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**THERMOSTABLE EXPLOSIVES AND THEIR EFFECTS
IN DEEP BOREHOLES**

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THERMOSTABLE EXPLOSIVES AND THEIR EFFECTS IN DEEP BOREHOLES

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[Text] ANNOTATION

The specific conditions for conducting explosive shooting operations in deep boreholes under high hydrostatic pressure and high temperatures led to the development and investigation of new thermostable explosives and products made from them.

As far as the conditions for the productive use of explosive materials are concerned, it is necessary to discuss a number of questions linked by the common idea that they are all related to the explosive materials' properties, the explosion, and its effectiveness under the conditions encountered in deep boreholes.

In this book the authors discuss questions of the effect of increased pressures and temperatures on the thermostability of explosives and their susceptibility to the detonation impulse, as well as on their detonative capability, the powder combustion processes, and the effect of the explosion.

During the investigation of the thermostability of explosives, the authors determined the parameters of their thermal ignition under different conditions and defined the basic regularities of the thermal explosion of a number of thermostable explosives.

Research has shown that under production use conditions, the susceptibility to the detonation impulse and the detonative

capacity of explosives deteriorate. This resulted in the necessity of improving the explosives' characteristics by introducing various additives (sensitizers) into their composition. Under conditions of increased hydrostatic pressures, the addition of additives to the explosives proved to be quite effective.

In order to create scientifically substantiated prerequisites for the development of explosive shooting equipment, research was done in the field of exciting explosive detonations with shock waves. This made it possible to determine the critical parameters for the triggering of a number of thermostable explosives.

Other interesting and new features discussed in this book are the theoretical and experimental investigations that were conducted to study the effect of increased hydrostatic and rock pressures on the effect of an explosion (in particular, on the parameters of the underwater detonation of explosive charges), on pipe deformation processes during the underground detonation of explosives in order to form a cavity, and on the penetration of the cumulative jet into liquids, metals and rock.

On the basis of thermostable powders, compositions have been developed for propelling the striker and the pellets in deep boreholes, and their ballistic characteristics at increased temperatures and pressures have been investigated in detail. Tables 40; illustrations 85; bibliography of 104 titles.

INTRODUCTION

Methods based on the use of explosive materials (VM) -- explosives (VV), powders, blasting and burning agents (SV) -- have come into widespread use for the performance of some of the important operations involved in the drilling and testing of exploratory and production gas and oil wells. Explosive materials have been used successfully to eliminate various emergencies in boreholes by torpedoing (freeing and breaking loose trapped pipe strings, destroying metal left at the bottom of a well, and so forth), for lateral sampling of rock from the walls of boreholes with the help of shooting coring tools, for opening beds and increasing their yield by perforation of the boreholes' walls (cumulative, pellet and torpedo perforation), as well as by formation fracturing with the help of powdered pressure generators, for the separation plugging of casing strings (shooting plugging equipment, explosive bridges), for the triggering of a number of geophysical instruments, and other operations.

However, the existing industrial explosives that are used in various branches of the national economy (blasting operations during the exploitation of ore deposits and the extraction of construction materials, in construction, in the stamping and welding of metals, and so on) are designed to be used at the temperatures that are characteristic of the Earth's surface or at shallow depths; that is, from -50 to $+70^{\circ}\text{C}$, and at atmospheric pressure.

At the present time, the average depth of the gas and oil wells in the Soviet Union is 2,000 m. At this depth the temperature reaches $70-100^{\circ}\text{C}$ and the hydrostatic pressure is 200-300 atm (tech.), while at depths of 3,000-4,500 m the temperature and pressure reach 200°C and 1,000 atm (tech.), respectively.

The development of deep exploratory drilling for gas and oil made it possible to reach a depth of 6,000-7,000 m, where the temperature reaches 250°C and the hydrostatic pressure is 1,500

atm (tech.). Plans are now being made to drill wells to a depth of 15-20 km, where it is expected that the temperature will be 350-400°C and the hydrostatic pressure will reach 2,000-3,000 atm (tech.).

In order to conduct shooting and blasting operations at great depths, VV's and SV's that are highly thermostable are required. In most cases, the items that are made of them (charges, electric detonators, detonating cords) are placed in hermetically sealed equipment casings and shells, so that the only demands made on them are for thermal stability. In some cases, however -- such as in torpedoes with unsealed housings, cord torpedoes, and unhoused cumulative drills -- the VV can also be under the same pressure as the surrounding liquid and is sometimes in direct contact with it.

At high temperatures and (sometimes) pressures, the VV's used for shooting and blasting operations in deep boreholes must have high specific power and the ability to detonate when the charge diameter is small, while SV's must have a good triggering capability. These requirements are related to the extremely small lateral dimensions that are typical of deep boreholes and to the high resistance to destruction of the obstacles in such holes.

The special features of the use of VM's in deep and ultradeep boreholes that are listed above mean that they are essentially different from standard industrial VM's. Their creation is an extremely complex scientific and technical problem.

This book is devoted to an examination and discussion of the results of scientific research and experimental work that has been done for the purpose of studying the effect of high temperatures, hydrostatic pressures, and other factors on the thermostability and detonative capacity of the VM's created by a number of specialized organizations and higher educational institutions and on the combustion of powders, as well as work that has been done on the mechanical action of an explosion. It also contains materials on the theoretical and experimental research conducted at the Ramenskoye branch of VNIIGeofizika [All-Union Scientific Research Institute of Geophysical Exploration Methods] under the guidance and with the direct participation of the now-deceased Professor F.A. Baum, doctor of technical sciences, who took part in the writing of all the chapters in this book.

This book is the first monograph devoted to an investigation of the conditions in boreholes on explosive materials and the effect of an explosion and, naturally, has a number of flaws, information on which the authors would be grateful to receive from readers.

The writing of the various sections of this book was done as follows: Chapter 1 -- L.A. Shipitsin, Chapters 2-4 -- A.S. Derzhavets, Chapters 5-7 -- N.S. Sanasaryan, Chapter 8 -- A.M. Duvanov, and Chapter 9 -- N.G. Grigoryan and N.S. Chikhladze.

The authors wish to express their gratitude to B.I. Shekhter and Yu.N. Ter-Grigoryan for the valuable suggestions that they made during the writing of this book.

CHAPTER 1. THERMAL EXPLOSION UNDER CONDITIONS OF INCREASED HYDROSTATIC PRESSURE

The performance of shooting and explosive operations in boreholes has required the development and study of a number of explosives which retain their properties under conditions of high temperatures and liquid pressures.

Table 1 presents values of critical and limiting diameters (d_{cr} , d_l) and detonation velocities (D) of explosives with the operating charge densities ρ_{VV} and diameters exceeding the limiting values.

Table 1. Explosive Characteristics of Thermostable Explosives

Взрывчатое вещество (1)	Плотность, g/cm^3 (2)	Критический диаметр, мм (3)	Предельный диаметр, мм (4)	Скорость детонации, м/сек (5)
Тротил (6)	1,58	3,0	8,0	6950
ГФГ-2 (7)	1,65	1,0—2,0	5,2	7800
ГФГ-2 (8)	1,0	3,0	—	—
ГНДС (9)	1,66	1,8	3,0	7150
ЛТ-4 (10)	1,60	2,0	10,0	7500
В-5 (11)	1,62	2,5	7,5	7200
В-5 (12)	0,7	15,9	—	—
П-90 (13)	1,80	3,0	12,0	6600
НТФА (14)	1,62	1,5—2,0	8,0	7200
НТФА (15)	0,95	6,3	—	—
Доденит (16)	1,55	—	12,0	6400
Доденит (17)	0,80	15,3	—	—

Key:

1. Explosive	8. GNDS
2. Density, g/cm^3	9. LT-4
3. Critical diameter, mm	10. V-5
4. Limiting diameter, mm	11. P-90
5. Detonation velocity, m/sec	12. NTFA
6. TNT	13. Dodenite
7. GFG-2	

The limiting diameter is determined by measuring the detonation velocity of charges of thermostable explosives of various

diameters using a Type SFR [streak camera] high speed photo-recorder. With a charge diameter greater than the limiting diameter, the detonation velocity remains constant.

Measurements performed also allowed determination of the heat of the explosion (Q) and specific volume (V_0) of explosion products (Table 2).

Table 2. Heat of Explosion and Specific Volume of Explosion Products of Thermostable Explosives

Взрывчатое вещество	Плотность, г/см ³	Теплота взрыва, ккал/кг	Удельный объем, л/кг	Взрывчатое вещество	Плотность, г/см ³	Теплота взрыва, ккал/кг	Удельный объем, л/кг
(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
ГФГ-2 (5)	1,68	1380	565	В-5 (8)	1,55	980	525
ГНДС (6)	1,72	1120	580	П-90 (9)	1,68	875	450
ЛТ-4 (7)	1,52	1010	585	НТФА (10)	1,46	1010	585

Key:

1. Explosive	6. GNDS
2. Density, g/cm ³	7. LT-4
3. Heat of explosion, kcal/kg	8. V-5
4. Specific volume, liters/kg	9. P-90
5. GFG-2	10. NTFA

SPECIFICS OF THERMAL EXPLOSION AT LOW PRESSURES

The basis for a complete and proper understanding of the processes of thermal ignition occurring under high temperature conditions is the theory of the thermal explosion [67,72,73].

The theory of the thermal explosion allows us to establish the quantitative relationship between the critical self-ignition temperature T_{cr} , separating the explosive and nonexplosive course of the reaction, and the charge diameter as a function of kinetic characteristics of explosive decomposition and heat transfer conditions.

Few works have been dedicated to investigation of thermal ignition under conditions of elevated or high pressure, although this problem is of significant interest, for example in connection with the problem of initiating an explosion by shock waves and mechanical impact.

Yu.N. Ryabinin [62] determined the influence of high pressure (25,000-33,000 atm (tech.)) on the flash point of barium azide, fulminate of mercury, TNRS [trinitroresorcinol lead complex], and PETN [pentaerythrityl tetranitrate] and found that the flash point changes slightly (usually by 5-10°). F.P. Bouden et al. [23] studied the same problem for cyanurtriazide, lead azide and PETN at pressures up to 20,000-22,000 atm (tech.) and

noted a slight increase in flash point with increasing pressure. However, the results of these works, performed under thermal flash conditions (supercritical mode) at constant charge temperature with slight quantities of explosive, do not give us a sufficiently full conception of the process of thermal explosion under high pressure conditions. The reasons for the phenomena observed remained unexplained.

In the work of A.G. Merzhanov and F.I. Dubovitskiy [57], we find information on the specifics of thermal explosion of condensed explosives at low pressures (up to 50 atm (tech.)). It is noted in this work that with increasing pressure, the critical temperature drops (by approximately 30°), this decrease stopping at pressures over 20 atm (tech.). The decrease in critical temperatures explained by the fact that as pressure increases, elimination of gaseous decomposition products from the reaction zone becomes more difficult and the catalytic effect of these gasses on the process of thermal decomposition taking place increases.

The constancy of critical temperatures at higher pressures is explained, according to these researchers, by the fact that the corresponding gaseous products are converted to the condensed state and are not removed from the reaction zone.

Our studies have shown that generally under high pressure conditions (400-1,000 atm (tech.)), the threshold of thermal stability¹ drops by 20-30°C.

Thus, thermal explosion under increased hydrostatic pressure has not yet been studied in the theoretical aspect, and has been only incompletely studied experimentally. The only exception is the area of low pressures.

During our preliminary investigations, we detected certain qualitative differences in the course of thermal explosions at pressures of not over 20-50 atm (tech.) and at higher pressures. We found that at low pressures, the critical self-ignition temperature (T_{cr}) and corresponding induction period (t_{cr}) decrease significantly (up to a certain limit), which agrees with the data of A.G. Merzhanov and F.I. Dubovitskiy [57]. In connection with this, we performed studies of the specifics of thermal explosions under these conditions.

¹The threshold of thermal stability is the maximum permissible temperature which the explosive can withstand under practical utilization conditions in a borehole for 6 hours without a noticeable change in its explosive characteristics.

Experimental Method

The experiments were performed using an installation diagrammed in Figure 1.

Figure 1. Diagram of installation for study of thermal explosion at up to 1,000 atm (tech.).

A pressed charge of explosive 4, contained by plug 3, was placed in Wood's alloy 1 or any inert fluid (for example, organosilicon fluid No 5), heated to the required temperature in thermostat 5. The temperature of the Wood's alloy was maintained constant with an accuracy of $\pm 1^\circ\text{C}$ using contact thermometer 2, placed in Wood's alloy and connected to the electrical circuit heating the thermostat 8.

Sealing of the working volume of the thermostat was performed by the contact between the conical surface of the plug and the cylindrical surface of the hole; the remaining joints were sealed using flat copper inserts. The working pressure was created using a Type NZhR pump 7 and recorded by Type MTI manometer 6. The decomposition mode (explosive or nonexplosive) was generally determined by the increase in pressure in the working volume of the thermostat caused by decomposition of the explosive (Figure 2).

The critical self-ignition temperature was determined by the "sighting" method with an accuracy of $\pm 1^\circ\text{C}$, the corresponding induction period -- with an accuracy of ± 10 percent.

The experiments were performed with cylindrical charges, diameter equal to height.

Comparison of the heat conductivity factors (λ) of the explosive charges ($\lambda \approx 3 \cdot 10^{-4}$ cal/cm·sec·deg) and Wood's alloy ($\lambda \approx 4 \cdot 10^{-2}$ cal/cm·sec·deg) indicates that first order boundary conditions are realized on the charge surface. A similar

Figure 2. Increase in pressure (Δp) as a function of time (t): 1. explosive mode; 2. nonexplosive mode.

15.0 mm in diameter in the 168-226°C temperature interval and 1-800 atm (tech.) pressure interval. Charge density was 1.63 g/cm³.

The experimental data on the critical parameters of the thermal explosion at normal pressure, necessary at high pressure:

d , mm	T_{cr} , °C	t_{cr} , min
3.8	223	150
6.0	215	300
7.0	209	510
8.0	207	560
9.2	205	700
15.0	193	3,000

Figure 3. Critical temperature (T_{cr}) as a function of pressure (p) for octogene: 1. for 3.8 mm diameter charge; 2. for 6.0 mm diameter charge; 3. explosive mode; 4. nonexplosive mode.

conclusion was drawn in the work of E.I. Maksimov, A.G. Merzhanov and V.M. Shkiro [52]. The observations showed that Wood's alloy does not penetrate into the pores of the explosive and has no influence on the process of thermal decomposition of the explosives studied within the limits of error of the experiments.

Results of Experiments

Octogene. Experiments were performed with charges 3.8 to

The experimental data for determination of the dependence of critical temperature (T_{cr}) on pressure (p) are presented in Figure 3.

As we can see from Table 3, at a certain, comparatively low pressure (about 20 atm (tech.)), "saturation" occurs and the critical temperature remains unchanged within the limits of error of the experiments as pressure increases to 800 atm (tech.).

The maximum drop in critical temperature $\Delta T = T_{cr} - T_{cr}^S$ (where T_{cr}^S is the critical

Table 3. Results of Determination of Dependence of Induction Period (Minutes) in Supercritical and Critical Modes of Decomposition on Pressure With Charge Diameter 3.8 mm

Температура опыта, °C (1)	Давление, атм(2)				Температура опыта, °C (1)	Давление, атм(2)			
	20	200	600	800		20	200	600	800
226	20	16	16	16	216	—	40	—	—
223	—	23	20	24	212	—	45	56	59
220	—	—	27	—	208	111 *	80 *	78 *	85 *
218	—	38	45	40					

(3) Время (мин) достижения максимума скорости разложения в инжекритическом режиме.

Key:

1. Experimental temperature, °C
2. Pressure, atm (tech.)

3. Time (min) of attainment of maximum decomposition rate in subcritical mode.

Figure 4. Maximum critical temperature drop (ΔT) as a function of charge diameter (d) for octogene.

temperature in the "saturation" area) depends on charge diameter. Since in the saturation area the pressure can be selected rather arbitrarily, all experiments were performed only at 200 atm (tech.). The results of experiments for determination of ΔT as a function of charge diameter are presented in Figure 4.

The values of the period of induction were:

d, mm	T_{cr} , °C	t_{cr} , min
3.8	209	70
6.0	192	200
7.0	181	380
8.0	176	510
9.2	178	500
15.0	168	1,200

Substance LT-4. Experiments were performed with a charge from 6.0 to 15.0 mm in diameter at 170-234°C and 1-600 atm (tech.). Charge density was 160 g/cm³.

The critical parameters of thermal explosion at atmospheric pressure are:

d, mm	T _{cr} , °C	t _{cr} , min
6.0	261	300
8.0	252	400
10.0	245	610
12.0	240	820
15.0	232	1,200

Table 4 presents the values of induction period at 200 atm (tech.). The dependence of T_{cr} on pressure and ΔT on charge diameter at 200 atm (tech.) is shown in Figures 5 and 6.

Table 4. Induction Period (Minutes) as a Function of Temperature at 200 atm (tech.) for LT-4

Температура опыта, °C (1)	Диаметр заряда, мм (2)		Температура опыта, °C (1)	Диаметр заряда, мм (2)	
	6,0	15,0		6,0	15,0
230	—	14	190	—	350
223	105	—	180	—	650
210	270	47	174	—	2100
204	330	—	170	—	2600 *
200	360 *	68			

(3) Время (мин) достижения максимума скорости разложения в неэксплозивном режиме.

Key:

1. Experimental temperature, °C
2. Charge diameter, mm

3. Time (min) of achievement of maximum decomposition rate in subcritical mode.

Figure 5. Critical temperature (T_{cr}) as a function of pressure (p) for LT-4: 1. for 6.0 mm diameter charge; 2. for 15 mm diameter charge; 3. explosive mode; 4. nonexplosive mode.

Figure 6. Maximum critical temperature drop (ΔT) as a function of charge diameter (d) for LT-4.

NTFA. Experiments were performed with a charge from 5.8 to 15.0 mm in diameter at 260-300°C and 1-600 atm (tech.). Charge density was 1.54 g/cm³.

The critical parameters of thermal explosion at atmospheric pressure are:

d, mm	T _{cr} , °C	t _{cr} , min
5.8	295	180
7.5	293	330
9.8	289	720
11.8	285	1,050
15.0	279	1,470

The dependence of the induction period on pressure is shown in Table 5. Figure 7 shows the dependence of T_{cr} on pressure, while Figure 8 shows the dependence of ΔT on charge diameter at 200 atm (tech.).

Table 5. Induction Period (Minutes) as a Function of Pressure for NTFA

Давление, ат (1)	Температура, °C (2)				
	298	294	280	278	290
	Диаметр заряда, мм (3)				
	5,8	7,1			8,0
1	207	240	—	—	300
50	194	201	—	—	210
100	98	180	400	460 *	160
200	85	106	—	—	119
300	62	90	270	360 *	108
400	58	83	—	—	—
500	—	—	130	150 *	—
600	32	—	—	—	—

(4)* Время (мин) достижения максимума скорости разложения.

Key:

1. Pressure, atm (tech.)
2. Temperature, °C
3. Charge diameter, mm

4. Time (min) of attainment of maximum decomposition rates.

Hexogene, LT-5, thermol, TNT. Thermal explosion of these explosives under conditions of hydrostatic pressure was studied less completely (Table 6).

As a result of the study of the thermal explosion of a number of explosives, certain general regularities were established.

1. The critical temperature and critical induction period decrease significantly with increasing applied pressure up to 20-30 atm (tech.).

At higher pressures (up to 800 atm (tech.)), the values of T_{cr}, t_{cr} remain practically unchanged.

Figure 7. Critical temperature (T_{cr}) as a function of pressure (p) for NTFA: 1. for 5.8 mm diameter charge; 2. for 7.1 mm diameter charge; 3. explosive mode; 4. nonexplosive mode.

Figure 8. Maximum critical temperature drop (ΔT) as a function of charge diameter (d) for NTFA.

2. The time of maximum drop in the critical temperature ($\Delta T = T_{cr} - T_{cr}^s$) in the saturation area depends in a complex manner on charge diameter, reaching its greatest value with d_0 equal to 5-10 mm. Where $d < d_0$, the value of ΔT decreases significantly with decreasing d , where $d > d_0$ it does not increase.

Table 6. Critical Parameters of Thermal Explosion of Explosives

Взрывчатое вещество	Диаметр, мм	Плотность, г/см ³	Критическая температура, °C ($p = 1 \text{ atm}$)	Период индукции, мин ($p = 1 \text{ atm}$)	Критическая температура в области насыщения, °C	Период индукции в области насыщения, мин
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Гексоген	7,5	1,54	—	—	179	190
(8)	6,5	1,60	296	60	—	—
ЛТ-5	8,0	1,60	292	240	—	—
(9)	10,0	1,60	289	400	—	—
	15,0	1,60	274	1400	258	1700
Термол	10	1,60	304	360	—	—
(10)	15	1,60	292	1200	281	700
	20	1,60	285	1800	—	—
Тротил (жидкий)	17,6	—	214	330	180	800
(11)						

Key:

1. Explosive
2. Diameter, mm
3. Density, g/cm³
4. Critical temperature, °C ($p = 1 \text{ atm}$ (tech.))
5. Induction period, min ($p = 1 \text{ atm}$ (tech.))

6. Critical temperature in saturation area, °C
7. Induction period in saturation area, min
8. Hexogene
9. LT-5
10. Thermol
11. TNT (liquid)

3. The values of ΔT for the explosives studied has a tendency toward decreasing with increasing thermal stability. We

present below the results of experiments for a charge 15 mm in diameter:

Explosive	T_{cr}^S , °C	ΔT , °C
Octogene	168	30
LT-4	170	60
TNT	180	25
LT-5	258	16
Thermol	281	11

Our experiments confirmed the existence for many explosives of an area of saturation over a broad range of pressures, the beginning of which was detected earlier [57].

In correspondence with the primary statements of the theory of thermal explosion, the possible causes of the observed regularities might be changing conditions of heat transfer or rate of heat liberation.

Our studies showed that the change in the heat physical properties of inert materials [24], similar in physical properties to pressed explosive charges, is not great (≈ 1 percent). Apparently, we should ignore also the slight worsening of heat transfer conditions resulting from cessation of removal of gaseous decomposition products from the reaction zone, since under the conditions of our experiments the first order boundary conditions remain correct over rather broad limits.

Thus, a change in heat transfer conditions does not lead to a significant effect.

Studying the changes in heat liberation conditions, we must note that the possible change in the thermal effect of the reaction resulting from more complete development of intermediate oxidation-reduction reactions with the participation of oxides of nitrogen does not agree with the experimental data. Actually, using the Frank-Kamenetskiy critical conditions, we can show that, for example, as the heat of reaction doubles the maximum drop in critical temperature is about 7°C, i.e., significantly less than the observed values of T .

Generalizing the explanation of the regularities observed presented in the work of A.G. Merzhanov and F.I. Dubovitskiy [57], we can assume that the decrease in critical temperature and critical induction period with increasing pressure results primarily from the effects of the gaseous decomposition products, which accelerate the process of decomposition of the material, the removal of which from the reaction zone is greatly hindered at increased pressures (conditions of mechanical equilibrium).

Apparently, adsorption of the gaseous decomposition products on of the crystals of the material occurs. At a certain limiting pressure, equal to the saturated liquid vapor pressure ($p = p_s$), depending on temperature, volumetric condensation of vapors occurs and the crystals are completely covered with a layer of liquid. In this case, the further process of decomposition of the material is independent of the applied pressure.

In the simplest case, when the concentration of adsorbed decomposition products on the surfaces of material crystals is determined by the Langmuir isotherm, it follows from the Frank-Kamenetskiy critical conditions that the value ΔT for $d = \text{constant}$ is determined by the expression

$$\Delta T = \frac{RT_s^2}{E} \ln \frac{p_s}{p_1}, \quad (1)$$

where p_s is the saturated vapor pressure; $p_1 = 1 \text{ atm (tech.)}$; E is the activation energy; R is the universal gas constant

Equation (1) where $p = 20 \text{ atm (tech.)}$ and $E \approx 50 \text{ kcal/mole}$ properly reflects the order of experimental values of ΔT . It follows from this equation that for LT-4, which corresponds to a value of $E \approx 30 \text{ kcal/mole}$, the value of ΔT is anomalously high, which has also been confirmed experimentally.

We must note that in the 200-250°C temperature interval the saturated water vapor pressure is 15-40 atm (tech.), which is similar to the values of p_s determined in our experiments.

The decrease in ΔT with increasing charge diameter $d > d_0$ (see Figures 4, 6) also follows from equation (1) and results from the dependence of p_s on T_{cr} (according to the Clapeyron-Clausius equation).

In order to explain the decrease in ΔT where $d < d_0$, we must study the course of the process of material decomposition in greater detail. As was assumed in concluding equation (1), pressure p_s is reached no later than attainment of the maximum decomposition rate, i.e., where $\eta \leq \eta_{\max}$ (η being the depth of conversion). If the natural pressure of the gaseous decomposition products where $\eta = \eta_{\max}$ is $p_{\max} < p_s$, equation (1) gives elevated values of T and we should replace p_s by $p_{\max}$. The decrease in ΔT where $d < d_0$ is apparently explained by the dependence of $p_{\max}$ on experimental temperature.

The experimental data are also correct for the case when charges are placed in a sealed, strong shell, preventing removal of gaseous decomposition products but not transmitting external pressure to the charge. This conclusion was confirmed

experimentally for octogene and LT-4 in the case when the natural pressure of gaseous decomposition products exceeded the value of p_s .

THERMAL EXPLOSION AT ELEVATED PRESSURE (UP TO 800 ATM (TECH.))

The results of experiments showed that the critical temperature of self-ignition at 20-800 atm (tech.) remains practically constant. To determine the nature of further changes in the value of T_{cr} with increasing pressure, experiments were performed studying thermal explosion at pressures up to 8,000 atm (tech.).

Figure 9. Diagram of installation for study of thermal explosion of explosives at up to 4,000 atm (tech.).

Figure 10. Diagram of installation for study of thermal explosion of explosives at up to 8,000 atm (tech.).

Experimental Method

Studies were performed using two installations, differing in the maximum permissible working pressure due to design specifics.

In the installation for studies of thermal explosions at up to 4,000 atm (tech.) (Figure 9), explosive charge 5, pressed directly into a depression in plug 4, was placed in a special thermostat 2, the temperature of which was maintained constant with an accuracy of $\pm 1^\circ\text{C}$ using contact thermometer 3, installed in a depression in the body of the thermostat and connected to heating circuit 8. To produce high pressures, a multiplication type installation was used with relative piston area selected so that liquid 6 was under pressure of about 150 atm (tech.), created by hand pump 9, generating a maximum pressure on the order of 4,000 atm (tech.) in the small cylinder, which was recorded by type SV manometer 7 with an accuracy of ± 1 percent of the assigned pressure. The maximum pressure was determined by the sealing method used (rubber rings 1). The method

and accuracy of determination of critical thermal explosion conditions as well as charge shape remained as before.

In the installation for studying thermal explosions at pressures up to 8,000 atm (tech.), (Figure 10), explosive charge 5 and sealing inserts 4 were placed in cylinder 2, into which tightly fitted pistons 3 were inserted at each end. Cylinder 2 was heated using a double-walled vessel, through which heat-transfer medium 6 (fluid No 5) was circulated, after being heated in TS-15 thermostat 7 to the required experimental temperature. The temperature was maintained constant with an accuracy of $\pm 0.5^\circ\text{C}$. The high pressure was created using press 1 and hand pump 8. The maximum pressure was determined by the strength characteristics of pistons 3, which were made of high quality steel and heat treated. The decomposition mode was established on the basis of phenomena accompanying ignition of the explosive charge in the closed volume (sharp sound effect, deformation of pistons, and so on). At the beginning of each experiment at various pressures, the explosive charge was preliminarily compressed to the maximum pressure of $8 \cdot 10^3$ atm (tech.) in order to produce comparable results.

The pressure acting on the specimen was determined by the known ratio of areas of pistons and press and indications of the standard manometer installed on the hand press. The error arising in this case in the pressure interval studied [65] is not over a few percent.

Results of Experiments

Octogene. Experiments were performed with charges 5.0 mm in diameter at $198\text{--}214^\circ\text{C}$ and $(1\text{--}8) \cdot 10^3$ atm (tech.). The primary results of the experiments determining the changes in critical temperature $\Delta T_1 = T_{\text{cr}} - T_{\text{cr}}^{(0)}$ with increasing pressure are shown in Figure 11 ($T_{\text{cr}}^{(0)}$ is the critical temperature at low pressures).

Figure 12 shows the experimental data of the dependence of induction period in the supercritical mode on pressure ($T = 230^\circ\text{C}$) in semilogarithmic coordinates $\ln t$, p . The critical period is 130–160 min.

Material LT-4. The diameter of the charges was 5.0 mm, the temperature $200\text{--}206^\circ\text{C}$, pressure $(1\text{--}3) \cdot 10^3$ atm (tech.) (see Figure 13). The induction period under critical conditions is independent of pressure within the limits of the experimental area and equals 100–120 min.

Figure 11. Changes in critical self-ignition temperature ($T_{cr} - T_{cr}^{(0)}$) as functions of pressure (p) for octogene: 1. on installation operating at up to 8,000 atm (tech.); 2. on installation operating at up to 4,000 atm (tech.).

Figure 13. Change in critical self-ignition temperature ($T_{cr} - T_{cr}^{(0)}$) as a function of pressure (p) for LT-4.

generally 10^3 atm (tech.), while the change in pressure may influence the reaction rate only when it exceeds 10^3 atm (tech.) [21]. According to A. Stern and others, for reactions in the solid phase the value of $\Delta V_a/RT$ is still lower.

In the case $\Delta V_a = \text{constant}$ in the interval of temperatures and pressures studied, it follows from equation (2) that

$$K \sim \exp\left(-\frac{E + p\Delta V_a}{RT}\right). \quad (3)$$

Figure 12. Induction period as a function of pressure ($T = 230^\circ\text{C}$) for octogene.

As we can see from the data presented, the influence of pressure on critical self-ignition temperature does exist in this pressure interval, but is so slight that it could not be detected at lower pressures (up to 800 atm (tech.)).

According to M. Evans, the dependence of reaction rate constants (K) on pressure is approximately defined by the formula

$$\frac{\partial \ln K}{\partial p} = -\frac{\Delta V_a}{RT}, \quad (2)$$

where ΔV_a is the activation volume (cm^3/mole).

Equation (2), as experiments have shown [21,31], is well confirmed for reactions occurring in the liquid and solid phases. For reactions in solutions, the value of $\Delta V_a/RT$ is

If equation (3) is also correct for decomposition of explosives at temperatures corresponding to thermal explosion, the following relationships should obtain for a charge of fixed diameter under critical conditions:

$$\frac{E + p \Delta V_a}{RT_{cr}} \approx \frac{E}{RT_{cr}^{(0)}}; \quad (4)$$

$$t_{cr} = B \exp \left(\frac{E + p \Delta V_a}{RT_{cr}} \right). \quad (5)$$

Using equation (4) and the experimental data produced, we found the effective values of activation volume ΔV_a . It was found that for octogene at $T_{cr} = 472^\circ\text{K}$ and $E = 38,000$ cal/mole, $\Delta V_a = 4 \pm 1$ cm³/mole, while for LT-4 at $T_{cr} = 472^\circ\text{K}$ and $E = 32,000$ cal/mole, $\Delta V_a = 3 \pm 1$ cm³/mole. The value of ΔV_a determined from the angle of inclination of the straight line $\ln t = f(p)$ (see Figure 12) is approximately 10 cm³/mole. The increase in the value of ΔV_a is apparently explained by the fact that in the supercritical mode the experiments were actually performed at different distances from the critical mode due to the existence of dependence $T_{cr} = f(p)$ (see Figure 11). Since as we move further away from the critical mode the induction period drops rapidly, these experiments show a certain summary picture, which results in elevated values of ΔV_a .

In processing the data produced by F.P. Bouden and A.D. Ioffe [23], we produce a dependence similar to that shown in Figures 11 and 13. Calculations have shown that where $p > 100$ -200 atm (tech.), the value of $\Delta V_a \approx 10$ cm³/mole, which is similar to the values which we have produced.

In processes dependent on pressure, quantity ΔV_a plays a role similar to the role of activation energy in processes occurring with variable temperature; therefore, we should upon the value of ΔV_a in equations (4) and (5) as the effective value of activation volume, depending on the change in explosive parameters (heat conductivity and so forth) with increasing applied pressure. In particular, the value of ΔV_a , as we will show below, may be significantly determined by state conversions in the material during the process of decomposition.

THERMAL EXPLOSION AT TEMPERATURES NEAR THE MELTING POINT OF THE EXPLOSIVE

For certain explosives used in the performance of shooting operations in boreholes, the threshold of thermal stability of charges of comparatively small diameter is near the melting point of the explosive and the influence of pressure is felt in a specific manner. This problem is also of scientific interest.

The study of thermal explosions was performed using the installation we have already described (see Figure 1).

The dependence of induction period on pressure for PETN charges 6.0 mm in diameter with a density of 1.47 g/cm³ at 136°C and for charges of hexogene 6.0 mm in diameter with a density of 1.56 g/cm³ at 188°C is shown in Table 7.

Table 7. Dependence of Induction Period (t) on Pressure (p) for PETN and Hexogene

ТЭН (1)		Гексоген (2)		ТЭН (1)		Гексоген (2)	
р, атм (3)	t, мин (4)	р, атм (3)	t, мин (4)	р, атм (3)	t, мин (4)	р, атм (3)	t, мин (4)
1	203	1	133	400	450	400	47
100	255	40	30	600	530	600	56
200	360	100	34			800	67
300	390	200	38				

Key:

1. PETN

2. Hexogene

3. p, atm (tech.)

4. t, min

When solid explosives decompose at temperatures near their melting point, the formation of liquid decomposition products plays a significant role. This phenomenon was observed during decomposition of PETN [71], EDNA [94] and certain other explosives. The study of the kinetic regularities of thermal decomposition of solid explosives under conditions of formation of liquid phase is the subject of a work by G.B. Manelis and F.I. Dubovitskiy, K. Boun [53]. A quasistable system of thermal explosion equations, considering the kinetic regularities detected, was produced by A.G. Merzhanov.

If we ignore the change in volume and heat conductivity of an explosive charge during the process of an experiment, the system of equations of a thermal explosion can be written as follows:

$$e^{\theta} \left(1 + \frac{\sigma e^{\theta} \eta}{1 - \sigma e^{\theta} \eta_0} \right) - \frac{\theta}{\alpha} = 0; \quad (6)$$

$$\frac{d\eta}{d\tau} = e^{\theta} \left(1 + \frac{\sigma e^{\theta} \eta}{1 - \sigma e^{\theta} \eta_0} \right). \quad (7)$$

where $\theta = E/RT_0^2(T - T_0)$; $\tau = K_0 t \exp(-E/RT_0)$; $\eta_0 = K_s/K_l$; K_s , K_l are the reaction rate constants in the solid and liquid

phases respectively; $\sigma \approx e^{[-Q_m(T_m - T_0)/RT_m T_0]}$; Q_m , T_m are the heat and temperature of melting; T_0 is the experimental temperature; $\omega = (Q_m/E)(T_0^2/T_m^2)$.

Substituting the known dependence of melting point on pressure into equations (6) and (7),

$$T_m = T_m^* + \left(\frac{\partial T}{\partial p} \right)_0 p + \dots \quad (8)$$

and solving the system of these equations using the known plan of A.G. Merzhanov, we can find the dependence of induction period on pressure. However, the expression for $t = f(p)$ produced is so cumbersome that its comparison with experimental data is difficult.

Considering that, according to the experimental conditions $(T_m - T_0)/T_0 \ll 1$ and, generally, $Q_m/E \approx 1/5 \ll 1$, we can simplify the initial system of equations and find:

$$t = \text{const} \exp \left(\frac{p \Delta V_a}{RT_0} \right), \quad (9)$$

where $\Delta V_a = [Q_m(\partial T/\partial p)_0]/T_m$ (cm^3/mole), and the value of the constant in the first approximation is independent of pressure.

The equation $\Delta V_a = [Q_m(\partial T/\partial p)_0]/T_m$ is the known Clapeyron-Clausius equation. Assuming that $Q_m = 10$ kcal/mole, $(\partial T/\partial p)_0 = 0.025$ deg/atm (tech.), $T_0 \approx 500^\circ\text{K}$, we find $\Delta V_a = 20\text{-}30$ cm^3/mole .

Figure 14. Induction period (t) as a function of pressure (p) for PETN.

Figure 15. Induction period (t) as a function of pressure (p) for hexogene.

In correspondence with equation (9), the experimental data presented in Table 7 were represented in semilogarithmic coordinates $\ln t$, p (Figures 14 and 15).

The values of ΔV_a determined from the angle of inclination of the straight lines are 30 cm^3/mole for PETN and 37 cm^3/mole for hexogene, which agrees with the theoretical estimate of ΔV_a if we assume $Q_m = 14.5$ kcal/mole for PETN and 12.5 kcal/mole for hexogene. The value of ΔV_a in this case has a precise physical sense -- the change in the specific volume of the material during a conversion of state (melting). The divergence between the experimental and calculated values of ΔV_a results apparently from distortions of the model.

THERMAL EXPLOSION AT PRESSURES ON THE ORDER OF 10^5 ATM (TECH.)

We can conclude from the data presented above that at pressures exceeding p_s throughout the entire interval of pressures studied (up to 8,000 atm (tech.)), the dependence of the reaction rate constant of thermal decomposition of the explosive on pressure is described well by equation (2). However, when the data produced are extrapolated into the area of pressures on the order of 10^7 atm (tech.) where $\Delta V_a = 3-4$ cm³/mole, we produce elevated values of effective activation energy which, as we will indicate, contradict the available experimental data.

On the other hand, during calculations involved in the determination of critical conditions of initiation of detonation of secondary explosives by shock waves, standard values of activation energy and pre-exponent are used, which also are not well founded.

We must consider, in our opinion, that at high pressures the energy of elastic compression ϵ of an explosive crystal will play an ever increasing role in the mechanism of activation of molecules.

As Ya. I. Frenkel' emphasized [74], establishment of closer contact between molecules must be accompanied by weakening of the coupling between the simpler particles forming the molecules (antagonism of internal and external bonds), which has been confirmed by many numerical experiments for inert materials. For example, the increasing dipole moment and decreasing frequency of intramolecular oscillations upon transitions in the gas-solid-liquid direction for polar molecules, the change in Raman spectra for nonpolar molecules upon transition from the gaseous to the solid state, the dissociation of one substance upon dissolution in another, phenomena of ionization, changes in valence under the influence of high pressure, and so on.

Consideration of the influence of crystal compression energy on the rate of thermal decomposition of the explosive can be performed using quantum mechanical ideas; however, the solution of this problem brings up tremendous mathematical difficulties due to the large number of atoms in an explosive molecule.

The influence of compressibility on activation energy and the pre-exponent can be formally considered in the following form:

$$E = E_0 + p \Delta V_a - f(\epsilon); \quad (10)$$

$$K = K_0 \varphi(\epsilon), \quad (11)$$

where $f(\epsilon)$ and $\varphi(\epsilon)$ are functions of compressive energy, which can be defined if we know the potential energy surface for the given reaction.

Let us expand $f(\varepsilon)$ into a series with respect to powers of ε near the point $\varepsilon = 0$:

$$f(\varepsilon) = f(0) + \left(\frac{\partial f}{\partial \varepsilon}\right)_0 \varepsilon + \frac{1}{2} \left(\frac{\partial^2 f}{\partial \varepsilon^2}\right)_0 \varepsilon^2 + \dots \quad (12)$$

Assuming that where $\varepsilon = 0$ compressibility can be ignored, we find $f(0) = 0$. Further, considering that where $\varepsilon \sim E_0$ the value of $f(\varepsilon) \sim E_0$, we find

$$\left(\frac{\partial f}{\partial \varepsilon}\right)_0 \equiv C_1 \approx 1, \quad \left(\frac{\partial^2 f}{\partial \varepsilon^2}\right)_0 \approx C_2 \approx \frac{1}{E_0}, \dots$$

Then in the first approximation:

$$E = E_0 + p \Delta V_s - C_1 \varepsilon \quad (13)$$

and equations (4) and (5) will look as follows:

$$\frac{E_0 + p \Delta V_s - C_1 \varepsilon}{RT_{cr}} \approx \frac{E_0}{RT_{cr}^0} \quad (14)$$

$$t_{cr} = B \exp \left(\frac{E_0 + p \Delta V_s - C_1 \varepsilon}{RT_{cr}} \right) \quad (15)$$

With impact compression, which occurs during excitation of detonation by shock waves, the internal energy and, consequently, its elastic component are determined by the Hugoniot equation

$$\varepsilon = \frac{p}{2} (V_0 - V) = \frac{p}{2} \Delta V_{com}$$

where V_0 , V are the specific volumes of the charge at atmospheric pressure and pressure p .

The value of ΔV_{com} is an increasing function of pressure, therefore, equation (14) indicates that the curve $T_{cr}(p)$ where $\Delta V_s > 0$ will have a maximum at a pressure determined by the condition

$$\frac{\partial}{\partial p} (p \Delta V_s - C_1 \varepsilon) = 0.$$

Using data on the compressibility of explosives [27], we find that for PETN the bend point on the curve of $T_{cr}(p)$ corresponds to a critical pressure on the order of $(30-40) \cdot 10^3$ atm (tech.).

At pressures higher than the critical pressure, the rate of the reaction of thermal decomposition of the explosives should increase markedly with increasing pressure, while the effective value of activation energy decreases. Similar considerations were set forth by E. Teller.

Ch. Mader [99] showed experimentally that with increasing pressure the critical size of an explosion center decreases. Thus, a center at 1,400°K in nitromethane, not subjected to impact, is no smaller than 0.27 cm, while the size of a center in

nitromethane subjected to explosive impact ($p = 95 \cdot 10^3$ atm (tech.)) is 0.03-0.06 cm in diameter at the same temperature.

Approximate calculations using equation (13) and considering the compressibility of nitromethane at $p = 95 \cdot 10^3$ atm (tech.) have shown that under these conditions there is a significant decrease in activation energy (on the order of 20 kcal/mole).

THERMAL EXPLOSION UNDER CONDITIONS OF HEATING AT A CONSTANT RATE

In order to determine the capabilities of the material studied, it seemed interesting to study the process of thermal explosion under conditions of heating at constant rate, corresponding to the rate of increase in temperature in shotting apparatus lowered into a borehole at $W = 1-2$ deg/min.

The heating rate of an explosive in the installation (see Figure 1) was fixed by mechanical rotation of the head of the contact thermometer at the required frequency. The critical heating rate W_{cr} separating explosive from nonexplosive decomposition was determined by sighting.

Octogene. The experiments were performed at normal and elevated pressures with charges 9.0 and 15.0 mm in diameter, density 1.6 g/cm^3 . Since the critical temperature of autoignition and the induction period under critical conditions are practically not influenced by pressure in the 20-800 atm (tech.) range, the experiments were performed only at atmospheric pressure and 200 atm (tech.). The medium used to surround the charge was primarily Wood's alloy (Figure 16).

Figure 16. Autoignition temperature (T_{cr+}) as a function of heating rate (W). Surrounding medium for curve 4 -- clay solution: 1. $d = 15$ mm, $p = 1$ atm (tech.), $W_{cr} = 1.6 \cdot 10^{-2}$ deg/min; 2. $d = 15$ mm, $p = 200$ atm (tech.), $W_{cr} = 0.5 \cdot 10^{-2}$ deg/min; 3. $d = 9$ mm, $p = 200$ atm (tech.), $W_{cr} = 2.5 \cdot 10^{-2}$ deg/min; 4. $d = 9$ mm, $p = 200$ atm (tech.), $W_{cr} = 2.5 \cdot 10^{-2}$ deg/min.

NTFA. Experiments were performed with charges 7.1 mm in diameter with a density of 1.54 g/cm³. The medium surrounding the charge was Wood's alloy (Figure 17).

Figure 17. Autoignition temperature (T_{cr+}) as a function of heating rate (W): 1. $d = 7.1$ mm, $p = 1$ atm (tech.); 2. $d = 7.1$ mm, $p = 100$ atm (tech.); 3. $d = 7.1$ mm, $p = 400$ atm (tech.)

The regularities of thermal decomposition under conditions of heating (and cooling) at constant rates and normal atmospheric pressure have been discussed in many works [54,69]. We note only one specific feature of thermal explosion under conditions of linear heating and atmospheric pressure, not described earlier.

At heating rates near the critical, T_{cr+} increases rather rapidly with increasing heating rate. However, where $W/W_{cr} \gg 1$ (the area of practical application of the explosives), there is an area of "saturation," where T_{cr+} increases very slightly with increasing W/W_{cr} .

The temperature T_{cr+} in the area of saturation is several dozen degrees (50°C) higher than the static critical temperature T_{cr} .

As we can see from Figure 16, the change in autoignition temperature (T_{cr+}) upon transition from atmospheric pressure to elevated pressure is generally similar to the change in critical autoignition temperature (T_{cr}) under static conditions and the corresponding values of $\Delta T_+ = T_{cr+} - T_{cr+}^s$ and $\Delta T = T_{cr} - T_{cr}^s$ are numerically similar. However, the dynamic mode, allowing the thermal ignition process to develop in time, contains somewhat greater information than the static mode. In particular, the experiments performed allow us to find an explanation for the sharp decrease in critical induction period for NTFA with increasing pressure (see Table 5).

Comparing the experimental data (see Figure 17) with the results of calculation of the dependence $T_{cr+} = f(W/W_{cr})$ for the

autocatalytic reaction [56], we can conclude that the value of η_0 (η_0 is the autocatalytic criterion) increases for NTFA upon transition from atmospheric pressure to elevated pressure throughout the entire pressure interval (for octogene, η_0 increases only upon transition from atmospheric pressure to pressures $p \leq p_s$). The result of this is a sharp decrease in T_{cr}^+ in the area of saturation with increasing pressure with fixed values of heating rate. However, the value of T_{cr} remains practically unchanged, since the critical Frank-Kamenetskiy conditions depend little on η_0 at comparatively low values.

The results of studies of thermal explosion of octogene, LT-4, LT-5, NTFA, hexogene, and TNT under elevated hydrostatic pressure conditions, both in static and dynamic modes, indicated the following.

1. In the area of low pressure ($p < p_s \approx 20$ atm (tech.)), there is a significant reduction (to a certain limit) in critical autoignition temperature (T_{cr}) and induction period (t_{cr}).

The function $\Delta T = T_{cr} - T_{cr}^S$ depends on charge diameter in a complex manner.

The regularities observed are apparently primarily related to the accelerating influence of gaseous decomposition products adsorbed on the surface of the crystals of the material. The calculation values of ΔT produced on the basis of this assumption are similar to the experimental values.

2. At pressures exceeding p_s , right up to 8,000 atm (tech.), a slight increase in T_{cr} occurs, while the value of t_{cr} remains practically unchanged. It has been demonstrated that the data produced can be explained using the known kinetic equation $\partial \ln K / \partial p = -\Delta V / RT$, where the value of ΔV (effective activation volume) must be looked upon as the primary kinetic constant, the value and sign of which determine the nature and degree of the influence of pressure on the parameters of the thermal explosion.

3. Near the melting point for PETN and hexogene, the induction period increases with increasing pressure over a broad interval of pressures. Based on analysis of the system of equations from the quasistable theory of a thermal explosion, it has been shown that the value of ΔV in this case has a precise physical sense and is determined by the Clapeyron-Clausius equation:

$$\Delta V = (Q_m \cdot \partial T / \partial p) / T_m.$$

4. The change in the ignition temperature T_{cr}^+ under conditions of linear heating occurs similarly to the change in T_{cr} under

static conditions upon transition from atmospheric pressure to increased pressure.

The value of T_{cr+} at a heating rate near that encountered in boreholes is significantly greater (approximately 50°C) than the value of T_{cr} .

CHAPTER 2. DETONATION SUSCEPTIBILITY AND DETONATION CAPACITY OF THERMOSTABLE EXPLOSIVES

DETONATION CAPACITY OF EXPLOSIVES AT INCREASED PRESSURE AND TEMPERATURE

The study of explosives under conditions of high temperature and pressure is of great practical significance.

Many researchers have investigated the question of detonation capacity and susceptibility of explosives [3,16,17,50,75]. However, the greatest part of the works were concerned with studying explosives at normal temperature and at atmospheric pressure.

The effect of temperature and pressure on the detonation capacity and susceptibility to a detonating impulse have been inadequately studied.

A.F. Belyayev and R.Kh. Kurbangalina [18], while determining the influence of temperature on the critical diameter of charges of certain explosives, found that with an increase in temperature the critical charge diameter of TNT during melting is first increased and then reduced.

We obtained similar results during the study of the detonation capacity of trinitrobenzene (TNB) which, like TNT, melts at a relatively low temperature (123°C).

Data encountered in the literature concerning the influence of pressure on the detonation capacity of explosives are quite contradictory. In a number of works a tendency is noted toward total loss of detonation capacity of explosives at a pressure of 10^4 atm (tech.) and above; however, this has not found confirmation in more recent works.

Cases of loss of detonating capacity by detonating cords (DSh) were observed during test-firing operations in boreholes with

high pressure. However, when a high-power detonator was used it was possible to cause detonation of such cords. The reason for impairment (but by no means loss) of the detonation capacity is a reduction in susceptibility of explosive charges at increased pressure.

An additional initiating impulse is required to overcome the influence of external pressure. Loss of detonation capacity by charges of small diameter and by detonating cords can set in (as will be shown below) when liquid penetrates into the pores of the charge under pressure; this leads to an increase in the critical diameter.

The effect of pressure on detonation capacity of liquid explosives was studied at the All-Union Scientific Research Institute of Drilling Technology. As a result of these works it was found that critical diameter of stoichiometric mixtures of tetranitromethane (TNM) with various combustibles (dichloroethane, nitrobenzene, solar oil, and so on) at 400 atm (tech.) is increased from 0.03-0.1 to 4 mm. It was also revealed that under the action of pressure the limits of possible detonation of composition V-6 (mixture of TNM with solar oil) are reduced; this mixture detonates at atmospheric pressure if the content of TNM falls within the limit 62-83 percent, while at 400 atm (tech.) its capacity for explosive transformation is retained only with a TNM content of 73-79 percent.

While studying the effect of pressure of a liquid on transmission of detonation, G.V. Dimza [35] detected no change in the distance of detonation transmission to charges of nitroglycerin and of a stoichiometric mixture of TNM and toluene, even at a pressure up to 300 atm (tech.). On the other hand, S.A. Lovlya and N.K. Kuz'mina emphasize that when pressure is increased to 1,000 atm (tech.) the distance of detonation transmission to charges of phlegmatized hexogene (charge density 1.60 g/cm³) is reduced by 50-67 percent.

Besides this, Yu.P. Nelasov, S.A. Lovlya and G.V. Dimza determined [58] that in the presence of high pressure of liquid in the borehole excitation of detonation of torpedo charges -- especially circular -- from an explosive cartridge is hampered. However, they did not consider the fact that with penetration of liquid into the pores of charges the critical diameter of the charges is increased and their susceptibility is reduced and that therefore to improve the conditions for exciting torpedo detonation it is not necessary (as these investigators recommend) to use ring charges in which the thickness of the walls is greater than the magnitude of critical charge diameter under the corresponding conditions.

The basic problem in this section is that of characterizing the susceptibility of explosive substances to be used in petroleum and gas bores when they are subjected to conditions of ambient temperatures and pressures.

EFFECT OF INCREASED TEMPERATURE ON DETONATION SUSCEPTIBILITY AND DETONATION CAPACITY OF THERMOSTABLE EXPLOSIVES

The susceptibility of explosives to detonation is usually characterized by the magnitude of the minimum initiating charge (MIZ) which will cause detonation of the explosive charge. This quantity depends not only on the properties of the initiating and tested high explosive, but also on a number of other factors -- for example, the presence of a shell, equipment conditions, density of the initiating explosive and the high explosive, particle size of the high explosive, and so on.

Ya.I. Leytman [50] showed that crushing an explosive leads to an increase in its sensitivity to a detonating pulse; however, the influence of particle size on explosive susceptibility may be effective (as experiments which we carried out indicated) only down to a certain charge density (see Table 8).

Table 8. Magnitude of an Initiating Charge of Explosive as a Function of Its Density

Плотность гексогена, г/см ³ (1)	Величина минимального инициирующего заряда азид свинца, г (2)		Плотность гексогена, г/см ³ (1)	Величина минимального инициирующего заряда азид свинца, г (2)	
	для частиц размером 100-200 мк (3)	для частиц размером 1-3 мк (4)		для частиц размером 100-200 мк (3)	для частиц размером 1-3 мк (4)
1,60 1,70-1,72	0,03 0,04	0,02 0,03	1,77-1,79 1,80	0,05 0,06	0,05 0,06

Key:

1. Density of hexogene, g/cm³
2. Magnitude of MIZ of lead azide, g
3. For 100-200 μ particles
4. For 1-3 μ particles

Results of experiments in determining the minimum initiating charge for certain TVV [possibly solid explosives] by standard procedure are given below.

Explosive	Density, g/cm ³	Magnitude of Lead Azide MIZ, g
GNDS	1.58	0.036
V-5	1.26	0.16
DA	1.27	0.25

The explosives were pressed into a shell case made from a No. 8 detonating cap at a pressure of 600 atm (tech.); charge detonation was judged with respect to penetration of a lead plate.

During test-firing operations in bores it is advisable to use high-density charges in order to raise the power of the explosion. However, an increase in density leads to a reduction in explosive susceptibility to detonation and consequently to an increase in the minimum initiating charge. In this connection it became necessary to study the detonation capacity of thermostable explosives with application to the conditions under which they are used.

Charges 10 mm in diameter were used in our experiments on determining the magnitude of the minimum initiating charge; this was made necessary by the large critical diameters of the studied thermostable explosives. Besides this, charges were pressed to the maximum possible density, which required the use of high-strength Duralumin cartridges with a wall thickness of 1 mm.

The values which we obtained for the minimum initiating charge of lead azide of different densities which will cause detonation of hexogene are given below.

Hexogene density, g/cm ³	Lead azide density, g/cm ³	Magnitude of MIZ, g
1.74	1.7	0.10
1.74	3.8	0.04
1.80	1.7	0.12
1.80	3.8	0.06

Subsequent determinations of minimum initiating charge size were carried out with a lead azide density of 3.8 g/cm³.

High thermal stability is a valuable property of lead azide. In pure form lead azide has a threshold of thermal stability equal to 250°C. Studies at the Leningrad Technological Institute established the fact that after 6 hrs of thermostating at this temperature up to 50 percent of the lead azide was decomposed. We took this into account during selection of the magnitude of minimum initiating charge (Table 9).

From Table 9 it is clear that the susceptibility of the investigated thermostable explosives to detonation is increased with an increase in temperature up to 200-250°C; in certain explosives (hexogene, V-5, NTFA) this increase is more significant, while in others (GNDS, dodenite, and others) it is less so. It

Table 9. Results of Determination of the Value of Minimum Initiating Charge of Lead Azide Causing Detonation of Various Explosives Under Conditions of Elevated Temperatures

Взрывчатое вещество (1)	Плотность, г/см ³ (2)	Величина минимального инициирующего заряда азидов свинца, вызывающего детонацию заряда термостойкого ВВ, г (3)					
		при нормальной температуре (4)	при нагревании до 200-250°С (5)	после 6-часового термостатирования при различной температуре, °С (6)			
				200	230-240	250	270
Гексоген (7)	1,80	0,06	0,04	—	—	—	—
(8) ГНДС	1,76	0,1	0,1	0,15	—	—	—
ДА (9)	1,78	0,6	0,5	1,0	1,5	—	—
(10) ЛТ-4	1,76	0,1	0,08	0,15	0,2	—	—
В-5 (11)	1,71	0,5	0,3	0,5	0,9	—	—
(12) НТФА	1,64	0,4	0,2	0,5	—	0,6	1,0
Доденит (13)	1,64	0,4	0,4	0,8	—	1,0	—
(14) П-90	1,92	0,5	0,4	—	—	0,4	—
ПК (15)	1,77	0,5	0,4	—	—	0,4	0,4
(16) К	1,62	0,065	0,05	—	—	0,1	—

Key:

1. Explosive	7. Hexogene
2. Density, g/cm ³	8. GNDS
3. Size of lead azide MIZ causing detonation of a charge of thermostable explosive, g	9. DA
4. At normal temperature	10. LT-4
5. With heating to 200-250°C	11. V-5
6. After 6-hr hold at various temperatures, °C	12. NTFA
	13. Dodenite
	14. P-90
	15. PK
	16. GK

is necessary, however, to bear in mind that in these experiments the charges were heated up to the given temperature in a time no greater than 30 min.

After a prolonged hold (6 hrs) at the increased temperature there is an increase in the magnitude of the minimum initiating charge required to cause detonation of the thermostable explosives, while their susceptibility to detonation drops accordingly.

Since in all cases the temperature (200°C) and consequently the degree of lead azide decomposition was identical, the reduction in susceptibility of the thermostable explosives may be due only to desensitization of the charges by products of prolonged thermal decomposition. With a further increase in temperature the process of decomposition of the lead azide and the tested thermostable explosives is accelerated, leading to a still stronger reduction in susceptibility of the explosives to detonation and to a corresponding increase in the MIZ.

Silver azide, studied at and recommended by the Leningrad Technological Institute, can be used as an initiating explosive to excite detonation of charges at a temperature above 250°C. As further studies showed, silver azide not only has higher thermal stability as compared with lead azide, but also has higher initiating capacity (Table 10).

Table 10. Comparative Initiating Capacity of Silver Azide

Взрыв- чатое вещество (1)	Плот- ность, г/см ³ (2)	Величина минимального инициирующего заряда ВВ, г (3)					
		при комнатной температуре (4)		после 6-часовой выдержки (5)			
				при 230° C (6)		при 270° C (6)	
				AgN ₃	PbN ₃	AgN ₃	PbN ₃
ЛТ-4 (7)	1,76	0,06	0,10	0,08	0,20	—	—
НТФА (8)	1,64	0,10	0,4	—	—	0,4	1,0
ПК (9)	1,77	0,10	0,5	—	—	0,1	0,4

Key:

1. Explosive	5. After 6-hr hold
2. Density, g/cm ³	6. At ...
3. Magnitude of MIZ of ex-
plosive, g	7. LT-4
4. At room temperature	8. NTFA
	9. PK

The data on the thermal stability and initiating capacity of silver azide were used in developing an electrical detonator with thermal stability to 270°C.

We investigated the temperature dependence of the critical diameter of thermostable explosive charges (Table 11). The magnitude of critical diameter was determined from the depth of imprint on a lead plate after explosion of cartridges of thermostable explosives with different diameters. The experiments were carried out at elevated temperature, approaching the limit of the thermal stability of the investigated material. The hold time in the thermostats under the test conditions comprises 6 hrs, in accordance with the technical requirements for thermostable explosive charges.

From Table 11 it is clear that:

- 1) holding a charge at a temperature below (by 20-30°C) its thermal stability threshold leads to a certain reduction in the magnitude of critical diameter (d_{cr});
- 2) when charges are heated at a temperature approaching the threshold of thermal stability (when the degree of explosive decomposition reaches ≈ 2 percent) their critical diameter is somewhat increased.

Table 11. Results From Determination of the Magnitude of Critical Diameter at Various Temperatures

Взрывчатое вещество (1)	Плотность, г/см ³ (2)	Температура, °C (3)	Критический диаметр заряда, мм (4)
ГФГ-2 (5)	1,50—1,60	Комнатная (6)	1,5—2
	1,50—1,60	150	1,5
	1,50—1,60	180	3,0—3,5
ГНДС (7)	1,30	Комнатная	3,5
	1,30	160	2,0
	1,30	220	5,5
	1,65	Комнатная	1,8—2,0
	1,65	160	2,0
	1,65	220	2,5—3,0
	1,70—1,75	Комнатная	1,5—1,6
	1,70—1,75	160	1,5
	1,70—1,75	220	2,0
В-5 (8)	1,30	Комнатная	3,0
	1,30	220	2,0—2,5
	1,30	240	3,5—4,0
	1,45	Комнатная	2,5
	1,45	240	3,5—4,0
НТФА (9)	1,10	Комнатная	6,0—7,0
	1,10	250	3,0—3,5
	1,10	270	7,0
	1,35	Комнатная	3,5—4,0
	1,35	250	3,5—4,0
	1,35	270	6,0
	1,62	Комнатная	1,5—2,0
	1,62	250	1,5—2,0
	1,62	270	3,0—4,0

Key:

1. Explosive	5. GFG-2
2. Density, g/cm ³	6. Room
3. Temperature, °C	7. GNDS
4. Critical charge diameter, mm	8. V-5
	9. NTFA

These data are in complete agreement with results obtained in determining the values of minimum initiating charge (see Table 9).

After the thermostated charges were cooled to room temperature there was a certain increase in d_{cr} ; this also indicates that an increase in charge temperature will in itself favor a certain increase in d_{cr} .

EFFECT OF HYDROSTATIC PRESSURE ON SUSCEPTIBILITY AND DETONATION CAPACITY OF THERMOSTABLE EXPLOSIVES

During work in boreholes explosives are frequently in direct contact with drilling fluid; under pressure the latter penetrates the pores of the charge relatively easily and thus changes charge susceptibility and detonation capacity.

During study of the detonation capacity of water-saturated explosives, A.Ya. Apin and I.M. Voskoboynikov [6] disclosed that the critical diameter of hesogene (at a dry-charge density of 1.0 g/cm^3) is increased from 2 to 7 mm when it is saturated with water. A certain increase is also observed in detonation velocity; this can apparently be explained by the increase in total charge density. However, available literature data are inadequate to draw unequivocal conclusions concerning the mechanism by which pressure influences the detonation capacity and susceptibility of explosives.

Figure 18. Setup of experiment on transmission of detonation over a distance: 1. acidified water; 2. gas-gasket; 3. openings; 4. explosive; 5. water stained with methyl orange.

When the pores of a charge are saturated by liquid one would expect a reduction in the susceptibility of the explosive to a detonation pulse. We determined the rate of such saturation of pores by liquid (water) on a specially constructed instrument (Figure 18) as the linear velocity of the passage of the front of the liquid along the charge, v_l . The explosive is pressed into the upper part of the instrument in the form of a cylindrical charge of determined height and density; the chamber of the lower part is filled with acid-

ified water. Then the two parts are connected; however, the upper part hermetically seals the lower to avoid entrance of external liquid. Before the instrument is installed in a high-pressure autoclave the top part is filled with water stained with methyl orange. As the pressure increases the stained liquid penetrates through the explosive layer and, in the case of complete saturation, passes through openings in the bottom of the upper portion of the instrument and stains the acidified water with a change in color.

The experiments were carried out with hexogene and GNDS; their relative densities ($n = \rho_{vy}/\rho_{max}$) fell within the limits 0.75-0.91 -- corresponding to the density of all types of detonating cords and charges used during test firing and explosive operations in boreholes. The experimental results are presented in Table 12.

From Table 12 it is clear that as the hydrostatic pressure of a liquid rises the rate of its penetration into the charge is noticeably increased. The density of the explosive charge has

Table 12. Results From Determinations of Rate of Liquid Penetration Into the Pores of Explosive at High Pressure

Взрывчатое вещество	Гидростатиче- ское давление, атм	Относительная плотность	Время воздей- ствия давления, ч	Скорость про- никновения жидкости, мм/ч
(1)	(2)	(3)	(4)	(5)
Гексоген (6)	500	0,75	2	10
	500	0,75	1	15
	200	0,75	1	10
	1000	0,83	4	1
	1000	0,83	8	0,8
	1000	0,83	12	0,8
	500	0,83	4	0,5
	500	0,83	10	0,4
	1000	0,91	4	0,15
	1000	0,91	12	0,1
ГНДС (7)	1000	0,82	6	1
	1000	0,82	12	0,7

Key:

1. Explosive
2. Hydrostatic pressure, atm (tech.)
3. Relative density
4. Time under pressure, hrs
5. Rate of liquid penetration, mm/hr
6. Hexogene
7. GNDS

a very great influence on the conditions for penetration of liquid into the pores of the charge. Thus, at a comparatively low explosive charge density $n = 0.75$ (for hexogene $\rho_{VV} = 1.35$ g/cm³) rapid saturation of the charge with liquid occurs even at relatively low hydrostatic pressure (on the order of 200-500 atm (tech.)).

With an increase in relative charge density to 0.85 (for hexogene $\rho_{VV} = 1.50$ g/cm³) the rate of liquid penetration into the pores is sharply reduced, comprising a total of 0.9-1.0 mm/hr at a pressure of 1,000 atm (tech.); with $n = 0.91$ (for hexogene $\rho_{VV} = 1.65$ g/cm³) at the same pressure the rate reaches only 0.1-0.2 mm/hr.

Susceptibility of Explosives to Detonation Under Conditions of High Liquid Pressure

We evaluated the effect of liquid pressure on the susceptibility of explosive charges to detonation in terms of transmission of detonation and the magnitude of the minimum initiating charge.

Transmission of Detonation. In order to refine the problem of the effect of hydrostatic pressure itself on the distance of detonation transmission we carried out experiments (Table 13) under conditions designed to eliminate the penetration of liquid into the explosive charge. For this purpose a cartridge of

Table 13. Results of Experiments on the Transmission of Detonation in Water

Относительная плотность гексогена (1)	Среда (2)	Давление, ат (3)	Расстояние передачи детонации, мм (4)	Скорость подхо- дящей ударной волны, м/сек (5)
1	Воздух (6)	Атмосферное (7)	50	2900
1	(8) Вода	"	15	2950
1	"	1200	15	2950
0,86-0,88	Воздух (6)	Атмосферное (7)	60	2800
0,86-0,88	Вода (заряд насыщенный) (9)	"	8	3800
0,86-0,88	То же (10)	1200	8	3800

Key:

1. Relative density of hexo-
gene	5. Velocity of the approaching
shock wave, m/sec
2. Medium	6. Air
3. Pressure, atm (tech.)	7. Atmospheric
4. Detonation transmission
distance, mm	8. Water
	9. Water (charge saturated)
	10. The same

pure hexogene pressed to a density equal to the density of the single crystal of this explosive ($\rho_{\text{PV}} = 1.80 \text{ g/cm}^3$) was used as a passive charge. The active charge was a special detonating cap capable of maintaining high pressure with a strictly constant thickness of the bottom of the housing and constant explosive weight. The outer diameter of the cap was 14 mm; the diameter of the passive charge (PZ) was 12 mm and its height was 15 mm. Activation of the passive charge was judged from the deformation of a blank lead plate sample.

With application of a passive charge with $n < 1$ the distance of detonation transmission is noticeably decreased. Thus, for hexogene with a density of $1.58-1.60 \text{ g/cm}^3$ ($n = 0.86-0.88$) the distance of detonation transmission after saturation of charge pores with water at atmospheric and hydrostatic liquid pressure of $1,000-1,200 \text{ atm}$ (tech.) was approximately half that for a passive charge with a relative density equal to one; this occurred in spite of the fact that the increased density of the charge will in itself lead to a certain reduction in its susceptibility to detonation.

In all cases charges were held under liquid pressure for identical periods of 2 hrs.

The experimental results lead to a convincing conclusion that the basic cause of a reduction in the range of detonation transmission at elevated hydrostatic pressures is the phlegmatizing effect of the water penetrating into the pore space of the passive charge.

Minimum Initiating Charge. During the experiments we selected a setup in which the initiating charge was isolated from the effect of pressure and penetration of liquid -- that is, isolated from the factors which might lead to a noticeable change in its explosive characteristics.

Figure 19. Instrument for determining explosive susceptibility to a detonating pulse under elevated pressure.

Key: 1. From high-pressure pump

The initiating charge was located in the upper part of the instrument used to study the effect of liquid pressure on explosive susceptibility to a detonating pulse (Figure 19). The tested charge, located in lower part, was subjected to the action of liquid pressure created by means of an oil pump.

Initiator 1 was a charge 12 mm in diameter consisting of 0.2 g lead azide and 0.8 g pure hexogene, placed in a common container -- a cartridge; there was an additional charge of standard phlegmatized hexogene with a density of 1.60 g/cm³. Changes in the weight of the additional charge were used to vary the magnitude of the initiating charge.

The thickness of the steel cross member 2, separating the initiating (1) and initiated (3) charges, was 2 mm. Hexogene and GNDS were studied. They were pressed into a perforated cartridge with an inner diameter of 12 mm. The relative density of the charges was varied within the limits 0.82-0.84.

The magnitude of the minimum initiating charge was determined for dry and water-saturated materials at pressures of 1 and 1,200 atm (tech.). In all cases impregnation of the charges with liquid was carried out at elevated pressures up to full saturation.

The experimental results showed that in the case of charge saturation with liquid the susceptibility to detonation is substantially reduced. In addition it was determined that the basic factor causing the reduction in susceptibility is not the pressure itself, but rather the phlegmatizing effect of the liquid penetrating into the charge pores under elevated pressures. These data are in complete agreement with previously derived results on the transmission of detonation.

Detonation Capacity of Explosives at Elevated Pressures

To clarify the degree of influence of a liquid penetrating into charge pores under elevated pressures and also that of the pressure itself on the detonation capacity of charges we determined the critical diameters of solid thermostable explosives under the action of pressure of gasses and liquids.

Results from experiments with the material NTFA ($\rho_{\text{VV}} = 1.35 \text{ g/cm}^3$) showed the following.

1. An increase in pressure (air and nitrogen) does not in itself have any influence on the magnitude of critical charge diameter d_{cr} :

Medium	p_0 , atm (tech.)	d_{cr} , mm
Air	1	3.5-4.0
Air	450	3.5-4.0
Nitrogen	450	3.5-4.0
Water	450	9.0
Water	1,000-1,200	9.0

2. If the charge is in contact with the liquid, with an increase in intrapore space there is a substantial increase in the value of d_{cr} , independently of the magnitude of hydrostatic pressure. In this case we must emphasize once again that with an increase in pressure the rate of saturation is significantly increased.

As charge density increases the magnitude of d_{cr} shows a corresponding decrease, while the degree of negative influence of hydrostatic pressure of a liquid on the value of d_{cr} is weakened (Table 14).

The charges were held under the test conditions up to total saturation of the explosive pores by the liquid. Depending upon the density of the charges, the duration of this process varied within the limits 2-6 hrs.

The results of these tests are of great practical significance and may serve as initial data during the designing of rational explosive charges and detonating means used in test-firing and explosive operations in deep and high-temperature boreholes.

The results of these investigations permit use to draw the following conclusions.

1. Under conditions of prolonged heating of charges at a temperature close to the threshold of thermal stability the

Table 14. Effect of Liquid Pressure on the Critical Diameter of Charges at Room Temperature

Взрывчатое вещество (1)	Плотность, г/см ³ (2)	Давление, ат (3)	Критический диаметр, мм (4)
Гексоген чистый (5)	1,50	Атмосферное (6)	6,0
	1,50	1000—1200	6,0
ГФГ-2 (7)	1,60	Атмосферное	4,0—5,0
	1,60	1000—1200	5,0
ГНДС (8)	1,30	1000—1200	9,0—10,0
	1,65	Атмосферное	7,0—7,5
	1,65	1000—1200	7,0—7,5
	1,72—1,75	Атмосферное	3,5
		1000—1200	3,5—4,0
НТФА (9)	1,10	1000—1200	10,0
	1,35	Атмосферное	9,0
	1,35	450	9,0
	1,35	1000—1200	9,0
	1,60—1,62	Атмосферное	6,0
		1000—1200	5,5—6,0
В-5 (10)	1,30	1000—1200	12,0—14,0
	1,45	Атмосферное	9,0—10,0
	1,45	1000—1200	10,0—11,0
	1,60—1,62	1000—1200	7,0

Key:

1. Explosive	6. Atmospheric
2. Density, g/cm ³	7. GFG-2
3. Pressure, atm (tech.)	8. GNDS
4. Critical diameter, mm	9. NTFA
5. Pure hexogene	10. V-5

susceptibility to detonation and the detonation capacity of the explosives are noticeably reduced.

2. At charge densities corresponding to conditions of practical application in test-firing and explosive operations in bores (relative charge density on the order of 0.75-0.90) the reduction in susceptibility to detonation and in detonation capacity is caused by the phlegmatizing effect of the liquid as it penetrates into the pore space of the charge under high pressure.

With an increase in charge density the negative influence of hydrostatic pressure on the indicated properties is substantially weakened, due to the reduction in porosity and rate of saturation with liquid.

3. During test-firing and explosive operations in bores it is most advisable to use charges with the maximum possible density for the given explosive.

CHAPTER 3. INCREASED SUSCEPTIBILITY OF EXPLOSIVES TO A DETONATION IMPULSE

The problem of increasing the susceptibility of explosives to a detonation pulse (sensitization of explosives) is of great practical interest, in particular in connection with the use of explosive charges of high density for explosive work in deep oil wells under the conditions of the action of high hydrostatic pressures on the charge.

Under the action of high hydrostatic pressures on a charge, its susceptibility to a detonation impulse is significantly reduced, and the critical diameter is increased, which complicates the construction of small-scale firing and explosive apparatus, especially of fuses intended for operation under a high pressure directly in a liquid.

The sensitivity of one explosive or another to a detonation type of explosion -- that is, its susceptibility to detonation -- can be increased by using it in mixtures or alloys with other explosives. However, this is not admissible in many cases.

The susceptibility of an explosive charge to detonation can also be increased by decreasing the particle dimensions of the explosive. The results of Ya.I. Leytman's tests [50], given in Table 15, serve as an obvious confirmation of this.

The effect of grinding on the sensitivity of explosives to detonation is easily explained from the point of view of the mechanism of the so-called explosive burning [5]. With decrease in the particle size, the width of the reaction zone and the time of passage of the reaction behind the front of the detonation wave change, which leads to a decrease in the critical diameter (d_{cr}) of the charge and the size of the minimal initiator.

It has been discovered that a substance with a definite particle size is the most sensitive to detonation in charges of low

Table 15. Effect of Grinding on the Susceptibility of Explosives

Взрывчатое вещество (1)	Величина минимального инициирующего заряда азида свинца (2)	
	для частиц, проходящих через сито с 2500 отв/см ² (3)	для ультрадиспергированных частиц (4)
Тринитротолуол (5)	0,10	0,04
Тринитробензол (6)	0,19	0,06
Тринитрохлорбензол (7)	0,14	0,05
Гексанитродифенил-амин (8)	0,03	0,02
Ксилит (9)	0,34	0,08

Key:

1. Explosive	5. TNT
2. Size of lead azide MIZ, g	6. Trinitrobenzene
3. For particles passing through a sieve with 2,500 holes/cm ²	7. Trinitrochlorobenzene
4. For ultradispersed particles	8. Hexanitrodiphenylamine
	9. Xylol

density of a number of explosives [7]. Thus, for hexogene, PETN, picric acid, and other explosives with a density of 1.0 g/cm³ the particle size causing the greatest distance of transmission of detonation is 0.5 mm. Decrease in the particle size, as well as increase in it, leads to a reduction in the susceptibility of explosives which, in the opinion of A.Ya. Apin and others [7], is explained by the favorable (for the given particle size and density of the explosive) conditions of ignition, determined by the optimal ratio of the permeability of the charge to detonation products to the value of the specific surface.

However, under real technological conditions the possibility of obtaining explosives with an accurately fixed particle size, and especially in an ultradispersed state, is fairly limited.

In addition, the effect of the particle size of explosives on the susceptibility to detonation will be only to a certain limit: with approach of the charge density to the density of a monocrystal, the efficiency of the effect of this factor must be reduced, and with a charge density equal to the density of a monocrystal it disappears completely. This is explained by the fact that with approach of the charge density to the density of a monocrystal of the explosive, the charge takes on the character of a solid homogeneous medium, in which the origination of an explosion is related to the adiabatic heat-up of the explosive as a result of dynamic compression of it by the initiating

shock wave; that is, in the given case there is observed a transition from explosive burning to a mechanism of the onset and passage of a chemical reaction behind the front of the shock and detonation waves, which is different in principle.

Sensitization of an explosive can also be insured by the introduction into the composition of explosives of small amounts of inert additions.

Avogadro used a number of inorganic compounds as sensitizing additions for gelatin dynamite. Inorganic salts and oxides and the powders of certain metals, in particular the oxides and salts (sulfates and carbonates) of lead, barium, tungsten, and others were sufficiently good sensitizers. This method of sensitization is, in our opinion, the most rational, since even with the introduction of an insignificant amount of additions a considerable increase in the susceptibility of the explosive to detonation can be achieved with preservation of its physico-mechanical properties and energy characteristics.

P.B. Dempster established that the introduction of a small amount of certain additions, in particular compounds of barium, lead, mercury, and others, promotes the transition of gelatin dynamite having a low detonation velocity into gelatin dynamite characterized by a high velocity. In his investigations only particles with a specific weight above 2.8 g/cm^3 and a size of $0.5\text{--}10 \mu$ were effective. He explained such a sensitizing effect of additions by the particles reflecting the front of the detonation wave, which led at the points of collision of the waves reflected from the particles to an increase in the temperature and pressure.

F.P. Bouden and A.D. Ioffe [22] assume that the determining factor which affects the increase in the sensitivity of explosives with the introduction additions is the melting point of the impurity particles.

A.Ya. Apin and L.I. Stesik [8] investigated the effect of powdered additions on the detonation capacity of ballistic powders of N and NB brands. Inorganic substances (CaCO_3 , NgO , PbO , W , and others) with a particle size on the order of 3μ were used for sensitization of the powder. It was shown that the introduction of inorganic additions into the powder decreased the critical diameter significantly.

K. (Khino) and M. (Iokogava) [76] studied a number of inorganic and organic catalysts of surface-active substances which significantly improve the detonation capacity of explosives consisting of ammonium nitrate and a combustible addition. In our opinion, such impurities, being catalysts, insure molecular

coupling and promote an increase in the rate of the reaction between the oxidizing agent and the fuel. The most efficient of the inorganic additions studied was potassium bichromate, and the best organic surface-active substances were anions: sodium dinaphthylmethane disulfonate, sodium laurylsulfate, and sodium dodecylbenzene sulfate.

K.K. Andreyev, I.Ya. Petrovskiy and others also studied the effect of inert additions on the detonation capacity and susceptibility of solid explosives.

HYDRODYNAMIC CONDITIONS OF DEVELOPMENT OF LOCAL HEAT-UPS IN PRESSED CHARGES OF EXPLOSIVES IN THE PRESENCE OF INERT ADDITIONS

To reveal the features of the process of development of detonation in the presence of inert additions and to establish the main rules of the effect of different factors on their sensitizing effect during the excitation in the charge of a detonation type of explosion, it is most expedient to use charges completely devoid of porosity. In this case one can exclude the effect of secondary factors on the results of the investigations, and the charge can be considered as a solid medium having a purely adiabatic compressibility. In the excitation of an explosion by a shock, the sensitizing effect of additions on an explosive is related to the development of local heat-ups -- "hot spots" -- caused by friction of the particles under the conditions of their rapid displacement, plastic flow of the explosive under increased stresses, and so on [22].

For charges of low and moderate density -- that is, with a relatively high porosity -- sites of local heat-ups in the reaction zone behind the front of the initiating shock wave must also play a significant role in the process of the onset of an explosion during the direct excitation of detonation in the charge.

The formation of these seats in a given case is caused, apparently, mainly by the same factors as during the excitation of explosion by a shock. For a charge of pure explosive completely devoid of pores, the possibility of the formation of "hot spots" according to the mechanism indicated above is excluded and the explosion arises as the result of adiabatic expansion of the explosive during its compression by the initiating shock wave. However, in the presence of additions, the conditions of development of detonation in such charges change markedly.

The heat-up of the explosive in the zone enveloped by the initiating shock wave occurs not only due to rapid shock compression, but also due to the action of two factors.

1. In the case of a noticeable difference in the densities of the explosive and the addition, their particles, in the process of the formation of a shock wave in the initial stage of transfer of flow behind its front, will move with a different velocity, and under the influence of the velocity gradients the explosive flows around the particles of the addition and, as a result, relatively high local heat-ups develop.

It is important to determine the movement of the particles in the flow of the explosive behind the shock wave front. For this, let us use the Newton rule

$$m \frac{dv}{dt} = q_c S \rho_{VV} \frac{v^2}{2}, \quad (16)$$

where m = mass of the particles, g; S = surface of the particles, cm^2 ; ρ_{VV} = density of the explosive, g/cm^3 ; q_c = coefficient of drag; v = rate of flow relative to a particle (m/sec), equal to $v_{f1} - v_p$ (v_{f1} = rate of flow, v_p = particle velocity).

Having rewritten equation (16) in the form

$$\frac{dv}{dt} = v \frac{dv}{dx} = a (v_{f1} - v_p)^2, \quad (17)$$

we get

$$\frac{x}{a} = \left[\frac{v_p}{v_{f1} - v_p} - \ln \left(1 + \frac{v_p}{v_{f1} - v_p} \right) \right], \quad (18)$$

where $a^{-1} = (q_c S \rho_{VV})/2m$ and x is the coordinate of the particle.

Assuming the shape of the particle to be spherical, we have:

$$a^{-1} = \frac{3 \rho_{VV} q_c}{8 \rho_p R_p},$$

where ρ_p = density of the particle; R_p = its radius.

Equation (18) determines the law of the movement of the particle in the flow of explosive. The value q_c depends on the Reynolds number

$$\text{Re} = \frac{v_{f1} R_p \rho_{VV}}{\eta},$$

where η = coefficient of viscosity of the flow.

Let us take $v_{f1} = 1,400$ m/sec, $R_p = 2 \cdot 10^{-4}$ cm, $\rho_{VV} = 1.8$ g/cm³, and $\eta = 0.3$ g/cm·sec; for this $\text{Re} \approx 380$, and for such values of it $q_c = 0.09$.

Calculations show that for $R_p = 2 \mu$ and $\rho_p/\rho_{VV} = 3$ the addition particles acquire in practice the rate of flow in a distance of 10^{-1} cm.

From this it follows that the possible realization of the above noted chemical processes, which lead to the development in the charge of local heat-ups, by no means contradicts the conditions of formation and propagation in the charge of an explosive mixture of a normal stable shock wave.

In the case considered by us, due to the flow of the explosive around the particles of the inert addition, in the charge there can arise fairly intense local heat-ups.

For an approximate quantitative estimate of the temperature in the local seats of heat-up, let us consider the problem of the movement of a body (particle) in a liquid. With such a movement, the part of the liquid directly adjacent to the surface of the particle (boundary layer) is carried into motion by it.

As is known, under the condition where the particles have the shape of a sphere, the associated mass in the process of movement of the particle is equal to:

$$m_a = \frac{1}{2} m_p \frac{\rho_{vv}}{\rho_p}, \quad (19)$$

where m_a = associated mass; m_p = mass of the particle.

In our case the opposite picture occurs -- the stream flows around the particle; that is, m is the mass of the substance retarded in the process of the flowing around on the surface of the particle. The value of m_a is determined by the average size of the seats of local heat-up.

The heat evolved during braking is

$$Q_r = -\frac{m_a v^2}{2} = \widehat{m_a c_{fl}} \Delta T, \quad (20)$$

where ΔT is the temperature rise and c_{fl} is the specific heat capacity of the flow of the explosive.

Let us estimate the rate of flow, starting from the conditions at the front of the shock wave:

$$p = \rho_{vv} D U_{vv} = \rho_p D U_p, \quad (21)$$

from which it follows that

$$v = U_{vv} - U_p = U_{vv} \left(1 - \frac{\rho_{vv}}{\rho_p} \right). \quad (22)$$

Calculations show that if pressed lead azide is used as an initiator and pressed PETN or hexogene is used as an initiated change, the initial pressure in the initiating shock wave

reaches a value on the order of $(1.35-1.50) \cdot 10^5$ atm (tech.), and the mass velocity of the explosive behind the front of the shock wave in the initiated charge is $U_{VV} = 2,000-2,185$ m/sec. Taking $\rho_{VV} = 1.8$ g/cm³, $\rho_p = 5$ g/cm³, and $U_{VV} = 2,185$ m/sec, we get $v_{f1} = 1,400$ m/sec.

For typical high explosives, $c_{f1} \approx 0.3$ cal/g·deg. Substituting the found values of v_{f1} and c_{f1} into equation (20), we find the temperature rise in a local seat of heat-up:

$$\Delta T = 780^\circ \text{C}.$$

The actual temperature at a seat of local heat-up is

$$T = T_{ad} + \Delta T,$$

where T_{ad} is the temperature of adiabatic heating arising during the dynamic compression of the explosive by the initiating shock wave.

Thus, with a sufficiently marked difference in the density of the explosive and the addition, due to hydrodynamic micro-processes, in actuality there can arise a high local temperature. The melting point of a substance, as is well known, increases markedly with increase in the pressure. Under the conditions considered by us for the excitation of detonation, the melting point of the substance depends on the initial pressure at the front of the initiating shock wave.

The relation between the melting point of the substance and the pressure is determined by the Clausius-Clapeyron equation:

$$\frac{dp}{dT} = \frac{\Delta s}{\Delta V} = \frac{Q_{me}}{T_{mp} \Delta V}, \quad (23)$$

where s = entropy; Q_{me} = specific heat of melting; T_{mp} = the melting point at atmospheric pressure; ΔV = change in the specific volume of the substance during the phase transition (from the solid to the liquid state).

It is known [60] that for TNT, $Q_{me} = 21.4$ kcal/kg and $\Delta V = 0.0652$ cm³. From this it follows that for TNT

$$\begin{aligned} \frac{dT}{dp} &= 0.025 \text{ deg/atm (tech.);} \\ T_{mp}^p &= T_{mp}^* + 2.5 \cdot 10^{-2} p. \end{aligned} \quad (24)$$

This dependence has been experimentally tested and confirmed under conditions with a pressure on the order of 10^4 atm (tech.).

Nevertheless, it is possible to assert that for the high pressure $((1.0-1.5) \cdot 10^5$ atm (tech.)), which arises in the

initiating shock wave, the melting point of the explosive will far exceed 1,000°C.

It should be noted that the reason for obtaining values of T_{mp}^p at high pressures that are too high is related to the fact that for $p = 10^5$ atm (tech.) and above, ΔV already cannot be assumed to be a constant value. With increase in the pressure, ΔV will decrease and the difference in the behavior of the explosive in the solid, liquid and even gaseous states will gradually disappear. As will be shown below, in practice a sharp increase in the sensitizing capacity of additions with very high density has not been established. This can be explained by the fact that the melting point of the explosive for a given pressure in the initiating shock wave, apparently, is below the limiting temperature which in principle can be attained for the given values of ρ_{VV} and ρ_p at the seats of local heat-ups.

In accordance with this it can be assumed that the higher sensitizing capacity of additions with high densities can be shown only under the conditions of using sufficiently powerful initiators, for which in the initiating shock wave a significantly higher pressure is realized.

2. When the densities of the explosive and the inert additions are the same or close, the development of intense local heat-ups by the mechanism considered above is excluded. Nonetheless, sufficiently high temperatures of local heat-up can nevertheless develop at the surfaces of contact of the particles of the explosive and the addition, under the action of the initiating shock wave, due to the difference in their physical properties. Sensitizing additions, as a rule, have a significantly lower compressibility than explosives.

The state of a substance during shock compression is determined by the thermal and elastic interaction of its atoms and molecules.

At pressures on the order of 10^5 atm (tech.) and above [15], the equation of state of a substance has the following form:

$$p = -\frac{\partial F_v}{\partial V_0} + \frac{BT}{V_0}, \quad (25)$$

where F_v = the part of the free energy not dependent on the temperature; T = temperature; V_0 = specific volume; B = coefficient of thermal pressure.

The first term in the right side of this equation is the elastic component of the pressure, which is not temperature-dependent.

During dynamic compression of a charge by an initiating shock wave, at the discontinuity of the explosive-inert particle media there must arise a temperature break -- a temperature gradient the magnitude of which depends on the pressure of the components of the charge at the front of the shock wave. This circumstance, in turn, leads to a peculiar redistribution of the energy in the layer of the charge compressed by the shock wave: in the zone of contact of the explosive with the inert particle the local temperature of the explosive is noticeably above the temperature of adiabatic heat-up of the pure explosive in the absence of additions.

A quantitative estimate of the local temperatures arising in a charge in a given case is hampered by the absence of sufficient information on the compressibility of the respective substances and the equation of state of these substances at high pressures. The reality of such a mechanism of sensitization is indirectly confirmed by the results of our tests on the effective use of substances having a density the same as the explosive as sensitizing additions.

The mechanisms described by us for local heat-ups of an explosive during the excitation in the charge of a detonation type of explosion, apparently, are correct not only for charges having the density of monocrystals but even generally for charges with a relatively high density.

Efficiency of the introduction of additions into the composition of an explosive can be assured only with the attainment of a high volume density of "hot spots" and a short distance between them. Such conditions can be realized only when the particles of the sensitizing substance and the explosive are sufficiently small and comparable. The smaller the distance between the "hot spots," the shorter will be, with other conditions equal, the time of passage of the chemical reaction behind the front of the shock wave, and, consequently, the size of the minimum initiating charge must also be smaller.

In the absence of additions and with a density of the charge equal to the density of the monocrystals, the size of the particles of the explosive cannot affect the susceptibility of the explosive to detonation. In the presence of additions, the size of the particles of the explosive of the charge has considerable importance, since their size (for a given size of the particles of the addition) determines the average distance between the "hot spots."

RESULTS OF EXPERIMENTAL STUDIES ON INCREASING THE SUSCEPTIBILITY OF THERMOSTABLE EXPLOSIVES

The main problem of the experimental studies was checking the above indicated hypotheses on the mechanism of the sensitizing effect of additions, as well as choosing the additions most favorable for introduction into the composition of thermally stable explosives to improve their detonating capacity and susceptibility to detonation under the conditions of the action of increased hydrostatic pressures on the charge of explosive.

In the investigation of the susceptibility to detonation, charges were pressed in a sleeve to a density approaching the density of the monocrystal, and in the study of their detonation capacity at increased pressures of the liquid, the relative density of the charges fluctuated within the limits of 0.75-0.83. Different inorganic substances (Table 16), certain metallo-organic compounds, and lead azide were tried as sensitizing additions.

Table 16. Characteristics of Sensitizing Additions

Добавка (1)	Плотность, г/см ³ (2)	Твердость по шкале Мооса (3)	Температура плавления, °C (4)
BaSO ₄	4,5	2-3	1580
PbCO ₃	6,2	2,5-3,5	Разлагается при >200
CaCO ₃	2,7	1	Разлагается при >500 (5)
B ₂ O ₃	1,84	8-9	При 300° переходит в вязкую жидкость
CoO	5,2	3-4	900 (6)
CoCl ₂	3,36	3-4	725
SiO ₂	2,6	6-7	1730
W	1,3 (7)	7-8	3400

Key:

1. Addition	5. Decomposes at ...
2. Density, g/cm ³	6. Changes into a viscous liquid at 300°
3. Hardness, by the Mohs scale	7. Possibly 19.3 (see Table 18)
4. Melting point, °C	

We used metallo-organic compounds (developed by the NIEOS AN SSSR [Scientific Research Institute of the EOS of the USSR Academy of Sciences]) of K-1 with a content of 20 percent iron and K-2 containing 30 percent tungsten. The melting point of these substances is 150-160°C; their specific weight is around 1.8 g/cm³.

The introduction of additions into the composition of an explosive was carried out by two methods: mechanical mixing and simultaneous precipitation of the explosive and the addition from a solvent. In the case of mechanical mixing, the additions were ground to an ultradispersed state in an eccentric mill (with such grinding the particles have a size of 1-3 μ). In the ultradispersed state the explosives were obtained by dissolving them in any solvent (most frequently acetone) with subsequent precipitation in water.

For the tests the components were carefully mixed and rubbed through a sieve with a cell size of $2-3\ \mu$ several times. Such mixing permits uniformly distributing the particles of the additions over the whole volume of the explosive. The size of the particles of the additions and explosives were measured under a microscope before and after mixing.

Figure 20. Diagram of apparatus for mixing sensitizer with explosive: 1. electric motor; 2. water; 3. stirrer; 4. crystallizing basin.

Key:

1. Solutions of starting products
2. Solution of explosive

However, a similar method of mechanical mixing of the components of the explosive is laborious; it is expedient to use it only in the case when the components are insoluble. More convenient from a technological point of view is the method of simultaneous coprecipitation of the explosive and the addition from solutions. Thus, for example, in the sensitization of an explosive using BaSO_4 or PbN_6 their starting products -- BaCl_2 , Na_2SO_4 and $\text{Pb}(\text{NO}_3)_2$ -- are dissolved in water and the explosive in the corresponding solvent (acetone, for example). Then the solutions are decanted into a crystallizing basin filled with water, where precipitation occurs during the intense operation of

a stirrer (Figure 20). The obtained precipitate is washed and dried. The studies showed that the sizes of the particles of the additions and the explosives were comparable, and the additions were uniformly distributed in the mass of the explosives.

We studied the sensitizing effect of different additions on the susceptibility of an explosive to a detonation pulse (on the size of the initiating charge and the distance of transmission of detonation) and on the detonation capacity of the explosive (critical diameter of the charge).

Effect of Sensitizing Additions on the Magnitude of the Minimum Initiating Pulse

The minimal batch of lead azide with a density of $\rho_0 = 3.8\ \text{g/cm}^3$ causing the detonation of a charge of the studied explosive, pressed to the density of a monocrystal in a strong duralumin case (10 mm in diameter, wall thickness of 1 mm) was determined.

The charges of explosive were pressed under a pressure of 4,500-5,000 atm (tech.) in press-forms heated to 60-80°C, which insured the maximum density of them. Preliminary investigations related to the determination of the effect of the size and content of the particles on their sensitizing capacity were conducted with hexogene.

Table 17. Effect of Sensitizing Additions on the Susceptibility of Hexogene

Добавка (1)	Размер частиц, мк (2)	Содержание добавки, % (3)	Величина минимального инициирующего заряда, г (4)
B ₂ O ₃	0,3	0,4	0,03
	0,3	1	0,05
	0,7-0,8	0,4	0,045
	0,7-0,8	3	0,03
BaSO ₄	1-2	2	0,03
	100	2	0,06
	100	5	0,06

(5) Примечание. Минимальный инициирующий заряд азиды свинца, вызывающий детонацию чистого гексогена (см. табл. 8), равен 0,06 г.

Key:

1. Addition
2. Particle size, μ
3. Content of addition, %
4. Size of MIZ, g

5. Note. The MIZ of lead azide causing the detonation of pure hexogene (see Table 8) is 0.06 g.

Table 18. Optimum Content of Inert Particles With Differing Density

Добавка (1)	Размер частиц, мк (2)	Плотность, г/см ³ (3)	Оптимальное содержание, % (4)
BaSO ₄	1-2	4,5	1
PbCO ₃	1-2	6,2	2
W	1-2	19,3	4,5

Key:

1. Addition
2. Particle size, μ
3. Density, g/cm³
4. Optimum content, %

The main results of the tests (Tables 17 and 18) permit making the following conclusions:

1. The size of the particles of the introduced additions has a very great effect on their sensitizing effect. With increase in the size of the particles, the sensitizing effect of the addition falls.

2. For a particle size of the addition of 1-2 μ , the optimum content of different additions, for which the maximum sensitizing effect is achieved, is different. However, the volume density of the particles (number of particles per unit volume)

and, consequently, the average distance between them are approximately the same.

The volume density of the particles fluctuates within the limits of 10^8 - 10^9 cm³ [sic].

The results obtained for B₂O₃ are very representative. For sizes of the boron anhydride particles of 0.3 and 0.7-0.8 μ the optimum content of them, for which the maximum sensitizing effect was observed, was respectively 0.4 and 3 percent (see Table 17). However, in the given case, the same volume density of the particles of the additions in the explosive occurred.

With deviation from the optimum content of the addition to either side, its sensitizing effect decreases. The reason for the drop in the sensitizing effect with increase of the content of additions in the charge as compared to the optimum, apparently, is the following. With an excessively high volume density of the particles of the inert addition, there can occur in the charge significant dissipative losses of energy in the initiating shock wave, which, in turn, can lead to a drop in the intensity of the initiating shock wave in the initial period of its propagation, when the wave cannot be supported to a sufficient degree by the energy of the chemical reaction in the primary seat of initiation.

3. Even in the cases when the density of the additions is equal to the density of the explosive, the inert additions can have, as is seen from tests with B₂O₃ and metallo-organic compounds, a high sensitizing capacity. This is an indirect confirmation of the above expressed considerations on the role of the compressibility of explosive assemblies in the mechanism of the sensitizing effect of additives.

According to the investigations of P.B. Dempster, the sensitizing effect of additions is limited by the particle size not only from above, but also from below: with a particle size less than 0.5 μ , the sensitizing effect of an addition on gelatinized nitroglycerin begins to fall rapidly. In our tests with hexogene, with an average size of the B₂O₃ particles on the order of 0.3 μ the normal sensitizing effect of this addition still occurred.

The possibility of decreasing the sensitizing effect of an addition with an extreme decrease in the size of the particles can be explained in the following way. As was noted above, under the dynamic compression of a charge by an initiating shock wave, at the explosive-addition particle discontinuity there arises a significant temperature gradient, caused by the different compressibility of the components of the charge.

However, for the excitation of an intense reaction and the development of an explosion it was necessary that this gradient did not noticeably level off after the time of compression of the substance by the shock wave.

The time required for leveling of the temperature depends considerably on the size of the particles, R_p , and the coefficient of thermal conductivity (μ) of the substance.

To maintain a sufficient temperature gradient in the period of compression of the particles by the shock wave it is necessary that the equation

$$R_p \geq \sqrt{\tau \mu}, \quad (26)$$

be fulfilled. Here, τ is the duration of the effective action of the initiating shock wave on the particle.

Calculations show that with regard to real conditions of initiation,

$$R_{cr} \approx 0,1 \mu.$$

Table 19 gives the sizes of initiating charges of lead azide causing under the conditions of our tests the detonation of charges of hexogene with the introduction into it of the optimum amount of different inert additions, for which the maximum sensitizing effect is achieved. The particles of the additions and explosive had a size of 1-2 μ .

Table 19. Sensitizing Ability of Additions

Добавка (1)	Содержание, % (2)	Плотность заряда, г/см ³ (3)	Величина минимального инициирующего заряда, г (4)
Гексоген чистый (5)	—	1,80	0,06
BaSO ₄	1	1,82	0,03
W	4,5	1,88	0,04
B ₂ O ₃	0,4	1,80	0,03
PbCO ₃	2	1,83	0,04
CoCO ₃	2	1,83	0,04
CoCl ₂	1,7	1,82	0,04
CaCO ₃	1	1,81	0,04
SiO ₂	1	1,81	0,04

Key:

1. Addition

2. Content, %

3. Density of charge, g/cm³

4. Size of MIZ, g

5. Pure hexogene

Lead azide is a very effective sensitizer of secondary explosives. The introduction into the composition of hexogene of 5 percent of lead azide already sharply increases the susceptibility of the charge to an initiating pulse:

Content of addition, %	Density of charge, g/cm ³	Size of lead azide MIZ, g
2	1.83	0.04
3	1.84	0.03
5	1.86	0.01

A similar picture is observed for the sensitization of NTFA by lead azide and silver azide. With the introduction of 5 percent of lead azide, the minimum initiating charge decreases from 0.4 g (for the pure substance) to 0.06 g, and for the introduction of the same amount of silver azide, to 0.03-0.05 g. A large amount of PbN_6 and AgN_3 (up to 15-20 percent) leads to a similar mixture being initiated directly from a strong light pulse.

The introduction into the composition of an explosive of metallo-organic compounds of K-1 and K-2 also leads to a considerable increase in the susceptibility of hexogene to detonation:

Metallo-organic compound	Content of addition in composition of explosive, %	Size of lead azide MIZ, g
K-1 (20 percent Fe)	2	3
	2	0.02
	4	0.05
	10	0.04
	15	0.06
K-2 (30 percent W)	2	0.05
	5	0.05
	10	0.03
	15	0.06

The introduction into the composition of an explosive of other hetero-organic compounds not containing metals does not cause an increase in the susceptibility to a detonation pulse.

Below are given the sizes of the minimum initiating charge with the introduction into an explosive of a silicon-organic resin of brand FG-9:

Content of resin in composition of hexogene, %	Size of lead azide MIZ, g
2	0.06
3	0.08
5	0.10

The sensitizing effect of the more effective additions was tested on the thermally stable explosives V-5 and NTFA.

From Table 20 it is seen that the introduction of inert additions into the composition of thermally stable explosives also leads to a considerable increase in their susceptibility to detonation for a density of the charges approaching the density of the monocrystal.

Table 20. The Effect of Additions on the Susceptibility of Thermally Stable Explosives

Взрывчатое вещество (1)	Добавка (2)	Содержание добавки, % (3)	Величина минимального инициирующего заряда азид свинца (4)
В-5 (5)	—	—	0,5
	BaSO ₄	1	0,35
	PbCO ₃	2	0,30
	PbN ₆	5	0,10
НТФА (6)	—	—	0,4
	BaSO ₄	1	0,25
	PbN ₆	5	0,06

Key:

1. Explosive

2. Addition

3. Content of addition, %

4. Size of lead azide MIZ, g

5. V-5

6. NTFA

Effect of Additions on the Transmission of Detonation

The introduction of sensitizing additions does not cause an increase in the distance of the transmission of the detonation through air and dense media for pressed charges of high density (Table 21).

Table 21. Effect of Additions on the Transmission of Detonation to Charges of Hexogene

Добавка (1)	Содержание добавки, % (2)	Плотность заряда, г/см ³ (3)	Предельное расстояние 100%-ной передачи детонации, мм (4)
Гексоген чистый (5)	—	1,80	25
BaSO ₄	1	1,82	25
BaSO ₄	4,5	1,83	25
—	—	1,76	40
BaSO ₄	1	1,76	40
PbCO ₃	2	1,76	40

Key:

1. Addition

2. Content of addition, %

3. Density of charge, g/cm³

4. Limiting distance of 100-% transmission of detonation, mm

5. Pure hexogene

The diameter of the passive charge in the tests was 12 mm. The active charge was a charge of phlegmatized hexogene of the same diameter and with a density of 1.6 g/cm³. The transmitting medium was air.

The reason for the absence of an effect of the additions on the distance of the transmission of the detonation has still not been adequately studied; however, it can be explained in the following way. The distance of transmission of the detonation is the limiting distance for which the initial parameters (pressure p_{sw} and temperature T_{sw}) of the initiating shock wave reach their critical values. The critical parameters, generally speaking, must depend only on the physicochemical properties of the explosive and the size of its particles, and for a density of the charges equal to the density of the monocrystals of the explosives, only on the first factor. Consequently, sensitizing additions cannot affect the distance of the detonation.

During the excitation of an explosion with a detonator, the initial parameters (p_{sw} , T_{sw}) of the initiating shock wave in the charge far exceed their critical values; therefore the size of the minimum initiating charge, with other conditions equal, will depend only on the limiting time, τ_{lim} , of the action of the temperature, T_{sw} , on the explosive of the charge of initial initiating shock wave, for which in the zone of initiation there is assured an intense self-propagating chemical reaction.

It is apparent that the value of τ_{lim} can be realized only for the conditions when the length of the initiating charge is greater than or equal to its minimum length ($l \geq l_{min}$).

With the presence in the charge of sensitizing substances, the time of passage of the reaction behind the front of the wave decreases, which, in turn, leads to a certain decrease in τ_{lim} and, consequently, in the minimum length, l_{min} , of the initiating charge. The studies conducted by us with a substance, V-5, having a reduced susceptibility to detonation showed that with the introduction into its composition of sensitizing additions there occurs some reduction in the time of lag and a very significant (by about a factor of 10) decrease in the length of the transition zone. This result is a consequence of the reduction in the time of passage of the reaction and the corresponding increase in the rate of heat evolution behind the front of the initiating shock wave in the initial part of its movement in the presence in the charge of initiating substances (Table 22).

Effect of Additions on the Critical Diameter

With rational introduction into the composition of explosives of inert additions, the critical diameter is significantly reduced. However, an effect of sensitizing additions on the value of d_{cr} is characteristic only for charges of high density or low porosity. Thus, for a substance of V-5 with a density of

Table 22. Transmission of Detonation in Charges of V-5 With Additions (With a Density of 1.62 g/cm^3) in a Sleeve 10 mm in Diameter From an Active Charge (TED-2) Through a Steel Bridge 1 mm Thick

Взрывчатое вещество (1)	Расстояние до начала детонации, мм (2)	Время задержки детонации, мксек (3)
В-5 чистый (4)	4,6	1,55
В-5+1% BaSO_4 (5)	0,6	1,0
В-5+5% PbN_6	0,25	1,0

Key:

1. Explosive
2. Distance to initial detonation, mm
3. Detonation delay time, μsec
4. Pure V-5
5. V-5 + ...

1.3-1.4 g/cm^3 , in the presence of sensitizing additions there was not observed a decrease in the critical diameter.

Some decrease in it occurred under the conditions of saturation of the pores of the charge with a liquid at a high hydrostatic pressure in the presence of sensitizing additions.

Comparative tests showed that with the introduction of 2 percent of BaSO_4 the critical diameter of hexogene with a density of 1.50 g/cm^3 under the conditions of saturation of its pores with water at a pressure of 1,000 atm (tech.) it decreases from 6.0 to 3.5 mm, and with the introduction into the composition of the V-5 of 1 percent of BaSO_4 after complete saturation of the charge with water at a pressure of 1,000-1,200 atm (tech.) the critical diameter of a charge with a density of 1.30 g/cm^3 decreases from 13 to 10 mm, and for a charge with a density of 1.45 g/cm^3 , from 11 to 9.0 mm.

These results have very great significance and can be used for the development of fuses intended for operation in a liquid under high hydrostatic pressures.

The data obtained permit making several conclusions.

1. The main factors affecting the sensitizing capacity of inert additions are their density, compressibility (hardness) and the size of the particles of the additions and their volume density.
2. The introduction of additions leads to a reduction in the susceptibility of an explosive to a detonation pulse and an improvement in its detonation capacity, which is expressed in a decrease in the size of the minimum initiating charge and the critical diameter of the explosive charge. The introduction of additions does not lead to an increase in the distance of transmission of the detonation.

3. The effect of sensitizing additions is shown only in the case of charges of high density or low porosity.

4. The most effective sensitizing additions which can be used to increase the susceptibility and improve the detonation capacity of thermally stable explosives are BaSO_4 , PbN_6 and other initiating explosives. The use of BaSO_4 is expedient not only from the point of view of its relatively high sensitizing capacity and high melting point, but also because of the technological simplicity of introducing it into the composition of the explosive. Lead azide can be used to increase the susceptibility of explosives intended for the preparation of detonators of increased power and thermal stability.

CHAPTER 4. PROCESSES OF EXCITATION OF DETONATION BY SHOCK WAVES

CONTEMPORARY CONCEPTS ON A MECHANISM FOR THE EXCITATION OF DETONATION

The excitation of the detonation of explosives can be realized under the direct action of an initiating impulse or by shock wave. For the excitation of the detonation of charges of thermostable explosives in test-firing and blasting borehole equipment, both methods are used.

The blasting of VV in detonators, as well as in charges with their direct contact with thin-walled detonators is accomplished with the aid of the initiating impulse. In this case, "critical" for the excitation of detonation is the effect of the initiating shock wave and the detonation products possessing high pressure and high temperature. The question of the excitation of the detonation of charges by the direct initiating impulse is sufficiently studied and described in the literature. In the transmission of the detonation to the detonating cords or to charges of VV through a connection piece, the excitation of detonation is achieved by a shock wave.

Let us examine in more detail the question of the mechanism for the excitation of detonation under conditions of the initiation of charges of VV by shock waves.

In the excitation of the detonation form of explosion by the initiating impulse in the presence of an air barrier, detonation in a passive charge appears as a result of the direct igniting action of a shock wave and products of the explosion which were formed during the detonation of an active charge.

The experiments carried out by us showed that at the maximum distances of reliable detonation the speed of the shock wave at the moment of its approach to a passive charge of phlegmatized hexogene (compound of GFG-2) with density $\rho_0 = 1.65 \text{ g/cm}^3$ is approximately equal to 3,100 m/sec, which corresponds to a

pressure at the wave front of 100 atm (tech.) and to a temperature of approximately 3,800°K. With the total reflection of the wave from the end of the charge the pressure increases to 900 atm (tech.) and the temperature exceeds 10,000°K.

It is evident that at so high a temperature the air wave will possess good initiating (igniting) capability even with the very small ($\tau \leq 10^{-6}$ sec) duration of its action. Furthermore, in this case the shock wave which arose in the most passive charge (with its sufficient density) will not play any noticeable role in the mechanism for the excitation of its detonation.

When detonation is transferred to a passive charge through solid media (water, metals, glass, and others), the only factor which causes its emergence is the shock wave which entered the passive charge from the transmitting medium -- the so-called initiating shock wave (IUV) -- which is capable of exciting detonation in VV only with sufficiently high intensity. Only in this case, as a result of local heatings or shock compression of the VV a temperature can arise in the charge sufficient for the emergence of an intensive chemical reaction.

Many works [10,19,36,40,63,87,90,92,93,95,96,97,99,102, and others] are devoted to the investigation of the blast effects on VV and the law of the impact compressibility of many explosives has been established. I. Scay and J. Seeby [102] showed that for VV with a sufficiently large charge density the linear dependence is well satisfied:

$$D = a + bv, \quad (27)$$

where D = speed of the shock wave; v = flow velocity behind its front; a , b = experimentally established coefficients which, over a wide range of pressures, remain constant (Table 23).

Table 23. Experimental Values of Coefficients a and b for Some Typical VV and Inert Materials

Взрывчатое вещество (1)	Плотность, g/cm^3 (2)	a , m/sec	b
Тротил (прессованный) (3)	1,60—1,62	2 390	2,05
Тротил (жидкий) (4)	1,47	2 000	1,68
Гексоген (5)	1,72	2 710	1,86
Состав "Д" (6)	1,62	2 400	1,66
Плексиглас (7)	1,18	2 710	1,57
Медь (8)	8,43	3 900	1,46

Key:

1. Explosive
2. Density, g/cm^3
3. TNT (pressed)
4. TNT (liquid)

5. Hexogene
6. Composition "D"
7. Plexiglass
8. Copper

For a number of explosives the critical parameters (D_{cr} and p_{cr}) of the initiating shock wave are determined with which it is still capable of exciting a stable detonation in the charge. These critical parameters increase substantially with an increase in the charge density. Thus, for TNT, with a density change from 1.0 to 1.63 g/cm³ the value of p_{cr} changes (according to data of different authors) from $(8.0-9.0) \cdot 10^5$ to $(1.30-1.50) \cdot 10^5$ atm (tech.). So abrupt a change in the value of p_{cr} is explained by the fact that in proportion to an increase in the charge density the role of local heatings decreases to an even greater extent and the role of the impact heating of the VV in the mechanism for the excitation of detonation increases accordingly.

The first experiments for the determination of the critical parameters of the initiating shock wave with the diameters of the charges considerably in excess of the maximum were conducted in 1946 by B.I. Shekhter [15]. Later, such experiments were conducted in a number of other works [10,19,36,40,63, and so forth].

V.S. Il'yukhin and P.F. Pokhil, during the investigation of the transmission of a detonation through solid media, determined the critical pressures of initiation for some explosives [40].

The work of A.F. Belyayev and others [19] is devoted to an investigation of the critical pressure of initiation during transmission through the air.

A.N. Afanasenkov and others [10] explained that with the transmission of the detonation through the air in the case of the use of cylindrical active charges, the excitation of detonation at a distance greater than 10 radii causes an air shock wave, and with the use of spherical active charges this distance is equal to 4.5 radii of the charge. With lesser distances, explosion products also participate in the process of the excitation of the detonation.

The values of p_{cr} given in the literature for VV's are sometimes contradictory. This is explained first of all by differences in the conditions of the experiment (different dimensions of the active and passive charges, and so forth), and consequently, by the dissimilar duration of the effective action of the initiating shock wave on the initial focus of initiation in a passive charge.

C. Johansson and others [96] convincingly showed that corresponding to each value of p_{cr} at the front of the initiating shock wave is a certain minimum duration (τ_{min}) of its action (Table 24).

Table 24. Minimum Duration of Action of the Initiating Shock Wave

Взрывчатое вещество (1)	Диаметр заряда, мм (2)	Критические параметры инициирующей ударной волны (3)	
		p_{cr}, ATM	τ_{min}, sec
Сплав тетрил—тротил (4)	33,0	$9 \cdot 10^4$	$1,1 \cdot 10^{-6}$
Сплав гексоген—тротил (83:17) (5)	33,0	$5 \cdot 10^4$	$0,6 \cdot 10^{-6}$

Key:

1. Explosive	4. Tetryl-TNT alloy
2. Diameter of charge, mm	5. Hexogene-TNT alloy (83:17)
3. Critical parameters of the initiating shock wave	

With the values of p_{cr} given in Table 24, but with $\tau < \tau_{min}$ a stable detonation in a charge cannot be excited. However, with an increase in the intensity of the initiating shock wave the detonation of charge can also arise in the case of a briefer action.

In the experiments of J.M. Charles [99] the initiating shock wave arose in the charge as a result of its collision with a fast-moving bullet. The advantage of this method is that the time of action of this wave is controlled by the dimensions of the compression wave along it and the path of the wave of rarefaction reflected from the end.

G.G. Rempel' [63] showed that the critical diameter of the initiating shock wave is changed noticeably to a certain limit with a change in the diameter of the initiated charge. The results obtained by him have mainly a qualitative significance. A quantitative estimation causes doubt since the excitation of detonation was achieved not by a pure shock wave, but by direct contact with the initiator.

The facts noted above and some regularities which occur with the excitation of detonation by shock waves can be explained on the strength of the correct representations of the process of the impact initiation of VV charges. This process is characterized by three stages: 1) excitation of a chemical reaction in the charge under the action of the initiating shock wave; 2) the development of the process; 3) the emergence of the shock wave.

Stage I. The amount of energy released during a reaction under the pressure of the initiating shock wave is an exponential function of the temperature which arises in the VV with its shock compression and its also depends on the time of its

action. For the emergence of a detonation in a passive charge, it is necessary that this energy be at least sufficient for maintaining the constancy of the parameters of the initiating shock wave on the section of emergence.

Stage II. The transition of a shock wave into a detonation wave with the critical parameters of the former usually proceeds at some distance from the origin of the charge. Let us call this section the transition zone. The processes which proceed in this zone were studied by A.N. Dremine and others [36,92].

The investigations showed:

1. Under the critical conditions of initiation, the parameters of the shock wave on a considerable part of transition zone remain more or less constant.
2. The detonation of the charge arises at a velocity close to critical.
3. Detonation is excited at the end point of the transition zone not right after the approach of the shock wave to it, but with a certain delay connected with the geometry of the charge and the circumstance that it arises in the depth of the charge on the surface of a shock wave not relieved by lateral waves of rarefaction.

Figure 21. Dependence of the detonation velocity and flow velocity on the pressure of the initiating shock wave [63]: 1. $p = 35,000$ atm (tech.); 2. $p = 18,000$ atm (tech.); 3. $p = 12,000$ atm (tech.).

In certain cases, for example during the transmission of the detonation through the air, the transition zone is absent and detonation begins practically after some delay at the end of the charge. With transmission through solid media the length of transition zone (l) depends on the intensity of the initiating shock wave which is approaching the charge. Figure 21 shows the dependence of this length as well as the detonation velocity (D) and the flow velocity (v_{fl}) for pressed TNT with a density of 1.59 g/cm^3 on the pressure of the initiating shock wave. The rapid chemical

reaction excited in the charge in the process of the motion of this wave, in turn, is the source of the successive emergence

of the elementary compression waves in it with aid of which the energy is pumped from the transfrontal zone to the shock wave front. These waves move along the medium excited by the shock wave at a rate of $v + c$, exceeding the initial velocity of the initiating shock wave. Every subsequent compressional waves moves along a denser medium, in consequence of which at a certain distance from the charge, as a result of their superposition, the velocity and amplitude of the shock wave begin to increase.

The expressed considerations about the mechanism of the accelerated chemical reaction are convincingly confirmed by the following experimental data:

- 1) under the limiting conditions of the excitation of detonation, the acceleration of the initiating shock wave, as a rule, does not begin immediately, but at a certain distance from the end of the charge [93];
- 2) in a transition zone first the velocity of the shock wave falls even more or less noticeably although soon the detonation arises all the same;
- 3) observed in some experiments [90] was the constancy of the velocity of the shock wave in the charge on the section of its emergence, then -- a sharp increase in its speed to a value which considerably exceeds the velocity of ideal detonation, and in the final stage -- reduction to the velocity equal to the latter.

The propagation of the process on the initial section with an anomalously high detonation velocity frequently takes place when the velocity of detonation of the initiator considerably exceeds the detonation velocity of the initiated charge. However, in the case examined above the initial parameters of the initiating shock wave were considerably lower than the parameters of the normal detonation of the corresponding charges.

Stage III. Detonation arises at the end of a transition zone with a relatively low velocity and is initially a clearly expressed irregular process which, with a sufficient length of charge, changes over to a stationary form of detonation. Before passing on to a more detailed examination of the process of the emergence of detonation, it is advantageous to explain the basic qualitative differences between the phenomena which proceed in the transition zone and at a given final stage of development of the process.

In the opinion of A.N. Dremine and others [36] the chemical reaction which arose under the effect of the shock wave should be

considered from the very beginning as a detonation under imperfect conditions. As will be shown below, there can be no agreement with this point of view.

It has been established that under critical conditions of initiation, simultaneously with the detonation wave in a passive charge a detonation wave which is propagated in the opposite direction and which fully completes the chemical reaction in the transition zone usually arises. When the detonation wave is not formed, the spread of the undecomposed matter on the initial section of the charge occurs.

The transition of a shock wave into a detonation at the final "point" of the transition zone is connected first of all with the fact that the parameters of the former in this case turn out to be sufficient for excitation, in a charge of a spontaneously developing chemical reaction leading, according to the conditions of a thermal explosion, to the spontaneous combustion of the VV and its violent "combustion" in the primary seat of initiation. This process, naturally, is accompanied by a more or less intense luminescence of the reaction products, which, in particular, also makes it possible to record the places of origin of the detonation and the speed of its propagation along the charge with the use of optical methods.

Thus, the maximum measure of the intensity of the chemical reaction in the initial seat of initiation and the minimum intensity of the initiating shock wave necessary for the excitation of detonation in it should be unambiguously determined by the critical parameters of the thermal explosion; the condition should be satisfied:

$$T_{sw} = T_{cr}; \quad \tau_{sw} = \tau_{cr}, \quad (28)$$

where T_{cr} = critical temperature of spontaneous combustion of the seat of initiation; τ_{cr} = delay time corresponding to it.

Hence, it is obvious that with a decrease in the time of the effect of the initiating shock wave on the VV, T_{cr} of the shock wave increases; that is, a more powerful shock wave is necessary for the excitation of detonation.

The duration of the effective action of the initiating shock wave is determined by the dimensions of the generator of the shock wave (length of the active charge, the diameter of the bullet, the dimension of the fragment element, and so on) and it depends substantially on the conditions for the penetration of the lateral waves of rarefaction and axial waves of relief into the initial seat of initiation.

The maximum time of the influence of the shock wave on the initial seat of initiation even with any large dimensions of active and passive charges cannot exceed the travel time of the lateral waves (τ_{lat}) determined by the relation $d_{s1}/2c$, where d_{s1} is the diameter of the seat of initiation and c is the speed of sound in a charge compressed by the initiating shock wave. Since in all our experiments the initial diameter of the seat of initiation was equal to the diameter of the charge, subsequently, by d_{s1} we will mean d_c . Obviously if as a result of the small value of the diameter of the charge $\tau_{lat} < \tau_{cr}$ -- that is, the travel time of the lateral wave of rarefaction is less than minimum time necessary for the realization of thermal explosion in the primary seat of initiation -- then with the given power of the initiating shock wave the ignition of the VV and detonation will not arise.

From this it follows directly that with an increase in the diameter of the charge to a certain limit ($d_c = d_*$) the values of the critical parameters (T_{sw} , D_{sw} , p_{sw}) of the initiating shock wave should decrease, which agrees with the data of G.G. Rempel' [63] and is in full conformity with the results of the experiments given below.

The value of d_* can be approximately determined on the strength of the following premises:

- 1) under conditions of the excitation of the detonation of the shock wave, the initial seat of initiation is that region within the charge into which the lateral wave of rarefaction does not manage to penetrate during the time of action of the shock wave;
- 2) the smallest possible detonation velocity cannot be less than the so-called "critical detonation velocity," approximately equal to the detonation velocity of a damped explosion approaching the speed of sound in the charge;
- 3) the detonation can be excited in a passive charge with minimum velocity, and consequently with the minimum parameters of the initiating shock wave, only when the dimensions of the initial seat of initiation are not less than the so-called limiting diameter d_{11} of the charge.

The critical parameters of the initiating shock wave should increase in proportion to a decrease in the size of the initial seat of initiation. The width of the seat of initiation (L_p) behind the detonation front in this case is approximately equal to the limiting diameter ($L_p = d_{11}$), and the time of the course of the reaction -- to the relation d_{11}/D .

The minimum diameter of the charge with which the rarefaction wave still will not have time to penetrate into the primary seat of initiation with a width equal to d_{11} will be determined by the condition:

$$t_{LAT} \approx \tau_p, \quad (29)$$

where

$$t_{LAT} = \frac{d_c - d_{L1}}{2c}.$$

From formula (29) it follows that

$$d_* \approx d_{L1} \left(\frac{2c}{D} + 1 \right), \quad (30)$$

where D = velocity of the initiating shock wave; c = the speed of sound in the VV compressed by the shock wave.

Since $c/D \approx 1$, it is possible to accept:

$$d_* \approx 3d_{L1}. \quad (31)$$

In the theory of thermal explosion [55,67,72,83], as is known, the quantitative connection between values T_{cr} , τ_{cr} , d_c and the kinetic characteristics of the VV is established. In the determination of the limiting conditions of the emergence of the detonation in the primary seat of initiation it is necessary to accept $d_c = d_{11}$ and $\tau_{cr} = [t_{lat}]_{cr}$, and knowing these values, on the strength of the dependences for a thermal explosion it is possible to calculate value T_{cr} .

Comparing the latter with the temperature of adiabatic heating of the VV by the initiating shock wave, it is possible to judge soundly the condition of the emergence and course of the chemical reaction in the primary seat of initiation. If the critical temperature is substantially higher than the temperature of adiabatic heating, then the basic role in the mechanism for the emergence of the reaction will be played by local heatings. The nearness of these values can serve as a reliable indication that the adiabatic heating of the VV plays the determining role.

If $d_c \geq d_*$, and the conditions for initiation remain unchanged, the only limiting factor affecting the duration of the effective action of the shock wave on the VV can be only the longitudinal relief wave. If the total time (t_{ax}) necessary for the travel of the shock wave from the primary seat of initiation to the end of the passive charge and the relief wave of that distance L_{s1} in the opposite direction is less than the value t_{cr} then detonation does not take place. The limiting value of L_{s1} , beginning with which the axial relief wave will not succeed in penetrating into the primary seat of initiation during the influence of the initiating shock wave on it, is determined

from the condition:

$$t_{AX} \approx t_{LAT}$$

(32)

RESULTS OF EXPERIMENTAL RESEARCH

To check the fundamental propositions expressed above experiments on the determination of the distances of transmission of the detonation through air and steel barriers depending on the diameter, casing and length of the passive charge were conducted. The limiting values of the minimum critical parameters of the initiating shock wave with which detonation in the charge is assured and the delay times corresponding to them were also determined.

Figure 22. Diagram of an experiment in the transmission of a detonation through the air: 1. electrical detonator No 8; 2. active charge; 3. passive charge; 4. lead plate control sample.

Figure 23. Diagram of an experiment in the transmission of a detonation through a steel plate: 1. electrical detonator No 8; 2. active charge; 3. steel connection piece; 4. passive charge; 5. lead plate control sample.

the excitation of a detonation in a charge during its transmission both through dense media and through air is connected with the very same physical processes in spite of some important specific features which occur in the initiation of an explosion by air shock waves.

Determination of the Limiting Diameter of Initiation

In all experiments, used as active charges were the cylindrical charges of regular phlegmatized hexogene with a density of 1.60 g/cm^3 ; the diameter of the charge 25 mm, length -- 40 mm. Used as passive charges were charges of TNT, GNDS and phlegmatized hexogene mark CFG-2 (Figures 22 and 23, Table 25).

As can be seen from Table 26 and Figures 24 and 25, the maximum transmission distance of the detonation for three explosives, regardless of the nature of the transmitting medium (air, steel) is attained with approximately identical values of d_c/d_{11} which equal approximately three, which is in full conformity with dependence (32).

This result also testifies to the fact that the mechanism for

Table 25. Characteristics of Passive Charges

Взрывчатое вещество пассивного заряда (1)	Плотность, г/см ³ (2)	Критический диаметр, мм (3)	Предельный диаметр, мм (4)
Тротил (5)	1,58	3,0	8,0
ГНДС (6)	1,66	1,8	3,0
ГФГ-2 (7)	1,65	2,0—2,5	5,0—5,2

Key:

1. Passive charge explosive	5. TNT
2. Density, g/cm ³	6. GNDS
3. Critical diameter, mm	7. GFG-2
4. Limiting diameter, mm	

Table 26. Dependence of the Distance of Reliable Detonation on the Diameter of the Passive Charge

Взрывчатое вещество пассивного заряда (1)	Относительная величина диаметра заряда (2)		Дальность (1) передачи детонации, мм (3)	
	d_c/d_{c*}	d_c/d_{c*}	через воздух (4)	через стальной барьер (5)
Тротил (6)	2	0,75	10	7
	3,3	1,25	35	10
	5,3	2,0	55	11
	8,0	3,0	60	12
	10,0	3,75	60	12
ГФГ-2 (7)	1,6	0,8	15	6
	3,2	1,5	45	8
	4,8	2,3	60	10
	6,4	3,1	80	11
	8,0	3,8	80	11
	9,6	4,6	80	11
	2,2	1,3	30	10
	3,3	2,0	60	11
ГНДС (8)	4,4	2,6	70	12
	5,5	3,3	90	14
	6,7	4,0	90	14

Key:

1. Passive charge explosive	4. Through air
2. Relative value of the diameter of the charge	5. Through a steel barrier
3. Distance (1) of transmission of detonation, mm	6. TNT
	7. GFG-2
	8. GNDS

The determining role of the lateral waves of rarefaction in the relationship of the dependence of the critical parameters of the initiating shock wave on the diameter of the passive charge is also confirmed by the results of experiments on the transmission of a detonation to charges enclosed in a casing. The charges were of phlegmatized hexogene GFG-2 with a density of 1.65 g/cm³, the transmitting medium -- air.

The results of experiments showed that with $d_c > d_*$ the presence of a casing, as one would expect, does not affect the distance of transmission of detonation.

Figure 24. Effect of the diameter of the passive charge on the distance of transmission of a detonation through the air: 1. GNDS; 2. GFG-2; 3. TNT.

Table 27. Effect of the Length of Passive Charge on the Distance of Transmission of Detonation

Длина пассивного заряда, мм (1)	Дальность передачи детонации, мм (2)	
	через воздух (3)	через сталь (4)
20	80	11
10	80	11
6	80	11
4	60	9
2	50	—

Key:

1. Length of passive charge, mm
2. Transmission distance of detonation, mm
3. Through air
4. Through steel

27) with passive charges of GFG-2 with $d_c > d_*$ (diameter of charge was equal to 20 mm) on the determination of the distance of transmission of the detonation depending on the length of the passive charge.

From the results of these experiments it can be seen that regardless of the transmitting medium (air, steel) a reduction in the distance of transmission of a detonation begins only with the length of passive charge equal to approximately 4 mm, which corresponds, in the case of the emergence of a detonation at the end of the passive charge, to the value $d_*/4$ and follows from relationship (32).

Figure 25. Effect of the diameter of the passive charge on the distance of transmission of a detonation through a steel barrier: 1. GNDS; 2. TNT; 3. GFG-2.

With the inclusion of a passive charge in a sufficiently strong casing the maximum possible distance of transmission of detonation under these conditions can be achieved (as a result of the suppression of the lateral waves of rarefaction) with any practically sufficiently small diameter of charge.

To check the previously expressed considerations about the limiting conditions under which the axial rarefaction waves begin to have an effect on the distance of transmission of the detonation, special experiments were conducted (Table

Photorecording of the Processes in the Exitation of the Detonation of Explosives

For determining the conditions of the emergence of a detonation in a passive charge and the parameters of the initiating shock wave experiments were accomplished in the photorecording of processes with specific distances of the reliable transmission of detonation with the use of an SFR-2 high-speed photorecorder.

In all cases, used as an active charge was regular phlegmatized hexogene with a diameter of 25 mm, a height of 40 mm, and density of 1.65 g/cm^3 ; that is, the same as in experiments for the determination of the dependence of the distance of detonation transmission on the diameter of the passive charge and other factors.

The velocity of the shock wave at various distances from the end of the active charge during the transmission through the air:

Distance, mm	Velocity of shock wave, m/sec
15	4,300
30	3,940
45	3,700
60	3,320
80	3,100
90	2,950

In the transmission of a detonation through the air a charge of phlegmatized hexogene GFG-2 with a diameter of 20 mm and a density of 1.65 g/cm^3 was taken as the passive charge.

As a result of these experiments, it turned out that the velocity of an air shock wave at the moment of approach to the passive charge (D_{sw}) comprised approximately 3,100 m/sec and the initial detonation velocity in the passive charge (D_i) is 2,900 m/sec. Detonation begins at the very beginning of the charge, and the delay time up to the moment of the emergence of the detonation is equal to $(1.67-1.7) \cdot 10^{-6}$ sec. Transition to the normal detonation velocity ($D_{max} = 7,800 \text{ m/sec}$) occurred, as a rule, at a distance of more than 20 mm from the end of the charge.

A typical photogram of the process of transmission of a detonation through the air is shown in Figure 26 (at the end of the passive charge a screen of cardboard was placed along its circumference).

In the transmission of a detonation through a steel barrier charges of TNT, GNDS substance and phlegmatized hexogene GFG-2

Figure 26. Photogram of the process of transmission of a detonation through the air: AB = shock wave; BC = the detonation of a passive charge.

Figure 27. Photogram of the process of the transmission of a detonation through a steel barrier: AB = detonation of an active charge; CE = detonation wave; CD = detonation of a passive charge.

ponds to the moment of the formation of a shock wave in water which is clearly fixed in the photograph.

The time of the passage of the initiating shock wave (t'') through a transition zone of sufficient length is determined with the use of the method developed by B.I. Shekhter and L.A. Shushko. Fine holes are drilled at the end of the passive charge and on a section of the transition zone at a certain distance from one another. The blasting of the charge is accomplished with its simultaneous brightening. With the movement of the initiating shock wave along the transition zone, the beams of light which are formed during the glow of the exploded wire or other light source and pass through the holes in

were used as the passive charge.

The distance (l) to the start of the detonation of a passive charge, the initial detonation velocity (D_1) of the passive charge and time (t_1) from the moment of the emergence of the arising of the detonation in the passive charge can be determined directly from the photogram (Figure 27).

Delay time of detonation (τ_{del}) in the place of its emergence can be calculated if we know the transit time (t') of the shock wave through a steel barrier and the transit time (t'') of the initiating shock wave over the transition zone of the passive charge

$$\tau_{del} = t_1 - t_2, \quad (33)$$

where $t_2 = t' + t''$.

For determining the value of t' special experiments were conducted in the photorecording of the processes according to the diagram scheme in Figure 28.

The moment of the emergence of the shock wave on the external surface of the metal corres-

Figure 28. Diagram of an experiment on determining the delay time of detonation: 1. water; 2. glass container; 3. steel barrier; 4. active charge; 5. electrical detonator.

Figure 29. Photogram of the passage of a shock wave in a passive charge: AB = detonation of the active charge; CDE = initiating shock wave in a passive charge; EK = detonation of the passive charge.

the passive charge will be darkened.

With the use of the photogram (Figure 29) the velocity (D_{sw}) of the shock wave in the passive charge is determined and the time of the passage of the initiating shock wave through the transition zone of the charge is calculated:

$$t'' = \frac{l}{D_{sw}}. \quad (34)$$

Furthermore, according to this method it is possible also to directly determine the time (t') of the passage of the shock wave through a steel barrier.

If distance to the origin of detonation is small and it is not possible to make a hole in a section of the transition zone, the initial velocity of the initiating shock wave in the passive charge should be determined using the data on compressibility of steel and the charge of VV as well as the speed of transit of the shock wave over the steel barrier which, under conditions of our experiments, is equal to 5,150-5,200 m/sec (Table 28).

Table 28 shows that with $d_c = d_*$ the distance to the origin of detonation for charges with a given density equals: for compound GFG-2 -- 1.7 mm; for the substance GNDS -- 4.6 mm; for TNT -- 6.2 mm.

The normal detonation velocity during transmission through a steel barrier, unlike transmission through the air, is attained at a distance of 2-3 mm from the origin of the detonation.

The critical velocity of the initiating shock wave with GFG-2 was somewhat higher than with TNT, which agrees with B.I. Shekhter's data [15] and, apparently, is a characteristic of the phlegmatized hexogene.

Table 28. Velocity of the Initiating Shock Wave and Delay Time of Detonation in Passive Charges

Взрывча- тое вещество (1)	Характеристика пассивного заряда (2)		Скорость иниции- рующей ударной волны, м/сек (3)	Длина переход- ной зоны, мм (4)	Началь- ная скорость детонации, м/сек (5)	Время задержки, мсек (6)	
	$\rho_{ВВ}$, г/см ³	$d_c = d_*$, мм				экспери- менталь- но (7)	расчетное (8)
Тротил (9)	1,58	24,5	3220	6,2	3050	2,30	2,23
ГФГ-2 (10)	1,65	16	3360	1,7	3200	1,30	1,40
ГНДС (11)	1,66	10	2900	4,6	3120	0,95	1,04

Key:

1. Explosive	5. Initial detonation velocity, m/sec
2. Characteristic of the pas-
sive charge	6. Delay time, msec
3. Speed of the initiating,
shock wave, m/sec	7. Experimental
4. Length of transition zone,
mm	8. Calculated
	9. TNT
	10. GFG-2
	11. GNDS

In accordance with the previously expressed propositions delay time (τ_{del}) of the detonation should be equal to the period of the delay of a thermal explosion of the primar seat of initiation; that is, to the value τ_{cr} which, with the limiting conditions of the excitation of the detonation, in turn, is equal to the time of the effective action of the shock wave:

$$\tau_{sw} \approx \frac{d_{cr}}{2c_{sw}}.$$

Calculations show that with the values of the critical velocities of the initiating shock wave obtained by us

$$c_{sw} \approx 1,15D_{sw}.$$

Table 28 also shows that the calculated values τ_{sw} and the values established from the experiment τ_{del} are of one order (maximum deviation does not exceed 10 percent), which can serve as the confirmation of our impressions of the processes of initiation by shock waves.

With a velocity increase in the initiating shock wave, which is attained by a decrease in the thickness of the steel barrier, the section of the transition zone (distance to the origin of the detonation of the passive charge) is reduced and the delay time of the emergence of the detonation noticeably decreases.

With $d_c < d_*$ the critical speed of the initiating shock wave increases noticeably and the delay time, as one would expect, decreases accordingly (Table 29).

Table 29. Effect of the Diameter of the Passive Charge and the Distance of Transmission of the Detonation on the Velocity of the Initiating Shock Wave

Взрывчатое вещество	Толщина стального барьера, мм	Диаметр заряда, мм	Скорость понижающей ударной волны, м/сек	Расстояние до начала детонации заряда, мм	Время задержки детонации, мксек
(1)	(2)	(3)	(4)	(5)	(6)
ГНДС(7)	14	10	2900	4,6	0,95
	11	10	3360	3,2	0,30
	7,7	10	3900	1,6	0,15
ГФГ-2(8)	11	6	3360	3,7	0,35
	11	16	3360	1,7	1,30
	8	10	3860	1,8	0,45

Key:

1. Explosive
2. Thickness of the steel barrier, mm
3. Diameter of the charge, mm
4. Speed of the initiating shock wave, m/sec
5. Distance to the origin of the detonation of the charge, mm
6. Delay time of detonation, sec
7. GNDS
8. GFG-2

The experiments also show that with $d_c < d_*$ the critical velocity of the initiating shock wave remains constant and no regular change in the values l and τ_{del} is observed.

For investigating the conditions of the excitation of the detonation of charges of thermostable VV, experiments were conducted on determining the distance of transmission of detonation and the photorecording of the process with limiting distances of reliable detonation of charges of thermostable VV pressed into a duralumin sleeve with an inside diameter of 10 mm. Used as an active charge was the thermostable electrical detonator mark TED-2. Charges of GNDS, NTFA and V-5 were investigated.

In the determination of the transmission of a detonation (Figure 30), it was clarified, that the distance of reliable transmission of a detonation through a steel barrier to a charge of GNDS and NTFA is equal to 1.5 mm, and to charges of V-5 -- 1 mm (Table 30).

The velocity of the initiating shock wave necessary for the excitation of the detonation of substances NTFA and V-5 is higher than for GNDS; it is highest in the product V-5 which possesses low susceptibility to a detonation impulse.

The results of the analysis and generalization of published data and of the theoretical and experimental research carried out on the mechanism for the initiation of the detonation of VV by shock waves make it possible to draw some conclusions.

Table 30. Values of the Initial Velocity of the Initiating Shock Wave, Distance to the Origin of Detonation of the Charges, and the Calculated Delay Time of the Detonation

Взрывчатое вещество	Плотность, г/см ³	Толщина пластины, мм	Скорость инициирующей ударной волны в пассивном заряде, м/сек	Расстояние до начала детонации, мм	Время задержки детонации, м/сек
(1)	(2)	(3)	(4)	(5)	(6)
ГНДС (7)	1,66	1,5	3000	3,5	0,50
НТФА (8)	1,62	1,5	3400	2,3	1,30
В-5 (9)	1,62	1,0	3700	4,6	1,55

Key:

1. Explosive
2. Density, g/cm³
3. Thickness of plate, mm
4. Velocity of the initiating shock wave in the passive charge, m/sec

5. Distance to the origin of the detonation, mm
6. Delay time of detonation, μsec
7. GNDS
8. NTFA
9. V-5

Figure 30. Photogram of the passage of an initiating shock wave along a charge of thermostable VV: AB = initiating shock wave in a passive charge; BC = detonation of the passive charge.

primary seat of initiation of a spontaneously developing chemical reaction which leads, in accordance with the laws governing a thermal explosion, to the spontaneous combustion of the VV in this seat.

In this case, the critical parameters of the initiating shock wave can be unambiguously determined from the conditions

$$T_{S_{0k}} = T_{cr}; \quad \tau_{S_{0k}} = \tau_{cr},$$

where T_{cr} = critical temperature of spontaneous combustion; τ_{cr} = delay time corresponding to this temperature.

3. Detonation can be excited in a passive charge with minimum velocity and, consequently, with the minimum parameters of the initiating shock wave only when the diameter of the initial seat of initiation is no less than the limiting diameter of the charge.

On the strength of this premise and with consideration of the effect of the lateral waves of rarefaction on the duration of the effective influence of the shock wave on the VV, the relationship is obtained which determines the minimum value of the diameter of the charge ($d_* = 3d_{l1}$), with a further increase in which a reduction in the critical parameters of the shock wave no longer takes place.

CHAPTER 5. EFFECT OF HYDROSTATIC PRESSURE ON THE PARAMETERS OF UNDERWATER EXPLOSIONS

A tendency toward increasing the depths of exploration and production drilling has been established in recent years. In connection with this, there has arisen the problem of investigating underwater explosion processes under conditions of elevated hydrostatic pressures (up to several hundreds or thousands of atmospheres).

Despite the large amount of both theoretical and experimental work that has been done in the field of underwater explosions, the question of the effect of elevated hydrostatic pressures on these processes has been almost completely ignored.

In his work [66] on point explosions in incompressible media, L.I. Sedov gives the period of pulsation ($t_{\max}$) and the maximum radius of expansion ($R_{\max}$) of a gas bubble as functions of the hydrostatic pressure p_0 :

$$t_{\max} = \frac{A}{p_0^{1/4}}; \quad R_{\max} = \frac{B}{p_0^{1/4}}.$$

With a degree of accuracy up to that of the proportionality factor without experimental confirmation, these relationships are presented in R. (Koul's) book [45], although in their derivation he ignores the residual energy in the explosion products, which is unfounded at elevated hydrostatic pressures.

O.Ye. Vlasov has investigated underwater explosions from the viewpoint that water is an ideal incompressible liquid. He explains this assumption by the fact that the shock waves carry such a small part of the explosion's energy that they can be ignored in the first approximation. This leads to exaggeration of the values of the maximum radius and time of expansion of the gas bubble. In actuality, more than 50 percent of an explosive's energy goes into the shock wave, so that -- naturally -- this value cannot be ignored.

K.P. Stanyukovich [16] gives a better substantiated determination of a gas bubble's maximum radius of expansion; he regards a liquid as incompressible beginning with some radius of expansion of the detonation products; that is, when the shock wave has been fully formed. However, inaccurate values of the variable p_{cr} (the pressure at which the adiabatic curves for detonation products with $\gamma = 3$ and $\gamma = 7$ are joined) and the corresponding value of R_{cr} (the radius of expansion of the detonation products at which the pressure in them becomes equal to p_{cr}) also lead to large errors.

As will be shown below, when accurate values of p_{cr} and R_{cr} are used, the relationships obtained for R_{max} and τ_{max} coincide quite accurately with the experimental ones.

RESULTS OF THEORETICAL INVESTIGATIONS OF THE BASIC PHYSICAL PHENOMENA OCCURRING DURING AN EXPLOSION IN WATER

When the detonation wave in a charge reaches its interface with the water, gaseous detonation products begin to escape and a shock wave arises in the water. Since its velocity significantly exceeds the rate of expansion of the VV-water interface (or the so-called gas bubble), between the shock wave and detonation product fronts there forms a diverging flow of water, the width and mass of which increase intensively. In the initial stage of detonation production expansion, the pressure in these products exceeds the hydrostatic pressure by a significant amount and the bubble's diameter increases precipitously. In the next stage of bubble expansion, the detonation products' pressure becomes less than the hydrostatic pressure; this is explained by the fact that at the moment when the pressure in the bubble reaches equality with the hydrostatic pressure, the detonation products have a rather large amount of kinetic energy that is the cause of their subsequent expansion.

The negative pressure differential on the bubble's surface leads to the cessation of movement of the diverging flow of water and, subsequently, to the collapse of the bubble at a continuously increasing rate of speed. However, after the bubble has passed the equilibrium position corresponding to the hydrostatic pressure, its rate of collapse again begins to decrease; simultaneously with this a positive pressure differential appears in the bubble, as a result of which a secondary shock wave arises at the moment of cessation of collapse and the entire process is repeated, although with less intensity. Expenditure of the detonation products' energy on the emitted shock waves, heating of the water and so forth leads to a gradual cessation of the gas bubble's oscillations. As R. Koul [45] notes, the gas bubble oscillations can have a number of cycles; under favorable conditions, 10 or more oscillations

have been observed. However, only the most intense (basic and secondary) shock waves are of practical importance.

Thus, the solution of the underwater explosion problem consists of the following elements.

1. Determining the initial parameters on the interface between the detonation products and the water.
2. Determining the parameters of the basic (primary) shock wave's movement in the water.
3. Investigating the regularities of gas bubble expansion and collapse.
4. Determining the parameters of the secondary shock wave's movement.

On such a broad scale, the analytical solution of this problem meets with considerable mathematical difficulties.

In view of this fact, we conducted our theoretical investigation of the question of the hydrostatic pressure's effect on the parameters of an underwater explosion on a narrower scale that was based on some initial experimental and theoretical data. This made it possible to obtain a qualitative -- and, for a number of important questions, quantitative (with a level of accuracy fully suitable for practical purposes) -- description of the features of an underwater explosion at great depths.

Figure 31. Emission of a shock wave in water: 1. rarefaction wave; 2. interface between detonation products and water; 3. shock wave.

Key:

1. Detonation products
2. Water

Effect of Hydrostatic Pressure on the Initial Parameters of Shock Waves

In view of the fact that for an initial (hydrostatic) water pressure of 1,000 atm (tech.), its density is less than that of the scattering products of an explosion, when the latter strike the water a shock wave passes through it, while a rarefaction wave passes through the detonation products (Figure 31).

In order to investigate the properties of the shock wave that has arisen and the nature

of its further propagation, it is first of all necessary to determine its initial parameters. In order to do this, it is sufficient to use the condition that must be fulfilled at the water-PV [explosion products] interface: the velocities and pressures must be identical on both sides of the interface.

On the basis of this condition, it is possible to write the following equations:

$$v_x = \frac{D}{\gamma+1} \left\{ 1 + \frac{2\gamma}{\gamma-1} \left[1 - \left(\frac{p_x}{p_0} \right)^{\frac{\gamma-1}{2\gamma}} \right] \right\}; \quad (35)$$

$$v_x = \sqrt{(p_x - p_0) \left(\frac{1}{\rho_0} - \frac{1}{\rho_x} \right)}, \quad (36)$$

where v_x = initial velocity of the interface; p_x = initial pressure at the shock wave's front; ρ_x = initial density at the shock wave's front; ρ_0 = density of undisturbed water; p_0 = initial pressure of the water; D = detonation rate; p_d = pressure at the detonation wave's front; γ = isentropy index for the detonation products.

The isentropy index for the explosion products can be taken as being equal to three. For pressure above 30,000 atm (tech.), the equation of state for water is written [16] as

$$p_x = 2940 \left[\left(\frac{\rho_x}{\rho_0} \right)^3 - 1 \right]. \quad (37)$$

By substituting $\gamma = 3$ into equation (35) and using the equation of state for water, we reduce equations (35) and (36) to the following form:

$$v_x = \frac{1}{4} \left[4 - 3 \left(\frac{p_x}{p_0} \right)^{1/3} \right] D; \quad (38)$$

$$v_x = \sqrt{\frac{p_x - p_0}{\rho_0} \left[1 - \left(\frac{p_x}{2940} + 1 \right)^{-1/3} \right]}. \quad (39)$$

It is most convenient to solve these equations graphically. By finding v_x and p_x , it is possible to determine ρ_x from the equation of state for water, and the shock wave's initial velocity D_{sw} from the mass conservation equation:

$$D_{sw} = \frac{\rho_x}{\rho_x - \rho_0} v_x. \quad (40)$$

These computations were made for a number of VV; the results that were obtained are presented in Figure 32.

Calculations show that for each 100 atm (tech.) increase in the initial pressure, the shock wave's peak pressure increases by an average amount of 0.4 percent, the velocity of the water particles at the front decreases by 0.3 percent, and the shock wave's velocity increases by 0.7 percent.

Figure 32. Determination of initial parameters of shock wave.

Thus, the initial parameters of a shock wave arising in water, as should have been expected ($p_x \gg p_0$), depend very little on the initial water pressure.

Effect of Hydrostatic Pressure on the Movement of a Gas Bubble in Water

Studying the movement of a shock wave in water without taking the latter's compressibility into consideration makes no physical sense. As follows from the motion equations for a continuous medium, in incompressible media the rate of propagation of disturbances is infinite. As will be shown below, however, the theory of an incompressible fluid makes it possible to describe the pulsation of a gas bubble quite accurately. The study of the question of the effect of the initial water pressure on a bubble's pulsation is of considerable importance for the solution of the entire problem that has been formulated. Actually, by knowing the rules governing the expansion of a gas bubble in water it is possible to compute such important shock wave parameters as energy and pulse.

As numerous experiments have shown, the dependence of pressure on specific volume is described for explosion products by two adiabatic curves:

$$\text{for } p > p_{cr} \quad pV^k = \text{const}; \quad (41)$$

$$\text{for } p < p_{cr} \quad pV^\gamma = \text{const}, \quad (42)$$

where p_{cr} = the pressure at which both adiabatic curves join. Variables $k = 3$, $\gamma = 7/5$. The value of p_{cr} is determined on the basis of the condition of preservation of the VV' 's energy, given the dependence of the PV' 's pressure on the expanding

volume in the form of two adiabatic curves; namely,

$$E_{VV} = \int_{V_1}^{\infty} p dV = \int_{V_1}^{V_k} p dV + \int_{V_k}^{\infty} p dV. \quad (43)$$

Substituting the dependences of pressure on volume in the first integral in the form of (41), and in the second integral in the form of (42), we obtain

$$p_{cr} = p_1 \left\{ \frac{\gamma-1}{k-\gamma} \left[\frac{(k-1) E_{VV}}{p_1 V_1} - 1 \right] \right\}^{1/2}, \quad (44)$$

where p_1 = value of the initial average pressure in the explosion products; V_1 = initial specific volume of the VV; E_{VV} = energy of the VV per unit of volume.

For condensed VV's, $p_{cr} = 2,500-5,000$ atm (tech.) (for TNT with $\rho_{VV} = 1.6$ g/cm³ and $D = 7,000$ m/sec, $p_{cr} = 2,800$ atm (tech.)). Consequently, the dependence of the pressure of the explosion products in a gas bubble on the radius of expansion can, in the case of a spherical explosion, have the form

$$p_{cr} = p_1 \left(\frac{R_0}{R_{cr}} \right)^3 \left(\frac{R_{cr}}{R} \right)^{11/4}. \quad (45)$$

Since the pressure in the explosion products drops off sharply beginning at a radius of expansion R equal to R_{cr} , from that point water can be regarded as incompressible and its movement under the influence of the explosion products can be described by the equations of motion of an incompressible fluid in Euler form:

$$\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial r} = - \frac{1}{\rho_0} \frac{\partial p}{\partial r}; \quad (46)$$

$$\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 V) = 0. \quad (47)$$

The boundary conditions are

$$r = \infty, \quad p = p_0; \quad (48)$$

$$r = R, \quad p = p_{cr}. \quad (49)$$

The solutions of equations (46) and (47) have the form

$$v = \frac{f(t)}{r^2} \quad (50)$$

$$p = p_0 \frac{f(t)}{r} - p_0 \frac{f^2(t)}{2r^4} + C(t). \quad (51)$$

Using condition (48), we obtain $C(t) = p_0$.

For the explosion products-water interface we have:

$$f(t) = vR^2 = \dot{R}R^2; \quad \dot{f}(t) = R(2\dot{R} + R\ddot{R}). \quad (52)$$

By substituting expression (52) into (51) and using the dependence of the pressure of PV's in a gas bubble on the radius of expansion (45), it is not difficult to obtain a differential equation to determine the law of expansion for the bubble:

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{p_{PV} - p_0}{\rho_0} \quad (53)$$

or

$$\frac{d}{dR}(\dot{R}^2 R^3) = \frac{2(p_{PV} - p_0) R^2}{\rho_0}.$$

Integrating (53) within limits from R_{cr} to R , we obtain the expression for the gas bubble's rate of movement:

$$v^2 = v_k^2 \left(\frac{R_{cr}}{R} \right)^3 + \frac{1}{R^3} \int_{R_{cr}}^R \frac{2(p_k - p_0) R^2}{\rho_0} dR \quad (54)$$

or, using (45),

$$v^2 = \left(\frac{R_{cr}}{R} \right)^3 \left\{ v_k^2 + \frac{5p_{cr}}{3\rho_0} \left[1 - \left(\frac{R_{cr}}{R} \right)^{1/3} \right] \right\} - \frac{2p_0}{3\rho_0} \left[1 - \left(\frac{R_{cr}}{R} \right)^3 \right]. \quad (55)$$

From (55) let us determine the expression for the gas bubble's maximum radius of expansion, having set $v = 0$ and ignoring terms v_k^2 , as well as $(R_{cr}/R)^{6/5}$ and $(R_{cr}/R)^3$, in comparison with unity:

$$R_{max} = \left(\frac{5p_{cr}}{2p_0} \right)^{1/3} R_{cr} \quad \text{or} \quad \frac{R_{max}}{R_0} = \left(\frac{p_l}{p_{cr}} \right)^{1/3} \left(\frac{5p_{cr}}{2p_0} \right)^{1/3}. \quad (56)$$

For PETN with $\rho_{VV} = 1.6 \text{ g/cm}^3$, $D = 7,970 \text{ m/sec}$ and $Q = 1,400 \text{ kcal/kg}$, we obtain

$$p_l = \frac{1}{8} \rho_{VV} D^2 = 131 \cdot 10^3 \text{ atm}; \quad p_{cr} = 5100 \text{ atm}; \quad R_{max} = \frac{34.2 R_0}{p_0^{1/3}}.$$

The value obtained for R_{max} coincides quite accurately with the experimental data of B.D. Khristoforov [77], according to which $R_{max} = 1,760(q/p_0)^{1/3} = 33.2 R_0/p_0^{1/3}$ (q = weight of the charge) for PETN.

Thus, despite the fact that we used an incompressible liquid that excludes the existence of a shock wave, the experimental and theoretical data agree fairly well. This is completely regular. As is known, a shock wave is represented by an abrupt change of pressure behind the wave front. Since there is also a sharp drop in pressure in the detonation products, from

100,000-200,000 atm (tech.) (p_1) to 2,500-5,000 atm (tech.) (p_{cr}), and a comparatively small change in the gas bubble's radius of expansion, from R_0 to $R_{cr} = 1.5R_0$, after the detonation of the VV, it is natural to assume that the shock wave is emitted until pressure p_{cr} is reached in the detonation products. Consequently, by adopting a setup with an incompressible liquid, beginning with pressure p_{cr} we thereby automatically exclude the shock wave's energy in achieving the maximum radius of expansion of a gas bubble in water.

Let us turn to the question of the regularities governing the gas bubble's movement.

Using expression (56) for the gas bubble's maximum radius of expansion, from formula (55) we obtain the following relationship for the gas bubble's rate of expansion:

$$v = \frac{dR}{dt} = \sqrt{\frac{2p_0}{3\rho_0}} \left[\left(\frac{R_{max}}{R} \right)^3 - 1 \right]^{1/2}. \quad (57)$$

Integrating expression (57) within limits from R_0 to R , we find the law of expansion for the gas bubble:

$$t = \sqrt{\frac{3\rho_0}{2p_0}} R_{max} \int_{R_0/R_{max}}^{R/R_{max}} \frac{dz}{(z^3 - 1)^{1/2}}. \quad (58)$$

The integral is not expressed in elemental functions, but with sufficient accuracy we can compute its exponential series expansion:

$$t = \sqrt{\frac{3\rho_0}{2p_0}} R_{max} \left[\frac{2}{5} \left(\frac{R}{R_{max}} \right)^{5/2} + \frac{1}{11} \left(\frac{R}{R_{max}} \right)^{11/2} - \frac{2}{5} \left(\frac{R_0}{R_{max}} \right)^{5/2} \dots \right]. \quad (59)$$

For the gas bubble's maximum expansion time (up to $R = R_{max}$), according to expression (5.24) [sic],

$$t_{max} = \sqrt{\frac{3\rho_0}{2p_0}} \int_{R/R_{max}}^1 \frac{dz}{(z^3 - 1)^{1/2}}$$

or

$$t_{max} = \left[\frac{\sqrt{\pi}}{3} \frac{\Gamma\left(\frac{5}{6}\right)}{\Gamma\left(\frac{4}{3}\right)} - \frac{2}{5} \left(\frac{R_0}{R_{max}} \right)^{5/2} \right] \sqrt{\frac{3\rho_0}{2p_0}} R_{max}, \quad (60)$$

where $\Gamma(5/6)$ and $\Gamma(4/3)$ are gamma-functions.

Substituting the values of the gamma-functions into formula (60), along with $\rho_0 = 1 \text{ g/cm}^3$ and $R_{max} = 34.2R_0/p_0^{1/3}$, for PETN we obtain $t_{max} = 3.05(R_0/p_0^{5/6}) \mu\text{sec}$.

According to expression (59), the gas bubble's law of motion for the same explosive will have the form:

$$R - R_0 = 27, 1 R_0^{3/5} t^{2/5} \text{ (mm).}$$

The law derived for the gas bubble's expansion, as well as $R_{\max}$, coincides quite accurately with B.D. Khristoforov's experimental data [77], according to which $R = 287 q^{1/5} t^{2/5} = 26.5 R_0^{3/5} t^{2/5}$. From formulas (57) and (59) and expression (45) it follows that, for $R \ll R_{\max}$,

$$v = \sqrt{\frac{2p_0}{3\rho_0} \left(\frac{R_{\max}}{R}\right)^{3/5}} = \sqrt{\frac{5p_{cl}}{3\rho_0} \left(\frac{p_i}{p_{cl}}\right)^{1/5} \left(\frac{R_0}{R}\right)^{3/5}}; \quad (61)$$

$$t = \frac{2}{5} \sqrt{\frac{3\rho_0}{5p_{cl}} \left(\frac{p_{cl}}{p_i}\right)^{1/5}} R_0 \left[\left(\frac{R}{R_0}\right)^{3/5} - 1 \right]. \quad (62)$$

From this it follows that the gas bubble's movement does not depend on the hydrostatic pressure during the initial stage of expansion: this is in agreement with the propositions advanced above. However, as the bubble's radius of expansion approaches its maximum value, this dependence begins to be felt quite sharply, since the maximum radius and expansion time depend on the hydrostatic pressure:

$$R_{\max} \sim \frac{1}{p_0^{1/5}}; \quad t_{\max} \sim \frac{1}{p_0^{1/5}}. \quad (63)$$

Inasmuch as the shock wave is moving ahead of the detonation products, for the gas bubble it is a "unique indicator" of the existence of hydrostatic pressure of a certain magnitude. Since this is so, the results obtained above indicate that only in the initial stage (as was noted earlier) of the shock wave's formation do its parameters not depend on the hydrostatic pressure.

After the gas bubble expands to $R = R_{\max}$, according to (45) the pressure in it is p_{pv} , which equals

$$\bar{p}_{pv} = p_i \left(\frac{R_0}{R_{cl}}\right)^3 \left(\frac{R_{cl}}{R_{\max}}\right)^{11/5} \quad \text{or} \quad \bar{p}_{pv} = \left(\frac{2}{5}\right)^{1/5} \left(\frac{p_0}{p_{cl}}\right)^{2/5} p_0. \quad (64)$$

Since $p_{pv} < p_0$, the process of bubble compression begins at moment $t = t_{\max}$.

The pressure in the gas bubble changes according to the law

$$p = \bar{p}_{pv} \left(\frac{R_{\max}}{R}\right)^{11/5} \quad (65)$$

The problem is solved analogously to the problem of gas bubble expansion; the following relationship has been derived for the

bubble's rate of compression:

$$v^2 = \frac{5\bar{p}V}{3\rho_0} \left(\frac{R_{\max}}{R_0} \right)^3 \left[1 - \left(\frac{R_{\max}}{R} \right)^{3/2} \right] - \frac{2p_0}{3\rho_0} \left[1 - \frac{R_{\max}}{R} \right]^3. \quad (66)$$

Ignoring the small values and taking $v = 0$, we determine the expression for the gas bubble's minimum radius:

$$R_{c0} = \left(\frac{5}{2} \frac{p_{cr}}{p_0} \right)^{2/3} R_{\max}; \quad R_{c0} = R_{ck}, \quad (67)$$

where R_{cr} = gas bubble radius corresponding to a pressure of p_{cr} in the explosion products.

Consequently, a pressure level is created in the gas bubble that is approximately equal to p_{cr} , which for condensed VV's is 2,000-5,000 atm (tech.). It is essential to mention that the compressed gas bubble's minimum radius does not depend on the hydrostatic pressure and, consequently, the intensity of the shock wave emitted during the repeated pulsation ($\Delta p_{11} = p_{cr} - p_0$) will depend on it substantially, because for secondary VV's, pressure p_{cr} is of the same order as p_0 . As the hydrostatic pressure increases, the intensity of the secondary pulsation waves will decrease and disappear completely at $p_0 \approx 1,000$ -2,000 atm (tech.), since $p_{cr} \approx 2,000$ -5,000 atm (tech.).

The peak pressure in the secondary shock wave is 10-20 percent of the basic shock wave's pressure [45], but since the duration of this wave significantly exceeds the acting time of the basic wave, the pulses of both waves are comparable. In connection with this, at low hydrostatic pressures the secondary shock waves play a rather important role in the effect of an underwater explosion. As the hydrostatic pressure increases, their role in the destruction of designs weakens and then disappears entirely.

Substituting expression (67) into (66), we obtain the following relationship for the gas bubble's rate of collapse:

$$v = \frac{dR}{dt} = \sqrt{\frac{2p_0}{3\rho_0}} \left(\frac{2p_0}{5p_{ck}} \right)^{1/3} \left(\frac{R_{c0}}{R} \right)^{5/6} \left[\left(\frac{R}{R_{c0}} \right)^{3/2} - 1 \right]^{1/2}. \quad (68)$$

Analyzing expression (68), we obtain the formula for the maximum rate of collapse:

$$\text{for } R = \left(\frac{7}{5} \right)^{2/3} R_{c0} = 1.32 R_{c0} \quad v = v_{\max} = 0.351 \sqrt{\frac{2p_0}{3\rho_0}} \left(\frac{2p_0}{5p_{ck}} \right)^{1/3}. \quad (69)$$

The collapse law can be derived by integrating expression (68) with respect to R within limits from $R_{\max}$ to R and with respect

to t , from 0 to t :

$$t = \sqrt{\frac{3\rho_0}{2p_0}} R_{c0} \left[\frac{2}{5} \left(\frac{R_{max}}{R_{c0}} \right)^{5/2} + \frac{5}{13} \left(\frac{R_{max}}{R_{c0}} \right)^{13/10} - \frac{2}{5} \left(\frac{R}{R_{c0}} \right)^{5/2} - \frac{5}{13} \left(\frac{R}{R_{c0}} \right)^{13/10} \right]. \quad (70)$$

Comparing expressions (70) and (59), we see that -- as should have been expected -- the bubble's expansion and collapse proceed according to the law

$$t \sim R^{1/2}. \quad (71)$$

For PETN, $t_{max} = 6.1(R_0/p_0)^{5/6}$. According to B.D. Khristoforov's data [77], $t_{max} = (272q^{1/3})/p_0^{5/6} = 5.13(R_0/p_0)^{5/6}$.

Derived relationships (56) and (60) make it possible to theoretically compute the maximum radius and time of expansion of the gas bubble as functions of the VV's parameters and the hydrostatic pressure in the water.

Effect of Hydrostatic Pressure on the Shock Wave's Basic Parameters -- Pressure, Pulse and Energy

In his book [45], R. Koul presented the results of a determination of the dependence of the pressure at the shock wave's front on the relative distance $\Delta p = f(R/R_0)$, as derived by (Penni) by numerical integration for distances $R/R_0 < 6$. These results agree quite well with the experimental data, but the method requires extraordinarily awkward computations, particularly when hydrostatic pressure is taken into consideration.

For a distance $R/R_0 > 6$, calculations by the (Kirkvul-Brinli) method [45] agree with the experimental data quite well, although this method does not allow for hydrostatic pressure.

At distances from the center of the explosion that exceed 2-3 radii of the charge, the instantaneous detonation field differs little from the real detonation field and it is possible to use approximate solutions [15] of spatial unidimensional movements. However, these solutions require additional cumbersome computational work and, in addition, are suitable only for equations of states with an adiabatic exponent $k = 3$, so they can be used by substituting the equation of state of water into the equation

$$p = A_1 \left[\left(\frac{\rho}{\rho_0} \right)^3 - 1 \right],$$

where A_1 takes on different values, depending on the pressure change interval.

In view of the difficulties in describing the regularities of the propagation of a shock wave in water, as explained above,

we will investigate the effect of hydrostatic pressure on the parameters of a shock wave by several other methods.

Dependence of a shock wave's peak pressure on hydrostatic pressure

On the basis of similarity theory and dimensional analysis, let us derive several relationships concerning the effect of hydrostatic pressure on the pressure at a shock wave's front.

The relative change in the medium's volume ($\Delta V/V$) at a given point is determined by the expression

$$\frac{\Delta V}{V} = \beta_s \Delta p, \quad (72)$$

where Δp = change in pressure at the given point.

The term β_s is adiabatic compressibility, which characterizes the relative change in a system's volume during adiabatic reduction of its pressure to unity.

It is known that $dE = -pdV + TdS$.

From this, the average compression of the medium by an explosion will be:

$$\left(\frac{\Delta V}{V}\right)_{AVE} = \beta_s \frac{\rho_{VV} Q_{VV} R_0^v}{R}, \quad (73)$$

where ρ_{VV} = density of the VV; Q_{VV} = latent heat of the explosion; R_0 = radius of the charge; $v = 2$ for cylindrical waves; $v = 3$ for spherical waves.

Since the relative compression at a point is a function of the medium's average compression, then

$$\beta_s \Delta p = f\left(\sqrt[v]{\beta_s \rho_{VV} Q_{VV} \frac{R_0}{R}}\right). \quad (74)$$

According to a large number of experimental and theoretical investigations, this function is quite accurately approximated in the form of an exponential function:

$$\Delta p = \frac{1}{\beta_s} \left(\sqrt[v]{\beta_s \rho_{VV} Q_{VV} \frac{R_0}{R}}\right)^\alpha. \quad (75)$$

If the values of Δp at the explosive-surrounding medium interface ($R = R_0$) and of β_s for $p_0 = 1$ atm (tech.) are designated as Δp_0 and β_{0s} , relationship (75) will take the form

$$\Delta p = \Delta p_0 \left(\frac{R_0}{R}\right)^\alpha \left(\frac{\beta_{0s}}{\beta_s}\right)^{\frac{\alpha}{v}}. \quad (76)$$

Let us determine the adiabatic compressibility, starting from the equation of state. It is known that in the area of pressures of several dozen or hundreds of thousands of atmospheres, condensed or dense media are governed by an empirical equation of state of the type

$$p = B(S) \left[\left(\frac{V_0}{V} \right)^n - 1 \right], \quad (77)$$

in which exponent n is regarded as a constant, while coefficient B is a function of entropy. In view of the relatively low compressibility of water at explosive pressures, coefficient B can be regarded as a constant.

From the equation of state of a medium of type (77), we obtain

$$\left(\frac{\partial p}{\partial V} \right)_S = - \frac{BnV_0}{V^2} \left(\frac{V_0}{V} \right)^{n-1} = - \frac{Bn}{V} \left(\frac{p}{B} + 1 \right)$$

or

$$\beta_S = - \frac{1}{V} \left(\frac{\partial V}{\partial p} \right)_S = \frac{1}{Bn} \left(\frac{p_0}{B} + 1 \right)^{-1}. \quad (78)$$

Since $B \gg 1$ atm (tech.) (for water, $B \approx 3,000$ atm (tech.)),

$$\beta_{0S} = \frac{1}{Bn}. \quad (79)$$

Finally, we obtain the following relationship, which is very important for the solution of our problem:

$$\beta_S = \beta_{0S} \left(\frac{p_0}{B} + 1 \right)^{-1}. \quad (80)$$

It shows that adiabatic compressibility depends only on pressure and the value of coefficient B in the equation of state.

It should be mentioned that coefficient B , as can be easily shown from the medium's equation of state, is calculated with the formula

$$B = \frac{\rho_0 C_0^2}{n}. \quad (81)$$

Thus, in order to determine the dependence of a medium's adiabatic compressibility on pressure, it is sufficient to know the value of B or n .

Substituting expression (80) into (76), we obtain the dependence of the pressure at the shock wave's front on the initial pressure:

$$\Delta p = \Delta p_0 \left(\frac{R_0}{R} \right)^n \left(\frac{p_0}{B} + 1 \right)^{\frac{n-\alpha}{\alpha}}. \quad (82)$$

For a known value of α , which determines the degree of attenuation of the peak pressure at $p_0 = 1 \text{ atm (tech.)}$, the formula derived by us expresses the effect of hydrostatic pressure on the pressure gradient at the shock wave's front.

Since coefficient α decreases as the shock wave spreads, the dependence of Δp on p_0 increases.

According to extensive experimental material, at a distance of $R/R_0 > 6$ during the explosion of a spherical charge ($\nu = 3$), $\alpha = 1.13$ [45].

Since $M \ll 1$ ($M = \text{Mach number}$) for water, even at relatively close distances from the charge, the shock wave can be studied in an acoustic approximation [15]; for a spherical charge we will then have: $v_y \approx 1/r$.

Since $p_y - p_0 = v^2/(v_0 - v_y)$, it can be assumed that

$$\Delta p \approx \frac{1}{r^2}, \quad (83)$$

that is, $\alpha = 2$, which is correct for a certain range of change in R/R_0 [44].

Taking into consideration the data on the effect of hydrostatic pressure on the initial pressure at the shock wave's front, it is possible to derive the value of $(\nu - \alpha)/\nu$ for $R = R_0$ from relationship (82) and, consequently, determine the value of α that will be correct in direct proximity to the charge (Table 31).

Table 31. Values of α for Different VV's

	Гексоген ($\rho = 1.62 \text{ g/cm}^3$, $D = 8000 \text{ m/sec}$) (1)	Тротил (2)		Тол ($\rho = 1.6 \text{ g/cm}^3$, $D = 7950 \text{ m/sec}$) (3)
		($\rho = 1.61 \text{ g/cm}^3$, $D = 7000 \text{ m/sec}$)	($\rho = 1.6 \text{ g/cm}^3$, $D = 6100 \text{ m/sec}$)	
3	2.57	2.61	2.59	2.57
2	1.71	1.74	1.72	1.71
1	0.857	0.869	0.862	0.855

Key:

1. Hexogene
2. TNT

3. PETN

As is obvious from Table 31, the values of α obtained for different VV's are very similar; it can be assumed that close to the charge, the pressure at the shock wave's front drops with distance according to an exponential law with the following exponents: $\alpha = 2.58$ for a spherical wave, $\alpha = 1.72$ for a cylindrical wave, $\alpha = 0.861$ for a plane wave.

Dependence of the shock wave's pulse on hydrostatic pressure

According to detonation theory, for the flow of a pulse passing through a unit of area at the distance of the charge's radius, the following formula [15] is correct:

$$i = \frac{16}{27} \frac{\sqrt{ME}}{4\pi R_0^2}, \quad (84)$$

where M = mass of the charge of VV ; $E = MQ$ = total energy of the VV .

Since for a given explosion energy, the pulse increases proportionally to the square root of the mass involved in the movement, at a distance r from the charge,

$$i = \frac{MD}{27\pi r^2} \sqrt{1 + \frac{M_s}{M}}$$

or

$$i = \frac{4}{81} \rho_{VV} D^2 R_0 \left(\frac{R_0}{r}\right)^2 \sqrt{1 + \frac{M_s}{M}}. \quad (85)$$

In the interval $R_0 \leq r \leq R_{\max}$, since $M_B = [4\pi\rho_0(r^3 - R_0^3)]/3$, then

$$i = \frac{4}{81} \rho_{VV} D R_0 \left(\frac{R_0}{r}\right)^2 \sqrt{1 - \frac{\rho_0}{\rho_{VV}} + \frac{\rho_0}{\rho_{VV}} \left(\frac{r}{R_0}\right)^3}. \quad (86)$$

In the interval $r \geq R_{\max}$, the mass of water involved in the movement is $4\pi\rho_0 r^3/3$, so that

$$i = \frac{4}{81} \rho_W D R_0 \left(\frac{R_0}{r}\right)^3 \sqrt{1 + \frac{\rho_0}{\rho_W} \left(\frac{R_{\max}}{R_0}\right)^3 \left[3 \left(\frac{r}{R_{\max}}\right)^2 - 3 \left(\frac{r}{R_{\max}}\right) + 1\right]}. \quad (87)$$

The pulse's dependence on hydrostatic pressure is expressed in terms of $R_{\max}$, which -- according to formula (56) -- is inversely proportional to the cube root of the hydrostatic pressure. The change in the pulse with distance is shown for $p_0 = 1$ atm (tech.) and $p_0 = 10$ atm (tech.) in Figure 33.

From expression (87) it is possible to derive the relationship of the specific pulses for $r \gg R_{\max}$:

$$i = \frac{4}{81} D \rho_W R_0 \sqrt{3 \frac{\rho_0}{\rho_W} \left(\frac{R_{\max}}{R_0}\right)^{1/2} \left(\frac{R_0}{r}\right)}. \quad (88)$$

Since, according to expression (56), $R_{\max} \sim 1/p_0^{1/3}$, then

$$i \approx \frac{1}{p_0^{1/6}}. \quad (89)$$

Figure 33. Change in a shock wave's pulse with distance:
1. $p_0 = 1$ atm (tech.); 2. $p_0 = 10$ atm (tech.).

As is obvious from relationship (86), at distances of up to $R = R_{\max}$ the effect of hydrostatic pressure on the pulse is completely insignificant, since it is manifested as a change in the density of the water, which even at pressures of 2,000-3,000 atm (tech.) does not exceed 10 percent.

As is obvious from expression (87), at distances $R > R_{\max}$ the degree of the hydrostatic pressure's influence on the pulse increases noticeably and at $R \gg R_{\max}$ becomes extremely substantial (89). At a pressure of 1,000-2,000 atm (tech.) the reduction in the pulse is triple what it is at a hydrostatic pressure of 1 atm (tech.).

Dependence of the shock wave's energy on hydrostatic pressure

Another parameter of an underwater explosion that is no less important than the shock wave's peak pressure and specific pulse is the energy borne by the shock wave. The dependence of the gas bubble's maximum radius of expansion on the hydrostatic pressure makes it possible to determine the latter's effect on the shock wave's energy.

Let us formulate the VV's energy balance:

$$E_{VV} = E_{sw} + E_w + A_{p_0} + E_{res}, \quad (90)$$

where E_{sw} = the shock wave's energy; E_w = energy of the flow of water; A_{p_0} = work done to overcome the hydrostatic pressure; E_{res} = residual energy in the explosion products.

When the explosion products reach the maximum radius of expansion ($R_{\max}$),

$$E_w = 0, \quad A_{p_0} = \frac{4}{3} \pi (R_{\max}^3 - R_0^3) p_0, \quad E_{res} = \frac{4}{3} \pi R_{\max}^3 \frac{p_{R_{\max}}}{\gamma - 1},$$

where $p_{R_{\max}}$ = pressure in the explosion products at $R = R_{\max}$.

We determine the pressure in the explosion products at $R = R_{\max}$ from expression (64), while the value of $R_{\max}$ is substituted in the form of formula (56), so that

$$A_{p_0} = \frac{4}{3} \pi R_0^3 p_0 \left[\frac{5}{2} \frac{p_{cr}}{p_0} \left(\frac{p_w}{p_{cr}} \right)^{1/\gamma} - 1 \right]; \quad (91)$$

$$E_{res} = \frac{4}{3} \pi R_0^3 p_0 \left(\frac{p_w}{p_{cr}} \right)^{1/\gamma} \left(\frac{5p_{cr}}{2p_0} \right)^{1/\gamma}. \quad (92)$$

Substituting expressions (91) and (92) into the energy balance equation and using $E_{VV}(4/3)\pi R_0^3 \rho_{VV} Q$ [sic], we obtain

$$\frac{E_{SW}}{E_{VV}} = 1 - \frac{p_0}{\rho_{VV} Q} \left\{ \left(\frac{p_W}{p_{CR}} \right)^{1/2} \left(\frac{5p_{CR}}{2p_0} \right) \left[\left(\frac{5p_{CR}}{2p_0} \right)^{2/3} + 1 \right] - 1 \right\}. \quad (93)$$

Figure 34. Dependence of shock wave's energy on the hydrostatic pressure.

Figure 34 shows this dependence for PETN, with $\rho = 1.6 \text{ g/cm}^3$ and $D = 8,000 \text{ m/sec}$.

As is obvious from relationship (93) and Figure 34, as the hydrostatic pressure increases, the portion of the VV's energy that has passed into the shock wave decreases; this reduction is noticeable at pressures up to 1,000 atm (tech.), after which it slows down.

RESULTS OF EXPERIMENTAL INVESTIGATIONS

Modeling Techniques and a Description of the Experiments

The scientifically substantiated formulation of the experiments we conducted and the processing of their results requires the use of the methods of similarity and dimensional analysis.

In the problem of investigating the parameters of the gas bubble's expansion and the shock wave related to an underwater explosion under conditions of elevated hydrostatic pressures, the decisive parameters will be: t = time, r = radius of propagation of the shock wave, R_0 = radius of the charge, R = radius of expansion of the gas bubble, E = energy of the explosive charge, ρ_{VV} = density of the explosive, ρ_0 = density of water, p_0 = hydrostatic pressure, β_S = adiabatic compressibility of water.

According to the π -theorem of the theory of similarity and dimensionalities, it is possible to formulate six dimensionless combinations from the nine available decisive parameters:

$$\frac{p_0^{v+2} t}{E^{1/v} \rho_0^{1/2}}; \quad \frac{R p_0^{1/v}}{E^{1/v}}; \quad \frac{R_0 p_0^{1/v}}{E^{1/v}}; \quad \frac{t}{E^{1/v} \beta_S^{2v} \rho_0^{1/2}}; \quad \frac{\rho_{VV}}{\rho_0}; \quad \frac{r}{E^{1/v} \beta_S^{1/v}}; \quad (94)$$

where $v = 1, 2$ and 3 , respectively, for the plane, cylindrical and spherical cases.

We will not consider the effect of the dimensionless parameter ρ_{VV}/ρ_0 on the processes being studied, since we are interested in the explosion mechanism of condensed VV's with a density on the order of 1.6 g/cm^3 , which shows almost no change with hydrostatic pressure; consequently, ρ_{VV}/ρ_0 is a constant value in all the experiments.

For a hydrostatic pressure of up to several thousand atmospheres, the effect of the dimensionless parameter $(R_0 p_0^{1/\nu})/E^{1/\nu}$ on the studied processes will also be insignificant, since it is nothing else than the ratio of the liquid's potential energy, acquired as the result of the formation of an empty cavity with radius R_0 , to the explosive's energy. Let us estimate at what values this parameter equals unity; that is,

$$\frac{R_0^3 p_0}{R_0^3 \rho_{VV} Q} = \frac{p_0}{\rho_{VV} Q} = 1$$

or

$$p_0 = \rho_{VV} Q \approx 68,3 \cdot 10^3 \text{ atm (tech.).}$$

From this it is obvious that at a hydrostatic pressure (p_0) equal to several thousand atmospheres (which is encountered in practice), this parameter's effect can be ignored. However, since we are interested in the near zone of the explosion, it will be physically valid (this has been confirmed experimentally, as will be demonstrated later) to replace the dimensionless parameters $(R_0 p_0^{1/\nu})/E^{1/\nu}$ and $r/(E^{1/\nu} \beta_S^{1/\nu})$ with the dimensionless parameters

$$\frac{(R^v - R_0^v)^{1/\nu} p_0^{1/\nu}}{E^{1/\nu}} \text{ and } \frac{(r^v - R_0^v)^{1/\nu}}{E^{1/\nu} \beta_S^{1/\nu}}, \quad (95)$$

where $R^v - R_0^v$ and $r^v - R_0^v$ characterize the volumes of liquid involved in the movement.

In view of what has been said above, we will have the following dimensionless combinations:

$$\frac{p_0^{\frac{\nu+2}{2\nu}} t}{E^{1/\nu} \rho_0^{1/\nu}}; \quad \frac{(R^v - R_0^v)^{1/\nu} p_0^{1/\nu}}{E^{1/\nu}}; \quad \frac{t}{E^{1/\nu} \rho_S^{\frac{\nu+2}{2\nu}}}; \quad \frac{(r^v - R_0^v)^{1/\nu}}{E^{1/\nu} \beta_S^{1/\nu}}. \quad (96)$$

Having a system of dimensionless combinations that define the essence of the phenomena occurring during an underwater explosion under conditions of elevated hydrostatic pressures, it is not difficult to represent the underwater explosion parameters that interest us as functions of the dimensionless parameters that we have found:
the gas bubble expansion law --

$$\frac{(R^v - R_0^v)^{1/v} p_0^{1/v}}{E^{1/v}} = f_1 \left(\frac{p_0^{2v} t}{E^{1/v} \rho_0^{1/2}} \right); \quad (97)$$

the shock wave propagation law --

$$\frac{(r^v - R_0^v)^{1/v}}{E^{1/v} \rho_S^{1/2}} = f_2 \left(\frac{t}{E^{1/v} \rho^{2v} \rho_0^{1/2}} \right). \quad (98)$$

After using the theory of similarity and dimensionalities to find the dimensionless criteria on which the underwater explosion parameters that are of interest depend, the goal of the experimental investigations is to test the correctness of the laws that have been found and to establish the form of functions f_1 and f_2 .

It should be mentioned that the dependence of the gas bubble's maximum radius of expansion and pulsation period on the hydrostatic pressure is determined directly from expression (97). Actually, for $t = t_{\max}$ and $R = R_{\max}$, both dimensionless parameters equal constant values:

$$\frac{(R_{\max}^v - R_0^v)^{1/v} p_0^{1/v}}{E^{1/v}} = \text{const}; \quad (99)$$

$$\frac{t_{\max} p_0^{2v}}{E^{1/v} \rho_0^{1/2}} = \text{const}. \quad (100)$$

From these expressions,

$$(R_{\max}^v - R_0^v)^{1/v} \frac{(R_{\max}^v - R_0^v)^{1/v}}{p_0^{1/v}}; \quad (101)$$

$$t_{\max} = \frac{t_{\max}}{p_0^{2v}}. \quad (102)$$

Subscript "0" designates the values at $p_0 = 1 \text{ atm (tech.)}$.

Since $R_0^v \ll R_{\max}^v$, we obtain:
for a spherical explosion --

$$R_{\max} = \frac{R_{0\max}}{p_0^{1/3}}; \quad t_{\max} = \frac{t_{0\max}}{p_0^{2/3}}; \quad (103)$$

for a cylindrical explosion --

$$R_{\max} = \frac{R_{0\max}}{p_0^{1/2}}; \quad t_{\max} = \frac{t_{0\max}}{p_0}; \quad (104)$$

for a plane explosion --

$$R_{\max} = \frac{R_{0\max}}{p_0}; \quad t_{\max} = \frac{t_{0\max}}{p_0^{3/2}}. \quad (105)$$

For a spherical explosion, these expressions were derived earlier by another method.

The experiments were performed in a high-pressure device (autoclave) with an inner diameter of 350 mm. The autoclave had two optical ports that were 50 mm in diameter and consisted of cylinders of plexiglass. The use of plexiglass made it possible to use the optical ports repeatedly, despite the simultaneous effect of the optical and dynamic loads on them. As a rule, under these conditions silicate glasses are destroyed after the first explosion. The autoclave was filled with tap water, although an air cushion 50-100 mm thick was left at the top. Pressures of up to 400 atm (tech.) were created by an air compressor.

Spherical and cylindrical charges were placed in the center of the autoclave opposite the windows, where it had been calculated that the complete radius of the bubble's pulsation could be registered during photographic recording. The charges were made of PETN that had been compressed to a density of 1.67 g/cm³. In order to seal them, they were covered with a layer of epoxy resin. The spherical charge weighed 0.72 g and was 10 mm in diameter, while the cylindrical one weighed 1.7 g and was 6 mm in diameter, with its length being equal to 6 times the charge's diameter. Lead azide constituting 5-7 percent of the charge's total weight, along with a small amount of powdered PETN, was used as the detonator.

The process was photographed with the help of a ZhFR unit, at a rate of 7,500 rpm when investigating the gas bubble's pulsation and 45,000 rpm when recording the shock waves.

The high-voltage impulse from the ZhFR's control panel was simultaneously directed to the ignition of an IFK-500 flash lamp and to a discharger, through which the capacitance was discharged to the resistance of the detonator's filament. The duration of the lighting was determined on the basis of the gas bubble's period of pulsation, and was controlled by the magnitude of the battery's capacitance.

Results of Determining the Parameters of the Gas Bubble's Movement (Maximum Time and Radius of Expansion)

As was shown above, during the theoretical investigation of the effect of hydrostatic pressure on the parameters of an underwater explosion, the regularities of the gas bubble's expansion as a function of the hydrostatic pressure make it possible to make both qualitative and -- in some cases -- quantitative judgments about the effect of the latter on the entire underwater explosion process. The formulation of the experiments

Figure 35. Graph of function $R(t)$ for explosions of cylindrical charges.

Figure 37. Graph of function $R_{\max}(p_0)$ for explosions of cylindrical (1) and spherical (2) charges.

(H = height of the charge; d = its diameter), the time of the first pulsation is much greater than the time of the passage of the detonation wave through the charge and the penetration of the rarefaction wave into the depths of the charge, and the value of the maximum radius of gas bubble expansion corresponds to the explosion of an equivalent spherical charge.

The relationship $R_{\max}/R_0 = f(p_0)$ is described by the formula

$$\frac{R_{\max}}{R_0} = \frac{A}{p_0^{1/3}}, \quad (106)$$

where $A = 36.3$ for a spherical charge and 51.1 for a cylindrical charge.

Figure 36. Graph of function $R(t)$ for explosions of spherical charges.

had as its goal the confirmation of the theoretical conclusions that had been reached.

The experiments were conducted in water, at pressure increments of 100 atm (tech.) up to 400 atm (tech.) (Figure 35 and 36).

As is obvious from Figure 37, the dependence of $\log R_{\max}/R_0$ on $\log p_0$ corresponds to a straight line with angle of inclination α that equals one-third for both spherical and cylindrical charges. The latter is explained by the fact that for charges with $H/d = 6$

Figure 38. Graph of function $t_{\max}(p_0)$ for explosions of cylindrical (1) and spherical (2) charges.

Figure 40. Gas bubble expansion for explosions of spherical charges.

Figure 39. Gas bubble expansion for explosions of cylindrical charges.

The theoretical value of A for a spherical charge, as calculated with formula (56), is 37.2.

The dependence of $\log t_{\max}$ on $\log p_0$ corresponds to a straight line with an angle of inclination equal to five-sixths (Figure 38).

The relationship $t_{\max} = f(p_0)$ is described by the formula

$$t_{\max} = \frac{B}{p_0^{5/6}}, \quad (107)$$

where $B = 15.4$ msec for a spherical charge and 18 msec for a cylindrical one.

The theoretical value of coefficient B for a spherical charge, as calculated with formula (60), is 16.6 msec.

Figures 39 and 40 show the dependence of gas bubble expansion on time for the explosion of cylindrical and spherical charges.

Results of Determination of the Pressure at a Shock Wave's Front

In the experiments, the value of $r(t)$ for a shock wave's front was recorded. This function made it possible [44] to change over to the dependence of the shock wave front's rate of propagation on distance R/R_0 , and then -- by using the shock adiabat for water [15,45,81] -- to the dependence of the pressure at the shock wave's front on distance $p(R/R_0)$.

All of these relationships are described quite well by exponential functions with exponents that differ over different intervals:

for a spherical charge --

$$\Delta p = 85,5 \cdot 10^3 \left(\frac{R_0}{r} \right)^2 \quad \text{for } 2 < \frac{r}{R_0} < 7; \quad (108)$$

$$\Delta p = 195 \cdot 10^3 \left(\frac{R_0}{r} \right)^{2,55} \quad \text{for } 1 < \frac{r}{R_0} < 2; \quad (109)$$

for a cylindrical charge --

$$\Delta p = 195 \cdot 10^3 \left(\frac{R_0}{r} \right)^{1,7} \quad \text{for } 1 < \frac{r}{R_0} < 3; \quad (110)$$

$$\Delta p = 35 \cdot 10^3 \left(\frac{R_0}{r} \right)^{1,2} \quad \text{for } 3 < \frac{r}{R_0} < 15. \quad (111)$$

In these distance change intervals, hydrostatic pressures up to 400 atm (tech.) exert practically no influence on the pressure at the wave's front.

Analysis and Theoretical Generalization of the Experimental Data

The experiments that were performed with spherical and cylindrical charges of PETN at pressures up to 400 atm (tech.) show that the hydrostatic pressure has a substantial influence on the maximum radius and pulsation period of a gas bubble. The experimentally established relationships $R_{\max} = f(p_0)$ and $t_{\max} = \varphi(p_0)$ agree quite well with the results of the theoretical investigations.

The use of modeling techniques makes it possible to apply the experimental data obtained for PETN to other condensed VV's when their density is the same.

We did not investigate the effect of parameter ρ_{VV}/ρ_0 on underwater explosion processes. However, as B.D. Khristoforov's investigations have shown [78], the similarity is destroyed when VV's with sharply different densities are used in the experiments.

According to expressions (99) and (100), for a spherical explosion

$$\sqrt[3]{R_{\max}^3 - R_0^3} = A \left(\frac{Q \rho_{VV}}{Q_{\text{PETN}} \rho_{\text{PETN}}} \right)^{1/2} \frac{1}{p_0^{1/2}}$$

or for $R_{\max} \gg R_0$

$$R_{\max} = A \left(\frac{Q \rho_{VV}}{Q_{\text{PETN}} \rho_{\text{PETN}}} \right)^{1/2} \frac{1}{p_0^{1/2}}; \quad (112)$$

$$t_{\max} = B \left(\frac{Q_{VV}}{Q_{\text{PETN}} \rho_{\text{PETN}}} \right)^{1/2} \frac{1}{P_0^{5/2}}. \quad (113)$$

For the reasons stated above, these gas bubble relationships were not able to be derived for a cylindrical explosion.

The experimentally obtained relationships for the pressures at the shock wave's front agree quite well with the results of the theoretical investigations.

In direct proximity to a spherical charge, the experimental value of coefficient α for PETN proved to be 2.55, while its theoretical value was 2.57; in the case of a cylindrical charge, the experimental and calculated values were identical.

Generalizing the experimental results for the investigation of pressure at the shock wave's front for PETN, according to (82) and (98) we obtain:

$$\Delta p = C \left(\frac{\rho_{VV} Q_{VV}}{\rho_{\text{PETN}} Q_{\text{PETN}}} \right)^{\frac{\alpha}{v}} \left(\frac{R_0}{R} \right)^{\alpha} \left(\frac{P_0}{B} + 1 \right)^{\frac{v-\alpha}{v}}, \quad (114)$$

where coefficients α and C change as functions of the change in distance according to expressions (108)-(111).

The results of the investigations we performed into the effect of elevated hydrostatic pressures on the parameters of an underwater explosion permit us to draw the following conclusions.

1. Hydrostatic pressure on the order of 2,000-3,000 atm (tech.), which cannot be encountered in even ultradeep boreholes (10-15 km), has no noticeable effect on the initial velocity and pressure jump of the shock wave.
2. At the relatively close distances ($R/R_0 < 10$) realized during blasting operations in boreholes, hydrostatic pressure on the order of 2,000-3,000 atm (tech.) also has no noticeable effect on Δp and other parameters at the shock wave's front.
3. The shock wave's attenuation factor (α) depends substantially on the interval of change in R/R_0 and the shape of the charge being detonated.
4. In accordance with the theoretical results, the gas bubble's maximum radius of expansion and pulsation period in the case of a spherical explosion are determined by relationships (106) and (107).
5. The shock wave's parameters for spherical and cylindrical explosions agree with the theoretical data.

6. Hydrostatic pressure affects the shock wave's energy as determined by relationship (93). For a hydrostatic pressure level of 1,500 atm (tech.) in comparison with 1 atm (tech.), the shock wave's energy is reduced by 25 percent.

7. The degree of the hydrostatic pressure's effect on the pulse of an underwater explosion at distances of up to $R_{\max}$ from the center of the explosion is insignificant, while at greater distances it increases noticeably and at distances $R \gg R_{\max}$ becomes extremely substantial; it is determined by the relationship $i \approx 11^{1/6}/p_0$ [sic -- probably $(1/p_0)^{1/6}$]. From this it follows that at pressures of 1,000-2,000 atm (tech.), the pulse decreases by a factor of 3 or more in comparison with a level of 1 atm (tech.).

It should be mentioned that the values found for the pulses exceed those given by R. Koul [45]. The discrepancy is explained by the fact that the relationships presented by us allow for the total pulse of an underwater explosion, while Koul pays no attention to the pulse in the tail end of the shock wave, the total amount of movement of which is quite large and is comparable to the pulse calculated by Koul, since it is the momentum of the liquid flow diverging from the center of the explosion.

8. Hydrostatic pressure has a substantial effect on the intensity of the secondary shock waves. Their intensity drops as the hydrostatic pressure increases, and at pressures above 1,000 atm (tech.), in general they apparently do not participate in the destruction. This conclusion follows qualitatively from a theoretical examination of the question of the gas bubble's collapse.

9. Since the hydrostatic pressure has no substantial effect on the parameters of an underwater explosion near the charge, at distances $R/R_0 < 3$ (that is, at distances that are frequently encountered during blasting operations in boreholes), the cause of the reduction in the destructive effect of an underwater explosion as the hydrostatic pressure increases (which has been observed during test-firing and blasting operations in deep boreholes and during the explosive method of drilling) must be sought primarily in a change in the material deformation and destruction conditions at elevated hydrostatic pressures.

10. For $R/R_0 > 3$ (which is realized during explosive operations not requiring a strong destructive effect, such as during the use of cord torpedoes, and so on), we cannot ignore the effect of hydrostatic pressure on the shock wave's parameters, particularly on the magnitude of its pulse.

CHAPTER 6. DEPENDENCE OF PIPE DEFORMATION DURING AN EXPLOSION ON THE SURROUNDING MEDIUM'S PROPERTIES

FACTORS AFFECTING DEFORMATION PROCESSES DURING AN EXPLOSION

In the practice of conducting explosive and test-firing operations in boreholes, as well as during the designing of the equipment needed for these purposes, we must constantly deal with the little-studied question of the dependence of pipe deformation during the explosion of a VV on the properties of the surrounding medium.

It is natural that the deformation processes will, in the first place, depend on the surrounding medium's initial pressure and temperature, which the pipe material itself acquires, and, in the second place, on the force (pressure) that arises in the surrounding medium and hinders deformation. Since the hindering force owes its appearance to the shock wave emitted into the surrounding medium during the movement of the pipe wall, the magnitude of this force will consequently depend on those properties that determine the intensity and shape of the shock wave. As is well known, those properties include density, compressibility, and initial pressure and temperature.

The study of this question is primarily complicate by the fact that the behavior of metals under transient loads is complex and not completely clear. Many technical applications in which the behavior of metal under transient loading plays a paramount role are based on engineering experience. Despite this fact, however, a huge amount of both experimental and theoretical material has been accumulated on the subject of pipe deformation. The situation is not as good relative to the question we are investigating: the effect of the surrounding medium's properties on pipe deformation. In the literature there is not even a qualitative explanation of the fact that during the explosion of a cylindrical VV charge in a pipe, the degree of destruction of the latter in air differs considerably from the degree of destruction in water (in the latter case, the extent of the

destruction is much less). When such a charge is detonated in water, there is a reduction in the degree of pipe deformation as the hydrostatic pressure increases.

As a detailed study of the question of the effect of hydrostatic pressure on the parameters of an underwater explosion has shown, close to the charge (that is, at distances frequently used during explosive operations in boreholes) they do not change substantially under the influence of hydrostatic pressure, so it is necessary to look for the reasons for the reduction in the destructive effect of an underwater explosion as the hydrostatic pressure increases (during test-firing and explosive operations in deep boreholes and when the explosive drilling method is used) primarily in the change in the deformation and material destruction conditions under elevated hydrostatic pressures.

MODELING TECHNIQUES AND A DESCRIPTION OF THE EXPERIMENTS

The theoretical study of the question of the deformation of a pipe when an explosive is detonated inside in air or water, with due consideration for the effect of hydrostatic pressure, is made more difficult because of the mathematical complexity of the solution of this type of problem, which is based on the integration of nonlinear partial differential equations, so that the experimental study of this question is of paramount importance.

Let us discuss the modeling of the deformation of a pipe located in an air or liquid medium when an explosive charge that completely fills the pipe is detonated.

Let us write out a system of dimensional and dimensionless parameters that define the phenomenon described above.

The parameters defining the VV: Q = heat of explosion; ρ_{VV} = density of the VV; R_0 = radius of the charge or inner radius of the pipe.

The parameters defining the pipe: δ = thickness of the pipe wall; ρ_t = density of the pipe material; ϵ_{cr} = critical relative deformation that causes destruction of the pipe material when it is attained; c_t = speed of sound in the pipe material.

The parameters defining the surrounding medium: ρ_0 = density of the medium; c_0 = speed of sound in this medium; n = exponent in the equation of state of a liquid

$$p = A \left[\left(\frac{\rho}{\rho_0} \right)^n - 1 \right]$$

and adiabatic exponent for an air medium; β_s = adiabatic compressibility;
for a liquid,

$$\beta_s = \frac{1}{V} \left(\frac{dV}{dp} \right)_s = \frac{1}{An \left(\frac{p_0}{A} + 1 \right)},$$

for air,

$$\beta_s = \frac{1}{np_0};$$

A = a constant in the surrounding medium's equation of state;
 t = current time; R = current inner radius of the pipe.

We have a system of 14 defining parameters. According to the π -theorem of the theory of similarity and dimensionalities, from the 14 defining parameters it is possible to formulate 11 dimensionless combinations:

1. R_0/δ = geometric similarity.
2. R_0/R = equality of relative deformations.
3. ρ_{VV}/ρ_t = equality of the VV's relative density.
4. ρ_0/ρ_t = equality of the surrounding medium's relative density.
5. ε_{cr} = equality of the magnitude of the relative critical deformation.
6. $c_0\rho_0/c_t\rho_t$ = equality of conditions on the pipe-medium boundary.
7. $(\rho_{VV}\sqrt{Q})/c_t\rho_t$ = equality of conditions on the VV-pipe boundary.
8. $\beta_s\rho_{VV}Q$ = equality of the VV's relative energy used to compress the surrounding medium.
9. n = equality of the exponent in the surrounding medium's equation of state.
10. $A/(\rho_{VV}Q)$ = equality of the relative energy of the shock wave emitted into the surrounding medium.
11. $(t\sqrt{Q})/R_0$ = equality of the ratio of current time to the time of excitation of the detonation of the entire charge.

The purpose of the experiment is to determine the relative deformation of the pipe as a function of the other dimensionless combinations:

$$\frac{R-R_0}{R_0} = f\left(\frac{\delta_0}{R_0}, \frac{\rho_{VV}}{\rho_r}, \frac{\rho_0}{\rho_r}, \varepsilon_{\alpha}, \frac{c_0 \rho_0}{c_r \rho_r}, \frac{\rho_{VV} \sqrt{Q}}{c_r \rho_r}, \beta_{SV} \rho_{VV} Q, n, \frac{A}{\rho_{VV} Q}, \frac{t \sqrt{Q}}{R_0}\right). \quad (115)$$

In the experiments we conducted, the surrounding medium and the pipe's wall thickness were changed, so that

$$\frac{R-R_0}{R_0} = f_1\left(\frac{\delta}{R_0}, \frac{\rho_0}{\rho_r}, \frac{c_0 \rho_0}{c_r \rho_r}, \beta_{SV} \rho_{VV} Q, n, \frac{A}{\rho_{VV} Q}, \frac{t \sqrt{Q}}{R_0}\right). \quad (116)$$

In the case where the surrounding medium is air, we obtain:

$$\frac{R-R_0}{R_0} = f_2\left(\frac{\delta}{R_0}, \frac{t \sqrt{Q}}{R_0}\right). \quad (117)$$

However, if water is used as the surrounding medium, under different hydrostatic pressures it is the case that

$$\frac{R-R_0}{R_0} = f_3\left(\frac{\delta}{R_0}, \beta_{SV} \rho_{VV} Q, \frac{t \sqrt{Q}}{R_0}\right). \quad (118)$$

Thus, in the experiments it is necessary to maintain the dimensionless parameters in the written functions as constants; the unknown dimensionless variable $(R - R_0)/R_0$ will then also be a constant.

The investigation of the process of the deformation of pipes and hollow, thin-walled steel cylinders in air and in water, under different hydrostatic pressures, during the detonation of a VV that completely fills their inner cavity, was carried out with charges consisting of a hollow steel (45 steel) cylinder with walls of various thicknesses ($\delta = 1-16$ mm) and the same inner radius ($R_0 = 4.8$ mm), which were filled with an explosive charge of phlegmatized hexogene.

In order to determine the effect of the surrounding medium's properties on the deformation of the charge's casing, the charges were set off in both air and water. In the latter case we used square aquariums that were made of glued glass plates and filled with water. The aquariums' dimensions made it possible to photograph the process until the shock wave reflected from a wall approached the charge's casing.

In order to determine the effect of hydrostatic pressure on the process of charge casing deformation, the charges were set off in a specially designed high-pressure cylinder with an inner diameter of 160 mm that could be used repeatedly. The use of this cylinder made it possible to photograph the process until the reflected shock wave approached the charge's casing.

The cylinder had two optical ports that were 60 mm in diameter and were made of plexiglass cylinders. The plexiglass was destroyed during each experiment. The cylinder was filled with distilled water, which provided the transparency needed for the photography. The pressure was created by a hydraulic pump. The charges were placed in the center of the cylinder opposite the ports, so that the deformation of the casing before and after its destruction can be recorded photographically. The charge casing deformation process is photographed with the help of an SFR unit.

PIPE DEFORMATION AND DESTRUCTION IN AN AIR MEDIUM

As was pointed out above, the deformation of charge casings when the same material and explosive are involved and the charge is detonated in air, depends on the casing's relative thickness and the relative time:

$$\frac{R-R_0}{R_0} = f\left(\frac{\delta_0}{R_0}, \frac{t\sqrt{Q}}{R_0}\right).$$

The goal of the experiments was to determine the form of this relationship. In order to do this, the charges described above were set off in casings with different wall thicknesses. In the experiments, we recorded the change in external radius R_{ex} during time t . Figure 41 is a photograph taken during the explosion of a charge with a casing thickness of 4 mm.

Figure 41. Detonation in air of a charge with $\delta = 4$ mm.

As is obvious from Figure 42, the deformation of the outer wall takes place at a constant rate (v_0) that depends on the casing's thickness (δ):

$$\frac{R_{ex} - (R_0 + \delta)}{R_0} = \frac{v_0 t}{R_0}. \quad (119)$$

The experiments in an air medium make it possible to determine the dependence of the mass velocity of the particles of the

Figure 42. Rule governing the expansion of a pipe's external wall during an explosion in air.

charge casing's external surface on the relative distance R/R_0 (Figure 43).

This dependence is approximated quite well by the formula

$$v_0 = 1670 \left(\frac{R_0}{R} \right) \exp \left[-0.41 \left(\frac{R}{R_0} - 1 \right) \right] \text{ m/sec.}$$

If we assume that the velocity of the particles is approximately doubled on the external wall, then for the mass velocity (v_y) of particles at the front of a cylindrical shock wave propagating in 45 steel, we obtain

$$v_y = 835 \left(\frac{R}{R_0} \right) \exp \left[-0.41 \left(\frac{R}{R_0} - 1 \right) \right] \text{ m/sec.}$$

Figure 43. Graph of function $v_0(R/R_0)$.

The change in v_y as a function of R/R_0 is caused by the cylindrical shape of the shock wave, while the term $\exp[-0.41 \cdot (R/R_0 - 1)]$ characterizes irreversible losses due to friction.

Knowledge of the rule governing the change in the pressure at the front of a cylindrical shock wave propagating in the charge casing is also of great value. As is known from the

theory of shock waves, the relationship between the pressure

(p_y) and the mass velocity is defined by the expression

$$p_f - p_0 = \frac{\rho_f v_f^2}{\frac{\rho_f}{\rho_0} - 1}.$$

Figure 44. Graph of function $v_y(p_y)$ in steel.

Figure 45. Graph of function $p_y(R/R_0)$ in steel.

thickness of the casing, or

$$2R_0\delta_0 + \delta_0^2 = 2R\delta + \delta^2.$$

It obviously can be assumed that after destruction no longer changes, so that by knowing the thickness of the fragments it is possible to determine the internal radius at which destruction of the charge casing takes place:

$$\left(\frac{R}{R_0}\right)_{cr} = \frac{\delta_0}{\delta} \mp \frac{\delta_0^2 - \delta^2}{2\delta R_0}.$$

The value of δ was determined by analyzing the fragments of the charge casing.

Figure 46 shows the dependence of $(R/R_0)_{cr}$ on δ ; the value of R/R_0 at which destruction of the charge casing occurs is a constant value that equals $(R/R_0)_{cr}$.

For 45 steel, if we assume an equation of state in the form

$$p = \frac{\rho_0 c_0^2}{n} \left[\left(\frac{\rho}{\rho_0} \right)^n - 1 \right],$$

where $n = 4$ and $c_0 = 5,300$ m/sec, then it is easy to obtain p_y as a function of v_y (Figure 44).

Since there exists the function $v_y(R/R_0)$ (see Figure 43), it is easy to convert to the function $p_y(R/R_0)$ (Figure 45).

Let us move on to a discussion of the question of the charge casing's destruction. If we ignore the change in the pipe material's density, then according to the mass conservation equation, before destruction it will have:

$$(R_0 + \delta_0)^2 - R_0^2 = (R + \delta)^2 - R^2,$$

where R = current inner radius of the casing; δ = current

Figure 46. Graph of dependence of $(R/R_0)_{cr}$ on δ_0 .

From this it follows that casing destruction begins when a relative deformation of critical magnitude is reached. Since the relative deformation of a moving casing is greatest on its inner surface, the fracture appears in this surface and spreads to the outer surface.

According to our experiments, for 45 steel it is the case that

$$\epsilon_{cr} = \ln \frac{R}{R_0} = \ln 1.84 = 0.61.$$

This critical deformation value was obtained for deformation rates on the order of

$$\frac{d\epsilon}{dt} = 0.2 \cdot 10^5 - 3 \cdot 10^5 \text{ m/sec.}$$

For lower deformation rates (in analogous experiments, but with the use of a VV of lesser density or with lower charge densities), the value of ϵ_{cr} will decrease and, at the limit, approach the value seen under static loading.

On the films obtained by photographing the deformation process (see Figure 41) it is obvious that at a certain moment the fracture moves outward and explosion products, the velocity of which is higher than the pipe's rate of expansion, are issued from it. If we subtract the time required for the fracture to propagate outward from the time of departure of the explosion products, it is possible to obtain $(R/R_0)_{cr}$. In connection with this, the value of $(R/R_0)_{cr}$ is approximately the same for all charges as the δ values for fragments, if we assume that the rate of fracture propagation is 800 m/sec.

The determination of the law of motion of a charge casing's inner surface is also of interest.

If we ignore the change in the casing material's density, then

$$R_{ex}^2 - R_0^2 = (R_0 + \delta_0)^2 - R_0^2.$$

Using expression (119), we obtain:

$$\frac{\left(\frac{R_0 t}{R_0}\right)^2 - 1}{\left(\frac{\delta_0}{R_0} + 1\right)^2} = \left(1 + \frac{\frac{v_0 t}{R_0}}{1 + \frac{\delta_0}{R_0}}\right)^2 - 1.$$

This formula is the experimentally determined expression for the dependence of a casing's inner surface on time t and the relative thickness of the casing δ_0/R_0 , and this confirms the correctness of formula (117), which was derived from the theory of similarity and dimensionalities.

PIPE DEFORMATION AND DESTRUCTION IN WATER AT DIFFERENT HYDROSTATIC PRESSURES

As was shown above, the deformation of a charge casing made from the same material and with the use of the same explosive, is expressed by the following function when the charge is set off in water at different hydrostatic pressures:

$$\frac{R-R_0}{R_0} = f\left(\frac{\delta_0}{R_0}, \beta_S \rho_w Q_w \cdot \frac{t \sqrt{Q}}{R_0}\right).$$

The goal of the experiments was to determine the form of this relationship. In order to do this, charges were detonated inside of casings with different thicknesses (from 1 to 16 mm) in a glass aquarium and in a high-pressure cylinder filled with water. The experiments in the cylinder were performed at pressures (p_0) of 100, 200 and 400 atm (tech.). A recording was made of the change in the charge casing's external radius (R_{ex}) as a function of time t and the law governing the propagation of the shock wave emitted into the water $R_y(t)$.

Figure 47. Explosion in water of charge with $\delta = 6$ mm, $p_0 = 1$ atm (tech.).

Figures 47 and 48 show the filmed record made during the explosion of charges with $\delta = 6$ mm, $p_0 = 1$ atm (tech.) and $\delta = 1$ mm, $p_0 = 400$ atm (tech.).

The deformation of a charge casing's outer wall (Figure 49) takes place with a variable velocity, which decreases with the passage of time. However, the emitted shock wave will move at a constant velocity D_0 that is a function of the casing's thickness δ_0 ; that is,

$$R_y = R_0 + \delta_0 + D_0 t \quad \text{or} \quad \frac{R_y - (R_0 + \delta_0)}{R_0} = \frac{D_0 t}{R_0}. \quad (120)$$

Figure 48. Explosion in water of charge with $\delta = 1$ mm, $p_0 = 400$ atm (tech.).

If we assume that behind the front of the shock wave the water has some average density ρ_1 that is a function of δ , then for the outer wall of a casing charge we obtain, from the mass conservation law:

$$[R_f^2 - (R_0 + \delta_0)^2] \rho_0 = (R_f^2 - R_{ex}^2) \rho_1,$$

from which

$$R_{ex}^2 = R_f^2 \left(1 - \frac{\rho_0}{\rho_1}\right) + (R_0 + \delta_0)^2 \frac{\rho_0}{\rho_1}.$$

Substituting expression (120) into this one, we obtain:

$$R_{in}^2 = \left[(R_0 + \delta_0) + D_0 t\right]^2 \left(1 - \frac{\rho_0}{\rho_1}\right) + (R_0 + \delta_0)^2 \frac{\rho_0}{\rho_1}$$

or

$$\frac{R_{in}^2 - (R_0 + \delta_0)^2 \frac{\rho_0}{\rho_1}}{(R_0 + \delta_0)^2} = \left(1 + \frac{D_0 t}{R_0 + \delta_0}\right)^2. \quad (121)$$

Figure 49. Law of expansion of outer wall of pipe during an explosion in water.

The thickness of the fragments formed during an explosion in water is the same as for an explosion in air. Consequently, casing destruction begins when the relative deformation of the casing's inner surface reaches the same critical value as for an explosion in air.

The law governing the motion of the casing's inner surface can be derived from the mass conservation law for the casing, ignoring the change in its density:

$$R_{in}^2 - R_{0i}^2 = (R_0 + \delta_0)^2 - R_0^2$$

or, by using expression (121),

$$\frac{\left(\frac{R_{0t}}{R_0}\right)^2 - 1}{\left(1 - \frac{\rho_0}{\rho_1}\right) \left(\frac{\delta_0}{R_0} + 1\right)^2} = \left(1 + \frac{\frac{D_0 t}{R_0}}{1 + \frac{\delta_0}{R_0}}\right)^2 - 1.$$

This formula is the experimentally determined dependence of the deformation of a casing's inner surface on time t and the casing's relative thickness δ_0/R_0 , and confirms the correctness of formula (118), which was derived from the theory of similarity and dimensionalities.

The question of the dependence of the average density of the water behind the shock wave's front ρ_1 and the shock wave's velocity D_0 on the variables ρ_0/R_0 and β_s remains open; this dimensionless parameter includes the hydrostatic pressure p_0 , since

$$\beta_s = \frac{1}{An \left(\frac{p_0}{A} + 1\right)}.$$

Figure 50. Dependence of D_0 and ρ_1/ρ_0 on δ_0/R .

The dependence of D_0 on ρ_0/R_0 is obtained during the processing of the films for charges with different casing thicknesses (Figure 50).

Using the mass conservation law for water,

$$(R_1^2 - R_0^2) \rho_0 = (R_1^2 - R_{in}^2) \rho_1,$$

from the photograph we obtained the dependence of ρ_1/ρ_0 on δ_0/R_0 . In connection with this, ρ_1/ρ_0 -- as is the case with D_0 -- is independent of time.

At pressures of up to 400 atm (tech.), the hydrostatic pressure's effect on the casing's deformation is so insignificant

that that it lies within the limits of experimental error. However, the results of the investigations show that hydrostatic pressure reduces the deformation rate and the amount of deformation. Since shell destruction begins when the critical relative deformation is reached on the pipe's inner surface --

$$\epsilon_{cr} = \left(\ln \frac{R_{0t}}{R_0}\right)_{cr},$$

then as p_0 begins to increase starting with some certain value, R_{0t} does not reach a critical value.

Recordings of the deformation of a charge casing's external surface when the charge is set off in water make it possible to determine the attenuation of the pressure at the front of a cylindrical shock wave in 45 steel on the basis of the initial mass velocity of deformation of the casing (v_0). When the cylindrical shock wave approaches the metal-water boundary, a shock wave is emitted into the water and a rarefaction wave appears in the metal.

Let us use the condition of equality of the pressure (p_x) and the mass velocity (v_x) at the boundary.

The equations of state for metal and water have the following form:

$$p = A_m \left[\left(\frac{\rho}{\rho_m} \right)^{n_1} - 1 \right];$$

$$p = A_w \left[\left(\frac{\rho}{\rho_w} \right)^{n_2} - 1 \right].$$

The dependence of the particles' mass velocity on the pressure at the shock wave's front in water, at the moment when the shock wave forms, will take on the form

$$v_x = \sqrt{\frac{p_x - p_0}{\rho_w} \left(1 - \frac{\rho_w}{\rho_x} \right)} = \sqrt{\frac{p_x - p_0}{\rho_w} \left[1 - \frac{1}{\left(\frac{p_x}{A_w} + 1 \right)^{1/n_2}} \right]}. \quad (122)$$

For metal,

$$v_x = v_I + v_1, \quad (123)$$

where v_I = mass velocity at the front of a shock wave in metal;
 v_1 = mass velocity in the rarefaction wave.

Let us compute v_I and v_1 :

$$v_I = \sqrt{\frac{p_I - p_0}{\rho_m} \left(1 - \frac{\rho_m}{\rho_I} \right)} = \sqrt{\frac{p_I - p_0}{\rho_m} \left[1 - \frac{1}{\left(\frac{p_I}{A_m} + 1 \right)^{1/n_1}} \right]};$$

$$v_1 = \int_{p_x}^{p_I} \frac{dp}{\rho c};$$

$$\frac{\rho}{\rho_m} = \left(\frac{p}{A_m} + 1 \right)^{1/n_1};$$

$$c = \sqrt{\frac{\partial p}{\partial \rho}} = \sqrt{\frac{n_1 A_m}{\rho_m} \left(\frac{\rho}{\rho_m} \right)^{\frac{n_1-1}{2}}} = \sqrt{\frac{n_1 A_m}{\rho_m} \left(\frac{p}{A_m} + 1 \right)^{\frac{n_1-1}{2n_1}}};$$

$$v_1 = \int_{p_x}^{p_1} \frac{dp}{V^{n_1 A_m \rho_m} \left(\frac{p}{A_m} + 1 \right)^{\frac{n_1+1}{2n_1}}} = \frac{2}{n_1-1} \sqrt{\frac{A_m n_1}{\rho_m}} \left[\left(\frac{p_1}{A_m} + 1 \right)^{\frac{n_1-1}{2n_1}} - \left(\frac{p_x}{A_m} + 1 \right)^{\frac{n_1-1}{2n_1}} \right].$$

Substituting the obtained values into equation (123) and using formula (122), we derive the relationship between p_x and p_1 :

$$\sqrt{\frac{p_x - p_0}{\rho_m} \left[1 - \left(\frac{p_x}{A_m} + 1 \right)^{-1/n_1} \right]} = \sqrt{\frac{p_1 - p_0}{\rho_m} \left[1 - \left(\frac{p_1}{A_m} + 1 \right)^{-1/n_1} \right]} + \frac{2}{n_1-1} \sqrt{\frac{A_m n_1}{\rho_m}} \left[\left(\frac{p_1}{A_m} + 1 \right)^{\frac{n_1-1}{2n_1}} - \left(\frac{p_x}{A_m} + 1 \right)^{\frac{n_1-1}{2n_1}} \right].$$

Figure 51. Dependence of p_x on p_1 .

Figure 52. Dependence of p_x on v_x .

Figure 53. Dependence of p_y and v_x on R/R_0 .

cal shock wave's pressure in 45 steel (see Figure 53).

The function $p_y(R/R_0)$ for a cylindrical shock wave in 45 steel was also derived from the results of the experiments conducted in air. These functions are identical, which is confirmation of their reliability.

The data obtained as a result of the experiments make it possible to reach the following conclusions.

1. During an explosion in air, the deformation of a pipe's external surface takes place -- regardless of the casing charge's thickness -- at a constant rate, the magnitude of which decreases as the charge casing's thickness increases.

2. Pipe deformation during an explosion in water takes place at a variable rate that decreases as the motion does. In connection with this, the shock wave emitted into the water will move at an almost constant velocity; the greater the charge casing's thickness, the lower this velocity.

3. Pipe destruction in both air and water begins when some critical relative deformation level is reached:

$$\varepsilon_{cr} = 0,61.$$

4. Since the relative deformation is greatest on the pipe's inner surface, fractures propagate outward from this surface.

5. The following properties of the surrounding medium affect pipe deformation:

- a) density and initial pressure, with an increase in which the curve $R(t)$ sinks toward the time axis;
- b) compressibility, a reduction in which leads to a decrease in pipe deformation (R/R_0).

CHAPTER 7. DIMENSIONS OF THE CAVITY FORMED BY AN UNDERGROUND EXPLOSION

FORMULATION OF THE PROBLEM

During the solution of a number of problems related to controlling explosion processes, evaluating their possible effect, and selecting the parameters of explosive operations on a rational basis, it is necessary to know the regularities governing the gas cavity's expansion during an underground explosion. Under certain conditions, an underground explosion can be used to create underground storage capacities.

For the theoretical study of an underground explosion, it is first of all necessary to have a mathematical model of the soil (rock) that allows for its basic properties and behavior during an explosion with an adequate degree of accuracy.

The structure and properties of rocks and soils vary within wide limits. They can be loose, plastic, or friable, and both their specific weight and strength characteristics can be different. In view of these facts, the numerous attempts to use a single mathematical model for soils that would make it possible to investigate both gas cavity expansion and shock wave distribution have not met with any noticeable success.

In our opinion, in order to determine the parameters of an underground cavity and its expansion time (without detriment to the correctness of the results), there is no need to examine some generalized model or another that would make it possible to study the actual distribution of the shock wave at the same time. In confirmation of this, we can present the fact that the theory of an incompressible fluid (as was shown in preceding chapters), by eliminating the existence of a shock wave, gives an analytical solution for the regularities governing the expansion of a gas bubble in water that quite adequately coincides with the experimental data.

In connection with this, when determining the maximum radius and time of expansion of a gas cavity, we will -- without taking into consideration the various physical properties of soils -- consider soil during an explosion to be a fluid with an internal hydrostatic pressure equal to the strength resistance of the soil; that is, to the dynamic limit of its fluidity plus the rock pressure.

It is obvious that this soil model is unsuitable for describing shock wave distribution. In our particular problem, however, it quite correctly reflects the behavior of a large class of plastic rocks (such as water-saturated clays, clayey limestones and others) and, as will be shown below, leads to results that agree satisfactorily with the experimental results.

We will solve the problem as it applies to two soil models: 1) soil with an initial density ρ_0 acted upon by an explosion that compresses it to a state ρ_1 , after which the medium becomes incompressible (Model I); 2) beginning with distances from the explosion source of $R_k \approx 1.5 - 2R_0$, where R_0 is the radius of the charge, the soil -- because of the sharp pressure drop in the explosion products -- is regarded as an incompressible fluid (Model II). The assumption in Model I was earlier used in the works of A.S. Kompaneys [43] and K.P. Stanyukovich [16].

Model I is most suitable for media with relatively high "free" porosity (porous rocks and soils with a low degree of water saturation). The compression of these medium takes place because of the elimination of their porosity; in connection with this, we ignore their adiabatic compressibility when acted upon by an explosion.

To a large degree, Model II is suitable for low-porosity rock and highly water-saturated soil, the compressibility of which through elimination of their free porosity is extremely insignificant.

CAVITY DIMENSIONS AND FORMATION TIME FOR A SPHERICAL UNDERGROUND EXPLOSION

Given the assumptions made for Model I, the movement of the soil will be described by the following two equations of motion in Euler form:

$$\rho_1 \left(\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial r} \right) = - \frac{\partial p}{\partial r}; \quad (124)$$

$$\frac{\partial}{\partial r} (r^2 v) = 0, \quad (125)$$

where v = mass velocity of the soil; p = pressure; ρ_1 = density of the soil behind the shock wave's front; r , t = current radius and time.

The boundary conditions that are applicable to Model I are the conditions at the front of the shock wave:

$$\rho_0 \dot{R}_{sw} = \rho_1 (\dot{R}_{sw} - v_{sw}); \quad (126)$$

$$p_{sw} - p_0 = \rho_0 \dot{R}_{sw} v_{sw}, \quad (127)$$

where R_{sw} = radius of propagation of the shock wave.

Let us remember that the soil in both models is similar to a fluid with hydrostatic pressure p_0 that equals the soil's strength resistance.

At the VV-soil interface, it is necessary to equate the pressure in the explosion products to the pressure in the soil, as well as their velocities:

$$\bar{p} = p, \quad \bar{v} = v.$$

The solutions of equations (124) and (125) have the following form:

$$v = \frac{f(t)}{r^2}; \quad (128)$$

$$p = \rho_1 \frac{f(t)}{r} - \rho_1 \frac{f^2(t)}{2r^4} + C(t). \quad (129)$$

Substituting expression (128) into (126), we obtain:

$$f(t) = \left(1 - \frac{\rho_0}{\rho_1}\right) R_{sw}^2 \dot{R}_{sw}; \quad (130)$$

$$f(t) = \left(1 - \frac{\rho_0}{\rho_1}\right) R_{sw} (2\dot{R}_{sw}^2 + R_{sw} \ddot{R}_{sw}). \quad (131)$$

Substituting expression (129) into (127) and using (130) and (131), we will have:

$$p = p_0 + \rho_0 \left(1 - \frac{\rho_0}{\rho_1}\right) \dot{R}_{sw}^2 + \rho_1 \left(1 - \frac{\rho_0}{\rho_1}\right) (2\dot{R}_{sw}^2 + R_{sw} \ddot{R}_{sw}) \times \\ \times \left(\frac{R_{sw}}{r} - 1\right) - \frac{\rho_1}{2} \left(1 - \frac{\rho_0}{\rho_1}\right) \dot{R}_{sw}^2 \left[\left(\frac{R_{sw}}{r}\right)^4 - 1\right]. \quad (132)$$

For the future, let us introduce the designation

$$1 - \frac{\rho_0}{\rho_1} = \beta. \quad (133)$$

Using the mass conservation law, let us express the cavity's radius of expansion (R) in terms of the shock wave's radius of propagation (R_{sw}):

$$\frac{4}{3} \pi (R_{sw}^3 - R_0^3) \rho_0 = \frac{4}{3} \pi (R_{sw}^3 - R^3) \rho_1. \quad (134)$$

Ignoring the value of R_0^3 , which is small in comparison to R_{sw}^3 , we obtain:

$$R = \left(1 - \frac{\rho_0}{\rho_1}\right)^{1/2} R_{sw} = \beta^{1/2} R_{sw}. \quad (135)$$

Substituting the value of R from formula (135) into (132), let us write the equation obtained for the VV-soil interface:

$$p = p_0 + \rho_0 \beta^{1/2} \dot{R}^2 + \rho_0 \beta^{1/2} (2\dot{R}^2 + R\ddot{R}) (\beta^{-1/2} - 1) - \frac{1}{2} \rho_1 \beta^{1/2} \dot{R}^2 (\beta^{-1/2} - 1). \quad (136)$$

It is necessary to mention that p is a known function of R , since $\bar{p} = p$ according to expression (127), while the law for the change in the explosion product's pressure (p) is known.

Finally, we obtain the following differential equation for determining the cavity expansion law:

$$R\ddot{R} + \dot{R}^2 \left[2 + \frac{\rho_0}{\rho_1 (\beta^{-1/2} - 1)} - \frac{\beta (\beta^{-1/2} - 1)}{2 (\beta^{-1/2} - 1)} \right] = \frac{p - p_0}{\rho (1 - \beta^{1/2})}. \quad (137)$$

or

$$2R\ddot{R} + \dot{R}^2 [3 + \beta^{1/2} (1 + \beta^{1/2} + \beta^{1/2})] = \frac{2(p - p_0)}{\rho_1 (1 - \beta^{1/2})}.$$

Let us introduce the definitions:

$$a = 3 + \beta^{1/2} (1 + \beta^{1/2} + \beta^{1/2}); \quad (138)$$

$$f(R) = \frac{2(p - p_0)}{\rho_1 (1 - \beta^{1/2})}. \quad (139)$$

Equation (137) will become:

$$2R\ddot{R} + a\dot{R}^2 = f(R). \quad (140)$$

After the appropriate transformations, we will obtain:

$$\frac{d}{dR} (\dot{R}^2 R^a) = f(R) R^{a-1}. \quad (141)$$

By integrating the obtained equation within limits from R_0 to R , we find the rate of motion of the VV-soil interfaces:

$$v^2 = v_0^2 \left(\frac{R_0}{R} \right)^a + \frac{1}{R^a} \int_{R_0}^R f(R) R^{a-1} dR, \quad (142)$$

where v_0 = the value of v at $R = R_0$.

The pressure function for the explosion products' volume is expressed by the adiabatic curve:

$$pV^n = \text{const}, \quad (143)$$

it being the case that -- as was shown above -- $n = k = 3$ for $p > p_k$ and $n = \gamma = 7/5$ for $p < p_k$, where

$$p_* = p_I \left\{ \frac{\gamma-1}{k-\gamma} \left[\frac{(k-1) E_{VV}}{p_I V_I} - 1 \right] \right\}^{1/2}. \quad (144)$$

The average initial pressure p_I appearing in the charge itself is

$$p_I = \frac{1}{8} \rho_{VV} D^2. \quad (145)$$

Since the integral of the pressure in the explosion products is part of the expression for the gas cavity's expansion rate (142), the error will be insignificant if the dependence of the explosion products' pressure on their radius of expansion is given in the form

$$p = p_I \left(\frac{V_0}{V} \right)^3 = p_I \left(\frac{R_0}{R} \right)^9. \quad (146)$$

Substituting expression (146) into (142) and ignoring terms $(R_0/R)^{9-a}$ and $(R_0/R)^a$ ($a \approx 3$), which are much smaller than unity, we obtain:

$$v = \left\{ \frac{2p_0}{\rho_1 (1-\beta^{1/2})^a} \left[\left(\frac{R_{\max}}{R} \right)^a - 1 \right] \right\}^{1/2}. \quad (147)$$

In connection with this, we automatically obtain the expression for the gas cavity's maximum radius of expansion; that is, the radius at which the velocity of the detonation products-soil interface equals zero:

$$R_{\max} = R_0 \left[\frac{v_0^2 + \frac{2p_I}{(9-a)\rho_1(1-\beta^{1/2})}}{\frac{2p_0}{a\rho_1(1-\beta^{1/2})}} \right]^{1/a}$$

or, substituting $p_I = (\rho_{VV} D^2)/8$, we find that

$$\frac{R_{\max}}{R_0} = \left[\frac{\left(\frac{v_0}{D} \right)^2 + \frac{a-3}{4(9-a)} \frac{\rho_{VV}}{\beta^{1/2}\rho_0}}{\frac{2(a-3)}{a\beta^{1/2}} \frac{p_0}{\rho_0 D^2}} \right]^{1/a} \quad (148)$$

In order to determine the gas cavity's maximum expansion time, it is necessary to integrate the expression for $v = dR/dt$ of the gas cavity's expansion (147) within limits from R_0 to $R = R_{\max}$:

$$t_{\max} = \frac{R_{\max}}{v_0} \left[\frac{\rho_1 v_0^2 (1-\beta^{1/2})^a}{2p_0} \right]^{1/2} I, \quad (149)$$

where

$$\dot{I} = \int_{R_0/R_{\max}}^1 \left(\frac{1}{z^a} - 1 \right)^{-1/2} dz.$$

Let us compute the integral, after splitting it into the two integrals

$$\dot{I} = \int_0^1 z^{a/2} (1-z^a)^{-1/2} dz - \int_0^{R_0/R_{\max}} z^{a/2} (1-z^a)^{-1/2} dz.$$

The first integral reduces to the tabular expression:

$$I_1 = \frac{1}{a} \int_0^1 z^{\frac{2-a}{a}} (1-z^a) d(z^a) = \frac{\Gamma(1/2) \Gamma\left(\frac{2+a}{2a}\right)}{a \Gamma\left(\frac{a+1}{a}\right)} = \frac{\sqrt{\pi}}{a} \frac{\Gamma\left(\frac{2+a}{2a}\right)}{\Gamma\left(\frac{a+1}{a}\right)}.$$

We compute the second integral by expanding the subintegral expression into a series of powers of z :

$$\begin{aligned} I_2 &= \int_0^{R_0/R_{\max}} z^{a/2} \left(1 + \frac{1}{2} z^a + \frac{1 \cdot 3}{2 \cdot 4} z^{2a} + \frac{1 \cdot 3 \cdot 5}{2 \cdot 4 \cdot 6} z^{3a} + \dots \right) dz = \\ &= \frac{2}{a+2} z^{\frac{a+2}{2}} + \frac{1}{3a+2} z^{\frac{3a+2}{2}} + \dots \Big|_0^{R_0/R_{\max}}. \end{aligned}$$

Since $a > 3$ and $(R_0/R_{\max}) < 1$, then (with sufficient accuracy)

$$I_2 = \frac{2}{a+2} \left(\frac{R_0}{R_{\max}} \right)^{\frac{a+2}{2}}.$$

Finally, we obtain the following expression for the gas cavity's maximum time of expansion in plastic soil (rock):

$$\begin{aligned} t_{\max} &= \left[\frac{\sqrt{\pi}}{a} \frac{\Gamma\left(\frac{a+2}{2a}\right)}{\Gamma\left(\frac{a+1}{a}\right)} - \frac{2}{a+2} \left(\frac{R_0}{R_{\max}} \right)^{\frac{a+2}{2}} \right] \times \\ &\times \left[\frac{\rho_1 V_0^2 (1-\beta)^{1/2} a}{2p_0} \right]^{1/2} \frac{R_{\max}}{V_0}. \end{aligned} \quad (150)$$

Let us move on to the determination of the detonation products-soil interface's initial velocity v_0 . We will assume the detonation to be instantaneous.

Eliminating R_{sw} from the previously described conditions at the shock wave's front (125) and (126) [sic -- probably (126) and (127)] and ignoring p_0 , we obtain:

$$p_{sw} = \frac{\rho_0 v_{sw}^2}{1 - \rho_0/\rho_1} = \frac{\rho_0}{\beta} v_{sw}^2. \quad (151)$$

For an instantaneous detonation, for the detonation products we will have:

$$v_{sw} = \frac{2}{k-1} (c_I - c_{sw}) = c_I - c_{sw}, \quad (152)$$

where c_I and c_{sw} = speed of sound in the detonation products and at the shock wave's front.

Using the known relationships for the detonation products

$$c = \sqrt{\frac{3p_I}{\rho_{vw}}} = \sqrt{\frac{3}{8}} D \quad \text{and} \quad \frac{c_{sw}}{c_I} = \left(\frac{p_{sw}}{p_I} \right)^{1/2},$$

equation (152) takes on the form

$$v_{sw} = \frac{\sqrt{6}}{4} D \left[1 - \left(\frac{p_{sw}}{p_I} \right)^{1/2} \right]. \quad (153)$$

Eliminating p_{sw} from expressions (151) and (153), we obtain the following relationship for finding $v_0 = v_{sw}$:

$$\left(1 - \frac{4}{\sqrt{6}} \frac{v_0}{D} \right)^3 = \frac{\rho_0}{\beta p_I} v_0^3$$

or, since $p_I = (\rho_{vw} D^2)/8$,

$$\frac{8\rho_0}{\beta \rho_{vw}} \left(\frac{v_0}{D} \right)^3 = \left(1 - \frac{2\sqrt{6}}{3} \frac{v_0}{D} \right)^3. \quad (154)$$

If we ignore the term $(v_0/D)^3$ in equation (154), then

$$\frac{v_0}{D} = \frac{\sqrt{2 \left(\frac{4\rho_0}{\beta \rho_{vw}} - 1 \right)} - \sqrt{6}}{8 \left(\frac{\rho_0}{\beta \rho_{vw}} - 1 \right)}. \quad (155)$$

When model $\pi(\rho = \rho_0 = \text{constant})$ is used, the solution of the problem can be derived from the preceding solution, provided that $\beta \rightarrow 0$. In this case, equation (138) will take on the form:

$$R\ddot{R} + \frac{3}{2} R^2 = \frac{p - p_0}{\rho_0}.$$

Equation (142) is written thus:

$$v^2 = v_1^2 \left(\frac{R_{cr}}{R} \right)^3 + \frac{2}{R^3} \int_R^R \frac{p - p_0}{\rho_0} R^2 dR, \quad (156)$$

where v_1 = value of velocity v for $R = R_{cr}$.

According to this model, the integral of the pressure in the explosion products is taken for $R \geq R_{cr}$, where $R_{cr} \approx 2R_0$, so that it is necessary to give the dependence of the pressure in

them on the radius of expansion in the form

$$p = p_{cr} \left(\frac{v_k}{v} \right)^{1/3} = p_{cr} \left(\frac{R_{cr}}{R} \right)^{1/3} = p_I \left(\frac{p_{cr}}{p_I} \right)^{1/3} \left(\frac{R_0}{R} \right)^{1/3}, \quad (157)$$

where p_{cr} is determined by expression (144).

Substituting equation (157) into the expression for the gas cavity's rate of expansion (156), we obtain:

$$v^2 = \left(\frac{R_{cr}}{R} \right)^3 \left\{ v_k^2 + \frac{5p_{cr}}{3\rho_0} \left[1 - \left(\frac{R_{cr}}{R} \right)^{1/3} \right] \right\} - \frac{2p_0}{3\rho_0} \left[1 - \left(\frac{R_{cr}}{R} \right)^3 \right]. \quad (158)$$

From equation (158), let us determine the expression for the gas cavity's maximum radius of expansion, taking $v = 0$ and ignoring terms v_k^2 , which is small in comparison with $(5p_{cr})/3\rho_0$, and $(R_{cr}/R)^{6/5}$ and $(R_{cr}/R)^3$, which are less than unity:

$$R_{max} = \left(\frac{5p_{cr}}{2p_0} \right)^{1/3} R_{cr} \quad \text{or} \quad R_{max} = \left(\frac{p_I}{p_{cr}} \right)^{1/3} \left(\frac{5p_{cr}}{2p_0} \right)^{1/3} R_0. \quad (159)$$

Using formula (159), we find the expression for the gas cavity's rate of expansion:

$$v = \left(\frac{2p_0}{3\rho_0} \right) \left[\left(\frac{R_{max}}{R} \right)^3 - 1 \right]^{1/2}. \quad (160)$$

By integrating within limits from R_0 to R_{max} and using the result of the computation of the integral in expression (150), we find the relationship for the gas cavity's maximum expansion time with respect to Model II of the soil:

$$t_{max} = \left[\frac{\sqrt{\pi}}{3} \frac{\Gamma\left(\frac{5}{6}\right)}{\Gamma\left(\frac{4}{3}\right)} - \frac{2}{5} \left(\frac{R_0}{R_{max}} \right)^{1/3} \right] \sqrt{\frac{3\rho_0}{2p_0}} R_{max}. \quad (161)$$

CAVITY DIMENSIONS AND FORMATION TIME FOR A CYLINDRICAL UNDERGROUND EXPLOSION

The soil's movement will be described by the equations

$$\rho_1 \left(\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial r} \right) = - \frac{\partial p}{\partial r}; \quad (162)$$

$$\frac{\partial}{\partial r} (rv) = 0. \quad (163)$$

The solution of these equations is:

$$v = \frac{f(t)}{r}; \quad (164)$$

$$p = -\rho_1 f(t) \ln r - \rho_1 \frac{f^2(t)}{2r^2} + c(t). \quad (165)$$

Substituting expression (164) into boundary condition (125), which has the same form as in the case of a spherical explosion, we obtain:

$$f(t) = (1 - \rho_0/\rho_1) R_{sw} \dot{R}_{sw}; \quad (166)$$

$$\dot{f}(t) = (1 - \rho_0/\rho_1) (\dot{R}_{sw} + R_{sw} \ddot{R}). \quad (167)$$

Substituting expression (165) into boundary condition (126) and using formulas (166) and (167), we find:

$$p = p_0 + \rho_0 \beta \dot{R}_{sw}^2 + \rho_1 \beta (\dot{R}_{sw}^2 + R_{sw} \ddot{R}) \ln \frac{R_{sw}}{r} - \frac{\rho_1}{2} \beta^2 \dot{R}_{sw}^2 \left[\left(\frac{R_{sw}}{r} \right)^2 - 1 \right]. \quad (168)$$

Starting with the mass conservation law, let us express the cavity's radius of expansion R in terms of the shock wave's radius of propagation R_{sw} :

$$\pi (R_{sw}^3 - R_0^3) \rho_0 = \pi (R_{sw}^3 - R^3) \rho_1; \quad (169)$$

if we ignore R_0^3 , then

$$R = \beta^{1/3} R_{sw}. \quad (170)$$

According to expression (165), when (170) is taken into consideration, for the VV-soil interface we will have:

$$p = p_0 + \rho_0 \dot{R}^2 - \frac{\rho_1}{2} (\dot{R}^2 + R \ddot{R}) \ln \beta - \frac{\rho_1}{2} (1 - \beta) \dot{R}^2 \quad (171)$$

or

$$2R\ddot{R} + a\dot{R}^2 = f(R), \quad (172)$$

where

$$a = 2 + \frac{2(1-\beta)}{\ln \frac{1}{\beta}}; \quad (173)$$

$$f(R) = \frac{4(p-p_0)}{\rho_1 \ln \frac{1}{\beta}}. \quad (174)$$

Pressure p is a known function of radius R (143), since the pressure in the explosion products and the soil is identical at their interface.

Analogously to the case of a spherical explosion, the solution of equation (172) is:

$$v^2 = v_0^2 \left(\frac{R_0}{R} \right)^a + \frac{1}{R^a} \int_{R_0}^R f(R) R^{a-1} dR. \quad (175)$$

According to expression (142), the dependence of the VV's

pressure on the radius of expansion is:

$$p = p_I \left(\frac{v_0}{v} \right)^3 = p_I \left(\frac{R_0}{R} \right)^6. \quad (176)$$

Substituting formula (176) into expression (175) and ignoring the small terms, we will have:

$$v = \left\{ \frac{2p_0}{\rho_1 a \ln \frac{1}{\beta}} \left[\left(\frac{R_{\max}}{R} \right)^a - 1 \right] \right\}^{1/2} \quad \text{and} \quad R_{\max} = R_0 \left[\frac{v_0^2 + \frac{4p_I}{(6-a)\rho_1 \ln \frac{1}{\beta}}}{\frac{4p_0}{\rho_1 a \ln \frac{1}{\beta}}} \right] \quad (177)$$

or, having made the substitution $p_I = (\rho_{VV} D^2)/8$ and using expression (173),

$$\frac{R_{\max}}{R_0} = \left[\frac{\left(\frac{v_0}{D} \right)^2 + \frac{a-2}{4(6-a)} \frac{\rho_{VV}}{\rho_0}}{2 \frac{a-2}{a} \frac{p_0}{\rho_0 D}} \right]^{1/a} \quad (178)$$

Integrating equation (177) within limits of R_0 to $R_{\max}$ and using the corresponding calculations made for the case of a spherical explosion, we obtain the expression for the gas cavity's maximum explosion:

$$t_{\max} = \left[\frac{\sqrt{\pi}}{a} \frac{\Gamma\left(\frac{a+2}{a}\right)}{\Gamma\left(\frac{a+1}{a}\right)} - \frac{2}{a+2} \left(\frac{R_0}{R_{\max}} \right)^{\frac{a+2}{2}} \right] \times \left(\frac{a\rho_1 v_0^3 \ln \frac{1}{\beta}}{2p_0} \right)^{1/2} \frac{R_{\max}}{v_0}. \quad (179)$$

The value of the explosion products-soil interface's initial velocity is determined by expression (153) or, less accurately, by (154).

When model π ($\rho = \rho_0 = \text{constant}$) is used, it is not possible to solve the problem, since the condition of incompressibility of the medium means that infinite energy is needed for the expansion of the cavity. When $\beta \rightarrow 0$, however, according to expressions (173) and (178) we have

$$\lim_{\beta \rightarrow 0} a = \lim_{\beta \rightarrow 0} \left[2 + \frac{2(1-\beta)}{\ln \frac{1}{\beta}} \right] = 2 \quad \text{and} \quad \frac{R_{\max}}{R_0} = \left(\frac{p_I}{2p_0} \right)^{1/2}. \quad (180)$$

From Figure 54 and expressions (148) and (178) it follows that for identical radii of expansion, the gas cavity's volume in the case of a cylindrical explosion is noticeably greater than for a spherical explosion.

It is also interesting to compare the volumes of the gas cavities for both cases when the charge's weight (volume) is the same. It is obvious that

Figure 54. Dependence of underground cavity's radius on parameter $(\rho_0 D^2)/p_0$.
Key: 1. Cylindrical charge
2. Spherical charge

$$\frac{V_c}{V_v} = \left(\frac{R_{\max}}{R_0} \right)_c^2; \quad \frac{V_s}{V_v} = \left(\frac{R_{\max}}{R_0} \right)_s^2,$$

where V_c and V_s = maximum gas cavity volumes for cylindrical and spherical charges.

From this it follows that

$$\frac{V_c}{V_s} = \left(\frac{R_{\max}}{R_0} \right)_c^2 \left(\frac{R_0}{R_{\max}} \right)_s^2. \quad (181)$$

Figure 55. Dependence of V_c/V_s on parameter $(\rho_0 D^2)/p_0$.

From Figure 55, which characterizes (for a uniform type of charge) the relationship $V_c/V_s = \Phi([\rho_0 D^2]/p_0)$, it follows that for relatively low values of the dimensionless parameter $(\rho_0 D^2)/p_0$, the gas cavity's volume is greater for a cylindrical charge than for a spherical one. However, beginning with some value of $(\rho_0 D^2)/p_0$ that depends, in turn, on the value of β , the volumes become equal, and a further increase in the value of parameter $(\rho_0 D^2)/p_0$ will cause the pattern to reverse itself; that is, $V_s > V_c$.

All other conditions being equal ($D, \rho_0 = \text{constants}$), the value of V_c/V_s essentially depends on the rock's strength characteristics, as determined by the value of p_0 . For the relatively low values of p_0 that are typical of soils, a larger gas cavity forms during a spherical explosion than during a cylindrical one, while the opposite will be true when p_0 has the relatively high values typical of rock. For instance, for VV's of the ammonite No 6 type ($D \approx 3,800$ m/sec), rock density of 2.3 g/cm³, and $\beta = 0.1$, a spherical charge is more suitable when $p_0 < 800$ atm (tech.), while a cylindrical one is better when $p_0 > 800$ atm (tech.).

Figure 56. Graph of dependences of V_0/D [sic] on parameter $(\beta\rho_{VV})/\rho_0$ (1), a_s on β (2), and a_c on β (3).

VV's and rock's properties. Let us demonstrate this in the following example. Let us have the explosion of a spherical charge of the explosive ammonite No 6 ($D = 3,800$ m/sec, $\rho_{VV} = 1.1$ g/cm³) in soil with $\rho_0 = 1.9$ g/cm³, $\beta = 0.159$, $p_0 = 25$ atm (tech.). Using Figure 56, let us determine the value of V_0/D and a for $\beta = 0.159$; that is, $(\beta\rho_{VV})/\rho_0 = 0.092$. Substituting the values $a = 3.95$ and $V_0/D = 0.085$, as found from the graph, into formula (149), we obtain $R_{\max}/R_0 = 5.7$. This value agrees satisfactorily with the results of range experiments: for the same charge and soil parameters, $R_{\max}/R_0 = 5.9$.

Parameter β , which characterizes the degree of compression of the rock because of elimination of its porosity, also affects the gas cavity's maximum radius of expansion: as β decreases, which corresponds to a decrease in the soil's free porosity, the value of $R_{\max}/R_0$ increases, it being the case that the effect of this factor increases as $(\rho_0 D^2)/p_0$ does (see Figure 55).

Figure 56 shows the dependences of parameter a on β and V_0/D on $(\beta\rho_{VV})/\rho_0$.

With the help of these graphs, it is easy to determine the gas cavity's maximum radius of expansion as a function of the

CHAPTER 8. THERMOSTABLE POWDERS AND THEIR OPERATIONAL EFFICIENCY IN SHOOTING CORING TOOLS AND GUN PERFORATORS

For borehole temperatures up to 100°C , the charges used in shooting coring tools and gun perforators are mostly composed of the standard powder NBpl.

A number of thermostable powders have been developed for deep, high-temperature boreholes. In this case, however, flaked thermostable powders are of limited use, since charges composed of them tend to cake at a temperature lower than the thermostability threshold of a powder in poured form, which leads to a considerable reduction in the charge's ballistic characteristics.

For instance, when PTpl powder, which is thermostable in poured form at temperatures up to $180\text{--}190^{\circ}\text{C}$, is used in pressed charges, they are not suitable for use at temperatures above 150°C .

Modern thermostable powders for short-barreled borehole systems are fast-burning mechanical mixtures that can be pressed into charges with a high density that is close to the maximum for the given mixture. The use of high-polymer phlegmatizing additives in such mixtures, as well as the high density of the charges, limits the possibility of transforming their combustion into detonation at the high (up to $20,000\text{--}22,000$ atm (tech.)) pressures developed in perforator and coring tool chambers.

Thermostable powders and charges composed of them with thermostability thresholds up to 250°C have been developed in the Soviet Union. The most promising ones are the compounds G-80, O-75 and P-65, which have thermostability thresholds of 180, 210 and 250°C , respectively.

Under production conditions, powder charges of variable weight are used in shooting coring tools, with the weight being determined by the hydrostatic pressure in the borehole and the

hardness of the rock being sampled. In order to sample one or another type of rock with adequate efficiency, it is necessary to have a certain rate of striker movement that depends on the density of the charge, the type of powder used, and the liquid pressure on the striker. In order to choose the optimum charge density for sampling rock in boreholes, it is necessary to know the efficiency of charges made from the powders that are used, depending on the charging conditions and the external pressure.

The performance or efficiency of charges made from standard NBpl powder and used in gun perforators and shooting coring tools has been investigated under laboratory and production conditions [32,48]. Charges of thermostable powders have only begun to be used in test-firing and coring-tool operations, so it is extremely important to investigate the effect of different factors -- hydrostatic pressure, increased charge temperature and density -- on the ballistic characteristics and effectiveness of such powders.

CHARGING UNITS

Figure 57. Thermostable charge for coring tools of the MSG-90 type: 1. charge of thermostable powder; 2. igniting composition; 3. block with heating bridge and current-carrying wires; 4. lacquer coating.

Figure 58. Thermostable charge for coring tools of the MSG-90M type: 1. charge of thermostable powder; 2. igniting composition in drop form; 3. insulating disk; 4. foil band electric contacts; 5. heating bridge; 6. thermostable glue.

The designs of thermostable charges for coring tools are in accordance with the layouts of two types of modern, selective coring tools, the MSG-90 and the MSG-90M (Figures 57 and 58). The charge cartridges are produced by pressing G-80, O-75 and P-65 powdered compounds to their maximum density (1.79, 1.91 and 1.97 g/cm³, respectively).

Figure 59. Thermostable charge for perforators of the APKh type: 1. thermostable powder cartridges; 2. lacquer coating; 3. point where cartridges are glued together.

We also investigated powdered thermostable charges for gun perforators of the APKh type, the layout of which is shown in Figure 59. Each charge consisted of two cartridges that were equal in weight and were glued to each other. This charge arrangement was necessitated by the need for uniform density along its entire length.

The density of the thermostable powder cartridges was considerable higher than that of monotypical cartridges of standard NBpl powder, which made it possible to increase the charge density without changing the charge chamber's volume. For instance, for G-80 powder the charge density in the perfora-

tor was increased by 20 percent in comparison with NBpl powder, while for P-65 powder the increase was 40 percent.

Since the force (f) of P-65 powder is about 40 percent less than that of NB powder, the batches of charges made from it were enlarged by 40 percent.

RELATIVE EFFICIENCY OF THE CHARGES

During tests under laboratory or bench conditions, it is most convenient to determine the efficiency of charges for gun perforators on the basis of data on the initial (muzzle) velocity of the "bullet" and firing pin (v_1) or their penetrating power for the appropriate targets under conditions simulating those encountered when they are used for production purposes. In connection with this, however, it is necessary to allow for the possible effect of the target's temperature on the depth of penetration (H_{pen}).

For a more nearly complete evaluation of the effectiveness of a powder charge, it is also necessary to determine the maximum gas pressure (p_{max}) created during the powder's combustion in the perforator's or coring tool's chamber.

A comparison of the dependences of v_1 and p_{max} on the charge density (Δ) for different powders makes it possible to evaluate the nature of the burning of charges made from these powders in a given system.

Figure 60. Unit for ballistic investigations of APKh-type charges at elevated hydrostatic pressures and temperatures: 1. crusher gauge; 2. PPT-type igniting cylinder; 3. bullet; 4. set of targets; 5. model of APKh perforator; 6. charge; 7. autoclave; 8. electric heater; 9. igniting electric input; 10. thermocouple.
Key: 1. To compressor

Perforators (or models of them) are sometimes fired in air in nested pipes. The results of such tests cannot be accepted as being sufficiently representative, since there are substantial changes in both the charge combustion process and the bullet's interior and exterior ballistics during firing in a fluid under conditions of increased counterpressures. Actually, the effectiveness of a standard APKh-98 charge under a hydrostatic pressure of 100-1,000 atm (tech.) proved to be 27 percent higher than under atmospheric pressure.

The ballistic tests of the new thermostable powders were conducted by firing charges from the single-charge chambers of an APKh-type perforator and an MSG-type coring tool inside a high-pressure device. The charges' effectiveness was evaluated on the basis of data on the bullet's penetrating power, the striker's initial velocity and the powder gasses'

maximum pressure. In both cases, $p_{\max}$ was measured with the help of crusher gauges [32].

Identical targets (4 disks, each 10 mm thick, made of No 3 steel) were used in all the experiments in the device for testing APKh charges (Figure 60). The gap between the muzzle end face and the target was 41 mm; that is, the length of the bullet. Consequently, the bullet began to enter the target at its initial velocity v_i .

In order to investigate the effectiveness of MSG charges, we used a device (Figure 61) in which the autoclave's breech mechanism is also the experimental cylinder, since its interior layout is a model of an MSG-type coring tool. As in a real coring tool, the chamber's volume is 5 cm³. The striker's velocity v_i was measured by the oscillograph method [48], which is based on the flying striker coming into sequential contact with two wire sensors placed 10 mm apart (Figure 62). The time

Figure 61. Device for ballistic investigations of charges for MSG-type coring tools: 1. target; 2. wire sensors for determining the striker's velocity; 3. striker; 4. crusher gauge; 5. autoclave; 6. breech mechanism with interior layout that is a model of an MSG-type coring tool; 7. powder charge; 8. igniter.
Key: 1. To igniting line
2. To compressor

In order to compare the effectiveness of thermostable APKh charges with monotypical charges composed of NBpl powder, we conducted firings from an APKh-98 perforator under a constant hydrostatic pressure of 700 atm (tech.)

Figure 63. Typical oscillogram of recording of striker's initial velocity.

APKh charges is close to that of standard charges. In the case

Figure 62. Diagram of oscillograph method for measuring the striker's velocity in a liquid under pressure: 1. frequency generator; 2. supports; 3. wire sensors; 4. insulators; 5. striker; 6. ground wire.
Key: 1. To OK-17 oscillograph

of passage (τ) of the striker between the sensors was recorded on an oscillogram in the form of a sine curve with a frequency of 200 kc (Figure 63). The striker's initial velocity was defined as the average velocity of the striker's flight over the 10-mm path:

$$v_I = \frac{10}{\tau}.$$

The results of the experiments are presented in Table 32. (The average value was determined from a total of six to eight experiments.)

On the basis of the results that were obtained, it is possible to conclude that the effectiveness of thermostable

Table 32. Effectiveness of Charges for APKh-Type Perforators

Марка пороха (1)	Вес заряда, г (2)	Плотность заряжания, г/см ³ (3)	Глубина пробития, мм (4)	Максимальное давление пороховых газов, ат (5)
НБпл 14/10 (6)	5	1,25	28,0	17 000
Г-80 (7)	5	1,25	30,0	18 600
О-75	5	1,25	29,5	17 500
П-65 (8)	7	1,75	26,0	16 320

Key:

1. Brand of powder	5. Maximum pressure of powder gasses, atm (tech.)
2. Charge weight, g	6. NBpl 14/10
3. Charge density, g/cm ³	7. G-80
4. Depth of penetration, mm	8. P-65

where O-75 and G-80 powders are used, however, p_{max} and -- correspondingly -- H_{pen} are 5-7 percent higher than when NBpl is used. On the other hand, P-65 powder in comparison with NBpl provides 7 percent less depth of penetration than NBpl powder when the pressed charge's volume is the same (although it weighs 40 percent more when P-65 is used).

Figure 64. Dependence of initial velocity of MSG-90 coring tool's striker on charge density for a hydrostatic pressure of 400 atm (tech.): 1. G-80 powder; 2. O-75 powder; 3. NBpl 14/10 powder; 4. P-65 powder.

same v_i value as does NBpl when $\Delta'' = 1.0$ g/cm³. The pressure of the combustion products is also approximately the same when $\Delta''/\Delta' = 1.18$.

The relative effectiveness of charges for coring tools was investigated for $p_0 = 400$ atm (tech.). Charges of variable weight were used: from 3.5 to 5 g for G-80, O-75 and NBpl powders and from 4.2 to 7 g for P-65. The results of these experiments are presented in Figure 64 in the form of the graphic dependence of $v_i(\Delta)$ -- the striker's initial velocity -- on the charge density, and in Figure 65 in the form of the function $p_{max}(\Delta)$. A comparison of relationships $v_i(\Delta)$ and $p_{max}(\Delta)$ shows that O-75 powder differs most advantageously from NBpl. For identical charge densities it provides a v_i value that is approximately 18 percent higher than that produced by NBpl, and when $\Delta' = 0.85$ g/cm³, O-75 provides the

Figure 65. Dependence of p_{max} in an MSG-90 coring tool's chamber on charge density for $p_0 = 400$ atm (tech.): 1. G-80 powder; 2. O-75 powder; 3. P-65 powder; 4. NBpl 14/10 powder.

However, this still does not mean that O-75 powder is also 18 percent more powerful than NBpl, since a powder's power is characterized by its energy constants, which are determined for the complete combustion of a charge in a closed volume. Thus, as far as power (f) is concerned, O-75 powder exceeds NBpl by only 5-7 percent.

In our case, the increased effectiveness of O-75 powder charges in comparison with NBpl charges is explained by the fact that the former apparently have a relationship between combustion rate and pressure (density) that is more advantageous for this system.

The effectiveness of G-80 charges is close to that of charges made from O-75 powder,

although they create a noticeably higher maximum pressure.

As is obvious from Figures 64 and 65, in comparison with O-75 and NBpl, steeper $v_1(\Delta)$ and $p_{max}(\Delta)$ curves are typical of G-80 powder in the area of average values of Δ . This is also explained by the steeper curve representing the dependence of its combustion rate on pressure (density). Charges composed of P-65 -- as was pointed out above -- should be compared with NBpl on a volumetric rather than weight basis; that is, charges of the former weighing 40 percent more than charges of the latter should be compared. When such a comparison is made, P-65 provides an initial striker velocity that is approximately equal to that produced by NBpl. However, the ultrahigh charge densities that are used in this case result in a very rapid increase in pressure during the burning of the charge and, consequently, to very rapid burnout of the charge. The combustion process is approximately "instantaneous"; that is, complete combustion of the charge in a closed volume, so that significantly higher values of p_{max} are obtained for P-65.

EFFECT OF EXTERNAL HYDROSTATIC PRESSURE

In order to evaluate the effect of hydrostatic pressure on the ballistic characteristics of thermostable and standard charges for perforators of the APKh-98 type, such charges were studied

Figure 66. Dependence of depth of penetration of steel targets by APKh-98 perforator bullets on hydrostatic pressure: 1. thermostable G-80 powder charges; 2. standard NBpl 14/10 powder charges.

Figure 67. Dependence of $p_{\max}$ in chamber of APKh-98 perforator on hydrostatic pressure: 1. thermostable G-80 powder charges; 2. standard NBpl 14/10 powder charges.

at elevated liquid pressures (from 1 to 1,000 atm (tech.)) for the same charge density, which was 1.25 g/cm^3 . The results of the tests are shown in Figure 66, as a graph of the dependence of the bullet's depth of penetration (H_{pen}) on the hydrostatic pressure, and Figure 67, as a graph of the dependence of $p_{\max}$ on p_0 .

From these relationships it follows that:

- 1) the perforator's ballistic characteristics at atmospheric pressure and at elevated hydrostatic pressures differ noticeably;
- 2) in the 100-1,000 atm (tech.) pressure interval, the bullet's depth of penetration changes very little as p_0 increases;
- 3) at pressures from approximately 200 to 1,000 atm (tech.), $p_{\max}$ in the barrel increases insignificantly as p_0 does.

This indicates that even at $p_0 = 200-250 \text{ atm}$ (tech.), charge combustion is completed at the initial moment of bullet movement. If we allow for the degree of leakage of gases through the perforator's igniting channels, this fact makes it possible to use the case of "instantaneous combustion" of the charge [68] for ballistic calculations of perforator's of this type.

As is obvious from Figure 67, G-80 powder charges create a somewhat higher maximum pressure in comparison with NBpl, which (particular in the case of "instantaneous combustion" of the charge) should result in an increase in the bullet's initial velocity. This is confirmed by the fact that a slightly greater depth of bullet penetration was produced by a G-80 charge.

Figure 68. Dependence of v_1 and $P_{\max}$ on p_0 for MSG-90 coring tool at different G-80 powder charge densities: 1. v_1 ; 2. $P_{\max}$.

Figure 69. Dependence of v_1 and $P_{\max}$ on p_0 for MSG-90 coring tool at different G-80 powder charge densities: 1. v_1 ; 2. $P_{\max}$.

Figure 70. Dependence of v_1 and $P_{\max}$ on p_0 for MSG-90 coring tool at different P-65 powder charge densities: 1. v_1 ; 2. $P_{\max}$.

The influence of hydrostatic pressure on the effectiveness of thermostable charges for coring tools was investigated at pressures from 200 to 800 atm (tech.). Each type of powder was studied at four charge densities: G-80 and O-75 at 0.7, 0.8, 0.9, and 1.0 g/cm³; P-65 at 0.98, 1.12, 1.26, and 1.40 g/cm³.

Graphs of the dependence of the striker's initial velocity and the powder gases' maximum pressure on the hydrostatic pressure, as derived for the three types of powder, are presented in Figures 68-70.

From all the graphs (Figures 68-70) it is obvious that for a high charge density, as the external pressure increases the curve showing the dependence of $P_{\max}$ on p_0 for the investigated

powders becomes less steep. This is explained by the fact that as p_0 increases, the moment of completion of charge combustion moves away along the barrel toward the charging chamber: to an ever greater degree, the combustion process approximates the burning process for a constant volume. At the same time, the striker's velocity drops more sharply, since the resistance to the striker's flight that increases as the external pressure does is balanced to an ever lesser degree because of the increase in the powder gasses' pressure in the barrel.

Knowing the values of the experimental functions $v_i(p_0)$ and $p_{\max}(p_0)$ should make it easier to choose the optimum charge weight when sampling rock in a borehole under production conditions. In order to determine them it is necessary to the initial velocity of the striker or the weight of the NBpl powder charge required for the sufficiently effective sampling of rock of whatever degree of hardness. These relationships will prove to be extremely valuable for calculating and planning thermostable shooting coring tools.

EFFECT OF CHARGE DENSITY

In order to select the most rational conditions for using thermostable charges in a gun perforator, it is necessary to know the dependence of their ballistic characteristics on the charge density. For standard NBpl powder, this dependence was determined by L.A. Gorbenko [32] in a perforator of the SSP type, which in shape and dimensions of the charging chamber is identical to a perforator of the APKh type.

Table 32. Effect of Charge Density on Effectiveness of Charges for APKh-Type Perforators

Марка пороха (1)	Вес заряда, г (2)	Плотность зарядки, г/см ³ (3)	Глубина пробития, мм (4)	Максимальное давление пороховых газов, ат (5)
Г-80(6)	3,36	1,05	22	16 600
	3,68	1,15	25	17 800
	4,00	1,25	26	18 800
	4,32	1,35	27,5	19 900
	4,8	1,50	29	21 400
	4,0	1,50	29	21 300
НБпл(7)	4,0	1,25	22,5	17 500

Key:

1. Brand of powder	5. Maximum pressure of powder gasses, atm (tech.)
2. Charge weight, g	6. G-80
3. Charge density, g/cm ³	7. NBpl
4. Depth of penetration, mm	

The dependence of the bullet's penetrating power and the powder gasses' maximum pressure on the charge density for G-80 powder

was also investigated, by setting off charges in the chamber of an APKh-84 perforator. The external pressure in these experiments was 500 atm (tech.) (Table 33).

The charge density was changed by changing the weight of the charge in the APKh-84 perforator's chamber, as well as by reducing the chamber's volume while keeping the charge's weight constant at 4 g. In the latter case, the chamber's layout was changed somewhat, in accordance with the shape of the thermostable charge: its height was reduced by 5 mm and the base was made in the form of a truncated cone 3 mm tall so as to halve the critical cross-section of the bore's bottom part, since the powder gasses' greatest pressure and, consequently, the greatest bulging of the bore during repeated firings from the perforator arise in the bottom part of the chamber. In view of this, the use of a chamber with a conical base is fully justified when the charge density is increased. For a charge density of 1.5 g/cm^2 , both standard and altered chambers result in the same depth of penetration by the bullet.

Figure 71. Change in $v_1(\Delta)$ and $p_{max}(\Delta)$ as a function of charge density for an MSG-90 coring tool at a hydrostatic pressure of 800 atm (tech.): 1. $v_1(\Delta)$ curves; 2. $p_{max}(\Delta)$ curves.

since under such conditions the difference in the law governing the combustion rate must have considerably less influence on the nature of the $v_1(\Delta)$ curves.

The results of the investigations showed that the penetrating power of APKh-type perforators can be increased by 25-28 percent by using G-80 powder charges instead of standard charges.

The effect of charge density on the effectiveness of thermostable charges for coring tools under a hydrostatic pressure of 400 atm (tech.) is shown in Figures 64 and 65. As the pressure increases, the values of $v_1(\Delta)$ and $p_{max}(\Delta)$ change slightly. Actually, the $v_1(\Delta)$ curves for G-80 and O-75 no longer intersect at 800 atm (tech.) (Figure 71). At high external pressures, the combustion processes for charges made from both powders obviously approximate constant-volume combustion to the same extent,

If the charges burn in a closed volume in a given system, then for identical p_0 values, the difference in $p_{\max}$ for both powders becomes commensurate with the difference in striker velocities. Besides this, from the graphs of $p_{\max}(\Delta)$ it is obvious that as the charge density increases, the degree of the difference in the effectiveness of the given powders approaches the degree of difference in their power (f).

EFFECT OF INCREASED TEMPERATURE

Under the charging conditions that are characteristic of perforators and coring tools, increased initial temperatures can affect only the charge's combustion rate.

Figure 72. Breech mechanism for high-pressure ballistic unit with local charge heating: 1. striker; 2. charge; 3. igniter; 4. thermocouple; 5. breech mechanism housing; 6. model of MSG-type coring tool; 7. electric heater; 8. thermostable insulation; 9. wire sensors for measuring velocity v_1 .

model with local heating of the charge (Figure 72).

In general -- according to K.K. Andreyev's data [41] -- the combustion rate of powders depends relatively little on the initial temperature. Under elevated pressures (particularly for powders of the mixed type) the combustion rate's temperature coefficient drops significantly. Consequently, elevated initial charge temperatures at high charge densities should obviously not have any significant effect on the charge's combustion rate or the firing's final result -- the bullet's (striker's) initial velocity or penetrating power.

Charges were fired from the chamber of an APKh-98 perforator in the device shown in Figure 60, with surface heating of the entire autoclave until its internal medium reached a given temperature; coring tool charges were set off in the device shown in Figure 61. In this case, however, we used another breech mechanism that has a detachable coring tool

The effect of maximum temperatures on charge effectiveness was investigated for a hydrostatic pressure of 500 atm (tech.).

**Table 32. Effectiveness of Thermostable Powder Charges
at Maximum Temperatures**

Тип заряда (1)	Марка пороха (2)	Плотность заряжания, г/см ³ (3)	Температура заряда, °C (4)	Выдержка при заданной температуре, мин (5)	Начальная скорость обойки, м/сек (6)	Глубина пробития, мм (7)
АПХ(8) Г-80(9)		1,25	18—20	—	—	29,5
			180	10	—	29,5
			180	360	—	29,0
АПХ(8) П-65(10)		1,75	18—20	—	—	25,5
			250	10	—	26,0
			250	360	—	26,0
МСГ(11) Г-80(9)		1,00	18—20	—	284	—
			180	15	291	—
			180	360	286	—
МСГ(11) П-65(10)		1,40	18—20	—	222	—
			250	15	220	—
			256	360	218	—
МСГ(11) О-75		1,00	18—20	—	275	—
			200	15	278	—
			200	360	272	—

Key:

1. Type of charge	6. Initial striker velocity,
2. Brand of powder	m/sec
3. Charge density, g/cm ³	7. Depth of penetration, mm
4. Charge temperature, °C	8. АРKh
5. Aging and given tempera-
ture, min	9. G-80
	10. P-65
	11. MSG

The results of the experiments, which are presented in Table 34, confirm our assumption of the independence of the charge's effectiveness in relation to the initial temperature in the perforator. Holding the charges at the maximum temperature for 6 hours has practically no effect on the bullet's penetrating power and, consequently, its initial velocity.

In coring tools, elevation of the temperature of G-80 and O-75 powder charges has a slight effect on the striker's initial penetrating velocity. This is apparently caused by a slight increase in the charge's combustion rate. At the same time, P-65 powder charges show no increase in the striker's velocity and, consequently, there is no change in the powder's combustion rate at increased temperatures. For a high charge density this effect is insignificant, although it should increase slightly.

The aging of MSG charges for 6 hours at maximum temperatures does not reduce the striker's initial velocity, for all practical purposes.

On the basis of the results obtained from the investigations of the effectiveness of powder charges fired under different

borehole and testing conditions, we were able to draw the following conclusions.

1. In the interval from 200 to 1,000 atm (tech.), the penetrating power of a bullet and the powder gasses' maximum pressure change very insignificantly as the hydrostatic pressure increases. APKh charges made from G-80 are the most effective ones.
2. The nature of the combustion of charges made from different types of powders has a substantial influence on their effectiveness during firing from a coring tool.
3. The effectiveness of thermostable charges for coring tools of the MSG type depends substantially on the hydrostatic pressure (in the 200-800 atm (tech.) interval) and the charge density.
4. Increasing the initial temperature of an APKh charge has no noticeable effect on the bullet's penetrating power. For MSG charges, an elevated initial temperature has a very slight effect on the striker's initial velocity. This is apparently the result of the slight increase in the charge's combustion rate.
5. When thermostable G-80 powder is used, increasing the charge density makes it possible to increase the efficiency of APKh-type perforators by about 25-30 percent.

CHAPTER 9. EFFECT OF HYDROSTATIC PRESSURE ON THE CHANNEL FORMED IN METALS AND ROCKS BY A SHAPED JET

The basic characteristic of the performance of a shaped-charge type perforator in an oil or gas borehole is the quality of the exposure of the bed, which in the first approximation is determined by the depth and diameter of the channel punched out by the shaped charge in the casing string, the cement ring and the rock.

However, the direct evaluation of the effectiveness of a shaped charge by measuring the parameters of the formed channel directly in the borehole is a problem that has not yet been solved, while an evaluation of the channel formed in a composite target (borehole liquid + casing string + cement + rock) at atmospheric pressure is inaccurate. The situation is complicated by the fact that rocks are very sensitive to a change in their deformation conditions.

In a borehole, a shaped jet penetrates the layer of liquid between the perforators and the string, the steel string itself, and the productive rock stratum.

The parameters of the channel in the obstacle (string + rock) are determined by the characteristics of the jet (velocity, diameter, length, density, and others), the liquid that is penetrated, and the physicommechanical properties (density, strength and so on) and stressed state of the obstacle.

It is necessary to know the special features of the shaped jet's interaction with the borehole liquid, the casing string and the rock under high hydrostatic, rock and pore pressures in order to create high-efficiency shaped charges and perforators that do not react to a change in the working conditions in the borehole.

In view of all this, we formulated the problem: to determine the effectiveness of a shaped charge in a high-pressure chamber under conditions simulating those encountered in a borehole.

We studied the effect of hydrostatic pressure up to 1,500 atm (tech.), pressing in from all sides, on the depth and diameter of the channel opened by a shaped charge in metals (No 3 steel, Duralumin, lead) and rocks (marble, limestone). For the rock, we also investigated the effect of the pore pressure of a saturating liquid.

The effect of hydrostatic pressure up to 500-700 atm (tech.), pressing in from all sides, on the depth of the channel in metals (steel, lead) has been studied by many investigators [100, 101, 103]. They all established that in the investigated range, the pressure does not affect the shaped jet's depth of penetration in either steel or lead.

L.A. Gorbeno, I.I. Mel'nikov, B. Shneyerson, and Zh. Delakur also studied the dependence of the channel's entry diameter in soft steel on hydrostatic pressure of up to 200-500 atm (tech.) pressing in from all sides. According to their data, hydrostatic pressure reduces the channel's diameter substantially only when the layer of liquid between the shaped charge and the target being penetrated is quite thin (20-50 mm). In addition to this, the range of pressures in which there is a reduction in the channel's diameter depends on the thickness of the layer of liquid being penetrated: as a rule, the thicker the layer, the smaller the range of pressures over which the channel's diameter is changed.

EFFECT OF HYDROSTATIC PRESSURE ON THE SHAPED JET'S INTERACTION WITH THE LIQUID

When the shaped charge penetrates a liquid, a cavity is formed. After a certain amount of time passes, the walls of this cavity close.

Figure 73. Penetration of shaped jet into water at atmospheric pressure (scale of photographs -- 1:4): a. 27.5 μ sec after detonation of charge; b. after 87.5 μ sec; c. after 101.1 μ sec.

Figure 73 is three frames from a film showing the penetration of a jet into water at atmospheric pressure; these pictures were taken with the help of an SFR-2 streak camera. During the observed period of time the jet passed out of the viewing field and the cavity continued to expand.

If the cavity's time of existence is greater than the jet's time of movement through a given section, the liquid's effect on the jet is limited to an effect on that part of the jet that is in contact with the liquid.

When a high-speed shaped jet is moving in water, the pressure at the jet-liquid interface exceeds 10⁵ atm (tech.). Changing the pressure in the liquid by 1,000 atm (tech.) has a negligibly small effect on the penetration parameters and the characteristics of the jet, which has gone on to the next obstacle.

The picture changes radically if the cavity's converging walls capture elements of the jet. In this case, the "trapped" parts of the jet have to penetrate the same layer of liquid again. This phenomenon can occur repeatedly, depending on the shaped jet's parameters and the conditions in the liquid. The expenditure of the jet's energy to penetrate the liquid increases.

The theory of similarity and dimensionality [66] makes it possible to find the dependence of the pulsation period on the pressure and the shaped jet's properties.

When a shaped jet penetrates an incompressible liquid, the determining factors of the cavity formation process are: energy of the jet arriving per unit of length E_c (dimensionality MLT^{-2}), jet density ρ_c and obstacle density ρ_1 (ML^{-3}), diameter of the cavity in the liquid d_1 (dimensionality L), pressure in the liquid p_0 ($ML^{-1}T^{-2}$), and time t (T).

From the six dimensional parameters listed above, it is possible to formulate three independent, dimensionless combinations ($\alpha_1 = d_1 \sqrt{p_0/E_c}$, $\alpha_2 = \rho_c/\rho_1$, $\alpha_3 = (p_0 t)/\sqrt{E_c \rho_1}$). The cavity's dimensionless diameter will be an implicit function of another two dimensionless combinations:

$$d_1 \sqrt{\frac{p_0}{E_c}} = f\left(\frac{\rho_c}{\rho_1}, \frac{p_0 t}{\sqrt{E_c \rho_1}}\right).$$

Since, when the maximum diameter ($t = T$, $d_1 = D_m$) is reached,

$$D_m \sqrt{\frac{p_0}{E_c}} = \text{const}, \quad \text{then} \quad \frac{p_0 T}{\sqrt{E_c \rho_1}} = \text{const}$$

or

$$T = K \frac{\sqrt{E_c \rho_1}}{p_0}; \quad D_m = K_1 \sqrt{\frac{E_c}{p_0}}.$$

After expressing the energy in terms of the jet's velocity and diameter, we obtain:

$$T = K_2 \frac{v_c d_c \sqrt{\rho_l \rho_c}}{p_0}; \quad D_m = K_3 \sqrt{\rho_c} \frac{v_c d_c}{\sqrt{p_0}}.$$

From the known parameters of the shaped jet and the liquid, it is easy to find the time (t) required to achieve an element of the jet with velocity v_x ; the jet-liquid interface at a chosen moment of time is

$$t = \frac{\Delta l}{v_x},$$

where Δl = distance from the jet element having velocity v_x to the jet-liquid interface.

The capture of the chosen jet element by the cavity's walls takes place provided that:

$$t \geq T \quad \text{or} \quad p_0 \geq K_2 \sqrt{\rho_l \rho_c} \frac{v_c d_c v_x}{\Delta l}. \quad (182)$$

Experiments were performed on one type of charge (a laboratory ZPK-103 charge) for the purpose of determining the dependence of the pulsation period (T) and the maximum diameter (D_m) of the cavity in the water on pressure. Pressures of up to 900 atm (tech.) were created in a cylinder with optical ports. An SFR-2 streak camera operating in a continuous scanning mode was used to photograph the cavity walls' movement at a certain depth of penetration.

Figure 74. Dependence of pulsation period (T) and maximum diameter (D_m) of the cavity on hydrostatic pressure.

Since the obstacle and the diameter (d_c), velocity (v_c) and density (ρ_c) of the jet element were fixed, the cavity's parameters (T , D_m) could depend only on the hydrostatic pressure.

The results of the experiments (Figure 74) confirmed that the channel's pulsation period and maximum diameter are proportional to p_0 to a degree that is close to one and one-half, respectively.

If we know the distribution of the velocities along the length of the shaped jet, the distance from the charge to the first obstacle, the thickness of the penetrated layer of water, and

the function $T = f(p_0)$ for a given charge, it is possible to determine the pressure p_t above which the jet's rear elements will be trapped by the cavity's converging walls. Calculations show that for a laboratory charge of ZPK-103, a distance to the layer of water of 40 mm, and a water layer thickness of 50 mm, rear elements moving at a velocity of 1.6 km/sec will be trapped at $p_t \geq 1,600$ atm (tech.). The value $p_t = p_0$ in formula (182) depends on the jet's parameters and the density and thickness of the layer of liquid being penetrated.

As the pressure increases (when $p_0 > p_t$), the part of the jet captured by the liquid gets larger; correspondingly, the depth of the channel in the target decreases. However, the initial diameter of the channel in the target will decrease only when some other pressure is exceeded: $p_0^* > p_t$.

EFFECT OF HYDROSTATIC PRESSURE ON THE PARAMETERS OF A CHANNEL IN METAL

As is known [24,25,29,30,37,38,59], the physicomachanical properties of metals change at high hydrostatic pressures. In the range of pressures we are discussing, however, this change is extremely small. For instance, according to experimental data [24,29,37,38] the increase in ultimate strength, Young's modulus and the shear modulus is 0.1-1 percent for metals (steel and aluminum, for example). The Brinell hardness of high-strength steels increases by 0.25-1.4 percent [25], while that of carbon steel increases by 3 percent [30].

During penetration into an obstacle under conditions of compression of the medium from all sides, a shaped jet must overcome both the resistance of the obstacle itself and the compressive stresses caused by the hydrostatic pressure.

The pressure acting on the shaped jet-target interface throughout the entire jet penetration process is at least two orders greater than the compressive stresses (10^5 - $5 \cdot 10^5$ atm (tech.) as opposed to $1.5 \cdot 10^3$ atm (tech.)). The imposition of the latter cannot substantially change the kinematic parameters of the jet's penetration and, consequently, the depth of penetration. This is true, assuming that each element of the jet reaches the jet-obstacle interface and participates in the penetration process. Actually, the picture is somewhat more complicated. For a jet velocity greater than 3 km/sec, the depth of penetration is affected very little even by the strength of the target [11], which is almost an order greater than the stresses caused in the target by the pressure from all sides. For a given shaped jet, the diameter of the channel is basically determined by the target's strength characteristics [89], so that the effect of pressure on the pierced opening's diameter can be significant.

At the beginning of the walls' radial movement, the resistance to deformation is basically determined by the inertial forces. As the distance to the jet-obstacle interface increases, the deformation rate in a given cross-section and, consequently, the inertial resistance decrease quickly and the material's strength characteristics become of primary importance. At the same time, compressive stresses that increase the target's resistance are manifested.

Using the basic relationships of a hydrodynamic penetration system [49], M. Kuk theoretically derived the dependence of the diameter of the channel in the obstacle on the properties of the jet and the obstacle:

$$d = \frac{d_c v_c}{V^{2H}} \frac{V \sqrt{\rho \rho_c}}{V \rho_c + V \rho} \quad (183)$$

or

$$d_1 = d \sqrt{\frac{H}{H_1}} \sqrt{\frac{\rho_1}{\rho} \frac{V \rho_c + V \rho}{V \rho_c + V \rho_1}},$$

where v_c = velocity of the jet; d_c , d , d_1 = diameters of the jet and the channels in the obstacles; H , H_1 = dynamic strength characteristics of the obstacles; ρ_c , ρ , ρ_1 = densities of the jet and the obstacles' materials.

For materials of equal density, from formula (183) we obtain:

$$d_1 = d \sqrt{\frac{H}{H_1}}.$$

When there is pressure from all sides, the obstacle's total resistance to deformation is composed of the dynamic resistance strength, which in the general case depends on the pressure, and the compression stresses, which are determined by the pressure.

When the value of the pressure from all sides is p_2 , the channel's diameter will be:

$$d_{p_2} = d_{p_1} \sqrt{\frac{H(p_1) + p_1}{H(p_2) + p_2}}. \quad (184)$$

As the dynamic characteristic of resistance to deformation, we used the material's dynamic hardness (H), as determined by striking it with a cone moving at a speed on the order of tens of meters per second [28]. This is justified by the fact that at high deformation rates, the obstacle's material works under local softening conditions.

It has been experimentally established [28] that dynamic hardness depends only slightly on the cone's striking speed:

$$H = H_0 \left(\frac{v}{v_0} \right)^n, \quad (185)$$

where H_0 = hardness of obstacle material corresponding to a striking speed v_0 ; n = a constant determining the metal's sensitivity to the effect of the speed on its resistance to deformation ($n \ll 1$).

The values of n and the hardness of several metals are presented in Table 35 [20,28].

Table 35. Hardness of Different Metals

Характеристики металлов (1)	Железо (мягкая сталь) (2)	Свинец (3)	Алюминий (4)	Медь (5)	Дюралюми- ний (6)
n	0,04	0,025	0,020	0,018	0
Твердость по Бринеллю $H_B, \text{ кг/мм}^2$ (7)	113	4	22	42	75
Динамическая твердость $H, \text{ кг/мм}^2$ (8)	163	6,5	26	65	75

Key:

1. Metal characteristics	5. Copper
2. Iron (soft steel)	6. Duralumin
3. Lead	7. Brinell hardness $H_B, \text{ kg/mm}^2$
4. Aluminum	8. Dynamic hardness $H, \text{ kg/mm}^2$

The hardness (H_B) of the test pieces of No 3 steel, lead and Duralumin used in the experiments was also calculated (as H) by formula (185).

The described mechanism of the effect of pressure on a shaped jet and the parameters of the channel formed by it in a target were tested in the experiments. Shaped charge 1 (Figure 75) was placed in sealed chamber 2, which was set at a given distance from target bundle 4 with the help of thick-walled steel collar 3, which was 65 mm in diameter. The thickness of the layer of water between the chamber and the target was varied from 0 to 120 mm. With the help of vessel 5, the testing unit was placed in an autoclave, where pressures of 1-1,500 atm (tech.) were created. The target was a bundle of No 3 steel plates that were 10-20 mm thick, with the bundle's total height being 100-120 mm. In addition, the experiments in which the thickness of the water layer was zero ($h_w = 0$) were also performed with cylindrical targets made from D1 Duralumin measuring 80 x 200 mm and lead measuring 140 x 180 mm. A No 3 steel control plate 9.5 mm thick was placed between the charge chamber and the target.

Figure 75. Diagram of testing unit for determining parameters of perforated channel under varying hydrostatic pressure.

the Duralumin and lead targets.

A laboratory charge of ZPK-103 (Figure 76) was used in the tests. The weight of the charge's shaped cartridge 1 was 22 g, while its density was 1.66-1.67 g/cm³. Shaped facing 2, which was made of copper 0.8 mm thick, had a flare angle $\alpha = 75^\circ$, and a base diameter of 31 mm, weighed about 7.2 g. A supplementary pressed detonator 12 mm in diameter, 8 mm tall, and weighing 1.3 g was made of octogene. The entire charge was contained in thin-walled casing 4, which was made of AG-4 molding material that made it possible to center the charge exactly along the chamber's axis. Detonation of the charge was excited by TED-2 electric detonator 5. The velocity of the leading element of the jet from this charge was 6,100 m/sec, while the tail elements moved at 1,600 m/sec and the beater moved at 500 m/sec. The distribution of velocities along the jet's length was linear. When the jet reached the target, the diameters of its leading and tail elements were about 1.0 and 2.5 mm,

Figure 76. Laboratory charge of ZPK-103: 1. explosive charge; 2. shaped facing; 3. relay detonator; 4. charge casing; 5. electric detonator.

For each experimental point in layers of water 25-120 mm thick, 7-9 experiments were performed. In the absence of water, an average of 35 charges were fired at the point for a No 3 steel target, while 7 charges apiece were fired at

Figure 77. Dependence of depth of penetration of channel (h) in steel on hydrostatic pressure (p_0) for different thicknesses of the water layer in front of the target: 1. 25 mm; 2. 50 mm; 3. 80 mm; 4. 120 mm.

Figure 78. Dependence of depth of penetration (h) on hydrostatic pressure in No 3 steel (1) and D1 Duralumin (2).

respectively; at a distance of 100 mm from the base of the shaped facing, the shaped jet from this charge penetrates as a solid jet, while at greater distance it does so in the form of individual fragments.

Figure 79. Dependence of channel depth (h) and diameter (D_m) in lead on hydrostatic pressure (p_0).

Figure 77 shows the dependence of the depth of the channel's penetration in steel on the hydrostatic pressure for different thicknesses of the water layer between the charge and the target. The pressure had no observable effect. The observed change in penetration from point to point is not related to pressure, but is caused by variability of the experimental data. This is confirmed by the fact that the curves' angle of inclination is

negative in some cases and positive in others. Figure 78 depicts the dependence of the depth of penetration (h) in steel and Duralumin on the amount of obstacle compression from all sides (the layer of water between the charge and the target (h_w) is of zero thickness). The change in penetration does not go beyond the result variability limits. Figure 79 shows the graphs of the dependence of the channel's depth (h) and diameter (D_m) at a depth of 30 mm in lead on the pressure exerted

Figure 80. Dependence of diameter of pierced channel (d) on hydrostatic pressure (p_0): 1. Duralumin at a depth of 5 mm; 2. Duralumin at a depth of 30 mm; 3. No 3 steel.

from all sides. The reduction in the channel's depth -- as is the case for the stronger metals -- does not go beyond the limits of data variability, while the decrease in diameter in the 1-500 atm (tech.) range exceeds 20 percent. It was not possible to observe the diameter in lead under higher pressures, because the cavity's walls collapsed under the influence of the external pressure after cessation of the jet's action.

The dependence of the diameter of the channel in Duralumin and steel on the pressure (the water layer in front of the target being of zero thickness) is shown in Figure 80. In all cases, the diameters of the openings decrease as the pressure increases.

According to the results of the experiments, the laws $d = f(p_0)$ are approximated by the following equations (diameter in millimeters; pressure in technical atmospheres):

in steel: (186)

in Duralumin: 1) curve 1 -- $d = 12,5 - 1,0 \cdot 10^{-3} \cdot p_0$; (187)

2) curve 2 -- $d = 10,7 - 0,7 \cdot 10^{-3} \cdot p_0$; (188)

in lead: $d = 42,8 - 3,6 \cdot 10^{-2} \cdot p_0 + 0,32 \cdot 10^{-4} \cdot p_0^2$.

Because the hydrostatic pressure could affect only the target in the experiments where the shaped jet did not pass through the liquid, the change in diameter took place in accordance with the change in the target's resistance to deformation. The reduction in diameter according to equations (186), (187) and (188), which approximate the experimental data, and the figure produced by equation (184) are practically identical. This indicates that it is only the totality of the material's dynamic hardness and the hydrostatic pressure that determine the target material's total resistance to deformation to the penetration of a shaped jet.

The experiments in which the shaped charge was fired at steel through different thicknesses of water made it possible to check the effect of the liquid's effect directly on the shaped charge.

The average diameters of the channel in steel, at depths of 5 and 30 mm, under various hydrostatic pressures and water layer thicknesses, are presented in Table 36. The increased variability of the results is apparently caused by the great distances between the charge and the target.

Table 36. Dependence of Channel's Diameter in Steel on Pressure

Толщина слоя воды, мм (1)	Глубина замера диаметра, мм (2)	Давление, ат (3)				Аппроксимирующее уравнение (4)
		1	200	500	1000	
25	5	6,9	7,4	6,6	7,0	$d = 7,0 - 0,1 \cdot 10^{-3} p_0$
	30	5,5	5,2	5,3	5,3	
50	5	7,0	7,4	7,1	7,0	$d = 7,2 - 0,1 \cdot 10^{-3} p_0$
	30	4,9	4,5	4,6	4,7	
80	5	7,2	7,8	7,8	7,2	$d = 7,6 - 0,16 \cdot 10^{-3} p_0$
	30	4,8	5,2	4,7	4,8	
120	5	6,3	7,4	6,4	6,5	$d = 6,8 - 0,2 \cdot 10^{-3} p_0$

Key:

1. Water layer thickness, mm
2. Diameter measurement depth, mm
3. Pressure, atm (tech.)
4. Approximating equation

For different water layer thicknesses, the reduction in diameter caused by pressure is practically the same as when there is no layer of water. This indicates that pressure in the liquid has no effect on a shaped jet at pressures of 1-1,000 atm (tech.).

Thus, the experiments confirmed that a pressure of up to 1,000 atm (tech.) in water affects only the diameter of the channel formed by a shaped jet from a ZPK-103 charge, and only to that extent to which the target's total resistance to deformation changes.

EFFECT OF ROCK AND FORMATIONAL PRESSURE ON THE PENETRATING POWER OF A SHAPED JET IN ROCK

The data presented above on the mechanism of the effect of pressure on the parameters of a channel in a metal target are qualitatively correct for the penetration of a shaped jet into rock. On the degree of the effect of pressure on the strength properties of metals and rocks is different.

As was the case for metals, we used the dynamic hardness of rock as the characteristic of its resistance to deformation. In our investigation of the properties of rocks, we decided to determine hardness (p_s) by striking the rock with a cylindrical stamp [84].

For a quantitative evaluation of the parameters of the channel formed in rock by a shaped jet, it is necessary to know the hardness under conditions of uniform compression and a high deformation rate. Saturation of the rock with liquid and formational pressure can also affect hardness.

Rock strength (stamp hardness, flow limit, compressive strength) increases substantially under pressure from all sides [26,61,70,82,83].

Table 37 shows the values of the static hardness of red marble [82] in the 1-800 atm (tech.) range of uniform pressures; from this table it is obvious that when the pressure was increased from 1 to 800 atm (tech.), the stamp hardness and flow limit increased by 50 and 46 percent, respectively.

Table 37. Dependence of Stamp Hardness on Uniform Pressure

Характеристика пород (1)	Всестороннее давление, ат (2)					
	1	100	200	300	500	800
Твердость p_m , кг/мм ² (3)	142,1	151,6	156,2	165,8	189,5	213,5
Предел текучести p_T , кг/мм ² (4)	118,4	131,5	137,5	150,0	161,5	172,8

Key:

1. Rock characteristics
2. Uniform pressure, atm (tech.)
3. Hardness p_s , kg/mm²
4. Flow limit p_f , kg/mm²

Strength also increases as the deformation rate does. N.N. Pavlova and L.S. Shreyner [64] show that stamp hardness is determined as a function of the deformation rate (up to $v = 20-30$ m/sec) by the relationship

$$p_{s_2} = p_{s_1} \left(\frac{v_2}{v_1} \right)^n, \quad (189)$$

where n is a coefficient depending on the rock's properties; for the samples we tested, $n = 0.07-1$ [61].

Relationship (189) differs from (185) for metals [28] only in the higher value of the exponent. This expresses rock's great sensitivity to a change in the deformation rate. For a deformation rate v that is greater than 50-60 m/sec (in metals, for $v > 100$ m/sec), the determining factor is the medium's inertial resistance, so that $n = 2$ for all rocks [61]. One exception is quartzite, for which $n < 2$ (it is obvious that for the deformation rates achieved in the experiments, the strength resistance was comparable to the inertial resistance).

In the literature there is no information on investigations of the mechanical properties of rocks under uniform compression

and dynamic loading. The only descriptions are of dynamic tests of rocks in matrices, the results of which indicate that there is a sharp increase in the compressive strength of rock when it is subjected to longitudinal compression in matrices [61].

When core samples of rock are saturated with a liquid, their strength decreases. For instance, when low-porosity limestone is saturated with water, its strength decreases by 15-17 percent, while for marble the decrease is 12 percent. The flow limit also drops, but much less significantly [85]. When the uniform pressure is increased to 1,000 atm (tech.), these characteristics of saturated rock remain at a level 10-20 percent lower than those of unsaturated samples. Formational pressure (p_f) reduces the uniform compression of the rock skeleton [13]:

$$\sigma = \sigma_0 - \eta p_f, \quad (190)$$

where σ and σ_0 = compressive stresses in the rock in the presence and absence of formational pressure; $\eta = 0-1$ - a coefficient depending on the properties of the rock and the saturating liquid; for a rock-liquid combination, coefficient η is a constant.

According to formula (190), rock strength decreases as the formational pressure increases.

The quantitative evaluation of the effect of pressure on the efficiency of a shaped jet in rock is extremely difficult because of the lack of data on the properties of rock at high deformation rates under conditions where it is acted upon by both rock and formational pressure.

TESTING TECHNIQUES AND RESULTS OF THE EXPERIMENTS

The rock around a cased borehole is in a complex stressed state, although compressive stresses are the predominant ones. The pressure of the surrounding layers of rock can be simulated by creating hydrostatic pressure equal to the rock pressure and, in the core sample itself, to the formational pressure.

During the experimental investigation of the effectiveness of a shaped charge used in rock, the effect of a liquid on the shaped jet's parameters was eliminated by placing the chamber containing the charge directly on the target. Nevertheless, the results that were obtained are correct for the more general case where the water layer does not equal zero, since (this was shown above) the parameters of a shaped jet that has passed through a layer of liquid do not change until the pressure is reached at which the collapsing walls of the cavity in the liquid capture the jet.

Figure 81. Testing unit for determining the change in the parameters of perforated channels in rocks as a function of the magnitude of the uniform compression.

The effect of rock and formational pressure on the depth of penetration in rock was investigated with the testing unit shown in Figure 81. Cylinder 5 was placed in a thin-walled housing 6. Beneath the cylinder there was rock sample 3, which was insulated from the surrounding liquid by rubber casing 2. Control plate 4, made of No 3 steel 9.5 mm thick, was placed between the cylinder and the rock sample in order to simulate the casing string. The casing's inner volume connected with chamber 1, in which a pressure (equal to the rock pressure) differing from the external pressure was created.

The core samples were cut out of Koyelga marble (from the Koyelginskoye deposit in the Southern Urals) and limestone (from the Korobcheyevskiy quarry). Table 38 shows some of the physicommechanical and elastic characteristics of these rocks, as determined from both the data of N.N. Pavlova and L.A. Shreyner [61] and measurements made at the Laboratory of Physical Properties of the R

menskoye branch of VNIIGeofizika (in parentheses).

Table 38. Physicommechanical Characteristics of Rocks

Материал (1)	Плотность, г/см ³ (2)	Пористость, % (3)	Скорость продольных волн, м/сек (4)	Прочность на сжатие, атм (5)	Плотность после насы- щения г/см ³ (6)
Мрамор (7)	2,7 (2,7)	1	5500	1000	2,7
Известняк (8)	2,26 (2,28)	15 (14)	3000	280	2,44

Key:

1. Material
2. Density, g/cm³
3. Porosity, %
4. Velocity of longitudinal waves, m/sec

5. Compressive strength, atm (tech.)
6. Density after saturation, g/cm³
7. Marble
8. Limestone

After the core samples were cut out, they were worked to a diameter of 98 mm and a length of 200 mm. Comparative firings in order to check the effect of the samples' limited size on the penetration were conducted at atmospheric pressure for both the samples and a block of marble, and yielded identical results. Therefore, the experimental data are also correct for rock penetrated by a shaped jet in a borehole.

Four series of experiments were formulated in order to determine the effect of pressure on the depth of penetration. The first series was performed on marble (unsaturated), the other three on limestone: 1) unsaturated; 2) saturated with a formational pressure of 1 atm (tech.); 3) saturated with a formational pressure equal to the rock pressure.

The tests were performed on limestone core samples with a density of at least 2.30 g/cm^3 . In addition, the samples (both marble and limestone) could not have external flaws (cracks, holes). The limestone core samples were saturated with a 5-percent solution of sodium chloride after first being subjected to the effects of a vacuum. In the case of firings with unsaturated samples, the shaped charge was set off as soon as the given external pressure was reached (depending on the pressure, the time required to reach it was 0.2-0.5 hrs). During the experiments with the saturated rocks, the samples were held at the given external pressure for 20 minutes after it had been reached, in order to establish the assigned formational pressure. The number of experiments for each experimental point averaged seven. The depth of penetration was measured (after the core sample was split along the cracks that formed) from the apex of the deepest penetration element, with penetration of the jet along the cracks being ignored. A charge of ZPK-103 was used to form the shaped jet.

As a result of the experiments it was established that the following phenomena take place as the rock pressure increases.

1. The depth of penetration is reduced in both marble and limestone (saturated and dry).

In the range of pressures under discussion, the greatest relative reduction in penetration depth was seen in marble -- 33 percent (78 mm at 1,500 atm (tech.) as opposed to 117 mm at 1 atm (tech.)), while the least was seen in saturated limestone when the rock and formational pressures were equal -- 16 percent; in saturated limestone at a formational pressure of 1 atm (tech.) it was 18 percent, and in dry limestone -- about 16.5 percent (Figure 82).

The relationship between the depth of penetration and the rock pressure, for all four series of experiments, is approximated

Figure 82. Dependence of depth of penetration (h) in rock on uniform pressure (p): limestone -- 1. equal pore and rock pressure; 2. pore pressure of 1 atm (tech.); 3. unsaturated; marble -- curve 4.

Figure 83. Dependence of channel diameter (d) in marble on its depth (h) for rock pressures of 500 (1), 1,000 (2) and 1,500 (3) atm (tech.)

by the equation:

$$h = h_1 \exp [-\beta (p - p_1)],$$

where h_1 = depth of penetration at pressure p_1 ; p = rock pressure, atm (tech.); β = a coefficient, the value of which is given in Table 39.

Table 39. Coefficient β of Rocks

Порода (1)	$\beta \cdot 10^3$	Давление, атм (2)
Мрамор (3)	0,28	1—1500
Известняк насыщенный, $p_n = 1$ атм (4)	0,14	
Известняк, насыщенный, $p_n = p$ (5)	0,12	250—1500
Известняк сухой (6)	0,09	

Key:

1. Rock
2. Pressure, atm (tech.)
3. Marble

4. Saturated limestone, $p_1 = 1$ atm (tech.)
5. Saturated limestone, $p_1 = p$
6. Dry limestone

Here we should mention that the relationship between the depth of penetration of the shaped jet from a series of charges and rock strength was derived in [104]; it is approximated by the equation

$$h = h_1 \exp [-\alpha (\sigma - \sigma_1)],$$

where h and h_1 = depths of channels in the investigated and standard rocks, with compressive strengths of σ and σ_1 , respectively.

Figure 84. Dependence of channel diameter (d) in saturated limestone on its measured depth (h) at rock pressures of 250 (1), 500 (2), 1,000 (3), and 1,500 (4) atm (tech.).

Figure 85. Dependence of relative change in channel's diameter on rock pressure: 1. No 3 steel; 2. Duralumin; 3. marble; 4. limestone; 5. lead.

ogous graphs for saturated limestone are presented in Figure 84. The accuracy of the experiments did not make it possible to find a difference between the diameters of channels in limestone saturated at $p_1 = 1$ atm (tech.) and $p_1 = p$, so the results of these two series of experiments are combined in the graphs.

The dependence of the channel diameter, as measured at a certain depth, on the rock pressure is approximated in a linear approximation by the following equations (d given in millimeters, p in technical atmospheres):

in saturated limestone:

$$\left. \begin{aligned} d_{25} &= 8 - 1,4 \cdot 10^{-3} \cdot p \\ d_{50} &= 6,9 - 1,25 \cdot 10^{-3} \cdot p \\ d_{100} &= 5,8 - 1,3 \cdot 10^{-3} \cdot p \\ d_{125} &= 4,8 - 1,2 \cdot 10^{-3} \cdot p \end{aligned} \right\}; \quad (191)$$

in marble:

$$\left. \begin{aligned} d_{10} &= 7,5 - 1,2 \cdot 10^{-3} \cdot p \\ d_{25} &= 6,6 - 1,2 \cdot 10^{-3} \cdot p \\ d_{50} &= 5,8 - 0,95 \cdot 10^{-3} \cdot p \\ d_{75} &= 5,1 - 0,9 \cdot 10^{-3} \cdot p \end{aligned} \right\}. \quad (192)$$

where d_{10} , d_{25} and so on = channel diameter at a depth of 10, 25 mm and so on.

As is apparent from the equations (186, 187, 190, 191), the relative decrease in the channel diameter in rocks is considerably greater than in steel or Duralumin (Figure 85). Depending on the depth at which the channel is measured, at 1,000 atm

(tech.) it is 18-25 percent in limestone and 16-17 percent in marble, as opposed to 3 percent in steel and 6.5 percent in Duralumin. According to equations (184) and (188), the relative decrease in the channel diameter in lead at a pressure of 500 atm (tech.) is 24 percent, while at 1,000 atm (tech.) -- according to equation (184) -- it is 37 percent.

3. The diameter of the channel punched through rock at atmospheric pressure is substantially less than that of a channel in Duralumin, although the depths of two such channels differ very little. The difference in diameters becomes even more significant as the pressure increases (Table 40).

Table 40. Channel Diameters for Pressures of 1 and 1,500 Atm (Tech.)

Материал (1)	Диаметр канала на глубине 25 мм (2)		Плотность материала приgrade, г/см ³ (3)
	p = 1 Атм	p = 1500 Атм	
Дюралюминий (4)	10,7	9,75	2,78
Известняк (5)	8,0	5,9	2,44
Мрамор (6)	6,6	4,8	2,70

Key:

1. Material	4. Duralumin
2. Channel diameter at depth of 25 mm, mm	5. Limestone
3. Obstacle material's density, g/cm ³	6. Marble

At depths of 75 mm and more, the channel's diameter at high pressures (see formulas (191) and (192)) is only 20-100 percent greater than the diameter of the jet's rear elements ($d_r = 2.0-2.5$ mm); that is, even an insignificant deviation of an element of the jet from the proper axis means that it can be expended against the walls ("smearing").

4. For all rock pressure values, the depth of penetration in dry limestone is less than in saturated limestone (see Figure 82), although the latter's density is higher (2.44 g/cm³).

The greatest difference in penetration depth is seen at pressures of 1-250 atm (tech.) (15 mm, or 10 percent), while the least difference is observed at the maximum pressure (4-8 mm, or 3-6 percent).

5. For the limestone that was studied (porosity = 14 percent), the effect of formation pressure (p_1) on the channel's parameters proved to be insignificant.

As the formational pressure increases from 1 atm (tech.) to the value of the rock pressure for all rock pressure levels, the depth of penetration increases. However, the increase is only a few percentage points.

6. As the pressure increases (regardless of whether the core sample is saturated or not), so does the contamination of the channel punched through the rock. At atmospheric pressure the channel is not clogged and, as a rule, the beater reaches the end of the channel. As the pressure increases, however, an ever greater part of the channel fills with rock and jet residues, the beater remains close to the core sample's end face, and the jet residues are retained quite strongly by the channel's walls.

The change in the channel's parameters is explained by the increase in the rocks' total resistance to deformation as the uniform compression increases and by effect related to this phenomenon.

Because of the significant increase in rock hardness with pressure, the total resistance to deformation increases faster than in metals (see Table 37). In connection with this, the relative reduction in the channel's diameter is more substantial in rock (according to formula (184)).

With the decrease in the channel's diameter -- which in rock has a small absolute value (4-8 mm in all) that decreases with depth -- jet consumption because of "smearing" increases as the channel's length does. As the pressure increases, the ratio of the channel's diameter to that of the jet decreases to 1-2:1, so that an insignificant deviation of an element of the jet from the axis (as a rule, the deviation is greater for a fragmented jet and increases as the channel's length does) leads to "smearing." Clogging of the channel with jet residues and rock indicates that, in general, part of the jet has not reached the bottom of the channel. The greater the pressure, the greater the part of the jet that remains in the channel and, naturally, the lesser the channel's depth.

Despite the greater relative decrease in diameter than in rock, "smearing" does not occur in lead, since even at a high hydrostatic pressure, the channel's diameter in lead is 10-20 times greater than the jet's diameter. This also explains the fact that the depth of the channel in lead is practically independent of the pressure. On the other hand, despite the small diameter of the channel, the depth of penetration in steel also does not depend on the pressure because the small relative reduction in diameter as the pressure increases and the "smearing" remain unchanged.

Besides this, the lack of dependence of penetration depth on pressure in such a low-strength material as lead shows that pressure has practically no effect on the amount of afterflow occurring after the effect exerted by an individual element of the jet is completed. In connection with this, it is apparently impossible to obtain an increase in penetration by fragmenting the shaped jet under the working conditions in the borehole, where the distance between the fragments cannot be great.

The fact that the depth of penetration in more densely saturated limestone is greater than in dry limestone is related to the decrease in rock hardness caused by saturation. This has been confirmed by firings conducted in dry and saturated sand: in contrast to limestone, the penetration in saturated sand ($\rho = 2 \text{ g/cm}^3$) was less than in dry sand ($\rho = 1.65 \text{ g/cm}^3$).

The increase in penetration depth observed as the formational pressure increases is also explained by the reduction in the rock's dynamic stamp hardness (p_s) caused by the drop in uniform compression under the influence of formational (pore) pressure.

The results of the investigations we performed enabled us to draw the following conclusions.

1. The effect of pressure on the jet's interaction with the liquid becomes noticeable only when the cavity's walls capture elements of the jet while collapsing. The capture of a jet element with velocity v_x takes place at a pressure determined by the jet's and liquid's parameters (see formula (181)).

2. At pressures up to 1,000 atm (tech.), the jet from a charge of ZPK-103 is not captured and its effectiveness does not diminish.

Calculations made with formula (181), as well as the extrapolation of the results of experiments conducted at up to 1,000 atm (tech.), show that capture of the tail of a jet from this type of charge begins at a pressure of 1,600 atm (tech.), although a noticeable reduction in the jet's effectiveness does not occur until a level above 2,000 atm (tech.) is reached.

3. The mechanism of hydrostatic pressure's effect on the parameters of a channel in metals and rocks is the same. The difference in the change in penetration parameters is determined by the target's dynamic hardness and to what extent the target's dynamic hardness is sensitive to uniform compression. The diameter of a channel in metals decreases in connection with an increase in the total resistance to deformation as the pressure increases, in accordance with the equation

$$d_{p_2} = d_{p_1} \sqrt{\frac{H(p_1) + p_1}{H(p_2) + p_2}}.$$

Qualitatively, the decrease in channel diameter in rocks is subject to the same relationship.

4. In the range of pressures under discussion, the depth of the channel pierced in metals is practically independent of the pressure, while in rocks it decreases by 20-30 percent. The reduction in the depth of the channel in rocks is related to an increase in "smearing," which is caused by the considerable (25-30 percent) relative change in diameter because of pressure and its small (4-8 mm) absolute value.

When the channel's diameter is small, a reduction in its length as the pressure increases is facilitated by the reduction in the pulsation period of a channel punched through rock, which is characterized by greater compressibility than metal.

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