the shock front. It is precisely because of this that a sufficiently large layer of the compressed explosive fails to increase before the initiation of detonation behind the shock front. As a result, the initial volume of the compressed explosive, which is encompassed by detonation, turns out to be too small to initiate and sustain a diverging detonation wave in a noncompressed explosive. For the same reason the detonation of

a compressed explosive does not proceed in the least favorable direction, i.e., against the peripheral rarefaction wave. In this way the pulsation attenuates. However, in its place in the same way the following one arises and so on.

It is interesting to note that in pure nitromethane and in mixtures of it with acetone a picture similar to that described above is occasionally observed. This occurs when because of random reasons (apparently, due to microbubbles of gas) the induction time behind the shock front proves to be an order less than its normal value.

Let us return to nitroglycerine and dinitroglycerine. Depending on the tube diameter each subsequent flash behind the shock front can take place either before the total attenuation of the preceding one, or after it. This also apparently determines the value of d_{np} of the transition of detonation from the tube into the volume. Just as in the case of other liquid explosives, it was found that this diameter coincides with the critical detonation diameter of the same explosive in a glass shell. On this basis one can conclude that in the given explosives the critical diameter must be determined by the nonstationary theory, wherein the latter will significantly differ from the case of liquid explosives with a rough detonation front.

In conclusion let us make a few general remarks on the limits of detonation propagation with respect to the charge diameter in all liquid explosives. On the basis of what has been said it can be asserted that in all liquid explosives $d_{np} \gg d_{min}$. Therefore, the dependence $D(d)$ for all liquid explosives is broken off long in advance of a noticeable decrease in the detonation rate with a decrease in the diameter. This gives clarification to an experimental fact: the weak dependence of the detonation rate on the charge diameter in all liquid explosives. The second conclusion consists in the fact that the width of the reaction zone in

all liquid explosives does not have a direct relationship to d_{kp} and is much less than its value.

In the literature one sometimes encounters the comparison of the sensitivity of an explosive to a shock wave with the value of d_{kp} [137]. Such a comparison is not well-grounded for liquid explosives.

Actually, the sensitivity of an explosive during shock initiation is determined by the laws of development of the adiabatic thermal explosion during heating, which is fixed using the active charge. Consequently, the sensitivity of an explosive primarily depends on the activation energy and only secondly - on the heat of the reaction. For example, in nitromethane and mixtures of it with acetone at one and the same pressure of shock compression the induction period is almost identical. On the other hand, the critical diameter is determined either by the conditions behind shock front 4 (see Fig. 79), or by the conditions at the points of intersection of the shock front of detonation with its sonic surface. In both instances heating at the indicated sites depends on the power of the explosive, which determines the detonation rate, and through the latter - also determines the temperature of the shock compression. Consequently, the critical diameter depends both on the activation energy, as well as on the power of the explosive (in this respect liquid explosives are similar to solid).



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Fig. I. Experiment with light reflection in nitromethane. 1 - moment of entry of the shock wave into the liquid; 2 - light reflection from the shock wave; 3 - light reflection from the front of normal detonation; 4 - luminescence of normal detonation; 5 - luminescence of the second wave.

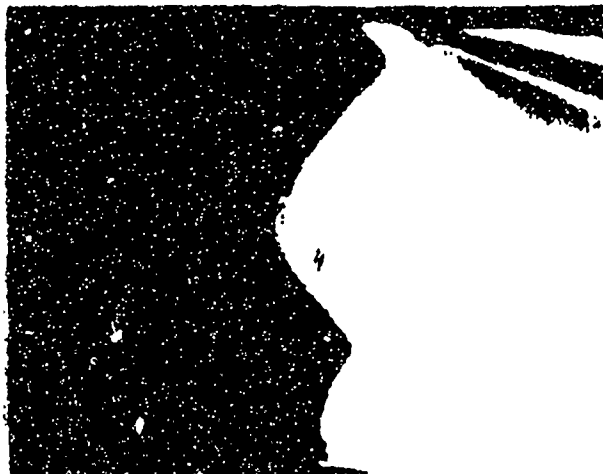


Fig. II. Photoscanning of the luminescence during the initiation of nitroglycerine. 1 - moment of entry of the shock wave into the nitroglycerine; 2 - "halo"; 3 - luminescence of the second wave; 4 - luminescence of normal detonation.

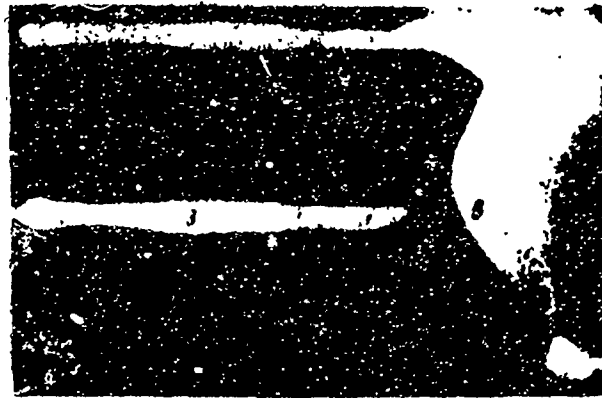


Fig. III. Experimentation with light reflection in nitroglycerine. 1 - moment of entry of the shock wave into the nitroglycerine; 2 - light reflection from the shock wave; 3 - light reflection from the surface of a boundary made from plexiglas with a deposited aluminum layer; 4 - "dark region," arising as a result of the cessation of light reflection from the boundary; 5 - luminescence of the second wave; 6 - luminescence of normal detonation.



Fig. IV. Experimentation with light reflection in tetranitromethane. 1 - light reflection from the surface of a boundary, covered with a thin aluminum layer, before the passage of the shock wave through it; 2 - moment of entry of the shock wave into the liquid (reflection from the interface immediately disappears); 3 - light reflection from the shock wave front; 4 - moment of formation of detonation in an undisturbed liquid; 5 - luminescence of normal detonation in tetranitromethane; 6 - light reflection from a normal detonation front.



Fig. V. Head-on photoscanning of the process in nitromethane with a flat foil, placed a certain distance from the interface. 1 - moment of passage of the second wave to the foil.

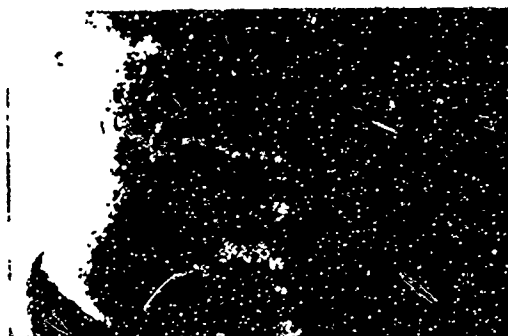


Fig. VI. Photoscanning of the process of detonation propagation in a mixture of nitromethane with acetone in a volumetric ratio of 72:28. 1 - start of detonation.



Fig. VII. Photoscar of the experiments with light reflection. 1 - light reflection from the interface prior to the appearance of the shock wave in the liquid explosive; 2 - moment of entry of the shock wave into the medium; 3 - "mirror" light reflection from the shock wave; 4 - luminescence of the detonation of shock-compressed nitromethane; 5 - luminescence of normal detonation in nitromethane; 6 - light reflection from the surface of the detonation front (reduction in the width of the image is caused by the convexity of the detonation front); 7 - region of overcompression.

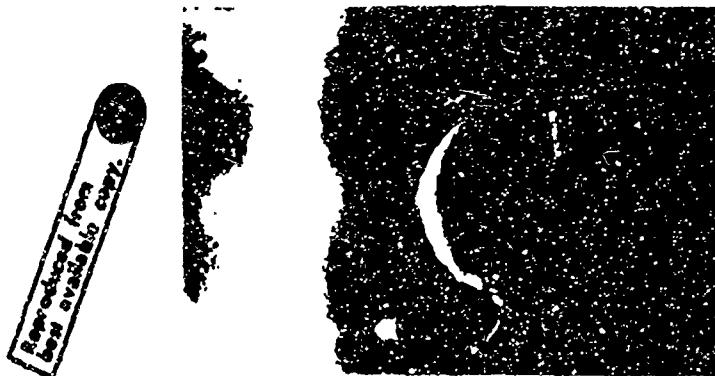


Fig. VIII. Photoscan of the process of detonation initiation in a mixture of nitromethane with acetone in a volumetric ratio of 60:40. 1 - moment of shock wave entry, fixed by the flash of the miniature charges, placed on the interface of the active charge; 2 - weak luminescence, corresponding to detonation of the shock-compressed mixture; 3 - luminescence of detonation in an undisturbed mixture; 4 - repeated adiabatic flashes in the shock wave.



Fig. IX. Photoscan of the experiments with artificial excitation of the detonation of a shock-compressed mixture. a) mixture of nitromethane with acetone in a ratio of 60:40; b) mixture of nitromethane with acetone 65:35; 1 - moment of entry of the shock wave; 2 - explosion of the initiating charge, placed on the interface; 3 - luminescence of detonation of the shock-compressed mixture; 4 - luminescence of detonation in an uncompressed mixture (the "fine structure" is visible); 5 - region of propagation of the shock wave without ignition.



Fig. X. Photoscans of experiments on observing the interaction of triple detonation configurations. a) free passage of configurations through one another; b) damping of configurations upon collision.

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Fig. XI. Photocopy of process of initiation of detonation in a mixture of nitromethane with acetone with a short powerful discharge. 1 - start of detonation; 2 - end of detonation.

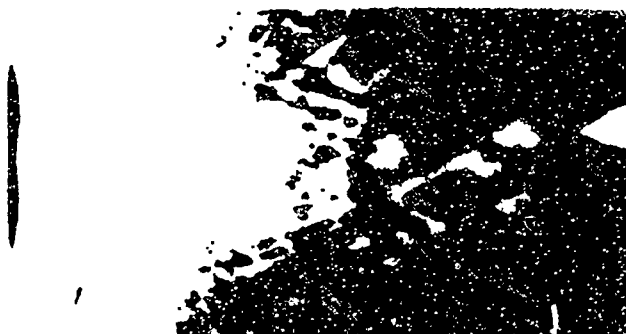


Fig. XII. Photocopy of experiment to observe separation of spherical detonation in a 75:25 nitromethane and acetone mixture. 1 - start of detonation; 2 - end of detonation.

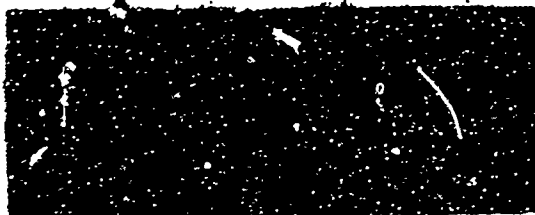


Fig. XIII. Photoscan of experiment to observe emergence of spherical detonation to steady-state regime in 78:22 nitromethane and acetone mixture. 1 - start of detonation; 2 - formation of detonation propagating in normal regime with constant dimension of configuration at the front.



Fig. XIV. Photoscan of experiment to observe damping of pulsating detonation at the limit. 1 - start of detonation in lower tube; 2 - passage of detonation through film; 3 - end of detonation in upper tube.

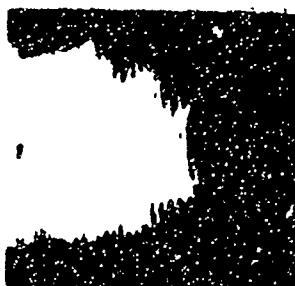


Fig. XV.



Fig. XVI.

Fig. XV. Raster photoscan. 1 - glow of detonation front before approach to the air gap.

Fig. XVI. Photograph of detonating charge of NB powder with longitudinal channels. 1 - glow of products flowing along the channels; 2 - glow of front of detonation process.