SHOCK WAVE FRONT FROM AN UNDERGROUND EXPLOSION

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Sometimes the law of motion of a shock wave front from a explosion in a continuous medium can be found without obtaining a complete solution to the explosion problem. For example, for a point explosion in an ideal gas, self-similarity makes it possible to obtain the motion of the front of a strong shock wave from considerations of dimensionality [1].

Motion is not self-similar for an explosion in a solid (for example, the ground). At small distances from the center of the explosion in the strong wave region, self-similarity does not exist because of the uncertainty in the location of the explosion. At larger distances, where the explosion can be taken as a point source, there is no self-similarity, because now the wave is not strong. Nonetheless, in the initial stage of an underground explosion, while the wave is strong, the law of motion and the front parameters of the wave can be found approximately without a full solution of the explosion problem. This can be done with the aid of a "crust" approximation or the expanding-shell approximation [2-4].

The moving ground between the explosion and the shock wave front is taken as the shell. The mass of the shell grows due to the work of the explosion products on its inner boundary (the gas—ground contact surface).

Use of the laws of conservation of mass, momentum, and energy and considering the conditions at the shell boundaries makes it possible to obtain an ordinary differential equation for one of the parameters of the shock wave problem. This makes it possible to complete the system of Rankine—Hugoniot equations, to find the law of motion of the front and the boundary of the explosion products. This method was used to calculate the parameters of the shock wave front for the explosion in an ideal gas [2, 3, 5] and in the ground [4]. However, in [4], the cold component of the pressure was ignored in the ground and in the compressed shock wave.

Here we consider both the hot and the cold component of the pressure in the material behind the shock wave front. It is shown that over almost the whole range of existence of shock wave from an underground explosion, the cold component of the pressure exceeds the hot component and cannot be neglected. A differential equation is obtained for compressing the ground in the shock wave front. By solving it, all the parameters of the front and the law of motion of the boundary of the gas cavity can be expressed for an underground explosion.

1. Formulation of the Problem. The medium in which the explosion occurs is assumed to be a porous solid body (ground). Let ρ_1 be the initial density, ρ_0 the density of the continuous uncompressed ground, $k = \rho_0/\rho$ the porosity, c_0 the speed of sound, and n a parameter which characterizes the compressibility of the ground.

The explosion is simulated by the adiabatic expansion of a plasma from the explosion products. The plasma is taken to be an ideal gas with an adiabatic index γ_3. The initial radius of the gas sphere a_3 is proportional to the cube root of the energy of the explosion E_3:

$$a_3 = \alpha_3 E_3^{1/3} \tag{1.1}$$

where $\alpha_3 \approx 0.16\text{-}0.47$ m/kton$^{1/3}$ [6]. The initial density of the explosion products ρ_3 is equal to the density of the surrounding ground. The initial pressure in the explosion p_3 is

$$p_3 = 3(\gamma_3 - 1) E_3/(4\pi a_3^3). \tag{1.2}$$

The pressure p_3 is so large that the spherically symmetric motion which arises in the ground is described by the equations of gas dynamics:

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$$\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial r}(\rho u)+\frac{2}{r}\rho u=0,\quad \frac{\partial}{\partial t}(\rho u)+\frac{\partial}{\partial r}[(\rho u)u]+\frac{2}{r}(\rho u)u+\frac{\partial p}{\partial r}=0,\tag{1.3}$$
$$\frac{\partial}{\partial t}\left[\rho\left(\varepsilon+\frac{u^2}{2}\right)\right]+\frac{\partial}{\partial r}\left[\rho\left(\varepsilon+\frac{u^2}{2}\right)u\right]+\frac{\partial}{\partial r}(pu)+\frac{2}{r}\rho\left(\varepsilon+\frac{u^2}{2}+\frac{p}{\rho}\right)u=0.$$

Here ρ is the density, u is the mass velocity, p is the pressure, ε is the internal energy per unit mass of ground; t is the time, and r is the coordinate, $0 \le t < \infty$, $r_3(t) \le r \le R(t)$, $r_3(t)$ is the law of motion of the boundary of the gas sphere, and R(t) is the law of motion of the shock wave front.

The equation of state of the shock front is used in the Mie–Grüneisen form [3]

$$p(V,T)=p_x(V)+p_T(V,T),\quad \varepsilon(V,T)=\varepsilon_x(V)+\varepsilon_T(V,T),\quad \varepsilon_x=\int_V^{V_0}p_x(V)\,dV,\quad p_T=\Gamma\varepsilon_T/V,$$

where $V = 1/\rho$ is the specific volume; T is the temperature; p_x and p_T are the cold and hot components of the pressure; ε_x and ε_T are the cold and hot components of the internal energy; V_0 is the initial volume; and Γ is the Grüneisen coefficient.

The dependence of the cold component of the pressure on the volume is taken as a power law

$$p_x(V)=\left(c_0^2/nV_0\right)[(V_0/V)^n-1]=\left(\rho_0c_0^2/n\right)\left(\delta^n-1\right)\quad(\delta=V_0/V=\rho/\rho_0).\tag{1.4}$$

The boundary conditions at the contact boundary are a discontinuity in the pressure and the normal components of the velocity:

$$p(r,t)|_{r=r_3(t)}=p_3\left[\frac{a_3}{r_3(t)}\right]^{3\gamma_3},\quad u(r,t)|_{r=r_3(t)}=\dot r_3(t)\quad(\dot r_3\equiv dr_3/dt).\tag{1.5}$$

The conditions at the shock wave front are the Rankine–Hugoniot conditions:

$$\rho_2(\dot R-u_2)=\rho_1\dot R,\quad p_2=\rho_2u_2(\dot R-u_2)+p_1,\quad \varepsilon_2=\frac{1}{2}(p_2+p_1)\left(\frac{1}{\rho_1}-\frac{1}{\rho_2}\right)+\varepsilon_1,\tag{1.6}$$

where the subscript 1 denotes values ahead of the wave front and 2 the values behind it, and $\dot R \equiv dT/dt$.

For a strong shock wave, $\varepsilon_1 \ll \varepsilon_2$ and $p_1 \ll p_2$; as a result, we assume $\varepsilon_1 = p_1 = 0$ in the conditions (1.6). Moreover, the shock adiabat $(1.6)_3$ of the solid body (1.4) is described by the interpolation formula of Zababakhin and Zel'dovich [3]:

$$p_2=\frac{(h-1)\,p_x-2\varepsilon_x/V_2}{h-V_1/V_2}=\frac{\rho_0c_0^2}{n}\frac{q(\sigma)}{h-k\sigma}.\tag{1.7}$$

Here $\sigma=\rho_2/\rho_0$; $k=\rho_0/\rho_1$; $q(\sigma)=\alpha_1\sigma^n+\alpha_2\sigma+\alpha_3$; $\alpha_1=h-(n+1)/(n-1)$; $\alpha_2=2n/(n-1)$; $\alpha_3=-(h+1)$; $h=2/\Gamma+1$. With the use of the variable σ, condition (1.6) for the strong shock wave is written in the form

$$\rho_2=\rho_0\sigma,\quad u_2=\frac{k\sigma-1}{k\sigma}\dot R,\quad p_2=\frac{\rho_0c_0^2}{n}\frac{q_0(\sigma)}{h-k\sigma}.\tag{1.8}$$

The initial conditions are

$$u(r,t)|_{t=0}=0,\quad 0\leqslant r<\infty,\tag{1.9}$$
$$\rho(r,t)|_{t=0}=\begin{cases}\rho_3, & 0\leqslant r\leqslant a_3,\\ \rho_1, & r>a_3,\end{cases}\quad p(r,t)|_{t=0}=\begin{cases}p_3, & 0\leqslant r<\infty,\\ p_1, & r>a_3.\end{cases}$$

The shock wave propagates as the result of the expansion of the explosion products in the ground. We must find the law of motion of the shock wave front, the boundary of the explosion products, and the material parameters at the front: the compression, the mass velocity, and the pressure.

2. Solution. Equation (1.3) is integrated over the volume which is included between the surface of the gas sphere $r_3 = r_3(t)$ and the shock wave front $R = R(t)$. By considering the conditions (1.5), (1.8), and (1.9) we obtain a system of equations which express the conservation laws for a layer of ground set into motion:

$$\int_{r_3}^{R} \rho r^2\, dr = \frac{\rho_0 (R^3 - a_3^3)}{R3k}, \tag{2.1}$$

$$\frac{d}{dt}\int_{r_3}^{R} \rho u r^2\, dr = 2\int_{r_3}^{R} pr\, dr + r_3^3 p_3 \left(\frac{a_3}{r_3}\right)^{3\gamma_3},$$

$$\int_{r_3}^{R} \rho\left(\varepsilon + \frac{u^2}{2}\right) r^2\, dr = \frac{a_3 p_3}{3(\gamma_3 - 1)}\left[1 - \left(\frac{a_3}{r_3}\right)^{\frac{3}{\gamma_3 - 1}}\right].$$

The adiabatically expanding explosion products act on the ground like to a spherical piston, which is moving and decelerating. Therefore, behind the shock wave front, the density, pressure, and velocity are decreasing functions of the distance from the front. The profiles of density, pressure, and velocity should be similar to the same quantities behind the front of a strong shock wave from a concentrated explosion [1]. For example, the density should have its largest value at the front and fall off sharply behind it. The pressure should vary approximately the same way, only it does not die out to zero like the velocity, but to some value equal to the pressure at the boundary of the gas cavity. For these reasons, we approximate the profiles of the density and pressure behind the shock wave front as Dirac delta functions, as in [5]:

$$\rho(r, t) = A(t)\delta(R - r); \tag{2,2}$$

$$\frac{p(r, t) - p(r_3)}{p_2 - p(r_3)} \approx \frac{\rho}{\rho_2} = \frac{A}{\rho_2}\delta(R - r). \tag{2.3}$$

By substituting (2.2) into Eq. $(2.1)_1$ for the conservation of mass, we have

$$A(t) = \rho_0 (R^3 - a_3^3)/(3kR^2). \tag{2.4}$$

By using Eqs. (2.2)-(2.4), we obtain from the conservation equations for momentum and energy $(2.1)_{2,3}$

$$\frac{\rho_0}{3k}\frac{d}{dt}\left[(R^3 - a_3^3)u_2\right] = p_3\left(\frac{a_3}{r_3}\right)^{3\gamma_3}\left[R^2 - \frac{2(R^3 - a_3^3)}{3k\sigma R}\right] + \frac{2\rho_0 c_0^2 (R^3 - a_3^3)}{3k\sigma R} P, \tag{2.5}$$

$$\frac{\rho_0}{3k}(R^3 - a_3^3)u_2^2 = \frac{p_3 a_3^3}{3(\gamma_3 - 1)}\left[1 - \left(\frac{a_3}{r_3}\right)^{3(\gamma_3 - 1)}\right] \qquad \left(P \equiv \frac{p_2}{\rho_0 c_0^2} = \frac{q(\sigma)}{n(h - k\sigma)}\right).$$

We now go to dimensionless variables and functions in the system (2.5)

$$\tau = c_0 t/a_3, \quad x = R/a_3, \quad x_3 = r_3/a_3, \quad U = u_2/c_0, \quad Y = \dot{R}/c_0, \, \Pi_3 = p_3/\rho_0 c_0^2. \tag{2.6}$$

In terms of the variables (2.6), the system (2.5) takes the form

$$\frac{1}{3k}\frac{d}{d\tau}\left[(x^3 - 1)U\right] = \Pi_3 x_3^{-3\gamma_3}\left[x^2 - \frac{2(x^3 - 1)}{3k\sigma x}\right] + \frac{2(x^3 - 1)}{3k\sigma x} P, \tag{2.7}$$

$$(x^3 - 1)U^2 = k\Pi_3(\gamma_3 - 1)^{-1}\left[1 - x_3^{-3(\gamma_3 - 1)}\right].$$

In the new variables, the conditions at the shock wave front are written as

$$U = \frac{k\sigma - 1}{k\sigma} Y, \quad P = \frac{k\sigma - 1}{k^2\sigma} Y^2, \quad P = \frac{q(\sigma)}{n(h - k\sigma)}. \tag{2.8}$$

By solving the system (2.7) and (2.8) for the quantity σ (the compression of the ground at the shock wave front) and changing the roles of the variables τ and x, we find the differential equation for the compression

$$(x^3 - 1) H_1(\sigma)\frac{d\sigma}{dx} + \left[x^2 - \frac{2(x^3 - 1)}{3k\sigma x}\right] H_3(\sigma) = 0, \tag{2.9}$$

where

$$H_1(\sigma) = \frac{P}{\sigma(k\sigma - 1)} + \frac{dP}{d\sigma}; \quad H_3(\sigma) = P - \Pi_3\left[1 - \Pi_3^{-1}(\gamma_3 - 1)(x^3 - 1)(k\sigma)^{-1}(k\sigma - 1)P\right]^m; \; m = \frac{\gamma_3}{(\gamma_3 - 1)}.$$

Equations (2.9) are basic for describing the parameters of the front of a strong shock wave from an underground explosion in this approximation.

The boundary condition for σ follows from the initial conditions of the original problem:

$$\sigma(x)|_{x=1} = \sigma_* \tag{2.10}$$

where σ_* is the root of the algebraic equation $P(\sigma_*) = \Pi_3$.

After we find the value of σ from (2.9) and (2.10), we express the other parameters of the front in terms of σ by relationships following from (2.8):

$$P = \frac{q(\sigma)}{n(h - k\sigma)}, \quad Y = k\left(\frac{\sigma P}{k\sigma - 1}\right)^{1/2}, \quad U = \frac{k\sigma - 1}{k\sigma} Y. \tag{2.11}$$

Then we obtain the law of motion of the shock wave front in the form

$$\tau = \int_1^x \frac{d\xi}{Y(\xi)}. \tag{2.12}$$

The law of motion of the boundary of the gas cavity, according to $(2.7)_2$, is written as

$$x_3 = \left[1 - \frac{\gamma_3 - 1}{k\Pi_3}(x^3 - 1)U^2\right]^{m_3}, \tag{2.13}$$

or, from (2.11),

$$x_3 = \left[1 - \frac{\gamma_3 - 1}{\Pi_3}(x^3 - 1)\frac{k\sigma - 1}{k\sigma}P\right]^{m_3}, \quad m_3 = -\frac{1}{3(\gamma_3 - 1)}. \tag{2.14}$$

3. Cases of Cylindrical and Plane Symmetry. Equations for the parameters of the shock wave front for cylindrical and plane symmetry of the motion from an explosion are obtained similar to the preceding case. The basic equation for compression of the ground at the shock wave front is written as

$$(x^3 - 1)H_1(\sigma)\frac{d\sigma}{dx} + \left[x^{\nu-1} - \frac{(\nu - 1)(x^\nu - 1)}{\nu k\sigma x}\right]H_\nu(x) = 0,$$

where $H_\nu(x) = P - \Pi_3[1 - \Pi_3^{-1}(\gamma_3 - 1)(x^\nu - 1)(k\sigma)^{-1}(k\sigma - 1)P]^{m_\nu}$; $m_\nu = -\frac{1}{\nu(\gamma_3 - 1)}$; and ν = 3, 2, and 1 for spherical, cylindrical, and plane waves, respectively. The boundary condition for σ stays the same as before (2.10). The law of motion of the shock wave front has the form (2.12), but the law of motion of the boundary of the explosion products is

$$x_\nu = [1 - (k\Pi_3)^{-1}(\gamma_3 - 1)(x^\nu - 1)U^2]^{m_\nu} \tag{3.1}$$

or

$$x_\nu = \left[1 - \frac{\gamma_3 - 1}{\Pi_3}(x^\nu - 1)\frac{k\sigma - 1}{k\sigma}P\right]^{m_\nu}, \quad m_\nu = -\frac{1}{\nu(\gamma_3 - 1)}.$$

4. Asymptotics for $x \gg 1$. At large distances form the center of the explosion, at which $x = r/a_3 \gg 1$, we can view the explosion as a point source and set $a_3 = 0$. Then it follows from Eqs. (3.1) that

$$U \approx \left(\frac{k\Pi_3}{\gamma_3 - 1}\right)^{1/2} x^{-\nu/2}. \tag{4.1}$$

It can be seen that the mass velocity in the shock wave front is expressed the same as in the self-similar case – as a point explosion in an ideal gas.

The shock adiabat of the ground at large pressures in $(\dot{R}, u_2)$ coordinates can be expressed as a straight line $\dot{R} = c_0 + \beta u_2$, where $\beta = h/(h - 1)$, or in dimensionless form as $Y = 1 + \beta U$.

For a strong wave $\beta U \gg 1$; then from (2.8) for $x \gg 1$, we obtain

$$\sigma \approx h/k, \quad Y \approx \beta U = \beta\left(\frac{k\Pi_3}{\gamma_3 - 1}\right)^{1/2} x^{-\nu/2}, \quad P \approx \frac{h\Pi_3}{\gamma_3 - 1}x^{-\nu}. \tag{4.2}$$

The law of motion of the shock wave front (2.12) becomes

$$x \approx \left(\frac{2 + \nu}{2}\beta\right)^{2/(2+\nu)} \left(\frac{\gamma_3 - 1}{k\Pi_3}\right)^{1/(2+\nu)} \tau^{2/(2+\nu)}. \tag{4.3}$$

From (4.1)-(4.3), it follows that at large distances (compared to the dimensions of the explosion location), the parameters at the front of a strong shock wave from an underground

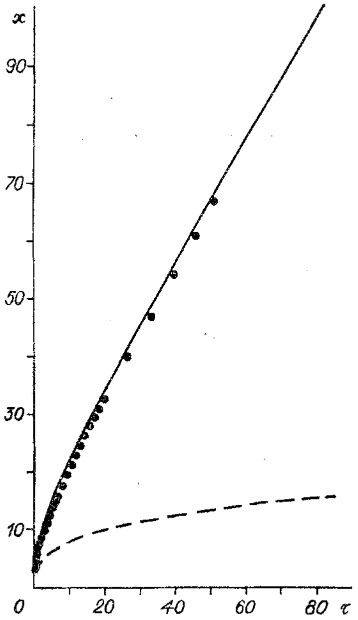

Fig. 1

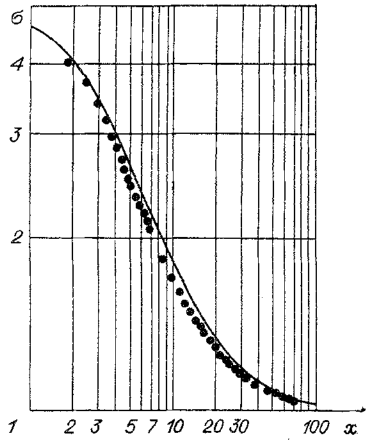

Fig. 2

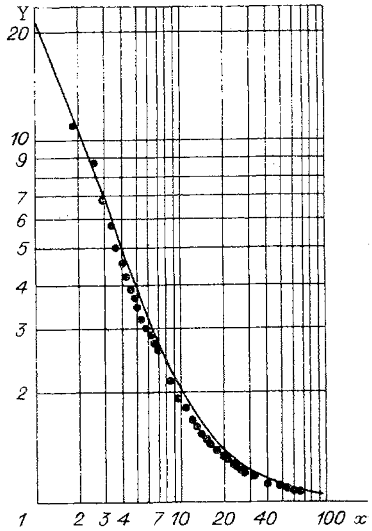

Fig. 3

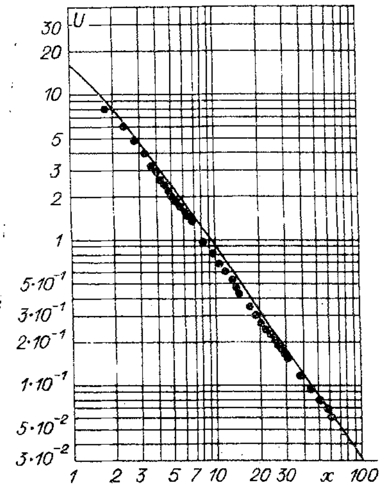

Fig. 4

explosion are described by relationships applied to an explosion by Sedov [1]. However, it can be seen that the self-similarity of the motion of the shock wave front, which follows from the asymptotic formulas (4.1)-(4.3), are derived in a very narrow interval of distances from the center of the explosion. We will show this in the case of a spherical symmetry ($\nu = 3$). Actually, on one hand, the inequality $x \gg 1$ is required for self-similarity, but on the other hand, we must have $\dot{R} \gg c_0$ or $Y \gg 1$. From the last inequality, it follows from a consideration of (4.2) that

$$x \ll \left[\left(\frac{h}{h-1}\right)\left(\frac{k\Pi_3}{\gamma_3-1}\right)^{1/2}\right]^{2/3}.$$

By combining both cases we have

$$1 \ll x \ll \left(\frac{h}{h-1}\right)^{2/3}\left(\frac{k\Pi_3}{\gamma_3-1}\right)^{1/3} = \beta^{2/3}\left(\frac{3k}{4\pi}\right)^{1/3}\left(\frac{r_0}{a_3}\right), \tag{4.4}$$

where $r_0 = (E_3/\rho_0 c_0^2)^{1/3}$ is the dynamic length of the explosion. For an explosion in nonporous rock ($k = 1$), the limiting compression is $h \approx 5$ and $r_0/a_3 \approx 10$. Then from (4.4) we have $1 \ll x \ll 10$.

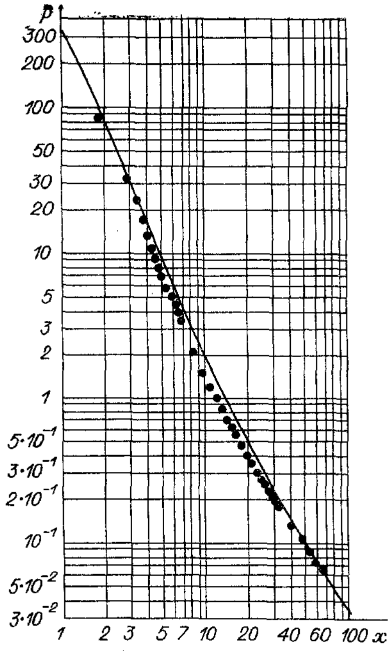

Fig. 5

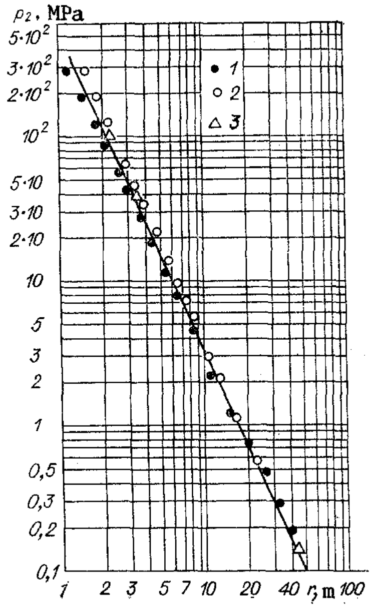

Fig. 6

From the last inequality it can be seen how small the interval of distances is, in which motion from an underground explosion can be considered approximately self-similar.

5. Calculated Results and Comparison with Other Data. In order to demonstrate the accuracy of the proposed method of finding parameters of a shock wave front from an underground explosion, calculations were performed for an explosion in rock salt by two independent methods: with the use of Eqs. (2.9)-(2.14) and on the basis of the "Volna" program, a numerical mathematical model of an explosion in a solid continuous medium [7]. In both cases, the mathematical formulation of the problem is identical to (1.1)-(1.9).

The parameters of the equation of state for rock salt were taken from results [8] of impact compression of salt. In the calculations, they are as follows: $\rho_0 = 2.16 \cdot 10^3$ kg/m^3, $c_0 = 3900$ m/sec, $k = 1$, $n = 3.2$, and $h = 4.95$. The explosion parameters are $E_3 = 4.18 \cdot 10^{12}$ J, $a_3 = 0.3$ m, and $\gamma_3 = 4/3$.

Results of calculating the x–τ diagram, the compression of the ground at the shock wave front $\sigma(x)$, the velocity of the front $Y(x)$, and mass velocity $U(x)$, and the pressure $P(x)$ are shown in Figs. 1-5, respectively; the solid lines are the calculations using the approximation, and the points are from the Volna program. The dashed curve in Fig. 1 shows the x–τ diagram of the boundary of the gas cavity, calculated from Eq. (2.14). As can be seen from Figs. 1-5, the x–τ diagrams differ by no more than 3%, the compression by 7%, and the pressure by 17% over the whole range of distances $1 \leq x \leq 70$.

The approximate method was used for calculations of parameters of the shock wave front for the "Ranier" explosion in tuff [9]. The constants in the equation of state of tuff were taken from the shock compression of this rock [10]: $\rho_0 = 2.3 \cdot 10^3$ kg/m^3, $c_0 = 1500$ m/sec, $k = 1.15$, $n = 3.7$, and $h = 5.0$. The explosion parameters are $E_3 = 1.7$ kton $= 7.1 \cdot 10^{12}$ J, and $a_3 = 1.2$ m. Two values were used for the adiabatic index of the explosion parameters: $\gamma_3 = 4/3$ (photon gas) and 5/3 (monatomic ideal gas).

The results of calculating the pressure at the wave front versus distance are shown in Fig. 6, where points 1 and 2 are data for the case $\gamma_3 = 4/3$ and 5/3, respectively, 3 is the result of the experiment [9], and the curve is a calculation of the "Ranier" explosion [11]. Figure 6 demonstrates the satisfactory correlation of our data and data from [9] and [il].

The calculated results, presented in Figs. 1-6, make it possible to compare the values of the cold and hot components of the pressure in the shock wave front of an underground explosion. Table 1 shows the ratio of the cold pressure to the hot pressure P_X/P_T as a function of the distance x ($x = r/a_3 \geq 1$) for an explosion in rock salt. It can be seen that for $x \approx 3.6$ ($r \approx 0.2\ r_0$), the magnitudes of both pressure components are the same. The hot

TABLE 1

x	r/r_0	σ	P_X+P_T	P_X	P_X/P_T
1,008	0,060	4,254	368,2	31,82	0,095
1,576	0,094	3,984	142,6	25,74	0,220
2,600	0,155	3,464	45,54	16,33	0,560
3,624	0,217	3,021	20,64	10,44	1,024
4,904	0,293	2,603	9,96	6,36	1,77

component dominates at smaller distances, and the cold component at larger ones. Even at a distance x = 1.6 ($r = 0.1\ r_0$), the cold component provides around 20% of the total pressure in the wave front.

Thus, it can be asserted that in the shock wave from an underground explosion the cold component of the pressure (and internal energy) is substantial and neglecting it compared to the hot component is incorrect.

From Figs. 1-6 it can also be seen that the calculated results of the parameters of the shock wave front in the expanding-shell approximation is valid even in the region where, strictly speaking, the front cannot be considered strong. The good agreement of the calculated results of the numerical model of the explosion and the experiments occurs to pressure values in the wave front on the order of $0.01\rho_0 c_0^2$, which corresponds to a distance $\sim 6r_0$ from the center of the explosion.

From what has been presented it follows that describing the shock wave front from an underground explosion in the expanding-shell approximation is rather accurate over the whole range over which this wave exists. The simplicity of the approximation makes it a convenient and useful method for calculating the parameters of the shock wave front of an underground explosion. Obviously this method is applicable for describing explosions not only in ground but it metals, liquids, and other condensed media.

LITERATURE CITED

1. L. I. Sedov, Methods of Similarity and Dimensionality in Mechanics [in Russian], GITTL [State Technical and Theoretical Press], Moscow (1954).
2. G. G. Chernyi, "The point explosion problem," Dokl. Akad. Nauk SSSR, 112, No. 2 (1957).
3. Ya. B. Zel'dovich and Yu. P. Raizer, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena, Academic Press, New York (1966).
4. S. R. Kurtz, "A back-of-the-envelope approach to prediction ground motion phenomena," J. Geophys. Res., 80, No. 32 (1975).
5. V. V. Struminskii, Aerodynamics and Molecular Gas Dynamics [in Russian], Nauka, Moscow (1985).
6. H. L. Brode, "Gas dynamic motion with radiation: a general numerical method," Astronautica Acta, 14, No. 5 (1969).
7. V. F. Kuropatenko and B. K. Potapkin, "Experiment in writing a large sequential computational program using 'Volna' as an example," [in Russian], ITPM SO AN SSSR [Institute of Theoretical and Applied Mechanics of the Siberian Department of the Academy of Sciences USSR], Novosibirsk (1972).
8. L. V. Al'tshuler, M. N. Pavlovskii, L. V. Kuleshova, and G. V. Simakov, "Investigation of the halogenoids of alkaline metals at high pressures and temperatures from shock compression," Fiz. Tverd. Tela, 5, No. 1 (1963).
9. G. W. Jonson, G. H. Higgins, and C. E. Violet, "Underground nuclear detonations," J. Geophys. Res., 64, No. 10 (1959).
10. F. W. Holzer, "Measurements and calculations of peak shock-wave parameters from underground nuclear detonations," J. Geophys. Res., 70, No. 4 (1965).
11. J. H. Nuckols, "A computer calculation of Rainier," Proc. 2nd Flowshare Symp., San Francisco, CA, May 13-15, 1959.