New data, obtained under strong shock wave conditions from an underground nuclear explosion, on the compressibility of aluminum, plexiglass, and quartz

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The shock compressibility of porous quartz (with initial density $\rho_{00}=1.35$ and 1.75 g/cm^3), plexiglass, and aluminum was investigated at pressures of 1.8, 2.0, 0.6, and 0.54 TPa, respectively. Experimental data were obtained on the two-stage compressibility of aluminum at 1.4 TPa.

1. INTRODUCTION

The compressibility of a number of light condensed substances (water, different modifications of silicon dioxide, lithium hydride, aluminum, and others) at ultrahigh pressures, produced in underground nuclear explosions, was investigated in a series of studies in the 1970s–1980s.[1–6] In many of these measurements, specifically the measurements performed by our group, aluminum was used as the reference screen material. The shock adiabat of aluminum was determined and represented in Ref. 7 in the variables pressure (P) versus density (ρ) by two branches of parabolas that join at the pressure $\simeq$220 GPa The initial section of the upper branch was characterized by a small slope ($dP/d\rho \gtrsim 0$), which increased rapidly with increasing pressure up to values typical of any condensed substance under these conditions. In other words, for $P \gtrsim 200$ GPa the shock adiabat of aluminum was similar to the adiabats of substances undergoing phase changes with a "smeared" jump in the density for $P \geqslant$ const.

To a certain extent this situation has been confirmed in the measurements performed in Ref. 8 and in a variant of the analysis, presented in Ref. 10, of the data from Ref. 9 (in both cases for one point with similar compression parameters). Previously published results also indicated the compression curve of aluminum has the same form in this pressure range.[11]

However, results indicating the absence of anomalies in the compression of aluminum were presented in later publications.[4,6,12]

Especially important in these treatments are the results obtained at pressures of 250–650 GPa produced by underground explosions,[6] i.e. in the pressure range of interest to us.

In the present paper we present for aluminum a new experimental point which we also obtained under the conditions of an underground explosion. On the basis of these data we present for aluminum an adiabat which is a single continuous curve up to pressures determined by the computational–theoretical models. The measurements of the compressibility of light substances, performed with a reference screen consisting of aluminum,[1,2,13,14] which because of discrepancies between experiments at $P>200$ GPa were essentially of a relative character, are now absolute.

Besides the adiabats of aluminum, in the present paper we present new information on the following:

The compressibility of porous silicon dioxide (α-quartz with an initial low density $\rho_{00}=1.35$ and 1.75 g/cm^3). The new data have expanded our knowledge on the behavior of quartz in shock waves, since these measurements, performed at pressures comparable to those employed in Ref. 1, make it possible to perform the required extrapolations.

The compressibility of plexiglass $(C_5H_8O_2)\cdot n$ at experimental pressures in a range exceeding by approximately a factor of 5 the range from laboratory determinations.[15]

The two-stage compressibility of aluminum. These measurements were performed in order to determine more accurately the thermal characteristics in states where such determinations have not been made.

All of these measurements were performed in the period from 1970 to 1975, but for a number of reasons they were not previously published.

2. EXPERIMENTAL ARRANGEMENT AND RESULTS

In all experiments a strong shock wave, produced by an underground nuclear explosion and propagating through the soil surrounding the zone of energy release, entered the experimental system on a chosen contact boundary between the soil and a metal screen. The experimental system consisted of a two-layer construction in which the sample of the experimental material was placed after the reference material.[1)] Special measures were taken to produce a shock wave front of a form required for the measurements. The experimental samples were oriented so that their planes were perpendicular to the direction of propagation of the shock wave.

The arrangement of the experiments is displayed in Fig. 1. In all cases the geometric characteristics of the construction employed were as follows: The screen (100–160 mm thick) on which the experimental sample (80–100 mm thick) was secured, was positioned after the comparatively thin (30–40 mm) interlayer consisting of a metal screen. The corresponding diameters of the screens and the samples were chosen so as to prevent the lateral unloading waves from influencing the parameters of the wave front in the zone where the waves were registered. The measurements were performed with electrocontact time-of-arrival sensors; a diagram of these sensors is also displayed in Fig. 1. A constant voltage of 600–800 V was applied to two current-carrying electrodes of this sensor. When the shock wave arrived, breakdown of the air gap occurred, and the pulse from this breakdown was recorded on the screen of a pulse oscillo-

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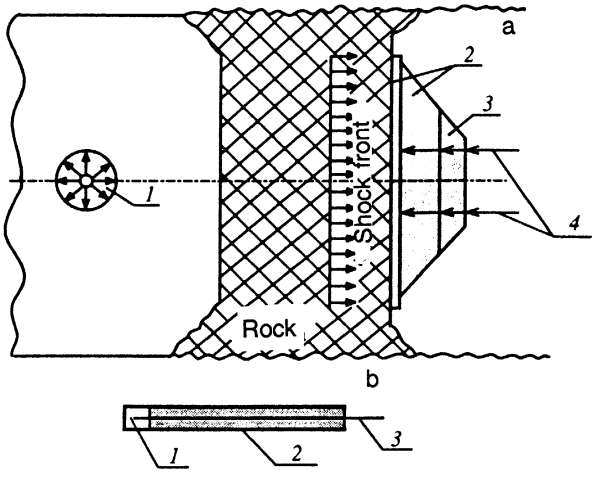

FIG. 1. a) Arrangement of the experiments: *1*—Energy source; *2*—screen; *3*—experimental material; *4*—electrocontact sensors. b) Construction of a time-of-arrival sensor: *1*—Air gap; *2*—metal screen; *3*—central electrode.

graph with maximum temporal resolution of $\pm 5 \cdot 10^{-9}$ s. At least four sensors were placed at each level of the measuring system. The symmetry of the shock wave passing through the experimental samples could be judged from the triggering times of the sensors. As a rule, it was $\lesssim 10^{-7}$ s on a plane with a diameter of the order of 1 m. The necessary corrections were made in the cases when the general curving of the wave was recorded.

In individual cases some electrocontact sensors did not work. This made it somewhat more complicated to interpret the data, but the total number of sensors which remained operative in such cases nonetheless made it possible to obtain an unequivocal interpretation of the results.

The measuring systems were placed 4 to 8 m from the center of the explosion. This resulted in relatively small damping of the shock wave over the base thickness of the samples; the specific values of this damping were determined from calculations and, as a rule, they were $\lesssim 1\%$.

Before discussing the results we shall examine the data obtained for aluminum and we shall comment on experiments, with which we are familiar, on the shock compression of aluminum at pressures $P \gtrsim 200$ GPa. These data are presented in Table I (see also Fig. 2), where together with the compression parameters (D – velocity of the shock wave, U – mass velocity of the motion of matter behind the shock wave front), citations are given to the works from which these data were taken.

The question of the choice of the parameters of the shock adiabat of aluminum is associated with the discrepancy between the data of Refs. 7, 8, 10, and 11 and the data of Refs. 4, 6, and 12. The new experimental point, obtained in the present work, falls between the data obtained in these groups of experiments. This point was obtained under the following conditions: the screen for aluminum consisted of a 100 mm thick steel disk, which was secured, through an intermediate 30 mm thick screen, to a polished surface made in the rock. The base aluminum disk was placed on a steel screen and was $\simeq 100$ mm thick. All planes of the measuring system, as we have already mentioned, were oriented approximately perpendicular (with a deviation of up to 2°) to the direction of the center of energy release (the center of the base planes of the metals). The corresponding corrections, taking into account the deviations from perpendicularity, were made in the final analysis of the results. Specifically, taking these corrections into account, satisfactory symmetry of the shock wave was recorded in the experiment: On all of the base interfaces between the screen and the sample the symmetry was $< 10^{-7}$ s. As usual (see, for example, Refs. 1

TABLE I.

D, km/s	U, km/s	P, GPa	ρ, g/cm^3	Source
9.13	2.80	69.3	3.91	[26]
10.39	3.70	104.2	4.21	
12.94	5.62	197.1	4.79	
6.21	0.69	11.6	3.05	[27]
6.90	1.14	21.3	3.25	
7.42	1.49	30.9	3.79	
13.19	6.00	214.5	4.97	
13.00	6.55	241.4	5.23	
13.96	6.98	264.1	5.42	
6.52	0.86	15.2	3.12	[28]
7.08	1.24	23.8	3.28	
7.28	1.38	27.2	3.94	
8.05	2.03	44.3	3.62	
8.99	2.72	66.3	3.89	
9.67	3.27	85.7	4.09	
9.88	3.30	88.4	4.07	
10.30	3.72	103.8	4.24	
13.08	6.38	226.0	5.285	[11]
13.21	6.73	241.0	5.501	
13.63	7.01	259.0	5.583	
18.31	9.935	493.0	5.921	[9]
17.71	10.29	494.0	6.471	[10]
17.34	10.10	475.0	6.49	[8]
13.4	5.8	210.6	4.77	[12]
14.0	6.3	239.0	4.96	
14.8	6.9	276.7	5.07	
15.5	7.2	302.4	5.09	
16.9	8.9	410.0	5.75	
13.87	6.6	248.0	5.171	[6]
15.59	7.65	323.2	5.32	
17.81	9.78	472.0	6.01	
19.17	11.02	572.0	6.37	
19.75	12.14	649.8	7.03	
26.45	17.7	1268.0	8.18	
18.44	10.5	524.7	6.294	This work
24.2	15.1	990.0	7.18	[4]
23.4	14.5	920.0	7.13	
40.0	30.0	3250.0	10.84	
30.52	21.04	1740.0	8.726	[29]
34.57	23.89	2230.0	8.77	[5]
39.36	27.57	2930.0	9.05	[24]
41.88*	29.96	3400.0	9.48	[25]
54.28*	40.11	5900.0	10.38	
66.38*	50.03	9000.0	11.00	
78.65*	60.05	12800.0	11.42	

*Computed values from the linear relation $D(U)$ presented in Ref. 25 for aluminum.

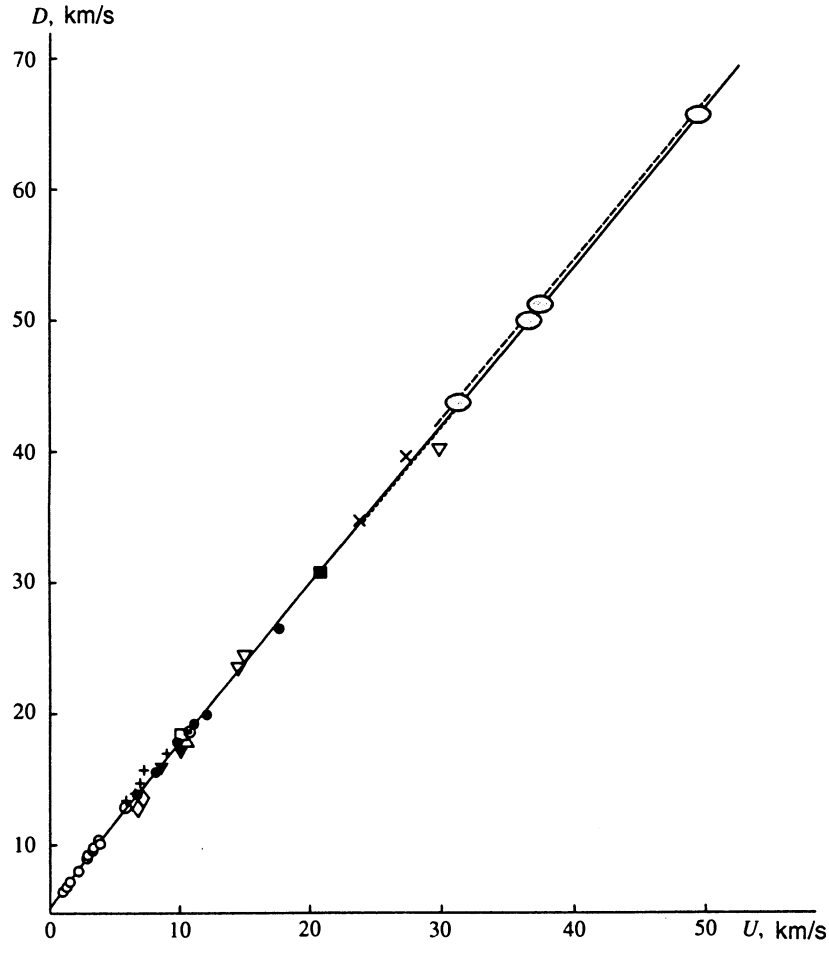

FIG. 2. D versus U diagram of aluminum. Laboratory measurements: ▼, □, △, ◇, +, −,— Refs. 8–11; ○—Refs. 26–28. Measurements in underground tests: ●— data of Ref. 6 using the adiabat of iron from Ref. 17; ▽, ×, and ■—Refs. 4, 5, 24, 29; ⊙—data of this work; the ellipses indicate the uncertainty of the possible states according to the data of Ref. 6 for different equations of state of aluminum; — interpolation of the data from Ref. 25; - - - - - - - —Thomas–Fermi calculation[19,20]

and 2), the wave velocities in the screen and the sample were compared at the interface of two media. The average values of the wave velocities were converted to instantaneous values (at the interface) on the basis of the computed damping of the shock wave.

In constructing the P versus U diagram by the method of reflection[16] the corresponding parameters from Ref. 17 were taken as the initial adiabat of iron. The difference between the position of the shock adiabat and the isentrope of expansion of iron (according to the equation of state given in Ref. 18) and the damping of the shock wave (computed corrections) as it passed through the iron and aluminum were taken into account. Variations, within reasonable limits, of the magnitudes of these corrections did not fundamentally change the position of the new experimental point, which falls between the data of Refs. 7, 8, 10, and 11 and Refs. 4, 6, 9, and 12. It seems to us that at the present time there are no sufficiently cogent reasons for preferring one or the other group of experiments over the other data. Questions and doubts can be raised for most of them. We shall examine from this standpoint the compressibility results presented in Table I.

We begin with the data of Refs. 7 and 8. These data were obtained on similar measuring setups and they could have a common error, as a result of which the data could fall in a "softer" range, i.e. there could be deviations in the direction of high densities. Specifically, the question of the possible small nanosecond preliminary closure of the electrocontact sensors located on the Fe (screen)–Al interface, and the perturbation produced by the strong air wave propagating in front of the striker must be additionally checked.

Of the points obtained in Refs. 9 and 10, the first one was published in Ref. 9 and corresponded to the "hard" position of the adiabat of aluminum. Later, however, the parameters of this point were re-examined in the direction of a softer position (Ref. 10, Table 6). This was done mainly because new values of the corrections for the damping of the shock wave in aluminum were obtained. Having in mind similar displacements of the points, it should apparently be accepted that they reflect the real accuracy of this series of experiments.[9,10]

In the case of the data of Ref. 11, judging from their arrangement on the adiabat, their accuracy is inadequate for our purposes and they are characterized by large deviations from the average curves $D(U)$ and $P(\rho)$. A similar conclusion can be drawn concerning the experiments of Ref. 12, which were performed on very thin samples (thicknesses of a fraction of a millimeter), where the kinematic parameters were recorded with an accuracy of at best 2%.

The data of Ref. 4 have evolved: The experimental points shifted in the softer direction when the neutron heating of the samples was taken into account. There arises the obvious question of whether or not this effect has been completely taken into account.

TABLE II.

Experimental material	D, km/s	U, km/s	P, TPa	ρ, g/cm^3
SiO_2, ρ_{00} = 1.35 g/cm^3	11.40	7.50	0.115	3.94
SiO_2, ρ_{00} = 1.35 g/cm^3	42.17	31.89	1.815	5.54
SiO_2, ρ_{00} = 1.75 g/cm^3	39.73	29.08	2.022	6.53
Plexiglass ρ_0 = 1.18 g/cm^3	25.19	16.96	0.504	3.61
SiO_2, ρ_0 = 2.65 g/cm^3 [1]	33.00	22.45	1.963	8.29
H_2O [2]	43.95	32.42	1.425	3.812

Finally, there are the data of Ref. 6. We recall that these data were obtained when strong shock waves generated by underground explosions acted on thick samples, so that the accuracy of the measurements should be high. However, the position of the first three points of this series (for lower shock-wave velocities) differ from the other three points: The first points are harder than the second ones.

As we have mentioned, the new experimental parameters obtained in the present work for aluminum fall between the other parameters (in the experimental range of wave velocities 13 km/s $< D <$ 20 km/s). Without giving any preference to any one of the groups of experiments in Table 1, the adiabat of aluminum presented in Fig. 2 gives an average description of the entire set of experimental data and consists of a continuous monotonic function, which merges at high pressures into the computed curve corresponding to the Thomas–Fermi model.[19,20 2)]

On the section of interest to us, the aluminum adiabat corresponds to a linear relation between D and U: $D_{Al} = 5.9 + 1.19U$ (D and U in km/s) for the density of the crystal state $\rho_0 = 2.71$ g/cm^3, which we employ to interpret the data obtained in the present work, as well as the results of measurements from Refs. 1 and 2. This relation is valid in the range 11 km/s $< D <$ 70 km/s.

The data on the compressibility of porous silicon dioxide and plexiglass are given in Table II, which gives the final values of the parameters, in which small corrections associated with the conversion of the average velocity of the shock

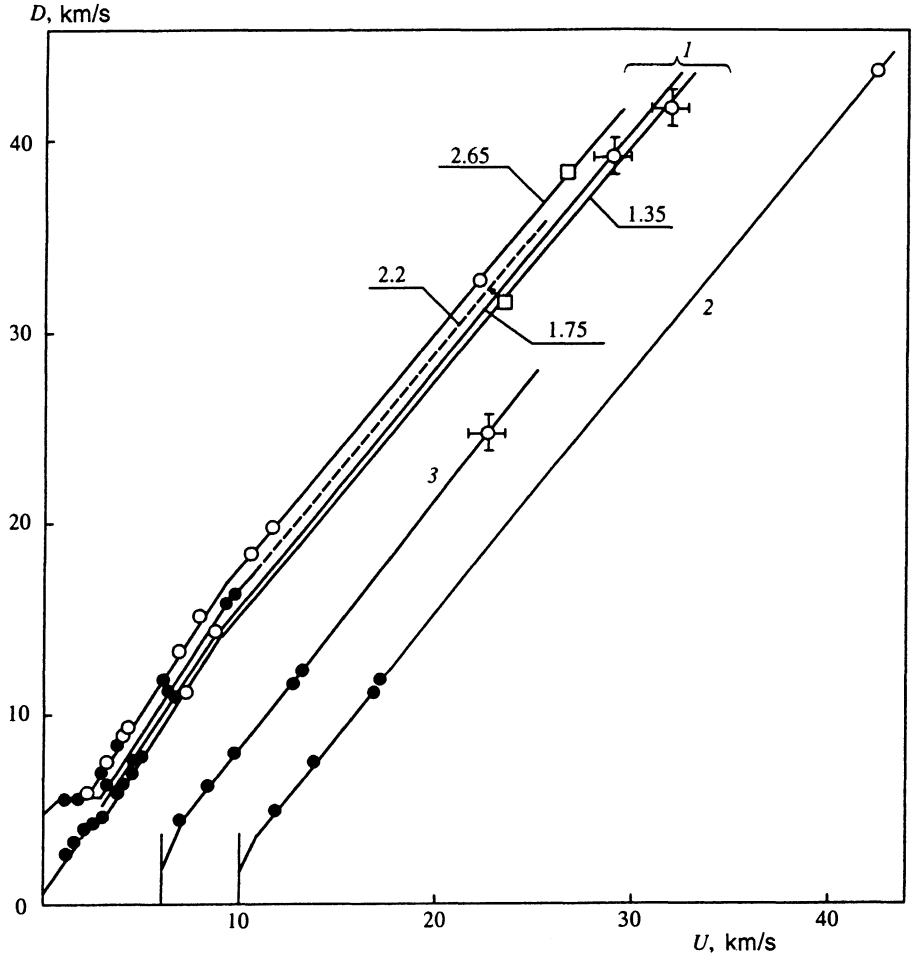

FIG. 3. D versus U diagram of quartz (1), water (2), and plexiglas (3). ● —laboratory experiment; ○, □—measurements under conditions of underground explosions (□—data from Refs. 5 and 24).

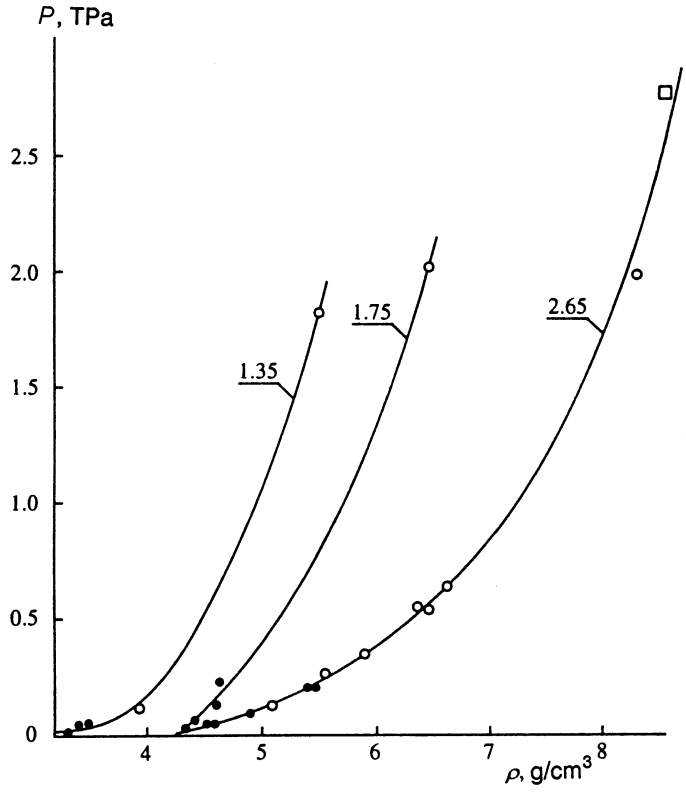

FIG. 4. P versus ρ diagram for quartz with different initial density (numbers on the curves). The notation is analogous to that in Fig. 3 (◒—Ref. 24).

wave to its value at the interfaces are taken into account. The table also gives the results taken from Refs. 1 and 2, respectively for quartz and water, recalculated according to the new relation $D(U)$ for aluminum. The data obtained are also presented in Figs. 3, 4.

In the D versus U diagram, the shock adiabats of quartz and plexiglass are straight lines with a slope of $dD/dU=1.2-1.3$ in the entire experimental range starting with $D>15$ km/h in the case of quartz and $D>5$ km/s in the case of plexiglass. It is well known[19,20] that this slope is characteristic for the range of maximum compressions of the elements under ultrahigh pressures.

We note that the shock adiabats, both for the standard modification of α-quartz (data of Ref. 1) and the porous initial states ($\rho_{00}=1.75$ and 1.35 g/cm^3), are straight lines which are approximately parallel to one another. These lines indicate that the rule of a close slope apparently extends also to similar, quite complicated, compounds.

The error in the data obtained is shown in Fig. 3. This error is $\lesssim 2\%$ of the average velocities. The deviation of the experimental point for amorphous (fused) quartz ($\rho_{00}=2.2$ g/cm^3)[5] from a linear relation $D(U)$ is apparently associated with the error in these experiments; we prefer the approximately parallel arrangement (in the $D-U$ plane) which we obtained for the SiO_2 adiabats with different initial densities.

In spite of these errors, the average values obtained for the parameters, judging from their mutual consistency, have been determined quite reliably. This makes it possible to estimate for SiO_2 the position of the experimental points in the phase diagram[21] where there exists a region, which has not been investigated and is bounded at low densities ($\rho<0.01$ g/cm^3) by a region of Saha-type solutions and at high densities ($\rho>1$ g/cm^3) by data obtained by standard dynamic measurements and solutions according to Thomas–Fermi and modified Hartree–Fock–Slater models.

It has been found that laboratory measurements in this region can be performed only on ultraporous samples of nickel[22] and silicon dioxide (Ref. 23). These data with porous silicon dioxide ($\rho_{00}=1.35$ g/cm^3) represent a new and successful attempt to penetrate into this uninvestigated region, its right-hand side (joining the zone of standard dynamic measurements), but under much higher pressures than in Refs. 22 and 23.

The average value of the Grüneisen coefficient can be estimated by comparing the positions of the dynamic adiabats in the $P-\rho$ plane (Fig. 4):

$$\bar{\Gamma}=\frac{\Delta P_T}{\rho \Delta E_T}$$

(the index T refers to the thermal components of the pressure and energy), a thermodynamic parameter which plays a determining role in the equations of state. Estimates of its value, based on a comparison of the shock adiabats, give $\bar{\Gamma}\simeq 0.66$ for $\rho_0=2.65$ and $\rho_{00}=1.75$ g/cm^3 and $\bar{\Gamma}=0.60$ for $\rho_0=2.65$ and $\rho_{00}=1.35$ g/cm^3. Since these values are approximate (we neglect the possible difference in the phase states on the adiabats being compared), the agreement can be regarded as satisfactory.

The shock adiabat of plexiglass for $D\lesssim 5$ km/s is of parabolic form (Fig. 3). The slope dD/dU changes on this initial section of its $D(U)$ curve. For this reason, this is where the different structures and phase changes, including

chemical decomposition reactions of complicated molecules of this organic compound into simple components, occur.

For wave velocities exceeding 5 km/s the function $D(U)$ for plexiglass is a straight line. This indicates that the processes leading to a restructuring of the initial structure of the plexiglass are completed. The data for quartz and quartzite changed in the direction of a harder arrangement compared to Ref. 1—especially in the pressure range 200 GPa $<P<700$ GPa, where the differences in the ν and previous positions of the aluminum adiabat are greatest.

For water [2] the new parameters are close to their previous values because of the closeness of the "old" and "new" adiabat of aluminum at these pressures.

We now consider the data on the two-stage compressibility of aluminum. Our method for determining the two-stage compressibility is now apparently the only possible method under the conditions of underground explosions and consists of registering the position of the point on the adiabat of two-stage compression of the experimental material (Al) from measurements of the compression parameters of a heavy metal (in our case Pb) placed in the path of the shock wave after the light metal. In this arrangement of the experiment, because the pressures and velocities on their interfaces are equal, the states of shock compression in the lead correspond to a point on the two-stage compression adiabat of aluminum.

The primary analysis of the results, just as in the preceding cases, included a conversion to the interface of the samples (Al–Pb) by introducing computational corrections to the experimental values of the velocities. Further interpretation is based on the $D(U)$ functions for aluminum (presented above) and lead, for which

$$D_{Pb}=3.19+1.167U,$$

$$\rho_0=11.34\,\text{g/cm}^3 \text{ (for } D>11\,\text{km/s}^{1)}).$$

On the interface we have $D_{Al}=22.34$ km/s and $D_{Pb}=13.70$ km/s. The initial and final states in aluminum are:

$$U_1=13.82\,\text{km/s} \quad P_1=836\ \text{GPa} \quad \rho_1=7.11\,\text{g/cm}^3$$
$$U_2=9.01\,\text{km/s} \quad P_2=1400\ \text{GPa} \quad \rho_2=10.04\,\text{g/cm}^3.$$

The experimental point on the two-stage compression of aluminum is presented in Fig. 5. The value of the Grüneisen parameter was estimated by comparing this experimental point with the one-stage compression adiabat. The result is $\bar{\Gamma}=0.67\pm0.08$, which is close to the limiting value. We recall that $\bar{\Gamma}=2.2$ for aluminum with $\rho=\rho_0$. Estimates using different equations of state with $\rho=1.5\rho_0$, $2.0\rho_0$, and $2.5\rho_0$ give $\bar{\Gamma}\simeq1.3$, 1.0, and 0.9, respectively, which agrees satisfactorily with the value obtained. This agreement makes it possible to make an appropriate choice of the function $\bar{\Gamma}(\rho)$ to find the parameters in the equation of state.

In conclusion, we shall summarize the basic results of this work.

We have obtained new data on the compressibility of light materials at ultrahigh pressures, exceeding, as a rule, the pressures which can be achieved in laboratory measurements. These data expand our knowledge of the of light materials close to maximum compression and they give new information about the thermal components in the equations of state.

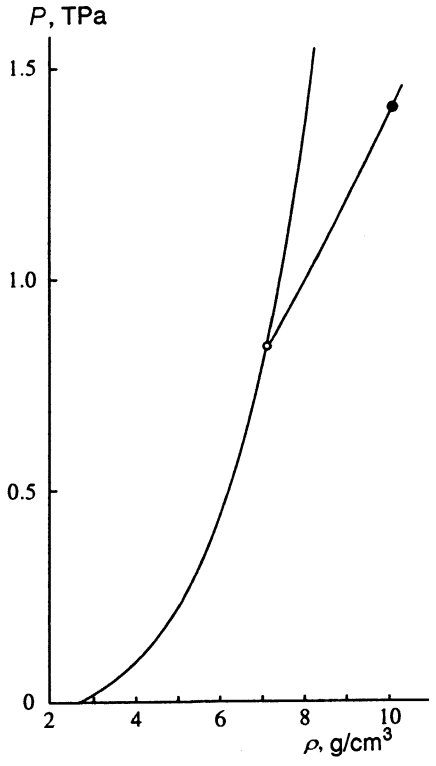

FIG. 5. Two-stage compressibility of aluminum. ○—initial state; ●—point on the two-stage-compression adiabat.

The data for aluminum indicate that its shock adiabat should be represented as a single continuous monotonic curve, with no sharp changes in the thermodynamic parameters in the region of "critical" pressures at 200 GPa.

Selecting an adiabat for aluminum makes measurements of the compressibility of light materials (in which aluminum is a screen) absolute.

[1)] With the exception of two-stage aluminum compression measurements, for which the desired states were found from the compression parameters for a lead sample placed after the aluminum.

[2)] We recall that the satisfactory agreement between the data for this model and experiment at pressures $P\lesssim5.5$ TPa for iron was recently confirmed in Ref. 17.

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