Thus, the total amount of energy liberated in an explosion can be estimated as ~22 kJ. The latent heat of the liquid-crystal phase transition for 1 mole of NaCl is 30.3 kJ. The mass of melt in the crucibles comprised about 1 mole, so that the energetic effect of the explosion corresponds to complete recrystallization of the melted material with losses due to recombination of a portion of the excitons with formation of a defective crystal structure.

Thus, the studies performed of the process of explosion upon contact of water with fused salts have shown that development of the process cannot be explained from the position of "boiling," the chemical model, or formation of a metastable state. The general model proposed herein satisfactorily describes all stages of explosion development, and quantitative estimates made with its use are in reasonable agreement with the actual energetic effect of the process.

The authors express their sincere gratitude to A. A. Tarakanovskii for his valuable remarks.

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# SHOCK-WAVE PARAMETERS ON EXPLOSION OF A CYLINDRICAL CHARGE IN AIR

A. A. Vasil'ev and S. A. Zhdan

At the present time it is assumed that initiation of detonation in an explosive gas mixture is determined not only by the total energy of the source, but also by the space–time characteristics of energy liberation. Of the various possible sources (exploding wire, electrical and laser breakdown, explosive charge), detonation of fuel–air mixtures is usually accomplished by a charge of solid explosive material, so that to determine the critical initiation energy it is important to know the character of liberation and redistribution of energy between the detonation products and the shock wave which excites them.

The solution of the shock-wave problem in the framework of classical point explosion theory can be found in a number of studies (see, e.g., the bibliography of [1]). Numerical calculation of the explosion of a spherical charge of solid explosive (TNT) in air was presented in greater detail in [2]. The case of cylindrical symmetry has been treated with less detail. Of experimental studies, one must note [3], which studied propagation of the shock wave excited by a long explosive charge (mixture of TH 50/50 and detonation fuse, pressed) at distances greater than 50 charge radii. Similar measurements were performed later in [4]. A number of problems concerning the shock wave formed by decay of a cylindrical high-pressure region were solved. Results of calculating the explosion of a cylindrical hexogene charge in air and argon at $p_0$ = 0.13 atm with consideration of radiation in the presence of a magnetic field were presented in [5]. We sould also note [6, 7], in which two-dimensional shock-wave calculations were performed for explosive charges of various form. Some estimates of shock-wave behavior in the near zone were presented in [8], where the equation of state of the explosion products was specified by a three-stage isentropic expansion. In all these studies the real pattern of explosion product parameter distribution was replaced by an ideal one with constant values, or else the equations of state for the products contained a large

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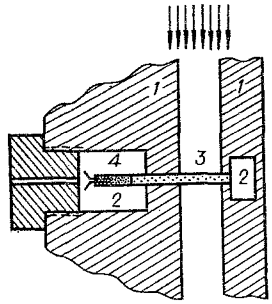


Fig. 1

number of parameters, as in [5, 8], the values of which depended on the concrete explosive.

The present study is dedicated to a solution of the problem of explosion of cylindrical charges of various explosives in air, and also to experimental verification of shock-wave parameters in the near zone, i.e., the region from the charge surface to the energy similarity zone.

## MATHEMATICAL FORMULATION OF THE PROBLEM

We assume that in air with initial pressure $p_0$ and density $\rho_0$ a cylindrical explosive charge with initial density $\rho_{ex}$, radius $r_{ex}$, and detonation rate $D_0$ is exploded.

From the moment at which the detonation wave arrives at the charge surface a cylindrical shock wave will propagate through the air. In view of the cylindrical symmetry of the problem, we may use the equation of one-dimensional gas dynamics, which are representable in the following form:

a) in the detonation product region from the axis of symmetry to the contact surface $0 \leqslant \lambda \leqslant \lambda_{cs}$ in Lagrangian variables

$$\begin{gathered}\partial\lambda/\partial T = U,\ \partial U/\partial T = -\rho_0/\rho_{ex}\cdot(\lambda/\xi)\cdot\partial P/\partial\xi,\\ \partial E/\partial T = -P\cdot\partial(1/\rho)/\partial T,\ 1/\rho = \rho_0/\rho_{ex}\cdot(\lambda/\xi)\cdot\partial\lambda/\partial\xi,\end{gathered} \tag{1}$$

b) from the contact surface to the shock front $\lambda_{cs} \leqslant \lambda \leqslant \lambda_f$, in Euler variables

$$\begin{gathered}\partial\rho/\partial T + 1/\lambda\cdot\partial(\rho U\lambda)/\partial\lambda = 0,\\ \partial(\rho U)/\partial T + 1/\lambda\cdot\partial(\rho U^2\lambda)/\partial\lambda + \partial P/\partial\lambda = 0,\\ \frac{\partial}{\partial T}[\rho(E + U^2/2)] + \frac{1}{\lambda}\frac{\partial}{\partial\lambda}[\rho U(E + P/\rho + U^2/2)\lambda] = 0,\end{gathered} \tag{2}$$

where $\rho = R/\rho_0$; $U = u/\sqrt{p_0/\rho_0}$; $P = p/p_0$; $E = e\rho_0/p_0$; $T = t\sqrt{p_0/\rho_0}/r_{ex}$; $\lambda = r/r_{ex}$; $\lambda_{cs} = r_{cs}/r_{ex}$; $\lambda_f = r_f/r_{ex}$; $\xi$, Lagrangian coordinate of the detonation products; R, density; u, mass velocity; p, pressure; e, internal energy; t, time; r, spatial variable; $r_{cs}$, $r_f$, distance from axis of symmetry to contact surface and shock wave, respectively.

## EQUATION OF STATE

Analysis of equations of state for the detonation products of the most widely used explosives (trotyl, hexogene, TH, PETN of various densities) shows that with sufficient generality the equation of state

$$P = [\gamma(\rho) - 1]\cdot\rho E + \varphi(\rho) \tag{3}$$

is valid, in which the functions $\gamma(\rho)$ and $\varphi(\rho)$, according to [9], have the following form:

$$\gamma(\rho) = \begin{cases}\gamma_\infty & \text{for}\quad x > 1,\\ \gamma_0 + (\gamma_\infty - \gamma_0)\,x(3 - 3x + x^2) & \text{for}\quad x \leqslant 1,\end{cases} \tag{4}$$

$$\varphi(\rho) = \begin{cases}\dfrac{\rho_* D_*^2}{p_0}A(\delta - \delta_*)^\alpha & \text{for}\quad x > 1,\\ 0 & \text{for}\quad x \leqslant 1,\end{cases} \tag{5}$$

where $x = \delta/\delta_*$; $\delta = \rho\rho_0/\rho_*$; $A = 0.1533$; $\alpha = 2.284$; $\gamma_0 = 1.375$; $\gamma_\infty = 1.67$; $\delta_* = 0.35$; $\rho_*$, crystalline density of the explosive; $D_*$, detonation rate of the explosive at that density.

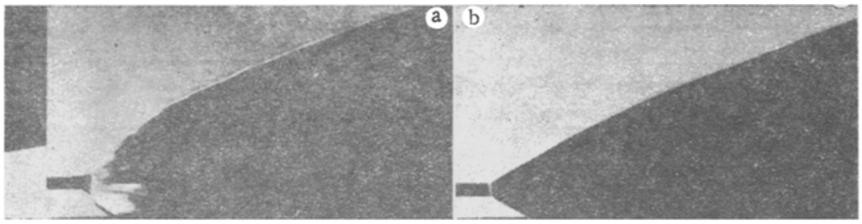


Fig. 2

We take special note that to obtain the equation of state of the detonation products of a concrete explosive substance, as was shown in [9], it is necessary to specify only two physical parameters $\rho_*$ and $D_*$, while the form of the equation of state and the constant values do not vary with variation of the initial charge density $\rho_{ex}$. The air is assumed to be an ideal gas with constant heat capacity ratio $\gamma_1$.

The boundary conditions are: on the axis of symmetry, zero mass velocity; on the contact surface, equality of pressures and mass velocities; in the shock wave, the recognized relationships at the discontinuity. As initial data for calculation of the problem it is necessary to have the distribution of gasdynamic variables in the explosion products at the moment of exit of the detonation wave to the charge surface. These values are found from calculation of a self-similar problem (see details in [10]) with use of equations of state (3)-(5) for the detonation products.

The numerical solution algorithm is constructed such that the detonation product region is calculated by the pseudoviscosity method [11], and the region between the contact surface and the shock front by the method of movable grids [12], which permits accurate distinction of the shock front.

Numerical solutions were obtained for standard values of air parameters: $p_0 = 1.013 \cdot 10^5$ N/m$^2$, $\rho_0 = 1.1842$ kg/m$^3$, $T_0 = 298.15$°K, $\gamma_1 = 1.4$. The detonation rate $D_0$ for various initial explosive densities was determined from the expression $D_0 = \Delta^{0.7} D_*$, where $\Delta = \rho_{ex}/\rho_*$ [9]. The total energy contained in the explosive at the moment of exit of the detonation wave onto the surface is found from the expression

$$W = \frac{\sigma_\nu}{\nu+1} \int_0^{r_{ex}} R\,(e + u^2/2)\, dr^{\nu+1} = \frac{\sigma_\nu}{\nu+1} p_{CJ}\, r_{ex}^{\nu+1} \cdot s,$$

where $\sigma_\nu = (\nu - 1)(\nu - 2) + 2\pi\nu$ ($\nu = 0, 1, 2$ for plane, cylindrical, and spherical explosions); $p_{CJ} = \rho_{ex} D_0^2 \cdot X$, pressure on the detonation wave front; $X = u_{CJ}/D_0$; $u_{CJ}$, mass velocity of the detonation products at the detonation wave front; $s = \int_0^1 \rho\,(E + U^2/2)\, d\lambda^{\nu+1}$. For detonation product equations of state (3)-(5), the values of s and X are independent of $\nu$, $\rho_*$, $D_*$, but are functions of the parameter $\Delta$ alone. Numerical values for certain $\Delta$ are presented below.

| $\Delta$ | 1 | 0.8 | 0.6 | 0.48 |
|---|---|---|---|---|
| s | 0.32465 | 0.4282 | 0.5731 | 0.6791 |
| X | 0.2562 | 0.2604 | 0.2698 | 0.2817 |

## EXPERIMENTAL VERIFICATION

Explosion chamber 1, used in studying the propagation of a cylindrical shock wave, consisted of a cylindrical gap between steel disks (Fig. 1), on the axis of which was mounted an explosive charge 3. The charge was initiated by an attached high-voltage detonator 4. The steel disks were provided with damping cavities 2 to eliminate the effect of the electrical detonator and reflected waves on the shock wave from the explosion charge. The working field lens of the schlieren system was protected by transparent windows of optically homogeneous glass. The Foucault knife of the schlieren system was installed parallel to the charge. The process of shock-wave propagation was recorded by schlieren photography. A pulse triggered the flash lamp of the schlieren apparatus and a pulse generator, which after a predetermined time applied a signal to the electric detonator.

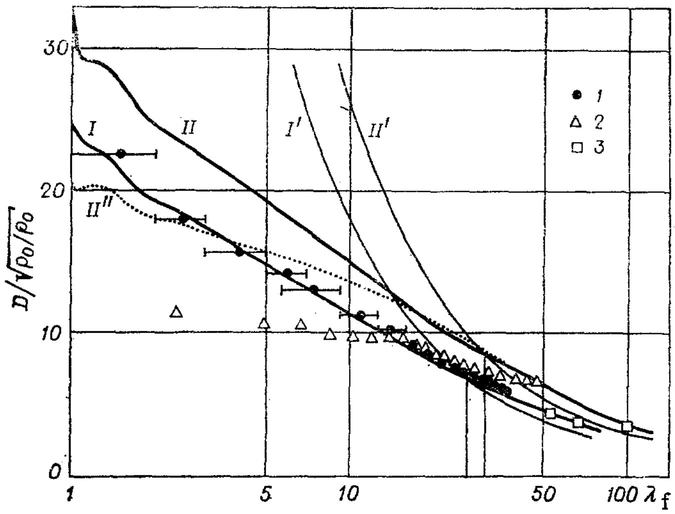


Fig. 3

The shock waves were excited in air by charges of detonation fuse or of powdered PETN, contained in a paper shell. The detonation parameters of these charges were determined independently. For the fuse the detonation rate was 7.3 km/sec, which corresponds to $\rho_{ex}$ = 1.5 g/cm³. The linear density of PETN, $m_{ex}$ = 110 mg/cm, in the detonation fuse corresponded to a charge radius $r_{ex} \simeq 1.53$ mm. For the PETN in paper shells $D_0$ = 5 km/sec, which gives $\rho_{ex}$ = 0.85 g/cm³. In the experiments charges with $m_{ex}$ = 100-150 mg/cm were used, with linear density of the paper shell ≈25 mg/cm.

Figure 2 shows typical schlieren photographs of the process for: a) a PETN charge in a paper shell, with a streak camera sweep rate of 30,000 rpm; b) the explosion of a fuse of the same sweep rate for comparison. The difference in shock-wave behavior near the fuse and paper-shelled charges should be noted.

## EVALUATION OF RESULTS

The propagation speed is one of the most important parameters of a shock wave. Figure 3 shows calculated and experimental values of dimensionless shock speed as a function the position of the front $\lambda_f$. Line I is a calculation for PETN with $\rho_{ex}$ = 0.85 g/cm³ at $\gamma_1$ = 1.4; I' is for a point explosion with the same energy; II is a calculation for PETN with $\rho_{ex}$ = 1.5 g/cm³ (density of the detonation fuse charge); II' is the corresponding point explosion with an energy equal to the chemical energy of the explosive charge; II" is a calculation for instantaneous detonation of a PETN charge with $\rho_{ex}$ = 1.5 g/cm³; the points represent: 1) experimental data of PETN (horizontal lines, uncertainty range); 2) data for detonation fuses.

The experimental results in the near zone agree well with calculated values for PETN charges in a paper shell (ratio of shell mass to explosive mass BB ≈ 0.25). In turn, the calculated velocity profile of the shock wave from the explosive charge in the near zone is low in comparison to the profile of the equivalent point explosion. With increase in $\lambda_f$ the difference decreases, and at some $\lambda_f^*$ the difference decreases, and in some explosions the velocities of shock waves from the charge and a point explosion becomes equal. With further increase in $\lambda_f$ the solution for the charge is somewhat higher than for a point explosion, the latter asymptotically approaching the solution for the charge from below at $\lambda_f > 200$. For PETN with $\rho_{ex}$ = 0.85 g/cm³ $\lambda_f^*$ = 26. It develops that at this value of $\lambda_f^*$ the mass of air encompassed by the shock wave is equal to the mass of the charge.

For fuses, the experimental points diverge markedly from calculations in the near zone. This is due to the strong effect of the charge shell on the initial stage of shock-wave propagation ($m/m_{ex}$ = 1.3). The shell significantly complicates the wave pattern of interaction between the leading discontinuity and perturbations existing in the compressed gas region. The role of the shell was also noted in [4, 5]. The calculated value of $\lambda_f^*$ = 35, with experiment, giving 47. These values for fuses practically coincide with those determined from the condition of equality of the mass of air enclosed by the shock wave with charge mass: for a fuse without a shell $\lambda_f^*$ = 35, and with a shell (m = 25 g/m, $m_{ex}$ = 11 g/m), $\lambda_f^*$ = 53.

Figure 3, curve 3 shows data of [4] for explosion of a long fuse charge ($\lambda_f > 50$). The velocities determined by measuring peak pressures in the shock wave [4] prove to be low in compar-

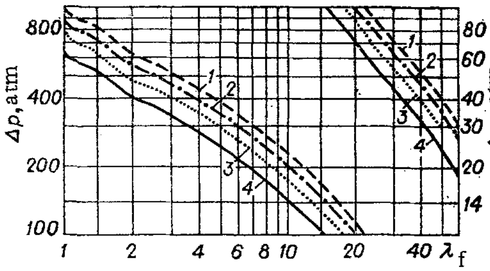

Fig. 4

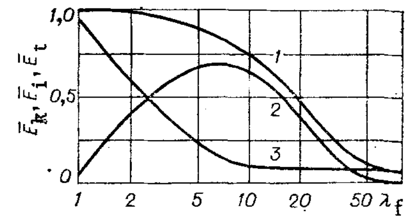

Fig. 5

ison to the experimental data for the region $50 < \lambda_f < 100$. The data of [4] for fuses agree with the numerical solution at $\lambda_f \approx 100$. The most probable reason for the low values of [4] is the high linear density of the fuse shell (19 g/m [4] instead of 14 g/m in the present study). There may also be some discrepancy due to the low resolving power of the piezoquartz pressure sensors used in [4]. Unfortunately, this last question was not considered in [4].

Figure 4 shows calculated values of excess pressure $\Delta p$ as a function of shock-front radius for cylindrical charges of hexogene, PETN, TH 50/50, and trotyl with monocrystalline density $\rho^*$ (curves 1-4, respectively) at the explosive parameters indicated below:

| | Hexogene | PETN | TH 50/50 | TNT |
|---|---|---|---|---|
| $\rho_*$, g/cm³ | 1.82 | 1.77 | 1.735 | 1.663 |
| $D_*$, km/sec | 8.80 | 8.35 | 7.83 | 7.15 |

In Fig. 5, for PETN with $\rho_{ex} = 0.85$ g/cm³, relative values of total $\bar{E}_t = E_t/W$, kinetic $\bar{E}_k = E_k/W$, and internal $\bar{E}_i = E_i/W$ energy of the detonation products (curves 1-3, respectively) are shown as a function of dimensionless shock-front radius. The redistribution of detonation product energy occupies a significant time interval. Thus, half of the initial energy of the charge is transferred into the air only when the shock-wave radius $\lambda \approx 19$. We note that by the time of maximum detonation product expansion ($\lambda_{cs} = 40.22$), which is reached at $\lambda_f \approx 78$, the total energy of the detonation products practically coincides with the internal energy, and comprises 6-7% of the initial value. For PETN with $\rho_{ex} = 1.5$ g/cm³ the first halt of the contact surface occurs at $\lambda_{cs} = 52.9$ ($\lambda_f = 103.4$), after which the products begin to compress to $\lambda_{cs} = 30.4$ ($\lambda_f = 182$), after which the surface performs decreasing periodic oscillations. The change in total energy of the detonation products in these pulsations does not exceed 2%.

Thus, in the present study the problem of propagation of cylindrical shock waves excited by charges of various solid explosives has been solved numerically, and the behavior of shock waves in the zone near the charge has been studied experimentally. It has been shown that the charge shell significantly reduces shock wave parameters in the near zone and greatly enlarges the latter. It has been established that the character of the charge detonation process has a marked effect on shock-wave parameters in the near zone. The boundaries of the energy similarity zone can be estimated from the condition of equality of the charge mass and the mass of air enclosed by the shock wave from the charge.

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# CALCULATION OF THE INITIATION OF A HETEROGENEOUS DETONATION WITH A CHARGE OF CONDENSED EXPLOSIVE

S. A. Zhdan

Theoretical problems of the dynamics of processes taking place during the initiation of a heterogeneous (gas-droplet) detonation have been investigated considerably less than those during the initiation of a gas detonation [1]. In [2], obviously, for the first time with a mathematical model formulated within the framework of the mechanics of a two-phase multi-velocity continuous medium [3], the dynamics of the yield in a self-sustaining heterogeneous detonation as a result of a point explosion is considered. The improvement of the mathematical models [4, 5] with a description of the two-phase reacting medium, in particular the calculation of the induction time, has allowed the existence of the critical energies of initiation of a heterogeneous detonation to be shown by a numerical method.

In this paper, the problem concerning the detonation of a charge of condensed explosive in a gas-droplet medium is numerically solved, for which a restriction is assumed in the mathematical model [5], concerned with the divided combustion of the vapor and drops of fuel after the lapse of the induction period.

Formulation of the Problem. We shall consider the one-dimensional motion of a monodispersed air suspension of a liquid fuel with a droplet diameter $d_0$ and a volume concentration of $\alpha_{20}$ in a gaseous oxidation with an initial pressure $p_0$ and density $\rho_0$, in the case of the explosion of a condensed explosive with a radius $r_{ex}$ and density $\rho_{ex}$.

We write the equations of gasdynamics in the region of the detonation products (DP) of the condensed explosive ($0 \leqslant r \leqslant r_c$) in Lagrangian variables

$$\partial r/\partial t = U,\ \partial U/\partial t = -1/\rho_{ex}(r/m)^{\nu} \cdot \partial p/\partial m,$$
$$\partial E/\partial t = -p \cdot \partial(1/\rho)/\partial t,\ \rho_{ex}/\rho = (r/m)^{\nu}\partial r/\partial m. \tag{1}$$

Here t is the time; r and m, Euler and Lagrangian coordinate, respectively; p, U, ρ, and E, pressure, mass velocity, density, and internal energy of the detonation products (DP); $r_c$, coordinate of the contact surface. The equation of state of the detonation products of the condensed explosive is given in the form

$$p = (\gamma(\rho) - 1)\rho E + \varphi(\rho), \tag{2}$$

where functions $\gamma(\rho)$ and $\varphi(\rho)$ for the most widely used explosives of the type of trotyl, hexogen, and PETN of different initial density have a universal form [6], and contain only two physical parameters: $\rho_*$, the monocrystalline density of the specific explosive and $D_*$, the detonation velocity of the explosive with this density.

Within the framework of the assumptions in [2, 5], the system of equations describing the behavior of the gas phase in the region between the contact surface and the shock front (SF) ($r_c < r < r_f$) is written in the form

$$\frac{\partial \rho_1}{\partial t} + \frac{1}{r^{\nu}}\frac{\partial}{\partial r}(\rho_1 u_1 r^{\nu}) = \rho_2^0\alpha_2 M, \tag{3}$$

$$\frac{\partial(\rho_1 u_1)}{\partial t} + \frac{1}{r^{\nu}}\frac{\partial}{\partial r}(\rho_1 u_1^2 r^{\nu}) + \frac{\partial p_1}{\partial r} = \rho_2^0\alpha_2(Mu_2 - F), \tag{4}$$

$$\frac{\partial(\rho_1 E_1)}{\partial t} + \frac{1}{r^{\nu}}\frac{\partial}{\partial r}\left[\rho_1 u_1\left(E_1 + \frac{p_1}{\rho_1}\right)r^{\nu}\right] = \rho_2^0\alpha_2\left[M\left(Q + e_2 + \frac{u_2^2}{2}\right) - u_2 F\right], \tag{5}$$

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