EFFECT OF THE CONDITIONS OF AN UNDERGROUND EXPLOSION ON THE MECHANICAL CHARACTERISTICS OF THE SURROUNDING MEDIUM

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The mechanical characteristics of an underground explosion can be controlled by changing the conditions under which the explosion takes place. There are various methods of influencing the characteristics of the explosion process. The authors of [1, 2] discussed the formulation and solution of the corresponding problems for the case when an underground explosion is carried out in a radially nonuniform medium. It was noted that radial nonuniformity may be created around a charge by inundation of the porous medium near the charge. If the medium to be flooded is first broken up by an auxiliary explosion, then after all of the cavities in the thus-fractured medium have been filled with the liquid (water, for example), it can be asserted that the medium will not be subject to shear stresses and that its stress state will be completely characterized by assigning the pressure. The expansion of a blasthole in a radially nonuniform medium was studied in [1, 2], but the characteristics of the shock wave were not calculated. Another method of controlling the mechanical characteristics of an explosion is surrounding the charge with a spherical interlayer of a porous material. An experimental and theoretical study was made in [3] of the explosion of a charge surrounded by a spherically symmetric plastic-foam interlayer; water was used as the medium. Finally, yet another method of controlling the effect of an explosion is to change the density of charging of the explosive. This is easily done in practice.

Here we give most of our attention to the effect of the conditions under which an underground explosion is carried out on the elastic characteristics of the explosion. We calculate the parameters of the elastic wave in an explosion in a radially nonuniform elastoplastic medium for the cases when the charge is surrounded by a flooded medium or a highly porous shell. Results are presented from calculation of the seismic efficiency of an underground explosion for different charging densities.

Explosion in a Flooded Medium

We will examine a spherically symmetric formulation of the problem. Let there be a cavity of radius a_0 containing gas at the pressure p_0 at the initial moment of time. The quantity γ is the adiabatic exponent of the gas in the cavity. At $t > 0$, a shock wave (SW) begins to propagate from the wall of the cavity into the surrounding medium. The medium in which the explosion takes place is radially nonuniform. In the region $r < b_0$ (b_0 is the radius of the prefractured and flooded medium), the shear stresses are equal to zero. At $r < b_0$, the substance at the SW front is irreversibly compressed from the density ρ_0 to the density ρ_1. This compaction, characterized by the parameter $\varepsilon_1 = 1 - \rho_0/\rho_1$, may be connected with the closure of cavities left after flooding of the fractured zone. In the region $r < b_0$, the following mass and momentum conservation conditions are satisfied at the SW front

$$u(R) = \varepsilon_1\dot{R}(t),\ p(R) = \varepsilon_1\rho_0\dot{R}^2(t) + p_h. \quad (1)$$

Here, R(t) is the radius of the SW front; p_h is the background pressure; u(R) is the mass velocity of the medium behind the front. Considering the medium behind the front to be incompressible, we have

$$\rho_1(\partial u/\partial t + u\,\partial u/\partial r) = -\partial p/\partial r,\ \partial(r^2u)/\partial r = 0 \quad (2)$$

(u is the velocity of the medium, p is pressure). It follows from the second equation of (2) that

$$u = \dot{a}a^2/r^2 \quad (3)$$

(a is the radius of the explosion cavity).

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Substitute (3) into Eq. (2) and by integration we get the profile of the pressure in the flooding region (for $r < b_0$)

$$p(r, t) = \varphi(t) + \rho_1 \left(\frac{a^2 \ddot{a} + 2a\dot{a}^2}{r} - \frac{a^4 \dot{a}^2}{2r^4} \right), \tag{4}$$

We can easily find $\varphi(t)$ by using the condition of adiabatic expansion of the cavity:

$$\varphi(t) = p_0 (a_0/a)^{3\gamma} - \rho_1 (a\ddot{a} + 3\dot{a}^2/2). \tag{5}$$

Equations (4) and (5), together with Eqs. (1), make it possible to find an equation to determine $a(t)$

$$\rho_1 \left(1 - \frac{a}{R}\right) a\ddot{a} = p_0 \left(\frac{a_0}{a}\right)^{3\gamma} - \rho_1 \dot{a}^2 \left[\frac{3}{2} - \frac{2a}{R} - \frac{2 - \varepsilon_1}{2\varepsilon_1} \left(\frac{a}{R}\right)^4 \right]. \tag{6}$$

Equation (6) is augmented by the well-known relation between R and a: $R = [a^3 - (1 - \varepsilon_1) \cdot {}_0{}^3]^{1/3} \varepsilon_1^{-1/3}$, as well as by the initial conditions $a(0) = a_0$, $\dot{a}(0) = \sqrt{\varepsilon_1 p_0/\rho_1}$; it describes the expansion of the cavity until the SW reaches the boundary of the flooded zone, i.e., to the moment of time t_1 determined by the condition

$$R(t_1) = b_0. \tag{7}$$

After the shock wave reaches the boundary of the flooded zone, it continues to propagate. It now propagates in a medium having shear resistance. In this medium (in the region $r > b_0$), we use the description developed in [4]. We assume that, in the region $r > b_0$, the medium is compacted at the front from ρ_{20} to ρ_2. The compaction is characterized by the parameter $\varepsilon_2 = 1 - \rho_{20}/\rho_2$. We also assume that the medium is fractured at the front and that the flow of the fractured medium is described by the plasticity condition $\tau = kp + m$ [$\tau = \sigma_r - \sigma_\varphi$, $p = -(\sigma_r + 2\sigma_\varphi)/3$, k and m being constants and σ_r and σ_φ being components of the stress tensor] and the equation for volumetric strains of a medium with allowance for dilatation: $\partial u/\partial r + 2u/r = \Lambda |\partial u/\partial r - u/r|$ (Λ is the dilatation rate).

We equate the pressure and the radial stresses, respectively, at the boundary $b = b(b_0, t)$ – the moving interface between the flooded zone and the zone with strength properties. Then, with allowance for the conditions at the shock front, we obtain

$$\begin{gathered} p_0 \left(\frac{a_0}{a}\right)^{3\gamma} + \rho_1 \left[\left(\frac{a}{b} - 1\right) a\ddot{a} - \left(\frac{3}{2} - \frac{2a}{b} + \frac{1}{2}\left(\frac{a}{b}\right)^4\right)\dot{a}^2 \right] = \frac{k}{3m} + \varepsilon_2 \rho_{20} \Big[\varepsilon_2 + \\ + (1 - \varepsilon_2)\left(\frac{b_0}{R}\right)^{n+1} \Big]^{-\frac{\alpha}{n+1}} \left\{ \dot{R}^2 + \frac{p_h - k/3m}{\varepsilon_2 \rho_{20}} + A\left(\frac{b_0}{R}\right) R\ddot{R} + n\dot{R}^2 \left[A\left(\frac{b_0}{R}\right) - F\left(\frac{b_0}{R}\right) \right] \right\}, \\ n = \frac{2 - \Lambda}{1 + \Lambda}, \quad \alpha = \frac{6m}{1 + 2m}, \quad b = [(1 - \varepsilon_2) b_0^{n+1} + \varepsilon_2 R^{n+1}]^{1/(n+1)}, \\ (b_0^3 - a_0^3)\rho_0 = (b^3 - a^3)\rho_1, \quad A(y) = \int_{1/y}^{1} s^2 \Phi^{\alpha - n - 2}(s)\, ds, \\ F(y) = \varepsilon_2 \int_{1/y}^{1} s^2 \Phi^{\alpha - 2n - 3}(s)\, ds \end{gathered} \tag{8}$$

where ($\Phi = \Phi(s)$ is the relation between the Eulerian and Lagrangian coordinates [4]). Equation (8) is valid from the moment of time t_1, determined from (7), to the moment t_2 – which is found from the condition $\dot{R}(t_2) = c_\ell$, where c_ℓ is the velocity of the longitudinal elastic waves. When the velocity of the front $\dot{R}(t)$ becomes equal to c_ℓ, the elastic wave begins to overtake the shock front. Here, the medium continues to fracture at the shock front.

All of the elastic displacements $f(\xi)$ [$\xi = t - t_2 - (r - R_2/c_\ell$, $R_2 = R(t_2)$ is the radius from which elastic energy begins to be generated].

The presence of the elastic wave affects the motion of the shock front. The conditions on the front take the form

$$u(R) - \dot{R} = \rho_{20}(\overset{e}{v} - \dot{R})/\rho_2, \quad \sigma_r(R) = \overset{e}{\sigma_r} - \varepsilon_2 \rho_{20} (\overset{e}{v} - \dot{R})^2.$$

Here, u(R) and $\sigma_r(R)$ are the mass velocity and the radial stress in the shock front; v^e and $\sigma_r{}^e$ are the mass velocity and radial stress in the elastic wave. Now we can obtain an equation for $a(t)$ with allowance for the radiation of the elastic wave:

$$p_0\left(\frac{a_0}{a}\right)^{3\gamma}+\rho_1\left[a\ddot{a}\left(\frac{a}{b}-1\right)-\left(\frac{3}{2}-\frac{2a}{b}+\frac{1}{2}\left(\frac{a}{b}\right)^4\right)\dot{a}^2\right]=\frac{k}{3m}+$$
$$+\left[\varepsilon_2+(1-\varepsilon_2)\left(\frac{b_0}{R}\right)^{n+1}\right]^{-\alpha/(n+1)}\left\{p_h+\rho_{20}c_l^2\left[\frac{\ddot{f}(\xi)}{c_l^2R}+\frac{2(1-2\nu)}{1-\nu}\left(\frac{\dot{f}(\xi)}{c_lR^2}+\frac{f(\xi)}{R^3}\right)\right]+\right. \quad (9)$$
$$\left.+\rho_{20}\varepsilon_2\left(\frac{\ddot{f}(\xi)}{c_lR}+\frac{\dot{f}(\xi)}{R^2}-\dot{R}\right)^2-\frac{k}{3m}+A\left(\frac{b_0}{R}\right)\ddot{R}R+n\dot{R}^2\left[A\left(\frac{b_0}{R}\right)-F\left(\frac{b_0}{R}\right)\right]\right\};$$

$$\frac{\ddot{f}}{R}=\frac{\sigma_*-p_h}{\rho_{20}c_l^2}-\frac{2(1-2\nu)}{1-\nu}\left(\frac{\dot{f}}{c_lR^2}+\frac{f}{R^3}\right) \quad (10)$$

(σ_* is the crushing strength; ν is the Poisson ratio). Thus, Eqs. (6) and (8)-(10) give a complete description of the motion of a radially nonuniform medium with allowance for the radiation of the elastic wave.

At $t \leq t_1$, we solve Eq. (6). At $t_1 \leq t \leq t_2$, the solution is given by Eq. (8). At $t > t_2$, Eqs. (9) and (10) must be solved. The equations were integrated numerically. Figure 1 shows the dependence of the radiated seismic energy e, calculated from the formula $e = \frac{4\pi\rho_{20}}{c_l}\int_0^\infty[\ddot{f}(s)]^2ds$, on the corrected flooding radius b_0/a_0 for the following initial data: p_h = 22 MPa, c_ℓ = 3500 m/sec, k = 15 MPa, m = 0.5, ν = 0.3, ε_1 = 0.01, ε_2 = 0.25.

In Fig. 1, energy is in units of radiant energy for the uniform case, when there is no flooded zone with diminished strength properties ($b_0 = a_0$). It is evident that the relation $e(b_0/a_0)$ is nonmonotonic in character. Flooding of the region around the charge leads to a situation whereby the shock wave decays more slowly than in the unflooded medium – since the flooded medium has no shear strength and no energy is dissipated in the course of plastic flow. As a result, high values of stress are propagated large distances, so that there is an increase in the size of the effective elastic radiator and the radiated elastic energy. When the radius of the flooded zone is large, an SW passing through it is weakened due to dissipation occurring as a result of pore collapse. Thus, the resulting elastic wave is weaker.

Figure 2 shows the dependence of the residual strains w (referred to the residual strains w_0 at $b_0 = a_0$) on b_0/a_0 at a certain distance from the center of the explosion (curve 1). An increase in the flooding radius is accompanied by a reduction in the fraction of energy dissipated at the shock front with compaction of the medium compared to the case of an unflooded medium. This reduction is connected with less compaction in the flooded medium ($\varepsilon_1 < \varepsilon_2$). In this case, there is an increase in the amount of energy transmitted by the unflooded medium – which in turn leads to an increase in the residual strains. Curve 2 sho the dependence of the final radius of the cavity on the flooding radius.

Explosion of a Charge Surrounded by a Porous Interlayer

The effect of a porous interlayer around the charge on the mechanical effect of an explosion is determined by the character of propagation of the blast waves in porous media. In a highly porous substance, a substantial portion of the energy of the SW is converted to internal energy of the medium. When this energy is sufficient for vaporization of the sub-

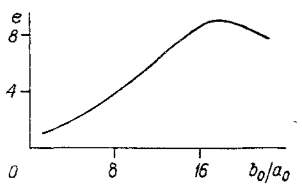

Fig. 1

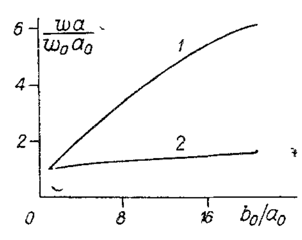

Fig. 2

stance, the medium is vaporized behind the front and the peak pressure at the front is greater than in the case when the medium is not vaporized. This feature of the effect of high porosity of the medium on SW propagation is characteristic of the near region of the explosion, where the medium is vaporized as the wave passes through the front. Later, when the substance on the front is not vaporized, a significant amount of the energy dissipated at the front is converted to internal energy of the solid phase of the medium — which does not contribute to pressure. At this stage of the explosion, the high level of energy dissipation at the front leads to rapid decay with increasing distance from the stress center on the front.

A typical feature of the explosion of a charge of a chemical explosive is the relatively low volumetric concentration of energy given off during the explosion. This makes it possible to realistically assume that in performing laboratory explosions in high-porosity substances, the effect of the latter amounts to weakening of the explosive effect with neglect of the vaporization phenomenon.

Let an explosion cavity of radius a_0, surrounded by a spherical shell of a high-porosity material, be filled by gases with the pressure p_0. A spherical SW propagates from the walls of the cavity, and the substance is compact at the front due to collapse of pores. It is assumed that the porosity of the material of the shell (the volumetric fraction of pores) is so great that the width of the post-front layer of compacted substance is small compared to the radius of the shock front. The equation of motion of the medium behind the front is written as follows in Lagrangian coordinates with allowance for the strength properties:

$$\rho_0 r_0^2 r^{\alpha-2} \frac{\partial u}{\partial t} = \frac{\partial}{\partial r_0}\left[r^\alpha\left(\sigma_r(r, t) + \frac{k}{3m}\right)\right]. \tag{11}$$

Integration of this equation with allowance for boundary conditions (1) and the continuity equation (2) yields

$$R^\alpha {}_r\ R + a^\alpha p(a) + (R^\alpha - a^\alpha)k/(3m) = \int_a^R \rho \dot{u} r^\alpha dr.^* \tag{12}$$

We find the value of $\rho\dot{u}$ similarly to [5], from the law of motion of the thin layer of compacted substance

$$\frac{d}{dt}(Mu) = \frac{d}{dt}\left[\frac{4\pi}{3}(R^3 - a^3)\rho u\right] = 4\pi a^2 p(a), \tag{13}$$

where M is the mass of the layer; $\rho = \rho_0/(1 - m_0)$ is the density of the compressed substance; u is its mass velocity; m_0 is the initial porosity; R is the radius of the shock front; $a(t)$ is the running radius of the cavity; k and m are the adhesion and friction coefficients; $\alpha = 6m/2m + 1)$. Assuming that the product $\rho\dot{u}$ is constant along the radius in the thin layer, we find from (11)-(13) that

$$\sigma_r(R) = -p(a)\frac{z^3 - 1 - 3(z^{\alpha+1} - 1)/(1+\alpha)}{z^\alpha(z^3 - 1) - 3z^2(z^{\alpha+1} - 1)/(\alpha+1)} - \\ - \frac{k(1 - z^{-\alpha})/(3m)}{1 - 3z^3(1 - z^{-\alpha-1})(\alpha+1)^{-1}(z^3 - 1)^{-1}} \tag{14}$$

($z = R/a$). It should be noted that in the near zone of the explosion (and for a granular substance with negligibly weak bonding and for all values of R), the second term in Eq. (14) can be ignored. In contrast to the solution reported in [5] — where it was assumed that $p(a) = p(R)/2$ at any moment of time, in Eq. (14) the proportionality factor between the indicated quantities depends on the ratio R/a and the coefficient of internal friction. The resulting solution is valid up to the moment the SW reaches the boundary separating the highly porous shell and the surrounding medium. In the present study, the propagation of the SW in the medium was described by a model of a porous, incompressible, variably compacted dilatating medium [6]. Solutions were also found for the problem of the radiation of elastic waves both from the moving front of a fracture wave and after its stoppage [7]. To join these solutions, use was made of the condition of continuity of the radial stress at the shock front during its passage across the shell-medium boundary.

Calculations corresponding to the results presented below were performed for an explosion in rocksalt of 2.2 g/cm³ density. The density of the solid phase of the shell material

*As appears in Russian original — Editor.

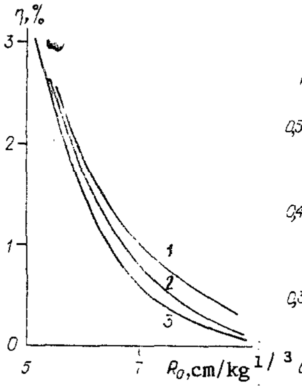

Fig. 3

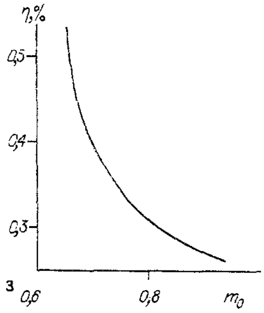

Fig. 4

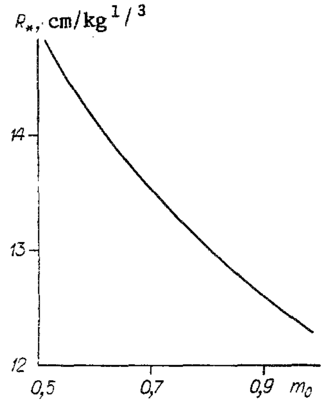

Fig. 5

was 2.5 g/cm³. Figure 3 shows the dependence of the seismic efficiency of the explosion, i.e., the fraction of explosive energy radiated to infinity in the form of elastic waves, on the radius R_0 of the high-porosity shell surrounding the charge (the porosity of the shell material m_0 = 0.65, 0.8, 0.95 — lines 1-3). The radius of the charge was 5 cm/kg$^{1/3}$. As shown by the calculations, the weakening of the seismic activity of the explosion due to the surrounding of the charge by the porous shell is proportional to the thickness of this shell and the porosity of its material. It follows from the mass conservation condition that $a^3 - (1 - m_0)a^3 = m_0R^3$, where a_0 is the initial radius of the charge, $a(t)$ is the radius of the explosion cavity, and R is the radius of the shock front. In our case, the second term in the given expression can be ignored. Also, if the shell is composed of a powdery material in which there is no bonding between particles, we can ignore the second term in Eq. (14). Here, the following expression is valid for the radial stresses at the shock front:

$$\sigma_r(R) = -p(a)K(m_0, \alpha) \tag{15}$$

[$K(m_0, \alpha)$ is a function of m_0 and α].

For adiabatic expansion of the detonation products $\sigma_r(R) \sim m_0^{-\gamma}R^{-3\gamma}$ (γ is the adiabatic exponent of the gaseous detonation products). It is evident that when the SW passes through the shell surrounding the charge, the stresses on the front decay more rapidly than in solid media — for which the exponent in the stress decay law is within the range 1.8-3.3.

Figure 4 illustrates the dependence of the seismic activity of the explosion on the porosity of a shell material of fixed radius equal to 7.5 cm/kg$^{1/3}$. This result shows that rapid decay of shock waves in high-porosity shells leads to more effective shielding from the explosive and seismic effects.

Equation (15), with allowance for the relation between a and R, makes it possible to determine the shell radius R_*, at which fracture will be absent in the surrounding medium. If σ_* is the crushing strength of the medium, then the sought relation is written in the form $\sigma_* = p_0(a_0/a)^{3\gamma}m_0^{-\gamma}K(m_0, \alpha)$, where $K(m_0, \alpha)$ is the first term in Eq. (14) with the assumption that $z = R/a = m_0^{-1/3}$. Thus, for R_* we can use the expression $R_* = a_0[K(m_0, \alpha)p_0/(m_0^{\gamma}\sigma_*)]^{1/3\gamma}$ (p_0 is the initial pressure of the gaseous detonation products). The dependence of R_* on m_0 is shown in Fig. 5. This result is in agreement with the previous results: an increase in porosity is accompanied by an increase in the rate of stress decay at the shock front, these stresses becoming lower than σ_* at lower values of the radius of the front.

LITERATURE CITED

1. E. E. Lovetskii, A. M. Maslennikov, and V. S. Fetisov, "Mechanical effect and dissipative processes during an explosion in a porous medium," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1981).
2. E. E. Lovetskii, A. M. Maslennikov, and V. S. Fetisov, "Spherical explosion in a radially nonuniform saturated porous medium," Fiz. Goreniya Vzryva, No. 3 (1979).
3. V. A. Batalov, V. A. Kotov, et al., "Underground explosion in water. Role of alleviating interlayers in the formation of the cavity," Izv. Akad. Nauk SSSR, Fiz. Zemli, No. 8 (1980).

4. S. Z. Dunin and V. K. Sirotkin, "Expansion of a gas-filled cavity in brittle rock with allowance for the dilatational properties of the soil," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1977).
5. Ya. B. Zel'dovich and Yu. G. Raizer, Physics of Shock Waves in High-Temperature Hydrodynamic Phenomena [in Russian], Nauka, Moscow (1966).
6. A. A. Zverev and V. S. Fetisov, "Expansion of a gas cavity in a variably compacted dilatating medium," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1982).
7. A. A. Zverev, E. E. Lovetskii, and V. S. Fetisov, "Radiation of an elastic wave in an explosion in a variably compacted porous medium," Zh. Prikl. Mekh. Tekh. Fiz., No. 6 (1983).

VARIATIONAL PROBLEMS OF RADIATIVE GAS DYNAMICS IN THE PRESENCE OF GAS INJECTION FROM A SURFACE

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The radiant heat flux to any part of a body moving with supersonic velocity at $M \gg 1$ can be reduced by various methods [1, 2]. In connection with this, it is interesting to study ways of reducing heat flow to the frontal part of a body. One effective method here is choosing the form of the body and its flight path so as to minimize its radiant heating. Several studies (see the survey [1]) have examined problems concerning optimization of the form of a body in the presence of radiative heat transfer (without injection of gas from the surface), given different additional restrictions.

The studies [2-4] obtained relations for radiant flux to a body with allowance for the effect of a screening layer of injected gas during the disintegration of a thermally protective coating. These relations were obtained on the basis of an asymptotic solution of the equations of radiative gas dynamics. The same relations will be used here to formulate variational problems of gas dynamics in the presence of injection of gas from a surface.

Analysis of the problem shows that it is presently efficient to solve variational problems and perform comparative analyses by using an approach in which the first step involves employing approximate expressions for the radiative heat-transfer coefficients and pressure for the body that are found on the basis of analytic and numerical solutions of the equations of radiative gas dynamics. After the solution of the corresponding variational problem in the second step, the gas dynamic parameters and aerodynamic characteristics can be calculated more accurately on the basis of established numerical methods of solution with allowance for the spectral properties of the gas.

The thus-obtained preliminary results point the way to practicable methods for solving problems involving a reduction in the thermal loads on aircraft by efficiently selecting their aerodynamic shapes and the distribution of the gas injection.

Correlations to Calculate Radiant Fluxes to the Body. Using the approximation of a locally uniform plane layer when calculating radiative heat transfer in a shock layer and assuming the surface of the body to be diffusely reflecting, we have the following for the radiant flux to the surface of the body [2]:

$$q_R(t) = \pi \int_0^\infty d\nu \varepsilon_\nu \left[2 \int_0^{\tau_{\nu_s}} B_\nu E_2(\tau'_\nu)\, d\tau'_\nu - B_\nu(T_w) \right], \tag{1}$$

$$\tau_{\nu_c} = \int_0^{z_c} k'_\nu dz', \quad \tau_{\nu_s} = \int_0^{z_s} k'_\nu dz',$$

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