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INTERACTION OF SHOCK WAVES FROM THE SUCCESSIVE UNDERWATER EXPLOSION OF SPHERICAL CHARGES

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§1. An experiment was carried out in an unbounded liquid according to the scheme shown in Fig. 1a-c (d is the distance between the centers of two identical spherical charges 1 and 2 and the initiation of the second charge can be effected with a specified time delay τ). Typical records of the shock-wave interaction corresponding to the cases a-c of Fig. 1 are shown in Fig. 1d-f.

In the case $\tau = 0$ (Fig. 1a, d), symmetrical interaction of the spherical shock waves occurs in the plane of symmetry OO_1, perpendicular to the axis of the system of charges aa_1. It is well known that when a spherical shock wave is incident on a plane at an angle greater than a certain critical angle, irregular reflection of the shock wave, accompanied by the formation of a Mach configuration occurs; GC_1C_2 is the region of its propagation. It should be noted that this case was considered in [1], where the process of the nonlinear interaction of spherical shock waves in water was investigated experimentally and numerically up to the instant of formation of the Mach wave.

When $\tau > 0$ (see Fig. 1b, e), two types of spherical shock-wave interaction occur. For $\tau < \tau_0 = d/D_1$, where D_1 is the velocity of the first shock front, the region of their nonlinear interaction is located between two curvilinear surfaces, formed by the rotation of the lines CC_1 and CC_2 around the axis aa_1. With increase of τ, the angles of inclination of the lines CC_1 and CC_2 to the axis are decreased, and, finally, when $\tau \geq \tau_0$, the explosion of charge 2 occurs in the region behind the shock front 1 (Fig. 1c, f), and the shock wave from the explosion of charge 2 is propagated with a high velocity, overtaking shock wave 1 (overtaking process). We shall call the point C at which the front of the second shock wave overtakes shock front 1 the overtaking point. The region of propagation of the resulting shock wave (RSW) is bounded by the surface C_1CC_2, which is symmetrical relative to the axis aa_1, and the surface area of the RSW front increases with time.

The experiment was conducted with a system of two charges (each with a weight of 2 g) in a water tank 1.5 m × 1.8 m × 2 m having transparent windows. Photography of the process was carried out by means of an SFR-1 high-speed moving-picture camera in a shadow facility with pulsed illumination. The frames clearly show that in addition to the interaction of the shock waves described above, after each of the shock waves s strikes the explosion bubble of the opposite charge, rarefaction waves r are formed. In the region of intersection of the rarefaction waves, a cavitation zone b is formed. It is interesting to note that in the experiments being considered, a Mach reflection of the rarefaction waves M was observed.

This paper is devoted to the investigation of the interaction of shock waves for $\tau > \tau_0$: the overtaking process and the parameters of the propagating RSW.

§2. In order to carry out and investigate the successive underwater explosion of two spherical charges, the following procedure was used. In an open reservoir of depth 6 m two identical cast spherical charges of Trityl/Hexogen 50/50 were positioned at a distance of 3 m from the free surface. The weight of each charge Q = 100 g, radius $r_0 = 2.5$ cm, and the distance between the centers of the charges was varied over the range $d = (2-30)r_0$. The axis passing between the charge centers is parallel to the free surface. Two piezoelectric pressure sensors for recording the shock waves were positioned along the axis of symmetry of the charges on the far side of charge 2 (Fig. 2). The distance from charge 2 to the sensor S1

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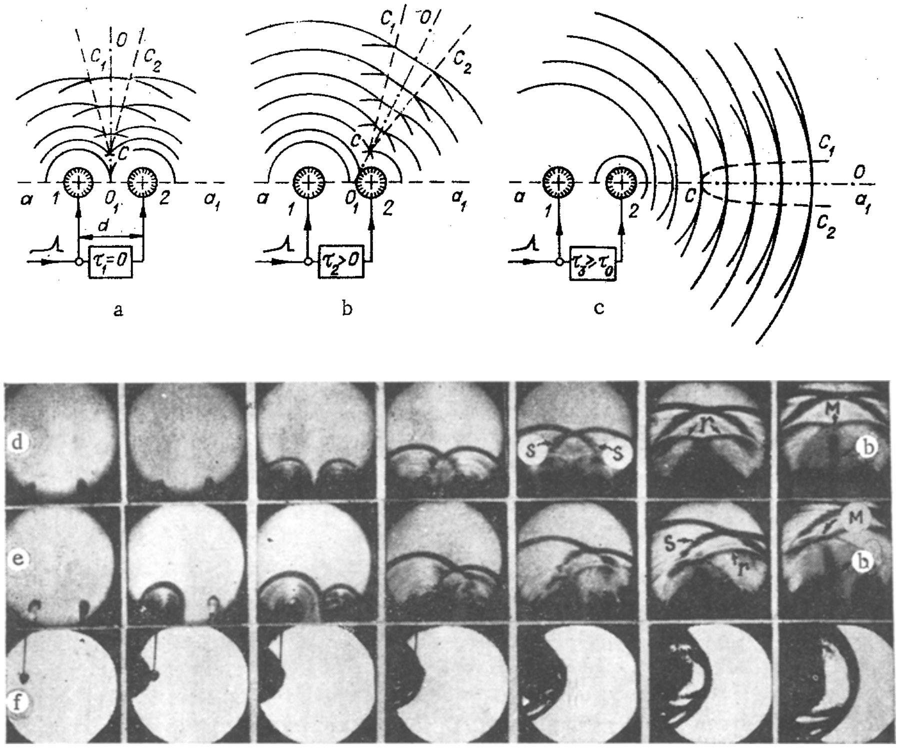

Fig. 1

was fixed and was equal to 20 m. The distance to sensor S2 was chosen within the limits 1.5 to 10 m. Signals from S1 and S2 were recorded on S1-49 and TR4602 oscilloscopes. The oscilloscopes were triggered from two pressure sensors, operating in pair with S1 and S2, respectively. The charges were exploded by electric detonators mounted in the charges, according to the scheme shown in Figs. 1 and 2. An electric pulse with amplitude 500 V exploded the electric detonator of charge 1 and then, with a delay time of τ, charge 2. With a fixed distance d, the value of τ was chosen so that charge 2 was exploded behind shock front 1, and overtaking of shock front 1 by shock front 2 took place at a specified distance r_2^* from the second charge.

The experimental data showed that the entire process of shock-wave interaction with $\tau > \tau_0$ can be divided into three stages: 1) the overtaking process of shock front 1 by the second shock wave; 2) the instant of overtaking of shock front 1 by shock front 2 and the formation of an RSW at the overtaking point C (see Fig. 1d and Fig. 2); 3) further propagation of the RSW, during which time expansion of the zone of interaction of the fronts and the defocusing of the RSW take place (see Fig. 1c, region C_1CC_2).

Investigations of the first stage showed that the coordinate of the overtaking point r_2^* depends strongly on τ (or on the initial distance between the shock fronts). Thus, in the case $d = 10r_0$ with $\tau = 0.205\cdot10^{-3}$ sec, we have $r_2^* = 2.5$ m; with $\tau = 0.211\cdot10^{-3}$ sec, $r_2^* = 5$ m; with $\tau = 0.217\cdot10^{-3}$ sec, $r_2^* = 10$ m and with $\tau = 0.224\cdot10^{-3}$ sec, $r_2^* = 20$ m. Thus, an insignificant increase of the delay time leads to a significant change of coordinate of the overtaking point. The following qualitative explanation of the nature of this dependence can be given. The pressure behind shock front 1 can be written as a function of time in the form [2, 3]

$$p_1(t)=\begin{cases}p_1^0\exp(-t/\theta_1) & \text{for} \quad t\leqslant\theta_1,\\ 0.368p_1^0\theta_1/t & \text{for} \quad t>\theta_1,\end{cases} \tag{2.1}$$

where $p_1^0 = 21{,}900/R_1^{1.2}$ atm, $\theta_1 = 8.5\cdot10^{-6}R_1^{0.25}$ sec, and $R_1 = r_1/r_0$ for $10 \leqslant R_1 \leqslant 200$. Taking account of the equation of state for the wave in theta-form, the time of propagation of shock front 1 from the point R_1 to the point R_1^0 is determined by the expression

$$t = I(R_1^0, R_1) = r_0 \int_{R_1}^{R_1^0} dR_1/D_1 = r_0 \int_{R_1}^{R_1^0} \left[\frac{\rho_0 \left(1 - \frac{B}{AR_1^{-1.2} p_0 + B}\right)^{1/n}}{AR_1^{-1.2} - p_0} \right]^{1/2} dR_1,$$

where $p_0 = 1$ atm, $A = 21{,}900$ atm, $B = 3050$ atm, and $n = 7.15$. Substituting Eq. (2.2) into (2.1), we obtain the expression for the pressure distribution along the profile of shock wave 1 at a fixed instant of time (the coordinate of the front of shock wave 1 is R_1^0):

$$p_1(R_1) = \begin{cases} AR_1^{-1.2} \exp\left[-I(R_1^0, R_1)/\theta_1(R_1)\right] & \text{for } I(R_1^0, R_1) \leqslant \theta_1(R_1), \\ 0.368 AR_1^{-1.2} \theta_1(R_1)/I(R_1^0, R_1) & \text{for } I(R_1^0, R_1) > \theta_1(R_1). \end{cases} \tag{2.3}$$

Since we can put $D_1(R_1) \approx C_0 = 1.5 \cdot 10^5$ cm/sec for $R_1 \geqslant 10$ and, consequently, $I(R_1^0, R_1) \approx (R_1^0 - R_1) r_0/C_0$, then Eq. (2.3) is simplified considerably:

$$p_1(R_1) \approx \begin{cases} AR_1^{-1.2} \exp\left[(R_1 - R_1^0) R_1^{-0.25}/1.275\right] \\ \qquad\qquad \text{for } (R_1^0 - R_1)/C_0 \leqslant \theta_1(R_1)/r_0, \\ 0275 R_1^{-0.25}/(R_1^0 - R_1) \quad \text{for } (R_1^0 - R_1)/C_0 > \theta_1(R_1)/r_0. \end{cases} \tag{2.4}$$

Hence,

$$\frac{\partial p_1(R_1)}{\partial R_1} \approx \begin{cases} \frac{21400}{R_1^{2.2}} \left(\frac{3R_1 + R_1^0}{5.1 R_1^{0.25}} - 1.2 \right) \exp\left(\frac{R_1 - R_1^0}{1.275 R_1^{0.25}} \right) \\ \qquad\qquad \text{for } \frac{R_1^0 - R_1}{C_0} \leqslant \frac{\theta_1(R_1)}{r_0}, \\ \frac{10275}{(R_1^0 - R_1) R_1^{0.95}} \left(1.95 - 0.95 \frac{R_1^0}{R_1} \right) \quad \text{for } \frac{R_1^0 - R_1}{C_0} > \frac{\theta_1(R_1)}{r_0}. \end{cases} \tag{2.5}$$

The pressure profile of shock wave 1 was plotted on the basis of Eq. (2.3) (Fig. 3a) for several fixed distances from the front of shock wave 1 to the center of charge: $r_2 = r_1^0 - d = 5.63r_0$, $6.08r_0$, $6.5r_0$, and $7.03r_0$, which correspond to delay times of explosion of charge 2 of $\tau = 0.205 \cdot 10^{-3}$, $0.211 \cdot 10^{-3}$, $0.217 \cdot 10^{-3}$, and $0.224 \cdot 10^{-3}$ sec. It can be seen from Fig. 3 that with increase of r_2, the pressure profile p_1 behind shock front 1 (ahead of shock front 2) becomes flatter. For $d = 10r_0$, with an increase of the delay time of the explosion $\tau = 0.205 \cdot 10^{-3}$ sec by 2.93% ($\tau = 0.211 \cdot 10^{-3}$ sec), p_1 at the point $r_1 = 10r_0$, according to Eq. (2.4), decreases by 3.34% and $\partial p_1/\partial R_1$, according to Eq. (2.5), by 28%. Thus, by a very slight displacement of the initial position of shock front 1 from the point r_1^0 to the point $r_1^0 + \Delta r$, the pressure gradient at the point $r_1 = 10r_0$ (i.e., the pressure gradient ahead of shock front 2) decreases more rapidly (by an order of magnitude) than the pressure p_1; i.e., the profile of shock wave 1 ahead of the front of the propagating shock wave 2 becomes flatter. This, in accordance with the experimental data given above, is found to be significant: The overtaking path r_2^* is increased considerably.

The strong effect of the profile of the leading shock wave on the overtaking path should follow also from the results of the theoretical paper [4], which considered the propagation of two spherical shock waves with a common center having a triangular profile in a gas.

By $p_\sigma(r_2^*)$ we denote the pressure at the front of the RSW at the instant of its formation (at the overtaking point C) and by $p_2^0(r_2^*)$, the pressure at the shock front 2 at this same distance r_2^* in the case of explosion of the single charge 2. We shall call the quantity $k_* = p_\sigma(r_2^*)/p_2^0(r_2^*)$ the enhancement factor at the overtaking point C; $k = p_\sigma(r_2)/p_2^0(r_2)$ is the enhancement factor at the point with the coordinate $r_2 > r_2^*$. Figure 4a shows the plot of $k_*(r_2^*)$ for $d = 10r_0$; it can be seen that as the distance between the overtaking point and the system of charges increases, k_*. It is natural to expect that for very large values of r_2^* ($r_2^* \gg d$), $k_* \to 2$, i.e., increases, the combination of shock waves with small amplitude takes place according to an acoustic law. For small values of r_2^*, however, as can be seen from the typical pressure oscillograms shown in Fig. 3b, a strong effect of combination nonlinearity of the shock waves is observed at different stages of interaction of the shock waves: $\overline{p}_2(r_2) < p_2^0(r_2) + p_1(d + r_2)$ or $\overline{p}_2(r_2) = \alpha p_2^0(r_2) + p_1(r_1 + d)$, while at the overtaking point $p_\sigma(r_2^*) =$

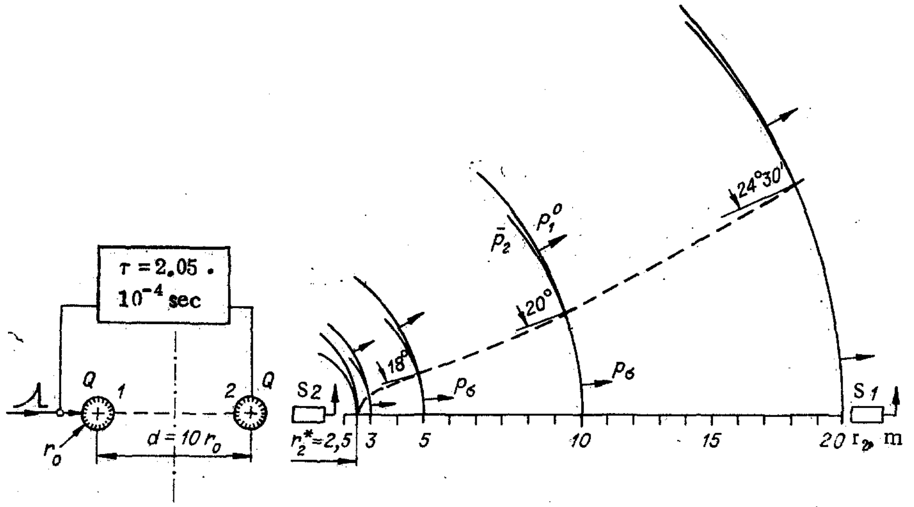

Fig. 2

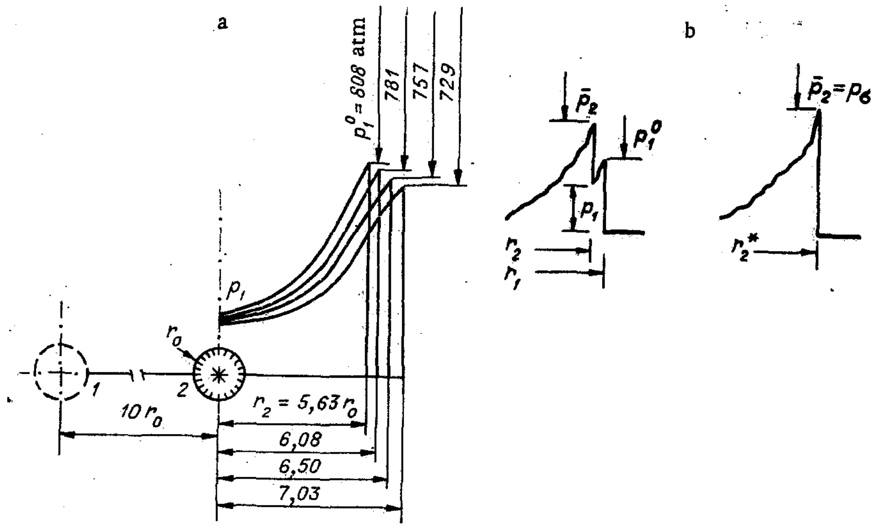

Fig. 3

$\alpha p_2^\circ + p_1^\circ(d + r_2^*)$ and, consequently, $k_* = p_\sigma(r_2^*)/p_2^\circ(r_2^*) = \alpha + p_1^\circ(r_2^*)/p_2^\circ$. Here $\bar{p}_2$ is the pressure at shock front 2, propagating through the medium in advance of compression by shock wave 1; p_2° is the pressure at shock front 2 at the same distance from charge 2, but in the case of its propagation through the unperturbed medium. The coefficient α $(0 < \alpha \leqslant 1)$ defines the nonlinearity of the shock-wave interaction. The nonlinearity for pressures of p_2° and $p_1 \gtrsim 10^2$ atm, where α is small, is particularly marked, whereas for pressures at the fronts of the interacting shock waves of order 10 atm or less, $\alpha \to 1$.

Figure 4a shows the dependence of $q = Q_e/2Q$ on r_2^*, indicating by what factor the charge weight Q_e, corresponding to the parameters of the RSW, is greater than the weight of the system of charges for different coordinates of the overtaking point. It can be seen from the graph that the gain in weight of charges subject to successive explosion, by comparison with the explosion of a single charge with a weight of 2Q, increases with distance of the overtaking point from the site of the explosion.

Let us fix the time of delay by choosing it so that the coordinate of the overtaking point is $r_2^* = 2.5$m. The pressure p_σ at the front of the RSW at the overtaking point with $d = 10r_0$ and $Q = 100$ g is equal to 117 atm. The weight of the equivalent charge Q_e corresponding to this pressure is determined by the well-known law of pressure damping for spherical shock waves and is equal to 261 g. It will be interesting to compare the law of pressure damping at the front of the RSW during its further propagation obtained from experimental data $[p_\sigma(r_2)$,

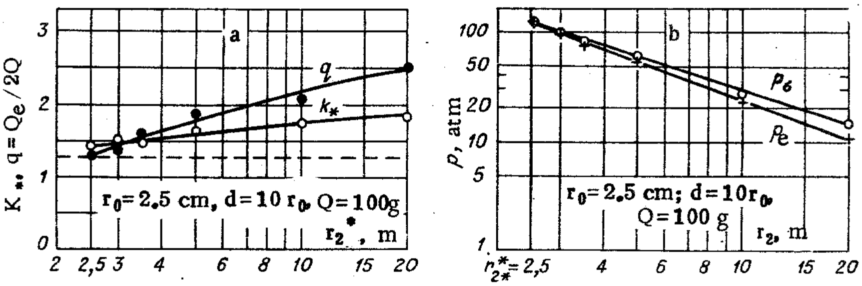

Fig. 4

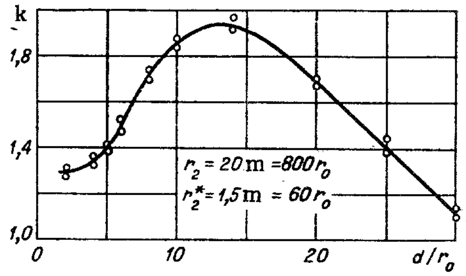

Fig. 5

see Fig. 4b] with the law of pressure damping in spherical shock waves obtained according to the power of 1.13(p_e). As a result, it was established that the pressure decreases by a r/r_2 law at the front of the RSW.

Figure 2 for the case r^*_2 = 2.5 m shows the nature of the change of surface area of the front of the RSW. These data were obtained experimentally by oscillograms of the structure of the RSW at points r_2 = 3, 5, 10, and 20 m by the rotation of a device for holding the charges at a specified position around the center of their system.

It is interesting to note that for a fixed value of r^*_2, a reduction of the distance between the charges leads to a significant increase of the surface area of the front of the RSW at a specified distance from the overtaking point: for r^*_2 = 2.5 m, distance r_2 = 10 m, and d = 6.4r_0, the coordinate of the overtaking point along the surface of the front of shock wave 1 amounts to ≈70° (the angle between the lines joining the sensors S1 and S2 and the lines joining the centers of the charges from the overtaking point at the surface of the shock wave 1) instead of 20° for d = 10r_0.

§3. The effect of the distance between the charge centers d on the pressure amplitude at the front of the RSW for fixed values of r^*_2 and r_2 was also considered. For this purpose, the parameter d was chosen in the range 2r_0–30r_0. In this case, the time delay for explosion of the second charge was chosen so that in all cases overtaking of the fronts occurred at a distance of r^*_2 = 1.5 m from charge 2. The pressure at the front of the RSW was measured at a fixed distance of r_2 = 20 m on the axis passing through the center of the charges on the side of charge 2. The results obtained are shown in the form of a plot of k = p_σ/p^0_2 versus d (Fig. 5), which has a maximum on the section d ≈ 13r_0–15r_0. In this case, with a reduction of d, k → 1.3 (this corresponds to the explosion of a double charge), and with increase of d, k → 1. In the case d = 2r_0 (the charges are touching one another), charge 2 detonates as a result of the explosion of charge 1, leading the delay of the initiating pulse. When d >> r_0, the effect of shock wave 1 on the parameters of the RSW almost disappears.

A similar phenomenon has been observed also in the case of the successive explosion of two charges with a delay time $\tau_0 = d/D_1$, i.e., when the explosion of charge 2 occurs immediately in the vicinity of the front of shock wave.

The limiting characteristics of the relation k(d) (i.e., as d → 2r_0 and for r >> r_0) are obvious, and the presence of the maximum obviously can be explained by the effect of the gradient of the back-pressure ahead of shock front 2, in the sense given above. In fact, the requirement of constancy of the coordinate of the overtaking point relative to the position of charge 2, assumed for investigating the function k(d), is stringently connected with the choice of the delay time of the second explosion and, consequently, also with the gradient of the back-pressure ahead of shock front 1 which determined by it.

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PHASE TRANSITIONS IN SHOCK WAVES (REVIEW)

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INTRODUCTION

The propagation of shock waves in a number of solids is accompanied by polymorphic transitions which change their atomic structure. The formation of new crystalline modifications in a short time of the order of 10 μsec is one of the most interesting problems in the physics of shock waves and high pressures. Dynamic recrystallization processes are extensively used in practice, e.g., in machine-building technology, for strengthening components, and for obtaining metastable high-pressure phases.

Phase transitions propagating in a metal at the detonation velocity were first detected in iron [1]. By now, polymorphic transitions in shock waves have been recorded in many metals, semiconductors, oxides, and almost all minerals and rocks. The characteristics of a few typical transitions, investigated under both dynamic and static conditions, are given in Table 1, where σ_{HYP} is the Hugoniot yield point, σ_1 is the transition stress from dynamic measurements, and p_1 is the transition pressure from static measurements (all quantities are in kilobars).

The problem of phase transitions in shock waves has various aspects. The thermodynamic analysis is based on the limiting parameters of the steady-state regimes of propagation of the shock waves. The set of stationary states determines the Hugoniot adiabat of the compressed medium. The intersection with the phase boundaries causes a break in the adiabats and under certain conditions can lead to decay of the shock front and formation of two-wave configurations from the advancing waves and the slower transition waves. A knowledge of the kinetics of the transitions is particularly important for obtaining a realistic picture of the phenomenon; transitions of martensite type have a number of special features and proceed in compression and discharge wave fronts in accordance with specific mechanisms of low-temperature recrystallization.

1. Hugoniot Adiabat in the Phase Plane

1.1. Phase-Transition Criterion. The effect of melting and polymorphic transitions on the configuration of the Hugoniot adiabat was investigated in [8-13]; the results from these studies are partially discussed in the review [14].

The thermodynamic characteristics of the medium change discontinuously at the boundary between the single-phase region and the region of existence of phase-mixture equilibrium. As a result, the shock-compression adiabat undergoes a discontinuous change on intersecting

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