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Shock compressibility of condensed materials in strong shock waves generated by underground nuclear explosions

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Contents

Abstract. An experimental investigation was made of the compressibility of condensed materials under the conditions of underground nuclear explosions. The majority of the measurements were absolute: they were carried out in the range 5 – 10 TPa for heavy materials and at 2 TPa for light materials. Iron, lead, copper, cadmium, molybdenum, aluminium, as well as quartz, water, and polymethyl methacrylate were investigated. The compressibility measurements were made not only on continuous samples, but also on porous samples of iron, copper, tungsten, and quartz. The results agree with the Thomas – Fermi calculation model with quantum and exchange corrections when nuclear interactions are taken into account. The slope dD/dU of the adiabats was 1.2 at ultrahigh pressures (above 1 and 0.3 TPa for heavy and light materials, respectively). In the range of pressures attainable in laboratory experiments the results were scaling-independent.

1. Introduction

The conditions agreed under the 1963 Moscow Nuclear Test Ban Treaty, applicable to all three media, left only one permitted type of test: underground explosions contained within rocks.

Investigators have thus been provided with a source of powerful shock waves, characterised by a hitherto unheard of energy concentration in condensed media. It would have been an unforgivable error not to use this source for scientific purposes. Therefore, beginning almost with the first underground tests, measurements of the explosion parameters have been accompanied by investigations of the various properties of materials, including their shock compressibility. This review presents the results obtained in this way.

The unique conditions in these investigations — the very wide range of pressures, the generally unidimensional growth of an explosion, the ability to carry out measurements on large samples (many orders of magnitude larger than those used in the laboratory) and the good (and sometimes also controllable) symmetry of shock wave propagation — have made it possible to design the following types of experiments:

(i) confirmation of the correctness of the experimental results obtained under laboratory conditions, but scaled up to much longer durations of the action of shock waves on samples (this aspect is related essentially to the relaxation phenomena that occur in samples subjected to the action of shock waves of the same amplitude but of different durations);

(ii) studies of the compressibility of matter under pressures amounting to a few terapascals, i.e. in the intermediate range between the pressures attainable in the laboratory (up to 1 TPa) and those used in theoretical calculations (tens and hundreds of terapascals), and determination of reliable interpolation dependences for this range of pressures;

(iii) measurements at ultrahigh (above 10 TPa) pressures with the aim of selecting the theoretical model of matter fitting best the experimental results and studies of oscillatory effects associated with the influence of the electron structure of atoms on their thermodynamic properties.

The aim of the planned experiments has included also acquisition of information on the absolute (in the method-

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ological sense) compressibility of condensed materials, particularly metals.

In the laboratory range of pressures up to 1 TPa the absolute compressibility can be determined quite simply, because this requires only identification of the states in the standard material used as the shield (the equation of state of which is known) and measurement of the wave velocity in the investigated material [1]. At pressures exceeding the laboratory range it is necessary to calibrate the shock adiabats of standards, i.e. to determine the compressibility of the standard metals in this range of pressures by the absolute methods† (in particular, the deceleration method [2]) or by any other methods, for example, those based on the use of strong fluxes of (n, γ) radiations specific to nuclear explosions.

The implementation of these methods at high pressures has initially presented such serious difficulties that it has been decided that attempts to carry out absolute measurements should be accompanied by investigations of the relative compressibility of materials by a simpler, more easily realisable method. This method consists in the determination of the velocity of a shock wave which is transmitted consecutively through layers of plates of the investigated materials, one of which acts as the standard. In the case of the standard materials the equation of state (EOS) is known and, in particular, its dynamic adiabat can be found by a sufficiently reliable interpolation between the experimental part and the calculated results found on the basis of suitable theoretical models. The velocity of a shock wave in the standard material is used to find the parameters of the initial states and the required characteristics of the investigated materials are found from the pressure–mass velocity diagram by a construction involving the reflection method [1].

Our first attempt to measure the compressibility utilising the energy of underground explosions was carried out at the end of 1965. Our aim was to determine the compressibility of rocks at pressures of 50–100 GPa, as well as the relative compressibility of the Pb–Fe system above 1 TPa. However, for technical reasons this attempt was unsuccessful.

The first useful measurements of the shock compressibility of rocks (granite) were carried out in the first half of 1966 by K K Krupnikov's group. The results obtained at pressures of 350 GPa were not in conflict with the laboratory data obtained by us up to that time in approximately the same range of pressures.

The threshold of 1 TPa was crossed in measurements carried out in the same year [3]: they yielded the compressibility of the Fe–Pb–U system (the pressure in Fe was 3.8 TPa and that in U was 4.0 TPa) and of the Al–SiO_2 system (quartzite), the compressibility of which was determined at 2 TPa [4].

The development of the programme in subsequent years has involved an increase in the number of investigated materials and broadening of the range of investigated pressures. The relative compressibility of water (against Al as the standard) has been obtained at 1.4 TPa, that of quartz of different densities (1.75 and 1.35 g cm^{-3}) at pressures of 2.0 and 1.8 TPa, of polymethyl methacrylate $(C_5H_8O_2)_n$ (PMMA) at 0.6 TPa, and of graphite (C), rutile (TiO_2), rocksalt, aluminium, some rocks (granite, shale, dolomite), and other materials (including porous substances) at relatively low pressures (up to 1 TPa).

The relative compressibility of metals in the Pb–Cu–Cd system was investigated in 1968 at 1.5 TPa [5] and then in 1970 at 5 TPa [6]. In 1970 the pressure 'ceiling' was increased for the Fe–Pb system to 5.2–5.8 TPa [6]. Measurements of the compressibility of porous metals — copper, iron, and tungsten [7], and of several other elements — were carried out in 1971–1975 at terapascal pressures.

Since up to 1976 the energy of the test charges was not limited, in many cases it had proved possible to carry out measurements with the shock wave parameters of interest to us (at pressures of a few terapascals) at relatively large distances (up to 10 m) from the centre of the explosion, which simplified the interpretation of the results and made the measurements more reliable. This was in particular due to the fact that at these distances the shock waves had a small curvature and the pressure behind the front fell relatively little.

1978 saw the first open publication of the measurements of the compressibility under the conditions of underground nuclear tests, reported by the group of Ragan III [8] working at the Los Alamos National Laboratory, which have been continued later [9–11]. The investigated materials have been basically the same as in our investigation.

By the early eighties the 'ceiling' of the relative measurements in the laboratory has risen to 20 TPa (for the system in which Fe was the standard, and Cu, Pb, and Ti were the investigated metals) [12]. The results obtained were characterised by approximately twice the error that we had assumed previously and this was the main reason why the results were not published.

A Chelyabinsk group reported in 1980 [13] on the relative compressibility of Pb, SiO_2, Al, and H_2O at pressures up to 10 TPa. This was the first time that pressures of 10 TPa were exceeded. In subsequent years the same group raised the pressure 'ceiling' to record values of 700 TPa, which were reached in 1983 [14, 15]. The first data on the relative compressibility of metals obtained at the Livermore National Laboratory were published in 1983 [16]. Chinese scientists published their results in 1990 [17].

As already mentioned, beginning from the early seventies, frequent attempts have been made to determine the absolute compressibility of one of the metals used in the laboratory as the standard (Fe, Al, Cu, Mo). Some of these measurements were carried out in our laboratory by the deceleration method, which involved determination of the velocities of a striker plate and of a shock wave created in a sample (made of the same material) struck by the striker. These measurements have proved technically difficult because of the problems encountered in ensuring a good symmetry (planar geometry) of flight of the striker plate, the need to reduce considerably the heating of this plate by the shock wave, the use (sometimes) of radiation-stable sensors, etc. Nevertheless, some results were obtained in these experiments. Three sets of the results will be described below (the measurements were carried out in 1970–1974).

In 1977 Ragan III proposed [8] a new method for determination of the absolute compressibility and applied it to molybdenum. The shock wave velocity in a sample was

†These are the methods in which two independent parameters, namely the mass (U) and wave (D) velocities, are measured and the remaining quantities (pressure P, density ρ, and shock compression energy E) are defined in terms of these parameters on the basis of laws of conservation.

deduced from light flashes corresponding to the emergence of the wave on control base surfaces. The mass velocity was measured by recording the shifts of the resonances of the interaction between neutrons and nuclei in the moving material, relative to the resonances in nuclei at rest, i.e. it was based on the Doppler effect. The source of high pressures was the energy of fission of the ^{235}U nuclei by the nuclear explosion neutrons. The required symmetry of the shock wave was achieved by the adopted configuration in which a slab of uranium irradiated with neutrons was in contact with a sheet of molybdenum. Nevertheless, under real conditions, because of the uncertainty about the duration of the neutron pulse and about the various resonance broadening mechanisms, the error in the determination of the mass velocity was about 5%, which was too high for calibration of the standard metal.

In 1980 V A Simonenko and L P Volkov proposed, and applied to aluminium, a different method for determination of the absolute compressibility known as the γ-marker method [18]. In this method the kinematic parameters of a shock wave were determined from the displacement of thin pellet-like layers, which were embedded in a sample and activated by the radiation flux. These pellets acted as γ-active tracers and their motion was followed (through special narrow collimator slits) by sensors in which the γ radiation was converted into a light flux. The velocity of the pellets was assumed to be equal to the mass velocity of aluminium and the wave symmetry was ensured by the geometry of the relative positions of the measurement unit and the explosive device. In some calculations it was necessary to take into account the heating of the investigated material by the energy released when neutrons were captured in the sample [18]. All this could result in some error.

We shall now consider the results of investigations of the shock compressibility (carried out by the relative and absolute methods) obtained mainly in our laboratory and we shall compare them with the results of other authors for the same materials and in the same range of pressures. The experimental data are split into three sections. Section 2 contains the results of investigations at relatively low pressures, corresponding approximately to the laboratory range, i.e. below 1 TPa. These are the results of the absolute measurements obtained by the reflection method. Section 3 gives the compressibilities measured by the absolute methods in the terapascal pressure range (up to 10 TPa). Section 4 deals with the results obtained by the relative methods. In the last case the range of pressures extends to gigantic values (hundreds of terapascals).

2. Measurements of the absolute compressibility of materials at pressures below 1 TPa

In the measurements discussed below the configuration corresponds to the requirements of the reflection method in which the experimentally determined states of shock compression of the shield and sample (in our experiments, this was the wave velocity D) and the EOS of the shield material are combined with certain constructions in the $P-U$ diagram and with the laws of conservation to find the pressure $P = \rho_0 DU$, the mass velocity U, the density $\rho = \rho_0 D/(D-U)$, and the shock compression energy $E = 0.5P(\rho - \rho_0)/\rho_0\rho$.

In the conventional reflection method a shock wave is transmitted to a sample through a shield made of a standard metal. The majority of the measurements of the compressibility of materials — rocks, rocksalt, porous copper and rutile, quartzite (including porous), etc. — have been carried out in this geometry.

In determination of the compressibility of rocks under underground explosion conditions it is preferable to use the 'inverted' reflection method [4] when a standard metal is placed behind the investigated rock sample. In this case the state *2* of shock compression in the standard (Fig. 1) is reached by loading the rock from state *1* located on the wave ray $P = \rho_0 DU$. If the adiabats of the standard and rock are similar, i.e. if $\Delta P = P_2 - P_1$ is small, line $1-2$ almost coincides with the expansion adiabat of the standard from state *2* to the wave ray $\rho_0 DU$. The only standard metal ensuring the proximity of the adiabats in the studies of the compressibility of the rocks is aluminium and it has been used by us as the shield in the inverted reflection method.

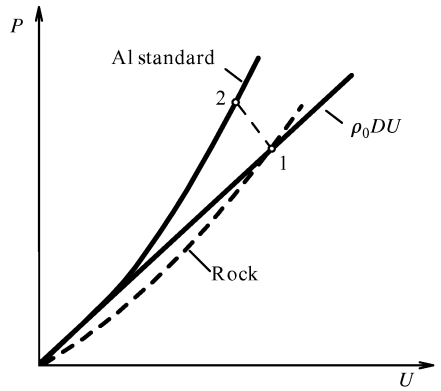

Figure 1. Schematic representation of the 'inverted' reflection method.

Since the range of pressures under discussion does not exceed that attainable in the laboratory, measurements under the conditions of underground explosions can be used to tackle specific problems associated with the unique conditions during these experiments and, in particular, to carry out measurements on samples of thicknesses exceeding by one or more orders of magnitude those used in the laboratory.

Among the problems requiring experimental investigation, the first has been the stability of the positions of the shock adiabats of materials that undergo phase transitions under the action of shock waves. This is a matter of the 'scaling factor', governed by the ratio of the phase transition time the characteristic time of the interaction of a shock wave with a sample.

In the laboratory experiments, carried out on relatively thin samples (with thicknesses of the order of several millimetres), the 'frozen' states of a nonequilibrium system of light and heavy phases can be identified immediately after the phase transition and the positions of the compression curves may in this case depend on time. If the reaction of formation of a heavy phase continues behind the front of a shock wave, the longer durations of the interaction with a sample under the conditions of underground explosions may drive the phase transition closer to completion and produce a larger amount of the heavy phase. Consequently,

Table 1.

Material	ρ_0/g cm^{-3}	Thicknesses of sample/mm	U_{sh}/km s^{-1}	Parameters of compression of investigated material				Reflection method
				D/km s^{-1}	U/km s^{-1}	P/GPa	ρ/g cm^{-3}	
Quartzite	2.65	80	2.19	6.06	2.50	40.1	4.51	conventional
		80	3.01	7.49	3.32	66.0	4.76	
		80	3.96	8.99	4.26	101.4	5.04	
		500	6.92	13.60	7.09	256.0	5.54	inverted
		500	8.24	15.28	8.40	340.0	5.89	
Shale	2.77	500	2.08	6.40	2.29	41.0	4.31	inverted
		500	3.07	8.10	3.24	73.0	4.62	
		500	4.23	9.75	4.41	119.0	5.06	
		500	6.05	12.00	6.21	206.0	5.74	
		500	9.07	16.32	9.06	410.0	6.23	
Dolomite	2.84	500	3.05	8.77	3.09	76.6	4.39	inverted
		500	2.21	7.72	2.24	49.1	4.00	
Graphite	1.878	70	3.26	8.13	3.97	60.6	3.67	conventional
Rocksalt	2.16	50	3.59	8.94	4.10	79.17	4.00	conventional
PMMA	1.18	80	0.73	4.61	1.10	5.99	1.55	conventional

the position of the shock adiabat in the $P-\rho$ plane should shift in the direction of higher densities.

Minerals and rocks have been the first objects of measurements intended to check the scaling factor. It is known that the majority of these materials undergo phase changes at pressures of 10–40 GPa (mainly due to structural transformations). These changes are manifested by a fairly strong increase in the density, a change in the slope of the shock adiabat, etc. The question of stability of the positions of the shock adiabats of these materials after phase transitions is not only of scientific, but of major practical interest.

Among the minerals, the first to be investigated have been quartz or, more exactly, polycrystalline quartzite, which consists almost entirely of quartz. Its compressibility under the 'full-scale conditions'† of underground explosions is considered in Refs [4, 19].

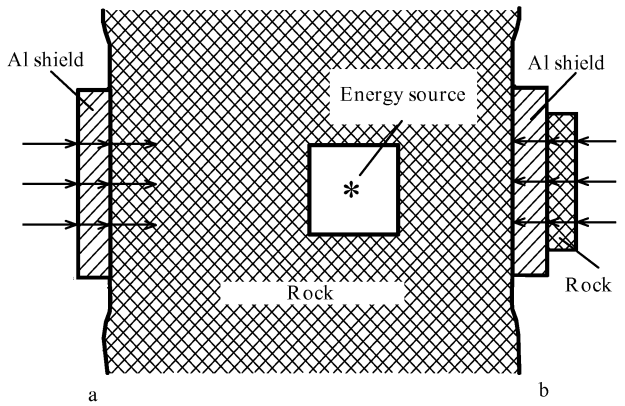

Figure 2. Schematic representation of the experiments carried out by the reflection method in the course of underground explosions: (a) 'inverted' method; (b) conventional method.

†The term 'full-scale conditions' will be adopted here for the conditions in underground explosions.

In the configuration shown in Fig. 2, experiments have been carried out in two variants: the conventional and inverted reflection methods. The thickness of quartzite samples has been varied from 80 mm (conventional method) to 500 mm (inverted method). In all the experiments carried out under the conditions of underground explosions the diameters and thickness of the samples have been selected to avoid the influence of lateral unloading waves on the parameters of the front of a shock wave in the zone where these waves are recorded. Aluminium has been used as the standard metal and up to pressures of 200 GPa ($D \leqslant 12$ km s^{-1}) its shock adiabat can be described by the following linear relationship

$$D/\text{km s}^{-1} = 5.333 + 1.356U/\text{km s}^{-1},$$

which is used to convert the measured wave velocities to the other parameters of compression of aluminium‡ Electric-contact sensors recording the times of the passage of a shock wave along a sample by detectors with an error of 5×10^{-9} s have been used. (This system has been employed in the majority of our experiments.) Similar measurements have also been carried out on two other rocks: dolomite and shale [20].

The results of investigations of quartzite, dolomite, and shale are given in Table 1. They are compared in Fig. 3 with the results of the laboratory measurements. We can see that they are in agreement. This is evidence that the scaling does not influence the results of measurements. These results are important for the understanding of the kinetics of phase transitions because the coincidence of the adiabats obtained in the laboratory and full-scale experiments proves the dominant role of the front of a shock wave in the formation of a new phase: this phase accumulates mainly at the front of the wave.

‡In the investigated range of pressures the expansion adiabats of aluminium starting from states on the shock adiabat coincide with the mirror image of its shock adiabat, and this is true of all the investigated materials considered in the present section (rocks, rocksalt, graphite, PMMA).

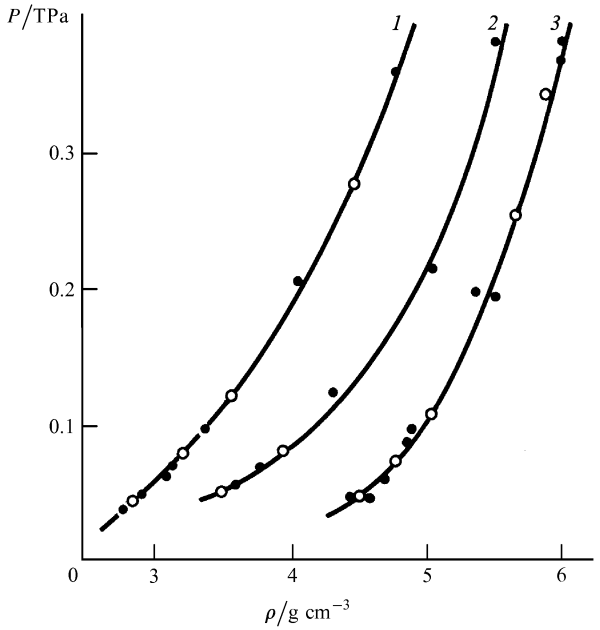

Figure 3. Comparison of the laboratory measurements of the compressibility of rocks (black dots) with the results obtained in the course of underground explosions (open circles): (*1*) shale; (*2*) dolomite; (*3*) quartzite.

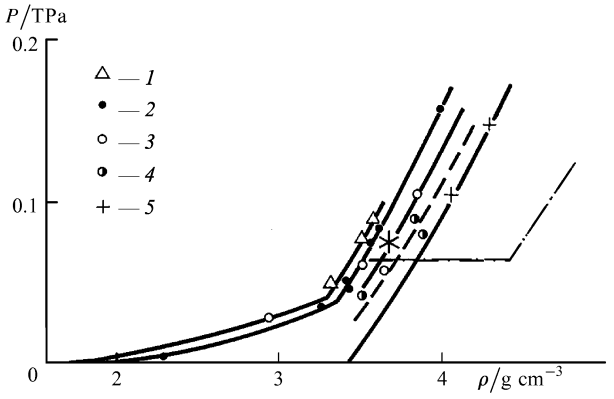

Figure 4. $P-\rho$ compression diagram of carbon based on the laboratory measurements, carried out on graphite samples with the initial densities 1.77 g cm^{-3} (*1*), 1.85 g cm^{-3} (*2*), 2.23 g cm^{-3} (*3*), 2.23 g cm^{-3} (*4*, samples of greater thickness), and a diamond sample with an initial density 3.51 g cm^{-3} (*5*). The point identified by an asterisk was obtained in the course of underground explosions and the chain line is used for the shock adiabat taken from Ref. [22].

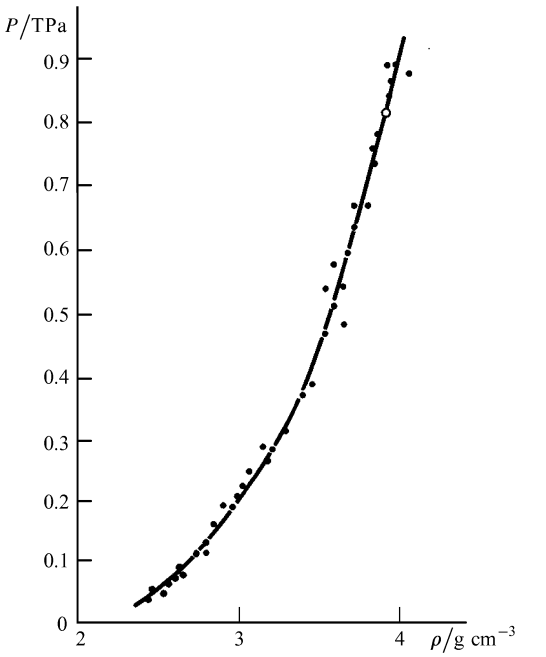

Figure 5. Shock adiabat of rocksalt. The designations of the points are the same as in Fig. 3.

The agreement of the data obtained on the stability of the shock adiabats of three different rocks (one of which is quartzite) dominating many mineral structures, shows that the problem of the scaling factor and its influence on the positions of the shock adiabats of rocks can be regarded as solved.

One general comment should be made. The results obtained in the measurements described above and later give the average wave velocities for the selected thicknesses of the investigated materials. In view of the wave attenuation in these experiments, the velocities are compared on the shared boundary separating a pair of materials. The conversion from the average wave velocities in the samples to their instantaneous values at the boundary is made either by experimental determination of the wave attenuation in the investigated materials (measurements at several wave intensities) or by corrections in the course of calculations. In some of the experiments the conditions are selected so that the attenuation of a shock wave can be ignored i.e. so that the wave profile is practically undamped. This will be mentioned specifically in the discussion below.

Graphite is another material which is interesting from the point of view of a possible influence of the scaling factor on the compressibility. According to Refs [21, 22], the position of the shock compression curve of graphite (at pressures above the transition to the diamond-like phase) depends on the thickness of a sample. According to Ref. [22], graphite becomes metallised at $P > 55$ GPa and this is accompanied by a strong increase in the density. Although the incorrectness of this view is demonstrated in Ref. [21] on the basis of the results of measurements on samples of thicknesses 2–4 times greater than those used by Alder and Christian [22], it has been thought that an additional check of these results on even thicker samples under the conditions of underground explosions would be useful. The results of an experiment of this type are given in Table 1 and are compared with the data of Refs [21, 22] in Fig. 4. The position of the new point obtained in this way supports on the whole the results of Ref. [21] and demonstrates the existence, in this range of states, of only the diamond-like modification of carbon.

Table 1 and Fig. 5 give the results of determination of the shock compressibility of rocksalt. The experiments have been carried out in the same way as in the case of graphite. We can see that there is no significant dependence of the positions of the experimental points on the scale of the experiments (in the investigated range of pressures).

In the experiments on the shock compressibility of PMMA a study has been made of a problem related to the scaling factor, which is the decomposition of organic

Table 2.

Material	ρ_0/g cm^{-3}	Thickness of sample/mm	U_{sh}/km s^{-1}	Parameters of compression of investigated material				Particle size/μm	
				D/km s^{-1}	U/km s^{-1}	P/GPa	ρ/g cm^{-3}	full-scale exp.	lab. meas.
Rutile	2.07	80	3.54	7.51	4.33	67.3	4.89	50 – 100	200
	2.04	75	2.41	5.43	3.14	34.8	4.84		
	2.16	75	2.18	4.92	2.85	30.3	5.13		
Quartz	1.35	80	5.76	11.40	7.50	115.4	3.94	50	150
Copper	2.23	70	1.95	3.84	2.68	22.9	7.38	10	10
	3.02	70	6.85	11.02	7.21	240.0	8.74		
	2.88	70	4.31	7.20	4.70	97.4	8.29		

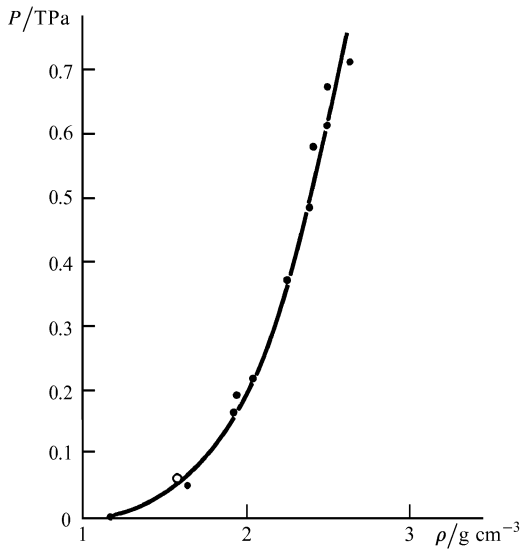

Figure 6. Shock adiabat of polymethyl methacrylate. The designations of the points are the same as in Fig. 3.

substances by shock waves acting for different periods. As in the preceding cases, the criterion of the occurrence of such reactions in experiments carried out on different scales has been the relative position of the shock adiabat of the material. The compression parameters obtained in these experiments are listed in Table 1. Fig. 6 demonstrates that the results agree with the laboratory experiments.

Another problem tackled under the conditions of underground explosions at relatively low pressures has been the influence of the 'roughness' of the front of a shock wave in porous samples on the experimental results. It is related to a check of the assumption that the front roughness is governed by the dimensions of the individual particles of the material and it affects particularly the laboratory measurements carried out on small samples. An increase in the duration of compression in full-scale experiments (carried out on large samples) might give results differing from those obtained in the laboratory.

The compressibility of porous samples of rutile (TiO_2), quartz, and copper has been determined in underground explosions [23]. The conventional reflection method has been used in these experiments: a sample has been placed behind an aluminium shield about 100 mm thick. A good symmetry (planar shock waves) has been maintained: in a region with linear dimensions of 800 mm (which is an area in a rock occupied by the aluminium shield) the differences between the times of emergence of a wave have been within the range† $\Delta t \leqslant 10^{-7}$ s.

The results of measurements and the characteristics of the investigated samples are listed in Table 2 and are also presented‡ in Fig. 7. We can see that for all these substances the results of the laboratory measurements are in good agreement with the full-scale experiments (in the case of rutile the experimental points are compared with the position of the calculated adiabat given in Ref. [25]). We can therefore assume that, within the limits of the particle dimensions and the parameters of shock waves in these experiments, the process of compression of porous samples is of a steady nature. The dimensions of the particles in the laboratory [23 – 26] and underground measurements have in some cases differed severalfold.

It can thus be seen that measurements of the compressibility of these materials with the aid of strong shock waves generated in underground explosions confirm the stability of the shock adiabats of the materials, i.e. that the positions of these adiabats in the $P-\rho$ plane are independent of the dimensions of the particles of which these materials are composed and they are also independent of the dimensions of the samples themselves.

3. Investigations of the absolute compressibility of materials at pressures above 1 TPa

The feasibility of expanding the range of 'working' pressures in measurements of the shock compressibility of materials is, in the final analysis, governed by the precision of recording the kinematic parameters of shock waves [6] and, at the current technical level, it is limited to 10 TPa. At higher shock pressures the error in the determination of the parameters of shock waves increases so much that the errors in finding the density may become comparable or even greater than the difference between the positions of the shock adiabats calculated on the basis of some particular theoretical models. Therefore, the task of selection of the theoretical model of a material closest to reality has presented a problem to investigators right from the beginning of the work at ultrahigh pressures. This problem is discussed in the first papers on the compressibility of materials determined under the conditions of underground nuclear explosions [3, 4, 6] and it has been tackled repeatedly in subsequent publications [12, 14, 15].

†This value applies also to other measurements reviewed here.
‡Here and later the numbers added to the velocities U and D indicate a shift of the velocity coordinate by this number (in kilometres per second).

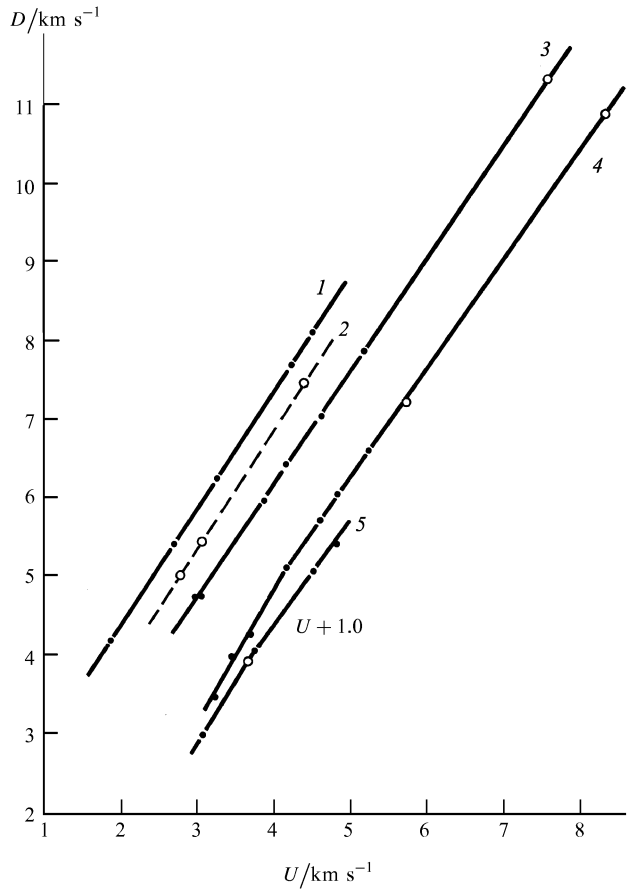

Figure 7. $D-U$ diagrams of porous samples of rutile (*1*, *2*), quartz (*3*), and copper (*4*, *5*). The designations of the points are the same as in Fig. 3. The dashed line represents conversion from the initial density of 2.6 g cm^{-3} (*1*, laboratory experiment) to 2.05 g cm^{-3} (*2*).

In the case of the shock adiabats the approach is as follows. There is a range of experimental data on the compressibility obtained under the conditions of validity of the absolute methods. There was also calculated shock adiabats, derived on the basis of a selected theoretical model regarded as the closest to reality on the basis of some criteria. These experimental data and the shock adiabats are linked by an interpolation dependence, which thus defines the shock adiabat of the material in the range of pressures needed to tackle the general physics and applied aspects of the problem.

In the first years of the studies under the conditions of underground nuclear explosions the main source of information on the thermodynamic properties of elements at ultra-high pressures (above 10 TPa) has been the Thomas–Fermi (TF) statistical model of electrons in a monatomic ideal gas of nuclei. Therefore, in practice there has been no problem of selection of the model for ultrahigh pressures. The task has been limited to the selection of a standard material for which the simplest interpolation between the laboratory and calculated range of ultrahigh pressures has been adopted. This situation has arisen because at the time the only method for investigating the compressibility has been that of relative measurements. Since the reliability of statistical calculations based on the TF model increases with atomic number Z of an element, in the first investigations the standard material has been lead, which is a relatively heavy metal with a large value of Z and a shock adiabat which can be interpolated quite simply and sufficiently reliably between the experiments and calculations. This selection has proved successful also because lead is an easily compressible material and the error in determination of its density depends, as shown in an analysis in Ref. [3], on the degree of compression of the standard (which decreases on increase of the compressibility).

The results published in Refs [3–6] have been analysed by interpolation to the range of states determined by the TF model. The model has been improved subsequently by what are known as the quantum and exchange corrections [27] and by taking into account the nonideal nature of the nuclei (as is done, in particular, in Ref. [28]). In this approximation it is known as the Thomas–Fermi quantum-corrected (TFQC) model. This model is statistical and it predicts monotonic dependences of the thermodynamic characteristics on the atomic number Z.

The relative simplicity of the TFQC model has made it widely popular in the description of the asymptotic parameters of materials at high energy concentrations, including the effects of shock compression of metals. In our calculations of the shock adiabats by the TFQC method, the initial conditions ahead of the front of a shock wave have been the initial density of the material ρ_0, the initial pressure $P_0 = 0$, and the initial energy of the material E_0 (assumed to be equal to the experimental value of the sublimation energy with the reversed sign).

The TFQC model ignores the shell structure of the atomic electron. When this structure is taken into account for materials subjected to pressures near the limiting values and to strong heating, consecutive ionisations of the shells should give rise to smooth oscillations of the thermodynamic functions relative to monotonic statistical dependences predicted by models of the TFQC type. Such oscillations are obtained on application of the Hartree–Fock model, which takes into account the exchange interaction in the Slater approximation (HFS), the modified Hartree–Fock–Slater (MHFS) model, the self-consistent field (SCF) model, and several others. The last two models are currently most thoroughly developed. They have been used to calculate the thermodynamic functions and the shock adiabats of some metals (mainly used as standards): Al, Pb, Fe.

The MHFS model [29] provides a number of approximations to the HFS model and these simplify greatly quantum-mechanical calculations. These approximations reduce to the two main simplifications:

(i) it is assumed that electrons can be described by the average atom approximation;

(ii) a quasiclassical account is taken of the contribution of the highly excited electrons (for which quantum calculations are almost impossible), which leads to the appearance in this model of what is known as the semiclassical spectrum limit, which in a certain sense can be used in the variation of calculated dependences.

Both models (HFS and MHFS) are the next step in the development of the model ideas that allow for the quantum-mechanical effects.

The SCF mode [30] differs from the MHFS model [29] by the quasi-ionic approximation:

(i) the edges of the energy bands (both upper and lower)

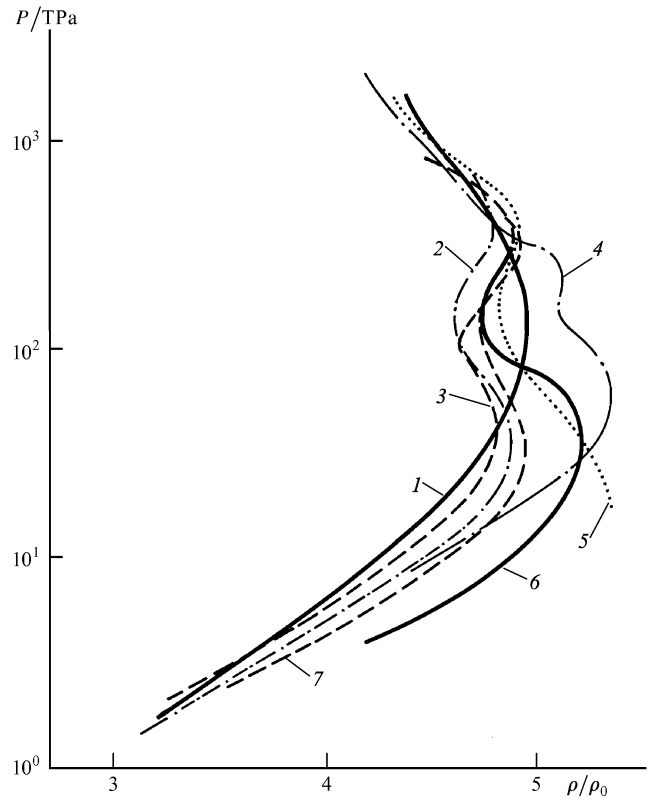

Figure 8. Compression diagrams of aluminium plotted on the basis of different models: (*1*) TFQC [27, 28]; (*2*) MHFS [29b]; (*3*) MHFS [29c]; (*4*) INFERNO [35]; (*5*) ACTEX [34]; (*6*) MHFS [29a]; (*7*) SCF [30].

are found by equating to zero the wave function and its derivative;
(ii) the density of states in each band is equivalent to that obtained by filling the states with free electrons.

The MHFS and the SCF models have evolved from very strong (sometimes unphysical) oscillation amplitudes, predicted by the first investigations, to relatively weak oscillations predicted more recently (the SCF model is discussed in Refs [30–32]). There has been also a change in the predicted compression curves (see, for example, the positions of the adiabats predicted by the MHFS model and shown in Fig. 8).

We cannot exclude the possibility that improvements in these models will result in a further reduction in the oscillatory effects and that shock adiabats at pressures above 10 TPa will 'converge' to the statistical model of the TF type.

Those discussed above and other available shell models [33–35] differ considerably in respect of the predicted positions of the shock adiabats and also (in some cases) in respect of the amplitudes and phases of the oscillations (see Fig. 8). If we bear in mind that these differences are governed not only by the electronic but also by the ionic interactions, we find that additional changes in the positions of the shock adiabats is possible, depending on the inclusion of the contribution of the ionic components†.

In view of this the selection of the model of matter has been one of the fundamental problems in the experimental investigations at ultrahigh pressures. To solve this problem (and also to obtain a more reliable interpolation between the calculated and laboratory ranges of investigations), it is desirable to reduce the interpolation interval, i.e. to extend the compressibility investigations of matter by the absolute methods to the highest possible pressures (naturally, subject to the limits set by the precision of determination of the kinematic parameters of shock waves). This applies particularly to the investigations of the standard metals by the reflection method.

The pressures of the order of 1 TPa reached under the laboratory conditions [26, 36, 37] are close to the maximum attainable. It is realistic to expect an increase in these pressures by 30%–40%, which does not make a fundamental difference to the problem in hand.

A considerable increase in pressure (by a factor of 5–10) has become possible under the conditions of underground tests of nuclear explosive charges. As pointed out already, over a number of years various groups of investigators in Russia and the USA have been measuring the absolute compressibility of the standard metals. In the USA these measurements have been carried out on Mo (Ragan III) and in Russia on Al (in V A Simonenko's and our laboratories) and on Fe (our laboratory). The absolute measure-ments of the compressibility of iron, molybdenum, and aluminium will be described below. At this stage we should note that, in tackling the task of reducing the range of pressures employed in the interpolation between the calculated and experimental ranges of values, a 'shortcoming' of the measurements on Mo and Al is the relatively small increase in the pressure compared with the laboratory values: in the case of Mo it is approximately a factor of 2 and for Al the increase is a factor of 3.5. Measurements of iron are free of this 'shortcoming' and the maximum pressures in the compression of this element have reached 10 TPa [38, 39], i.e. these pressures are 8–9 times greater than the laboratory values.

3.1 Adiabats of metals used as reference standards

3.1.1 Shock compressibility of iron at pressures of 4–10 TPa

Before reporting the results of the determination of the compressibility of iron at pressures of 4–10 TPa, let us consider the requirements which a striker–target system must satisfy. The main requirements are [38, 39]:

- a relatively weak shock-wave heating of the striker in the process of its acceleration;
- the velocity of the striker plate (at the moment of impact) close to twice the mass velocity of the shock wave in the target: $W = 2U$;
- the attainment by the striker of a velocity close to $W = \text{const}$ near the target;
- the conservation of continuity of the striker plate during its flight and a satisfactory symmetry of the striker plate and of the shock wave in the target;
- the absence of heating of the striker and target by the radiation generated during a nuclear explosion.

Fig. 9 shows two variants of an acceleration system which, on the whole, satisfies these conditions. The geometry of these variants has been selected in a series of preliminary calculations involving optimisation of the conditions during measurements‡. In these calculations, all

†This applies also to the statistical models.

‡These calculations were carried out by M A Podurets.

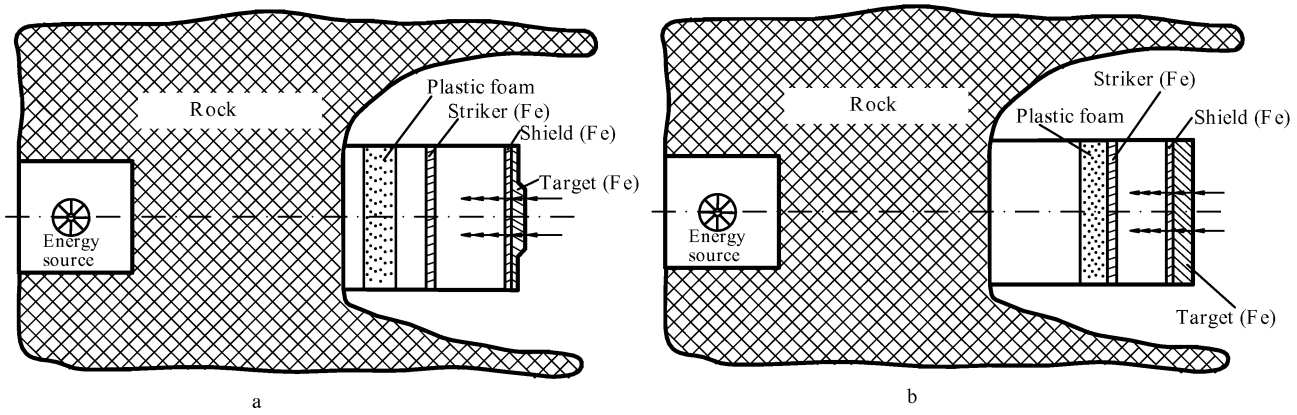

Figure 9. Two variants of an acceleration system for the determination of the shock compressibility of iron by the deceleration method.

the processes from the explosion of a nuclear charge (and its real energy release) to the propagation of a shock wave in the target are included. During the gasdynamic stage of motion of shock waves an EOS of the Mie–Gruneisen type is used. The EOS for the plastic foam used in these experiments is assumed to be that of an ideal gas with the polytrope exponent $\gamma = 5/3$ and the initial density $\rho_0 = 0.03$ g cm^{-3}.

The equality $W = 2U$ may, strictly speaking, be reached only in the course of smooth heating-free acceleration of the striker if its continuity is conserved. In fact,there are deviations from this equality and they are primarily due to the heating of the striker plate by a shock wave and due to the action of the evaporated-matter pressures on its rear side.

In the system shown in Fig. 9a [38] (the system in Fig. 9b has similar parameters [39]), the main characteristics obtained by calculation are as follows: the amplitude of the first shock wave in a steel striker is $P \leqslant 0.5$ TPa (with the corresponding temperature $T_0 \leqslant 2 \times 10^4$ K) and the average density at the moment of impact on the target is $\bar{\rho} = 1.05\rho_0$. This value is due to the push imparted to the striker plate by the evaporated 'explosion products'. Under real conditions it is practically impossible to avoid this push and also eliminate other factors that result in a deviation of W from $2U$; they have to be taken into account. Therefore, the acceleration system selected in the calculations should ensure that the equality $W = 2U(\bar{D})$ is approached as closely as possible; here, $\bar{D}$ is the average velocity of the shock wave in the target. The values of $\bar{D}$ and W are determined experimentally. The function $U(\bar{D})$ corresponds to the EOS of iron used in the calculations.

In the calculations, the criterion of optimality of the selected system is the parameter $\alpha = U(\bar{D})/W$. Under ideal conditions, when $W = 2U$, this parameter is $\alpha = 0.5$ and we have $U(\bar{D}) = 0.5W$. Under real conditions a system can be regarded as optimal when the deviation of α from 0.5 does not exceed 0.5% – 1.0%, because then the inaccuracy of the experimental determination of the kinematic parameters usually exceeds the errors due to nonoptimality and there is no need to introduce not quite reliable calculated corrections.

Fig. 10 shows, by way of example of the acceleration of a steel striker plate, the dependence of W on the distance x for the system shown in Fig. 9a. During the initial stage of motion the velocity of the striker plate changes abruptly

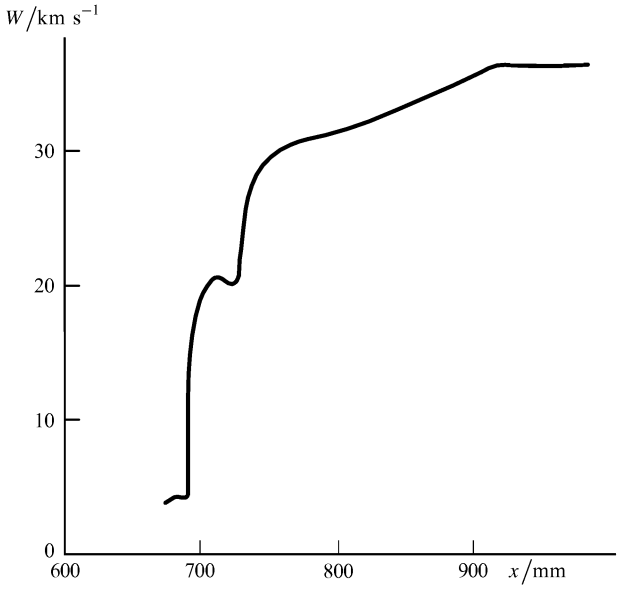

Figure 10. Acceleration of a steel plate illustrated by the dependence $W(x)$.

because fairly strong waves reflected from the rear side of the plate reach the front surface. The amplitudes of such waves decrease in the course of motion, which becomes smooth, and eventually reaches the W = const regime. About 90% of the velocity W is acquired by the striker plate during the initial stage of motion, which represents about 20% of the total distance travelled.

In this system the striker velocity near the target is $W_{\text{calc}} = 36.32$ km s^{-1}. The calculated average wave velocity in the target is $D = 29.1$ km s^{-1} and, consequently, $U(D) = 18.1$ km s^{-1}. Therefore, the calculated value is $W = 2U(D)$ with $\alpha = 0.498$, i.e. the system is quite optimal. The correction for the difference between W and $2U$ (at the front of the wave) is small and, on the basis of our conclusion that the system is optimal, it can be ignored.

We shall now consider two other experiments carried out using the variant shown in Fig. 9b. In the first of these experiments the calculation parameters have been found to be close to those obtained in the variant shown in Fig. 9a. In the second experiment a much more powerful source of

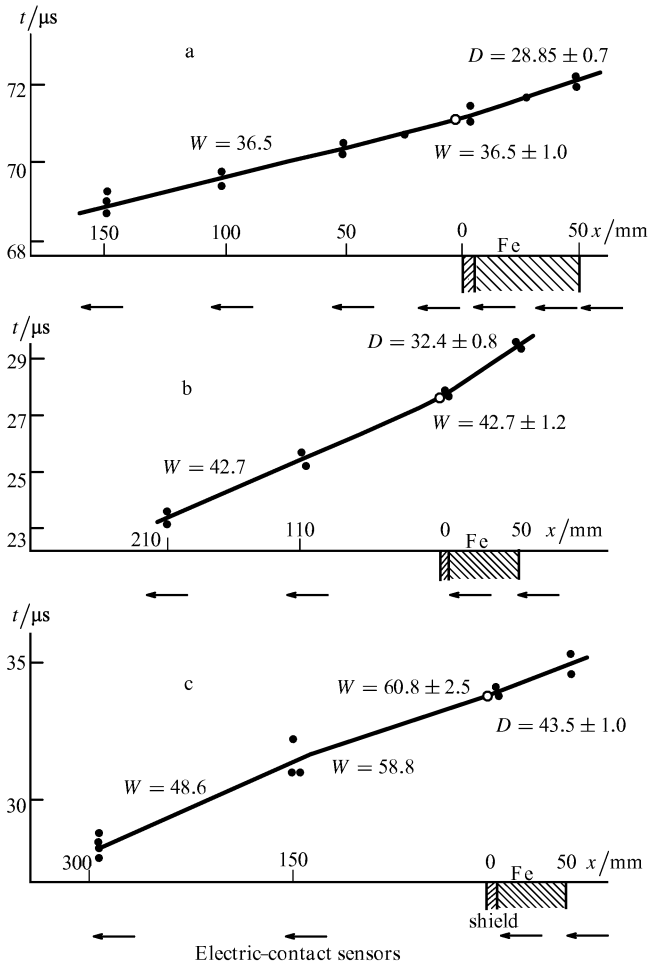

Figure 11. Experimental velocities of steel plates and of shock waves in targets subjected to pressures of 4.1 TPa (a), 5.5 TPa (b), and 10.5 TPa (c).

energy has been used and it has been possible to reach, for approximately the same (in respect of the distances) configuration of the measuring system as in the preceding cases, pressures of shock compression in iron approximately twice as high as in the preceding two experiments.

We shall now give some calculation parameters for the system under discussion. The pressure of a shock wave in the ground (before reaching the measuring area) is about 2.5 TPa and the pressure of the first wave in a steel striker plate is 0.4 TPa, which is even slightly less (because of the larger air gap) than in the system shown in Fig. 9a. In the absence of a plastic foam spacer the pressure in the striker plate is about 1.3 TPa. Before impact this plate reaches a near-constant velocity. The parameter is $\alpha = 0.503$, i.e. the selected system is near-optimal.

The velocities are measured by electric-contact sensors [38], representing pin electrodes separated from a metal current-conducting shield by an air gap about 1 mm thick. The passage of a shock wave causes breakdown in the gap and this is recorded on a screen of a fast-response oscilloscope. The sensors are located at several distances along the direction of motion of the striker plate. A separate group of sensors is used to record the wave velocity. Between two and four sensors are used at each distance.

The diagrams shown in Fig. 11 represent the experimental data plotted in terms of the coordinates of the distance travelled and time. The left-hand side of each graph represents operation of the electric-contact sensors recording the flight of the striker (velocity W) and the right-hand side represents the results obtained by the sensors for the velocity of the shock wave in the target. We can see from these graphs that the smallest experimental deviations from the average values of W and D occur in the experiment described by Fig. 11a, for which the kinematic parameters correspond to the pressure of $P = 4.13$ TPa.

In the other two experiments the differences between the separate experimental points from the average values of D and W are somewhat larger and this is clearly related to the deviation of the accelerated striker from the plane geometry. Moreover, in these experiments some of the experimental data have been lost, resulting in additional difficulties in the interpretation of the results obtained and, consequently, in a greater error in the determination of the shock-wave parameters of compressed iron.

It follows from the diagrams in Fig. 11 that there is a good agreement between the kinematic parameters of motion W and D at the striker–target interface. For a system with the maximum parameters ($P = 10$ TPa) the value of W at the impact interface between the striker and the target is obtained by a small extrapolation of the average values of W (in the middle of the recorded interval), in which the calculated nature of the acceleration of the striker is used.

The experimental results are presented in Table 3. They are compared in Fig. 12 with the results of the absolute measurements of the compressibility of iron under laboratory conditions [36, 37, 40, 42] and with the results of the relative measurements [3*, 5*, 10, 17] obtained under full-scale conditions (the asterisks indicate an analysis of the results given in the cited papers). Fig. 12 illustrates a smooth transition of the adiabat from the laboratory measurements to high pressures. The slope D'_U of the adiabat changes from 1.59 to 1.24 (this change in the slope occurs near $D = 13$ km s^{-1}). The value $D'_U = 1.2$ is known to be typical of the range of ultrahigh pressures predicted by the theoretical models [27, 28]. In the range of the maximum parameters the results of the absolute measurements are in satisfactory agreement with the relative measurements. In this connection it should be mentioned that the relative results [3, 5] have been obtained for the Pb–Fe measuring systems, in which lead is used as the standard metal.

Table 3.

Exp. config.	W_1/km s^{-1}	W_2/km s^{-1}	W_{av}/km s^{-1}	D/km s^{-1}	U/km s^{-1}	P/TPa	ρ/g cm^{-3}	$\sigma = \rho/\rho_0$
Fig. 11a	36.5	36.5	36.5 ± 1.0	28.85 ± 0.7	18.25	4.13	21.34	2.72
Fig. 11b	42.7	42.7	42.7 ± 1.2	32.4 ± 0.8	21.35	5.42	22.99	2.93
Fig. 11c	48.6	58.8	60.8 ± 2.5	43.5 ± 1.0	30.60	10.50	26.50	3.37

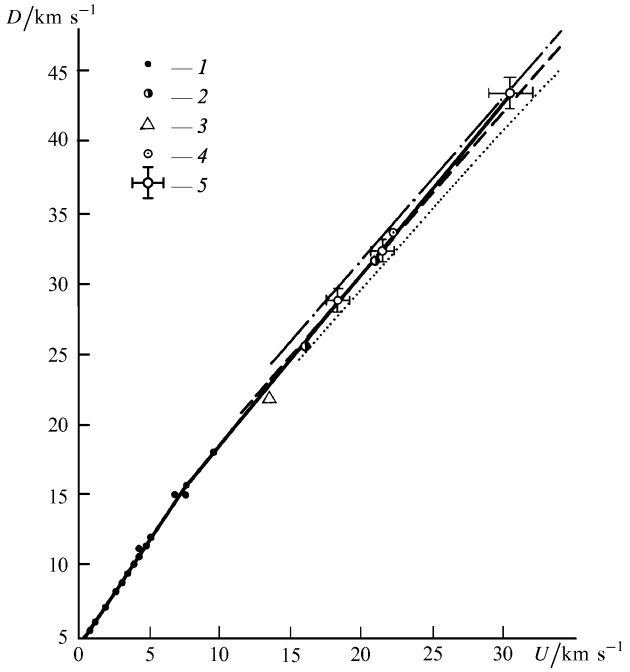

Figure 12. $D-U$ diagram of iron based on absolute measurements: (*1*) in the laboratory; (*2*) and (*3*, *4*) full-scale experiments involving relative measurements, reported in Refs [3, 5] and [10, 17], respectively; (*5*) absolute measurements. The continuous curve represents the experimental dependence, the chain curve corresponds to the SCF model, the dashed curve gives the results based on the MHFS model, and the dotted curve represents the TFQC model.

The agreement between the absolute and relative results confirms the correctness of the selected interpolation dependence. According to the absolute measurements of the compressibility of iron, the results obtained indicate a quadratic relationship between the wave and mass velocities

$$D/\text{km s}^{-1} = 3.99 + 1.463U/\text{km s}^{-1} - 5.62 \times 10^{-3}(U/\text{km s}^{-1})^2,$$

$$\rho_0 = 7.85 \text{ g cm}^{-3},$$

which is valid when $U > 8$ km s^{-1}.

At high pressures reached under the conditions of underground nuclear explosions, the experimental results can be represented satisfactorily by a linear relationship between the velocities:

$$D/\text{km s}^{-1} = 6.41 + 1.213U/\text{km s}^{-1}, \quad D > 18 \text{ km s}^{-1}.$$

The adiabat corresponding to the above relationship has been used in the interpretation of the majority of the results of the full-scale experiments in which iron has been employed as the standard metal.

In addition to the experimental $D-U$ relationship, Fig. 12 gives also the corresponding calculated results obtained on the basis of the SCF, MHFS, and TFQC models. In this case (the results for iron plotted as the $D-U$ dependences) the first two models give results close to the experimental values and the calculations based on the TFQC model coincide with experiments. If the selection of the calculation model suitable for higher pressures is ignored for the moment, it is possible to conclude that at pressures in this range (10 TPa for iron), the quantum-statistical TFQC model is preferable to the other two models.

The results obtained in investigations of the shock compressibility of iron at ultrahigh pressures solve the problem of the relative nature of the measurements made on many metals in apparatus in which the shield is made of iron [3, 5, 6]. In the reflection method these measurements become absolute.

One further conclusion can be drawn from these experiments. The linear relationship between D and U for iron, obtained in a fairly wide range of these two parameters (the corresponding maximum pressures are 10 TPa), means that up to these pressures there are no significant deviations from the monotonic shock adiabat.

3.1.2 Shock compressibility of aluminium at terapascal pressures

In investigations of the compressibility of relatively 'light' materials ($\rho_0 < 4$ g cm^{-3}), the standard material in the reflection method is aluminium, which is a metal with a density similar to the density of these materials. The compressibility of aluminium has been investigated on numerous occasions in the laboratory (see, for example, Refs [26, 40, 42, 51]) at pressures up to 0.5 TPa, which at present represent the limit for such light materials.

Under the conditions of nuclear explosions, the pressure 'ceiling' of the absolute measurements has been raised to 1.0–1.7 TPa [43, 44] (estimates of the compressibility have been obtained also at 3.0 TPa [44]). The relative compressibility of aluminium has been studied up to pressures of 24 TPa [15].

The absolute compressibility can also be determined by a new method [18], which is known as the γ-marker method. As pointed out earlier, in this method the velocity of the shock wave and the mass velocity of the motion of matter are found with the help of γ-active pellet-like markers embedded in the investigated material. The passage of these markers through certain fixed positions is recorded by means of γ-ray detectors. In this method it is necessary to solve a number of scientific and technical problems which are discussed in detail in Ref. [44]. One of the most important is the selection of the γ-active marker material. In the case of aluminium the marker material has been europium (usually in the form of europium oxide Eu_2O_3), because its nuclei have a radiative capture cross section which is approximately 10^3 times higher than the corresponding cross section of aluminium. Consequently, the activity of the γ-ray source is sufficient for reliable detection (against the background activity).

One further problem is the correct allowance for the preliminary (before the arrival of a shock wave) heating of the investigated sample by the primary flux of neutrons and γ rays from the marker, which can sometimes alter significantly the initial state of aluminium (for example, in the measurements reported in Ref. [44] the density of aluminium has decreased by 5% – 10%).

Specific allowance for the energy spectrum of neutrons makes it possible to 'delay' the arrival of a shock wave in a sample so as to ensure sufficient time for the moderation of high-energy neutrons to energies $E \leqslant 100$ eV, which are optimal for the (n, γ) reactions in europium.

Finally, one should point out the need to consider in the calculations such phenomena as the transient nature of the

shock wave, the perturbation of its front by inhomogeneities associated with the presence of the markers, etc.

The results of three experimental determinations of the compressibility of aluminium are given in Ref. [44]. Two of these experiments, carried out under the same loading conditions, have yielded similar and mutually confirmatory results (Table 4). The third experiment, carried out at much higher amplitudes of the shock waves ($P \approx 3.2$ TPa), is of a qualitative nature because of the large (about 10%) errors in the velocities.

Table 4.

Exp. No.	D/km s^{-1}	U/km s^{-1}	P/TPa	$\sigma = \rho/\rho_0$	Ref.
1	24.2 ± 0.7	15.1 ± 0.4	0.99 ± 0.03	2.65 ± 0.1	[44]
2	23.4 ± 0.6	14.5 ± 0.3	0.93 ± 0.02	2.63 ± 0.7	[44]
3	40.0 ± 5.0	30.0 ± 2.0	3.20 ± 0.5	3.90 ± 1.2	[44]
4	30.5 ± 0.7	21.0 ± 0.6	1.73 ± 0.07	3.21 ± 0.2	[43]

In the late seventies our group also carried out measurements of the compressibility of aluminium [43] by a method similar to that described in Ref. [44]. The main difference has been our use of a more powerful energy source of (n, γ) radiation, which has made it possible to increase the distance to the explosion source and thus reduce the influence of some of the factors which hinder interpretation of the results. Fig. 13 shows the configuration used in the measurements, which is generally similar to that described in Ref. [44].

An aluminium block (*1*) consists of three disks (a shield, a base disk 10 mm thick, and a substrate 100 mm thick) placed on an area oriented perpendicular to the direction towards the centre of energy release and separated from it by several metres. A wall consisting of a cement–sand mixture is placed between the explosive charge and the aluminium block. Since the aluminium block does not contain markers which could be used to judge the symmetry of the shock wave, this symmetry is ensured by careful alignment of the block and by the homogeneity of the spacer material.

In experiments of this kind the average wave velocity D is found from the time taken by the wave to travel between two markers (*2*) and the mass velocity is found from the corresponding time of passage of the first marker through both collimating slits (*4*). The results of these measurements, which include small corrections for the transient nature of the process, are given in Table 4 alongside the data taken from Ref. [44]. They are also plotted in Fig. 14,

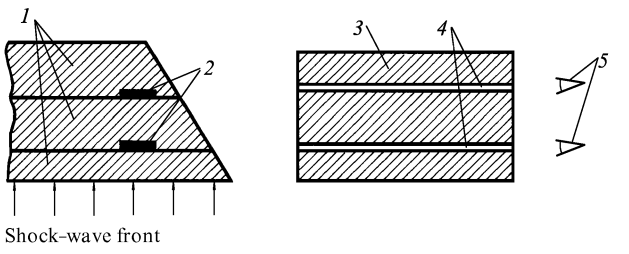

Figure 13. Schematic representation of the measurements carried out by the γ-marker method: (*1*) aluminium block; (*2*) marker pellets; (*3*) collimating device; (*4*) collimator slit; (*5*) photodetector.

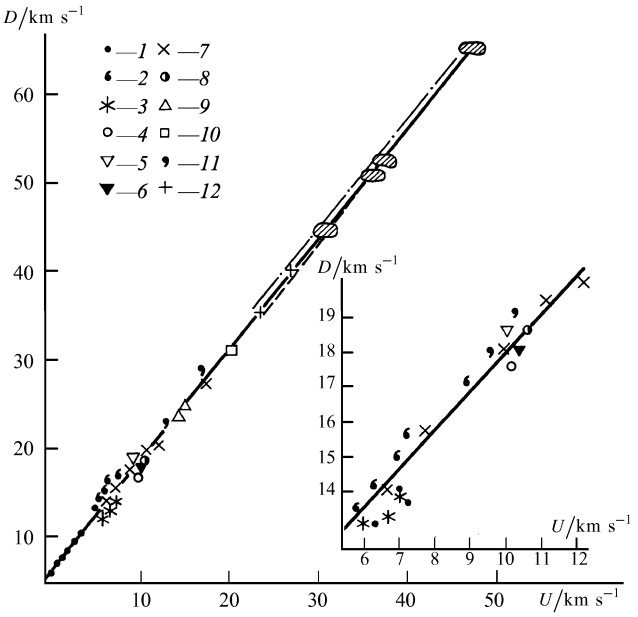

Figure 14. $D-U$ diagram of aluminium based on the laboratory experiments (*1–6*) and those carried out under the conditions of underground explosions: (*7–10*) absolute measurements; (*11*, *12*) relative measurements. The ellipses of possible variants in the analysis of the experimental results [15] are shaded. The chain curve represents the results of interpolation based on Ref. [45] and the dashed line gives the calculations based on the TFQC model.

where they are compared with the results obtained in nuclear test explosions [11, 15, 44, 45]. We can see that the results obtained by the γ-marker method are in mutual agreement and they are close to the data reported in Refs [11, 15]. The latter are of a relative nature and their position is governed by the selected shock adiabat of the shield. For example, in the case of aluminium it follows from Ref. [15], where the shield was made of iron (according to Refs [30, 46]), that a small deviation from the absolute measurements is related to the somewhat 'harder' adiabat of iron (compared with the TFQC model used in the interpolation of our experiments).

The data reported in Ref. [45] deviate in a similar manner. In both cases the deviations are not so large and they are less than the likely experimental errors in the range of pressures needed in the subsequent analysis. If we consider only the wave-velocity range 80 km s^{-1} > D > 11 km s^{-1}, we can represent the shock adiabat of aluminium in terms of the $D-U$ coordinates by a straight line, which on the average fits the experimental results (D and U are in kilometres per second):

$$D/\text{km s}^{-1} = 5.90 + 1.19U/\text{km s}^{-1}, \quad \rho_0 = 2.71 \text{ g cm}^{-3}.$$

We shall consider separately the results obtained for aluminium at lower pressures. This is mainly the range of the laboratory experiments ($P < 1$ TPa), although it includes a number of measurements carried out during nuclear explosion tests.

The shock adiabat of aluminium obtained from an analysis of all the known data in the range of pressures of interest to us is given in Ref. [24]. It is reproduced in Fig. 14 together with the experimental results (both those carried out in the laboratory and during underground tests),

on a larger scale in the right lower corner of the figure. This is the least certain part of the $D-U$ diagram of aluminium where the difference between the individual experimental results is the largest. We can see that the average aluminium adiabat describes all the results. However, the deviations of some of the experimental points from this average adiabat lie outside the usual (1% – 1.5%) error in the velocities. This applies particularly to the data taken from Refs [49, 51]. Judging by their overall position relative to the adiabat (including its low-pressure part), the results given in Ref. [49] do not satisfy the usual requirement of precision and this may be due to an unsatisfactory symmetry of the spherical device [49] or insufficiently rigorous estimates of the corrections for the transient nature of the wave velocity.

The small thickness of the samples (fractions of a millimetre) used in the study described in Ref. [51] could not have ensured the necessary high precision of the measurements, so that these results (apart from the point corre-sponding to the maximum parameters) differ from the remainder also by a steeper dependence ($D'_U \approx 1.4$ instead of 1.2). This is evidence of a small systematic error in these results.

The indeterminacy of the position of the experimental points taken from Refs [26, 27] is related to the different values of the corrections for the shock wave attenuation and it thus represents the real precision of these series of experiments. The results reported in Refs [48, 52] are characterised most probably by the same precision and, if a somewhat different approach is adopted to their interpretation, these results can be made more reliable.

We shall now consider the results given in Ref. [15]. They have been obtained in underground explosions by the reflection method. An iron shield has been used and its adiabat has been determined on the basis of the data of Refs [38, 39, 41]. The compression parameters of aluminium have been determined from the wave velocities in the shield and in the investigated sample (the interface between them) with the aid of the expansion adiabats of iron given in Ref. [53]. The positions of the first three results taken from Ref. [15] differ considerably from the positions of the next three results.

Fig. 14 includes also an experimental point obtained under underground explosion conditions and reported in Ref. [24]. Its position is approximately average between the results of the other experiments at pressures of about 0.5 TPa.

For a long time (until the publication of the experiments in Refs [15, 24, 51]) the shock adiabat of aluminium has been represented by two rectilinear sections of the dependence $D-U$ [52] shifted relative to one another (at $D \approx 11$ km s^{-1}) by $\Delta U \approx 400$ m s^{-1}. It follows from the above discussion that there is no real justification for this adiabat. It is more correct to represent the adiabat over the whole range of the wave velocities by a single smooth line free of discontinuities.

The following short comments can be made about the experimental data on aluminium.

At ultrahigh pressures the $D-U$ diagram of aluminium is based on experimental results and on theoretical calculations carried out on the basis of the TFQC model, which has proved successful in the case of iron. The agreement between experiments and calculations is quite satisfactory also in the case of aluminium. We are speaking here primarily of the range of pressures $P < 5$ TPa, essential when the reflection method is used in interpretation of the parameters of shock compression of light (including porous) materials investigated earlier [4, 7, 24, 54]. The shock adiabat of aluminium, like that of iron, is a monotonic dependence without any definite oscillatory effects.

The data on aluminium, taken as a whole throughout the full range of the wave velocities (from the laboratory range to the states reached in nuclear explosions), can be represented by the quadratic dependence

$$D_{\mathrm{Al}}/\mathrm{km\ s^{-1}} = 5.2 + 1.239U/\mathrm{km\ s^{-1}} - 0.7 \times 10^{-3}(U/\mathrm{km\ s^{-1}})^2 .$$

We have thus considered here the data on the compressibility of two standard metals, iron and aluminium, which are used as the shield materials in the reflection method, and we have determined the parameters of the shock adiabats and the range of validity of these adiabats for these two metals.

When the relevant data were made ready for publication in 1992, an opportunity presented itself to analyse once again the above results of the comparative measurements carried out by the reflection method, but in the case when the investigated material is placed behind a screen made of Fe (up to $P \approx 10$ TPa, experimental range) and Al (up to $P \approx 2$ TPa).

In the next subsection we shall consider the results of determination of the absolute compressibility of other metals under the conditions in underground nuclear explosions.

3.2 Compressibility of copper, lead, cadmium, and molybdenum

We recall that the first measurements of the compressibility metals in the terapascal range of pressures have been made in one of the experiments in 1966, concerned in particular with the Fe–Pb system. The results have been published [3] and they represent relative measurements. The same iron–lead system has been investigated again later [6]. The configuration in the experiments reported in Ref. [6] has been similar to that shown in Fig. 2a. In this case the shield (standard) has been iron on which a sample of lead has been placed. Electric-contact sensors and oscillographic recording of the signals have been employed, as usual. The average wave velocities in Fe and Pb, obtained in the central planes of the samples, have been converted (by small calculated corrections) to their values at the interface between the two materials, where they are

$$D_{\mathrm{Fe}} = 25.70\ \mathrm{km\ s^{-1}}, \quad D_{\mathrm{Pb}} = 20.72\ \mathrm{km\ s^{-1}},$$
$$D_{\mathrm{Fe}} = 31.90\ \mathrm{km\ s^{-1}}, \quad D_{\mathrm{Pb}} = 26.12\ \mathrm{km\ s^{-1}}.$$

These results are compared in Ref. [6] with the laboratory measurements plotted using the $D-D$ coordinates (Fig. 15). An earlier analysis of the laboratory data has shown that a comparison of the results on the basis of these two variables (which are the wave velocities in the shield and in the investigated material) is very convenient because it gives almost straight lines in a wide range of wave velocities and makes it possible to monitor the errors in the measurements. In this sense the agreement between the $D-D$ data obtained by the absolute measurements in the

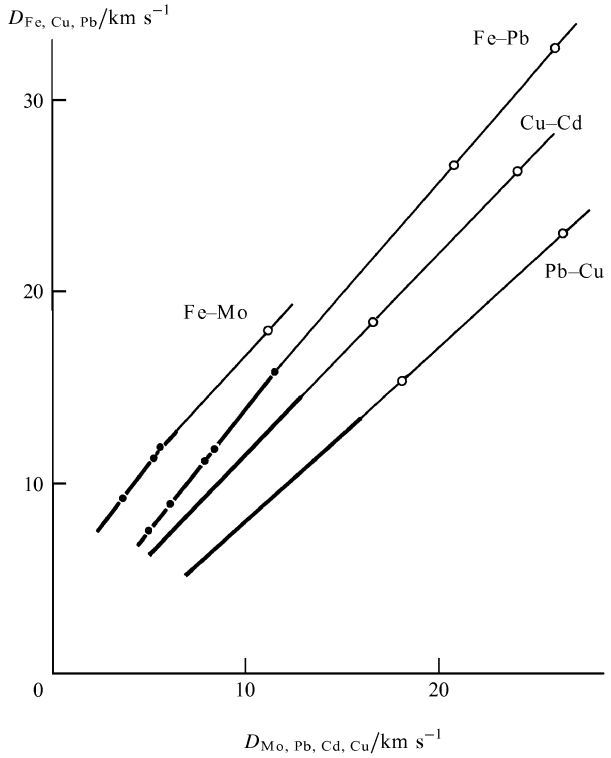

Figure 15. Experimental $D-D$ dependences, plotted for metals on the basis of the laboratory measurements (black dots) and measurements under the conditions of underground explosions (open circles). The thicker parts of the lines represent the laboratory measurements.

laboratory range of pressures with the results of the full-scale measurements in nuclear explosions provides a criterion of the validity of the latter measurements. It is evident from Fig. 15 that such an agreement is indeed obtained.

The whole set of results is approximated by two straight lines which intersect at the point $D_{Fe} \approx 15$ km s^{-1}. The first line represents

$$D_{Fe}/\text{km s}^{-1} = 2.04 + 1.205 D_{Pb}/\text{km s}^{-1} ,$$

and the second corresponds to

$$D_{Fe}/\text{km s}^{-1} = 2.35 + 1.343 D_{Pb}/\text{km s}^{-1} .$$

The results can be described alternately by the parabolic dependence

$$D_{Fe}/\text{km s}^{-1} = 0.400 + 1.343 D_{Pb}/\text{km s}^{-1} - 3.49 \times 10^{-3} (D_{Pb}/\text{km s}^{-1})^2 .$$

The above relationships, valid up to the velocities $D_{Fe} \approx 60$ km s^{-1} and $D_{Pb} \approx 53$ km s^{-1} (see below) represent direct experimental results†.

Investigations of the $D-D$ dependences, first proposed and implemented by Al'tshuler et al. [3] and by Trunin et al. [4] as the most direct representation of the experimental results, have since become a popular method in the analysis of these results [15, 55]. In addition to internal monitoring of the consistency of the results, such dependences make it possible to calculate the shock compressibility, represented in the form of the $D-D$ variables, of pairs of materials throughout the investigated range of the wave velocities and thus increase the statistical material suitable for subsequent analysis.

The transition from the $D-D$ variables to other shock-wave parameters is made by the reflection method involving certain constructions in the pressure–mass velocity diagram. Table 5 gives the results of calculations based on the above values of the wave velocities in iron and lead‡. They yield two experimental points on the adiabat of lead and these points make it possible to deduce the $D-D$ relationship in the required terapascal range of pressures. This is essential since lead is used as the shield material in the measurements [5, 6]. The result is the following linear relationship for lead:

$$D_{Pb}/\text{km s}^{-1} = 3.19 + 1.167 U/\text{km s}^{-1} ,$$
$$\rho_0 = 11.34 \text{ g cm}^{-3} ,$$

where $14 < D < 30$ km s^{-1}.

A system of consecutive lead shield–copper–cadmium layers has been used in two experiments carried out in 1967 and 1970. The distribution of layers in this case corresponds to the conventional reflection method. The initial states of the shield material (lead) are governed by the states in copper and then copper is used as the shield (after preliminary determination of its $D-U$ relationship). The compres-sion states of cadmium are then found. The mirror images of the shock adiabats of metals used as shields can

†At high velocities ($D_{FE} < 90$ km s^{-1}, $D_{Pb} < 80$ km s^{-1}) the relationship obtained with the aid of Ref. [15] is

$$0.435 D_{Fe}/\text{km s}^{-1} + 1.327 D_{Pb}/\text{km s}^{-1} - 2.33 \times 10^{-3} (D_{Pb}/\text{km s}^{-1})^2 .$$

‡The $D-U$ relationship is valid in experiment 7 (Table 5) in the range 13 km s^{-1} $< D <$ 25 km s^{-1}.

Table 5.

Exp. No.	Standard	$D-U$ curve of standard	Initial state of shield		Initial density ρ_0/g cm^{-3}	Parameters of compression of investigated material				
			D/km s^{-1}	U/km s^{-1}		D/km s^{-1}	U/km s^{-1}			P/TPa
ρ/g cm^{-3}		$\sigma = \rho/\rho_0$								
1	Fe	$D = 6.41 + 1.213U$	25.70	15.91	Pb 11.34	20.72	15.02	3.529	41.22	3.635
2	Fe	$D = 6.41 + 1.213U$	31.90	21.01	Pb 11.34	26.12	19.76	5.853	46.57	4.107
3	Pb	$D = 3.19 + 1.167U$	14.65	9.815	Cu 8.93	17.82	9.96	1.585	20.25	2.267
4	Pb	$D = 3.19 + 1.167U$	22.17	16.26	Cu 8.93	26.18	16.67	3.897	24.58	2.753
5	Cu	$D = 5.137 + 1.268U$	17.47	9.725	Cd 8.64	16.08	10.14	1.410	23.40	2.707
6	Cu	$D = 5.137 + 1.268U$	25.30	15.90	Cd 8.64	23.88	16.41	3.386	27.62	3.197
7	Fe	$D = 5.68 + 1.257U$	17.25	9.20	Mo 10.07	16.10	8.58	1.391	22.06	2.138

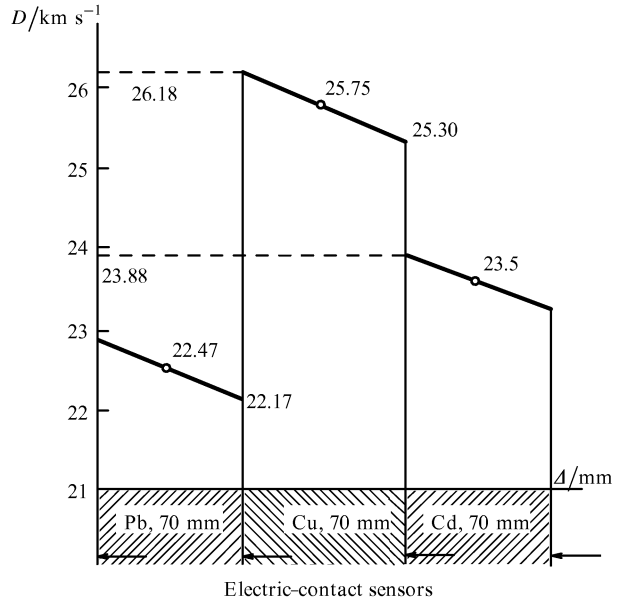

Figure 16. Attenuation of the wave velocities: the open circles represent the experimental results for the central planes of the samples and the continuous curves are the calculated values.

be employed in such constructions in view of the mutual proximity of the lead, copper, cadmium, and iron adiabats†.

By way of example, Fig. 16 shows schematically the results of direct determinations of the wave velocities [6]. The corrections to the average measured velocities are made on the basis of the calculated wave attenuation. The results are presented in Fig. 15 as the $D-D$ dependences. The range of the laboratory measurements is identified, as in the case of the Fe–Pb system, by a thicker line. The full-scale experiments are represented by two experimental points. We can see that they are in mutual agreement throughout the investigated range of the wave velocities:

$$D_{\mathrm{Pb}}/\mathrm{km\ s^{-1}} = 1.529 + 0.911 D_{\mathrm{Cu}}/\mathrm{km\ s^{-1}} - 0.22 \times 10^{-3} (D_{\mathrm{Cu}}/\mathrm{km\ s^{-1}})^2 ,$$

$$D_{\mathrm{Cu}}/\mathrm{km\ s^{-1}} = 1.318 + 1.005 D_{\mathrm{Cd}}/\mathrm{km\ s^{-1}} - 0.30 \times 10^{-4} (D_{\mathrm{Cd}}/\mathrm{km\ s^{-1}})^2 .$$

Table 5 gives the corresponding data for copper and cadmium obtained in these experiments.

We shall conclude this subsection with the results obtained on the compressibility of molybdenum at 1.4 TPa [56]. The interest in this metal is due to two circumstances. First, according to the laboratory experiments (up to $P \leqslant 1$ TPa), the shock adiabat of molybdenum is described by a linear relationship with the slope $D'_U = 1.27$. As mentioned earlier, this value is approximately equal to the values of D'_U deduced by calculations of the limiting states of elements based on the TFQC model. This evidently means that throughout the investigated range of the shock adiabat parameters of molybdenum (from the experimental range to the range covered by calculations and corresponding to ultrahigh pressures), the slope of the adiabat should not change significantly, i.e. throughout this range we should have $D'_U \approx 1.2-1.3$.

Second, the compressibility of molybdenum is of interest because it has been used as the standard metal (shield) by the American investigators. Therefore, any increase in the range of the absolute measurements of the compressibility of molybdenum will help to determine more accurately the compressibility of the materials investigated in the USA. Unfortunately, little progress has been made since in the known measurements of the compressibility of molybdenum under the conditions of underground explosions an increase in the pressure has been relatively small and the error in the determination of the compression parameters has been large [8, 57, 58]. Therefore, the range of measurements has not been extended greatly in our experiments. Nevertheless, out results fully support the conclusions drawn from the laboratory investigations.

The configuration used, similar to that shown in Fig. 2a, has included a steel shield 104 mm thick and a sample of molybdenum, 66.6 mm thick, placed behind the shield. As usual, in such experiments the planes of the samples are oriented perpendicular to the front of a shock wave. The results obtained are given in Table 5. They are presented as the $D-D$ dependences in Fig. 15. The data taken as a whole can be described by the dependence

$$D_{\mathrm{Fe}}/\mathrm{km\ s^{-1}} = 4.0 + 1.432 D_{\mathrm{Mo}}/\mathrm{km\ s^{-1}} - 2.19 \times 10^{-2} (D_{\mathrm{Mo}}/\mathrm{km\ s^{-1}})^2 .$$

The coordinates D and U are used in Fig. 17 for the adiabats of metals, the compressibilities of which have been investigated both under laboratory conditions and in the

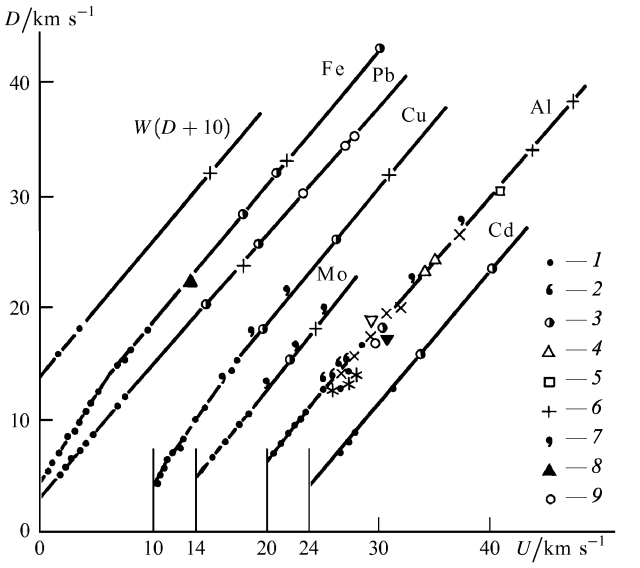

Figure 17. $D-U$ relationships for metals, based on the laboratory measurements (*1*, *2*) and on the experiments carried out in the course of underground explosions: (*3–5*) absolute measurements; (*6–9*) relative measurements.

†This is naturally an approximation since the required states should be governed by the expansion (or double compression) adiabats of the shield material. However, since the specific positions of these curves depend on the EOS used and since, in the investigated range of pressures, they may be located on either side of the shock adiabat, preference will be given to the mirror reflections. This reduces the ambiguity of the interpretation of the results. Moreover, possible deviations from the mirror reflection are in this case slight.

course of underground explosions. In the first approximation, the shock adiabats have similar slopes for all these metals and in the laboratory range of measurements the slope D'_U is a rule considerably greater (with the exception of molybdenum and tungsten) than at pressures corresponding to the 'underground' measurements. The experimental results for this range can be compared with the published data [9, 10, 16, 17, 57, 58]. With the exception of the results reported in Ref. [57, 58], which in the case of molybdenum and copper differ systematically from the results of other experiments (the $D-D$ dependences are steeper), the remaining measurements are in reasonable mutual agreement and the deviations of the wave velocities from the average dependences do not exceed 1% – 2%.

The deviation of the molybdenum and copper results reported in Ref. [57] from the other data is evidently due to an inappropriate selection of the standard material of the shield used in the reflection method. The shield was made of aluminium and the adiabat of this metal plotted in the form of the $P-U$ dependence was much 'softer' than the adiabats of copper and molybdenum. Therefore, in the interpretation of their compression parameters one would need to know not only the positions of the adiabat itself, but also the EOS of aluminium (which had to be used to calculate the double compression adiabats). The situation was made even worse by the considerable uncertainty about the EOS parameters and the unsuitably selected position of the aluminium adiabat itself, because — when plotted as the $D-U$ dependence — it passed on the left of the experimental points and missed most of them. A different EOS of aluminium used in the USA (known as EOS-2) definitely improves the description of molybdenum and copper. The reasons for the deviation of the results reported in Ref. [58] are not clear.

3.3 Compressibility of quartz, polymethyl methacrylate, and water

The compressibility of polycrystalline quartz samples of different initial densities, and also of water, PMMA, and several other light ($\rho_0 < 4$ g cm^{-3}) materials have been measured over a period of years (1966 – 1978). Some of the results have been published [24, 54]. In these measurements the shields have been made of aluminium, which (as already mentioned) is the only easily available material with the adiabat, plotted as the $P-U$ dependence, close to the adiabats of light materials. As a rule, these experiments have been carried out by the conventional reflection method and only measurements of the compressibility of polycrystalline quartz [3] and other rocks [20] have been made by the inverted reflection method (Fig. 2a). In the latter case the wave velocity measurements have been made on samples of several thicknesses, i.e. the wave attenuation has been found experimentally. Table 6 shows the values of the velocities being compared at the SiO_2 – Al interface, as well as the shock compression parameters of quartzite.

Measurements of the compressibility of porous α-quartz (α-SiO_2, with initial densities 1.75 and 1.35 g cm^{-3}), of water, and PMMA have been made [24] by the conventional reflection method (Fig. 2b). The dimensions of the assembly used in these measurements have been as follows: an aluminium shield, 100 – 160 mm thick, transmitting a wave to a sample, and a sample 80 – 100 mm thick.

In all these cases the measuring systems have been placed at a relatively large distance (4 – 8 m) from the centre of an explosion. Consequently, the attenuation of the shock wave in the base thickness of a sample has been relatively slight. Specific values of the attenuation have been found by calculation (except for quartzite in the inverted reflection method) and have usually amounted to less than 1% of the shock wave velocity. The experimental results obtained are presented in Table 6 (they apply at the shield – sample interfaces).

Fig. 18 gives the results of measurements of the wave velocities at the shield – sample interfaces. It is worth noting that, in contrast to Ref. [4] where the dependence $D_{Al}-D_{SiO_2}$ is based on a limited number of the experimental data and is described by a linear relationship $D_{Al}(D_{SiO_2})$, a large proportion of our more recent experiments has revealed that the relationship is more complex. It can be represented by two straight-line sections joined at $D_{Al} \approx D_{SiO_2} \approx 16$ km s^{-1}. The first section corresponds to the dependence

Table 6.

Exp. No.	Initial state of shield		Initial density ρ_0/g cm^{-3}		Parameters of compression of investigated material					Reflection method
	D/km s^{-1}	U/km s^{-1}			D/km s^{-1}	U/km s^{-1}	P/GPa	ρ/g cm^{-3}	$\sigma = \rho/\rho_0$	
1	32.54	22.39	SiO_2	2.65	33.00	22.45	1963	8.29	3.128	inverted
2	19.99	11.84	SiO_2	2.65	19.92	11.95	631	6.62	2.499	
3	18.66	10.72	SiO_2	2.65	18.43	10.87	531	6.46	2.438	
4	18.85	10.88	SiO_2	2.65	18.65	11.01	544	6.47	2.441	
5	36.40	25.63	H_2O	1.00	43.95	32.54	1430	3.852	3.852	conventional
6	22.10	13.61	PMMA	1.18	25.19	16.96	504	3.61	3.066	
7	36.70	25.88	SiO_2	1.75	39.73	29.08	2022	6.53	3.731	
8	37.59	26.63	SiO_2	1.35	42.17	31.89	1815	5.54	4.102	
9	29.90	20.17	W	6.27	21.55	16.45	2223	26.49	4.225	conventional
10	29.43	19.77	Fe	2.27	28.62	21.20	1353	8.60	3.857	
11	23.20	14.54	Fe	2.40	22.35	15.36	8270	7.71	3.197	
12	35.30	24.71	Cu	2.23	36.00	26.22	21000	8.21	3.681	
13	31.21	21.27	Cu	2.23	31.10	22.76	15780	8.32	3.729	
14	29.46	19.80	Cu	2.23	28.71	21.35	13670	8.70	3.901	
15	26.10	16.97	Cu	2.88	24.34	17.03	11940	9.59	3.330	

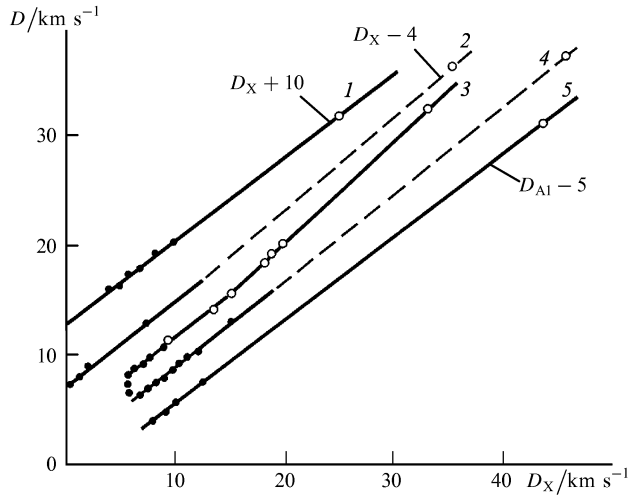

Figure 18. $D_{Al}-D_X$ dependences: (*1*) polymethyl methacrylate; (*2*) porous SiO_2 ($\rho_{00} = 1.75$ g cm^{-3}); (*3*) crystallographic-density α-SiO_2; (*4*) porous SiO_2 ($\rho_{00} = 1.35$ g cm^{-3}); (*5*) water.

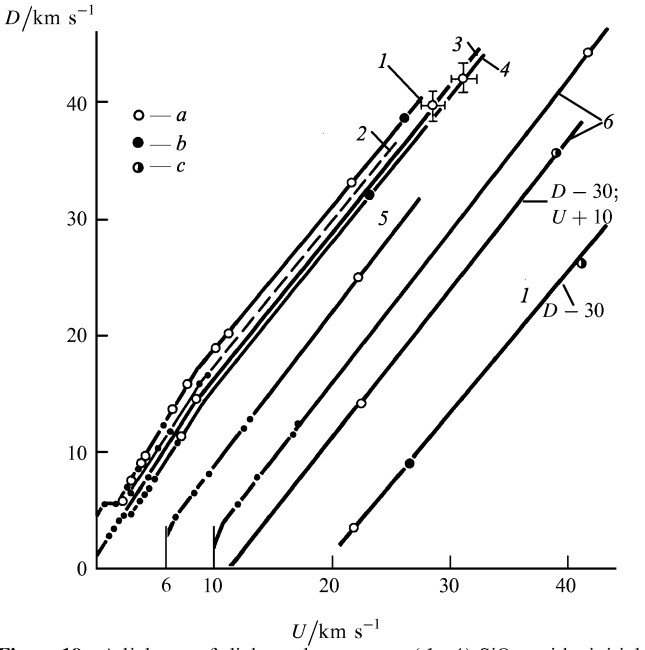

Figure 19. Adiabats of light substances: (*1–4*) SiO_2 with initial densities 2.65, 2.20, 1.75, and 1.35 g cm^{-3}, respectively; (*5*) polymethyl methacry-late; (*6*) water. The black dots represent the laboratory measurements and the open circles (a, b, c) are the results of full-scale experiments.

D_{Al}/km s^{-1} $= 3.3 + 0.81 D_{SiO_2}$/km s^{-1} and the second can be represented by D_{Al}/km s^{-1} $= 0.9 + 0.96 D_{SiO_2}$/km s^{-1} (where 16 km s^{-1} $< D_{Al} <$ 34 km s^{-1}). The wave velocities in aluminium and porous α-quartz probably behave similarly.

The results obtained for PMMA and water can be represented by straight lines throughout the investigated range of the wave velocities. The difference between the behaviour of quartz on the one hand and water and PMMA on the other, can be explained by the strength of the interparticle bonds in these compounds. Therefore, a change in the slope in the $D-D$ dependences occurs in the latter case during the initial stage of the compression process and is undetectable on the scale of Fig. 18. In the case of quartz these changes are greater and they occur at higher pressures. Moreover, the $D-D$ dependences obtained for PMMA and water are in full agreement throughout the investigated range of velocities.

Fig. 19 presents the experimental data as $D-U$ dependences. In addition to the results of the laboratory experiments [59–63] and those carried out by our group in the course of underground explosions [4, 19, 24, 54], this figure gives also the results of measurements reported for quartz [10, 11, 13] and for water [13]. The results are basically in agreement. The only exception is the point on the adiabat of fused quartz [11], which is in clear conflict with the positions of the other adiabats of silica. As far as the point representing SiO_2 is concerned, its parameters taken from the figure in Ref. [13] indicate only an approximate position of the $D-U$ dependence.

On the whole, the shock adiabats of quartz samples with different initial densities represent a family of approximately parallel lines with varying slopes. Up to the velocities $D = 14-16$ km s^{-1}, the slope is $D'_U \approx 1.6$, but at higher velocities the slope is $D'_U = 1.2-1.3$. Similar slopes (about 1.3) are obtained also for the adiabats of PMMA and water, which in terms of these variables are straight lines that begin from $D \geqslant 5$ km s^{-1}. The agreement between the slopes of the adiabats with the limiting values for the separate chemical elements demonstrates obviously that the 'rule of a single slope' $D'_U \approx 1.2-1.3$ applies also to such complex systems as quartz, water, and PMMA.

At the highest values of the parameters D and U the errors in our investigations have been about 2% of the average velocities. These errors are represented in Fig. 19 by mutually perpendicular bars. In spite of the fairly large errors in the positions of the experimental points, the most probable values of the parameters are fairly reliable, as judged by their mutual consistency. We can therefore estimate the Gruneisen coefficient

$$\Gamma = \frac{\Delta P_t}{\rho \Delta E_t}$$

(subscript 't' refers to the thermal components of the pressure and energy), which is the key thermodynamic parameter in the EOSs. Estimates of the values of this coefficient, made by comparison of the shock adiabats corresponding to the initial densities $\rho_0 = 2.65$ g cm^{-3} with $\rho_{00} = 1.75$ and $\rho_{00} = 1.35$ g cm^{-3}, leads correspondingly† to $\Gamma \approx 0.60-0.66$. In view of the approximate nature of these quantities, the agreement between the values obtained can be regarded as satisfactory.

The change in the slopes of the adiabats of PMMA and water occurs up to $D \leqslant 5$ km s^{-1}. Structural and phase transitions, as well as various chemical reactions including decomposition, all occur in this range. If $D > 5$ km s^{-1}, the $D-U$ dependences obtained for these substances correspond to straight lines and this is probably evidence that such modifications have reached completion.

The compression of aluminium by a factor of 2 under the conditions of underground explosions is reported in Ref. [24]. In this experiment, the wave velocities were determined for aluminium and lead, and a sample of the

†Here, ρ_{00} is the average density of a porous substance in which separate particles of the continuous matter are separated by voids.

latter was oriented along the direction of propagation of the wave after aluminium. In this configuration the equality of the pressures and velocities at the interface between the samples means that the states of shock compression of lead correspond to a point on the double-compression adiabat of aluminium.

In the initial analysis the results have been converted to the Al–Pb interface by introduction of calculated corrections for the wave attenuation. At the interface the velocities are $D_{Al} = 22.34$ km s^{-1} and $D_{Pb} = 13.70$ km s^{-1}. The initial and final states of aluminium are as follows:

$U_1 = 13.48$ km s^{-1}, $P_1 = 816$ GPa, $\rho_1 = 6.83$ g cm^{-3},

$U_2 = 9.02$ km s^{-1}, $P_2 = 1400$ GPa, $\rho_2 = 8.90$ g cm^{-3},

A comparison of the point representing the double compression with the single-shock adiabat of aluminium (Fig. 20) has then been used to find the Gruneisen parameter Γ. This parameter is $\Gamma \approx 0.67 \pm 0.08$, which is close to the limiting value of this quantity and is in satisfactory agreement with estimates of Γ deduced from various EOSs in the range of lower densities and pressures.

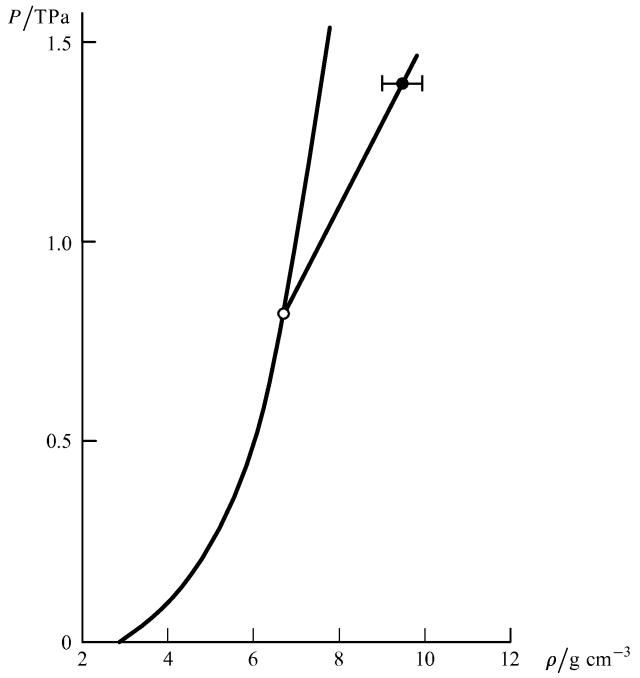

Figure 20. Adiabats of double compression of aluminium.

We shall conclude the discussion of the results obtained on the compressibility of light materials by strong shock waves in underground explosions by stressing that, as a rule, such results cannot be obtained in the laboratory and, consequently, they extend our knowledge on the limiting parameters of the compression of light substances and provide new information on the thermal components of the EOSs.

3.4 Shock adiabats of porous materials: iron, copper, and tungsten

These measurements have been carried out in order to obtain direct experimental data in the terapascal range of pressures, to determine on the basis of these data the general relationships governing shock compression at high pressures adjoining the theoretical range, and to estimate the thermal components of energy and pressure.

In selecting the porosity $m = \rho_0/\rho_{00}$ of metals we have tried to ensure that at terapascal shock pressures the densities of metals correspond to their crystallographic values, i.e. that the density of the shock-compressed material is approximately equal to the initial density: $\rho \approx \rho_0$. The attainment of such states can in some cases simplify greatly an analysis of the results because the pressures (energies) on a vertical adiabat centred at $\sigma = \rho/\rho_{0_{cr}} = 1$ are governed only by the thermal components in which the main role is played by the contribution of electrons. Such an important parameter as the electron analogue of the Gruneisen coefficient [26], $\Gamma_{el} \approx 2/(m\sigma - 1)$ is governed solely by the porosity $m = \rho_0/\rho_{00}$.

It has been found incidentally that the porosity of the investigated metals at which the adiabat corresponding to $\rho \approx \rho_0$ is approximately vertical represents the 'pouring' (subject to slight compression) density, which has simplified greatly the experiments. Since the initial densities of metals (with the exception of tungsten) are close to the normal density of aluminium, the latter has been used as the standard shield material. The conventional reflection method has been used: a porous sample is inserted into a special cylindrical matrix (80 mm thick and 300 mm in diameter) placed on the surface of an aluminium shield (100–160 mm thick). A shock wave has a gently falling profile, so that the conversion of the average wave velocities to the instantaneous values at the aluminium–sample interface requires only small corrections for the attenuation (less than 1% of the average values of D).

The wave velocities in these shields and porous samples (at the interface) and the shock compression parameters are listed in Table 6. The $D-D$ dependences obtained for porous metals are plotted in Fig. 21. All the dependences are linear and they are close to one another for Fe and Cu, nearly coinciding within the limits of the mutual experimental errors. In the case of tungsten the points fit a steeper dependence.

The results given in Table 6 are compared, in the form of the $D-U$ dependences, in Fig. 22 with the corresponding laboratory measurements and with the full-scale experiments on samples with normal initial densities. This figure demonstrates on the whole a good agreement between the results which fit logically the overall pattern of the adiabats (for both 'porous' and 'normal' samples) in the $D-U$ plane. In this pattern the experimental results determine two parts of the adiabats. In the first part (representing usually the laboratory measurements), the shock adiabats of porous metals are centred at the point with the coordinates $U = 0$ and $D_0 \geqslant 0$. Depending on the metal, D_0 lies in the interval 0.1–0.4 km s^{-1} [23]. The second parts of the adiabats represent approximately parallel lines with slopes close to the limit. In the case of W and Mo the shock adiabats corresponding to the normal initial density have the same slope ($D'_U \approx 1.2$) throughout the experimentally investigated range of velocities. In the case of the corresponding adiabats of Fe and Cu the slope decreases (from 1.7 to 1.2) between the first part of the $D-U$ dependence and the second. A change in the slope of

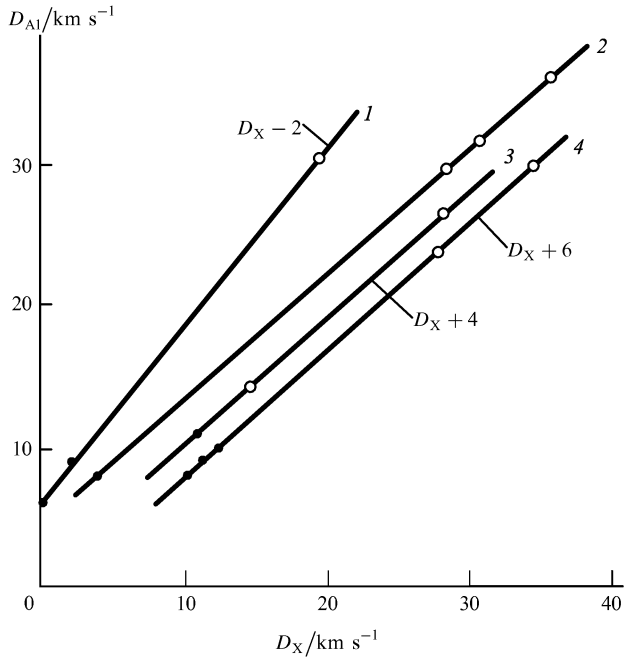

Figure 21. $D_{Al}-D_X$ dependences, based on the laboratory measurements (black dots) and on the results obtained in the course of underground explosions (open circles): (*1*) W, $m = 3.1$; (*2*) Cu, $m = 4.0$; (*3*) Cu, $m = 3.0$; (*4*) Fe, $M = 3.4$.

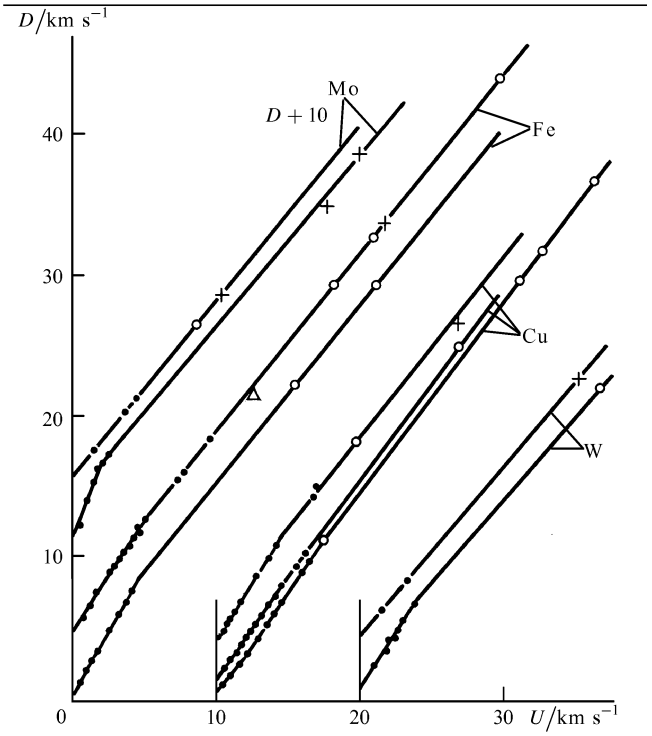

Figure 22. $D-U$ dependences for the adiabats of porous and continuous metals. The black dots represent the laboratory measurements and the open circles, crosses, and triangles are the results of measurements during underground tests.

the adiabats of 'porous' samples occurs at approximately the same values of D.

Estimates of the effective Gruneisen coefficient from the 'porous' shock adiabats at the maximum attainable pressures (in this range the electron contributions predominate, so that $\Gamma_{eff} \approx \Gamma_{el}$) show that in the case of the investigated metals the values of Γ represent approximately 0.5 for W and 0.7–0.9 for Cu and Fe. It follows that the Gruneisen coefficient Γ is most probably an individual characteristic of each chemical element and it does not depend on the group to which this element belongs.

4. Relative compressibility of titanium, iron, copper, and lead at pressures of 15–20 TPa

The results of measurements at pressures exceeding 10 TPa were first reported in Ref. [13]. For example, in the case of lead the results have been obtained at 16 TPa.

In 1984–1986 the pressure 'ceiling' increased [14, 15] reaching the gigantic value of 750 TPa [14]. This applies naturally to the relative measurements of the compressibilities of Fe–Al and Fe–Pb metal pairs in which only the wave velocities are determined experimentally. Nevertheless, pressures can also be determined quite reliably because they are given by $P = \rho_0 D^2(\sigma - 1)/\sigma$ and at the values of σ close to the limit the errors in the pressure depend mainly on the errors in the wave velocities.

The relative compressibility of the Fe(shield)–Pb–Cu–Ti system has been determined in 1981 by a team from our laboratory at pressures of about 20 TPa [12]. The experimental configuration used is shown in Fig. 23. Since we have been interested in the compressibility at pressures amounting to tens of terapascals, the measuring unit has been placed in the direct vicinity of an explosive charge. A polyethylene–lead system placed directly in front of the charge has served to moderate the (n, γ) fluxes and to form a shock wave amplitude with a near-constant pressure profile and with a plane front. The diameter of a cylindrical sample has been 250 mm and the total diameter of the measuring unit has amounted to 1000 mm. The measuring unit has been aligned to ensure that its planes are exactly perpendicular to the direction between the centre of the energy source and the centres of these planes. This has ensured a good symmetry of the shock wave.

The time taken by a wave to cross a sample has been found by recording light emitted by the wavefront on emergence at the shield–sample and sample–air (rear side of the sample) interfaces. Light has been collected from the surface of a sample unaffected by the perturba-

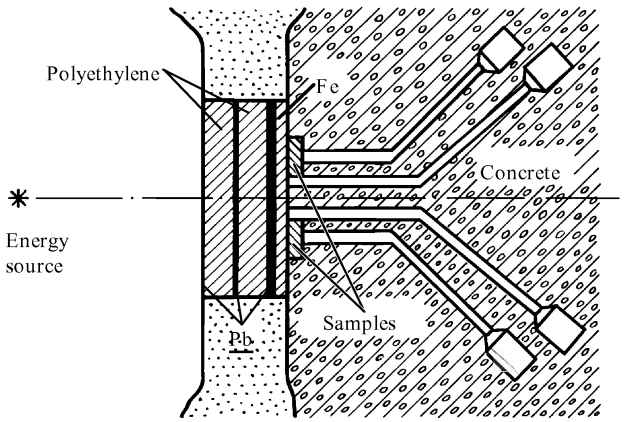

Figure 23. Schematic illustration of the method used in measurements of the relative compressibility of the Fe(shield)–Pb–Cu–Ti system.

tions propagating from its boundaries. This has been done by optical pipes of tubular shape with an inner diameter of 30 mm. The inner surfaces of the tubes have been polished to improve the collection of light. Premature emission of light by air because of heating with the (n, γ) radiation on explosion of a charge has been prevented by pumping out these tubes to pressures amounting to a few tenths of millimetres of mercury.

In the experiments the emitted light has been recorded with coaxial photocells of the SDF-7 type placed outside the direct light flux and protected by a thick concrete layer from the radiation emitted by the explosive charge. These optical pipes have been arranged along the same diameter of a sample (625 mm). Four measuring channels have been placed on a shield and the same number of channels has been placed at the centres of the samples (on their outer surfaces). One channel and the corresponding optical pipe have been located at the centre of the system.

A satisfactory symmetry of the shock wave (about 4×10^{-8} s) is indicated by the experimental results. Preliminary calculations show that the adopted measuring system ensures relatively weak wave attenuation in samples with the thicknesses employed in these experiments, so that the attenuation effects can be ignored. Unfortunately, because of errors in the determination of the starting points of the time intervals, associated with the uncertainty of the time scale of the oscillograms, and also because of some other factors the errors in the determination of the average wave velocities have been estimated to be 1.5% for Cu and Fe, 2.5% – 3.0% for Pb, and 4.0% for Ti. The large error in the determination of the wave velocity is one of the main reasons why the results have not been published immediately after the experiments in 1981. It has been hoped that the results can be refined in other similar experiments, but it has proved impossible to do this. It has therefore been decided to publish now the results of these experiments [12].

The wave velocities found directly are as follows: for the Fe standard

$$D_{\mathrm{Fe}} = 57.4 \pm 0.9 \text{ km s}^{-1} ,$$

and for the investigated metals:

$$D_{\mathrm{Cu}} = 55.87 \pm 0.8 \text{ km s}^{-1} ,$$

$$D_{\mathrm{Pb}} = 48.79 \pm 1.2 \text{ km s}^{-1} ,$$

$$D_{\mathrm{Ti}} = 62.3 \pm 2.5 \text{ km s}^{-1} .$$

These results are plotted in Fig. 24 in the form of the $D-D$ dependences. Each of these dependences represents two joined straight lines. The joint occurs near the wave velocity $D_{\mathrm{Fe}} = 14-15$ km s^{-1} and it determines the change in the slope of the lines. The steepest dependence (in the second part) is $D_{\mathrm{Fe}}-D_{\mathrm{Pb}}$ and the one with the smallest slope is $D_{\mathrm{Fe}}-D_{\mathrm{Ti}}$. The results obtained at high pressures are comparable with the results of the laboratory measurements and for the Fe–Pb pair they are also comparable with the full-scale measurements reported in Refs [13, 15]. The data given in Ref. [13] deviate quite strongly from the average $D-D$ dependence.

In the range of the wave velocities employed in the experiments reported in Ref. [12] the linear $D-D$ relationships for the investigated pairs of metals are as follows: For Fe–Pb

$$D_{\mathrm{Fe}}/\text{km s}^{-1} = 2.35 + 1.125 D_{\mathrm{Pb}}/\text{km s}^{-1} ,$$

$$15 \text{ km s}^{-1} < D_{\mathrm{Fe}} < 60 \text{ km s}^{-1} ,$$

for Fe–Cu

$$D_{\mathrm{Fe}}/\text{km s}^{-1} = 0.86 + 1.01 D_{\mathrm{Cu}}/\text{km s}^{-1} ,$$

$$15 \text{ km s}^{-1} < D_{\mathrm{Fe}} < 60 \text{ km s}^{-1} ,$$

For Fe–Ti

$$D_{\mathrm{Fe}}/\text{km s}^{-1} = 1.60 + 0.89 D_{\mathrm{Ti}}/\text{km s}^{-1} ,$$

$$15 \text{ km s}^{-1} < D_{\mathrm{Fe}} < 60 \text{ km s}^{-1} ,$$

The range of ultrahigh parameters taken from Ref. [15] for the Fe–Pb pair is shown on the right of Fig. 24.

The positions of the adiabats of the investigated metals have been found starting with the initial adiabat of iron represented by the dependence based on the TFQC model. Since in the experiments the shock wave has had a gently sloping profile, the thermodynamic parameters of Cu, Pb, and Ti can be determined by comparing directly the experimental values of the average wave velocities. Since the $P-U$ adiabats of Fe, Cu, and Pb are close to one another, they can be compared by relying directly on the shock adiabat of iron.

Calculations based on the TFQC model show that this procedure does not introduce any significant additional errors into the compression parameters of metals. In the case of titanium the differences between the position of the

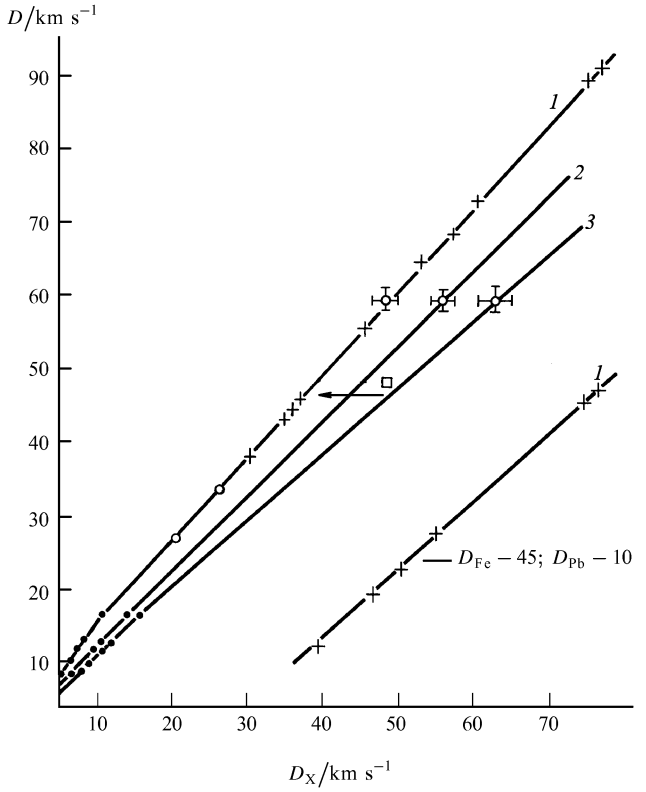

Figure 24. Relative compressibilities: (*1*) $D_{\mathrm{Fe}}-D_{\mathrm{Pb}}$; (*2*) $D_{\mathrm{Fe}}-D_{\mathrm{Cu}}$; (*3*) $D_{\mathrm{Fe}}-D_{\mathrm{Ti}}$. The black dots represent the laboratory measurements; the circles, crosses [15], and squares [14] are the results of measurements in the course of underground explosions.

shock adiabat and the expansion adiabat of iron are taken into account. The results obtained are given in Table 7. The initial states of iron corresponding to the adiabat calculated on the basis of the TFQC model are found for $D_{Fe} = 57.4 \pm 0.9$ km s^{-1}. In the case of the other metals the values of the parameters are found for the nominal D obtained by the reflection method.

Table 7.

Metal	D/km s^{-1}	U/km s^{-1}	P/TPa	ρ/g cm^{-3}
Iron	57.4 ± 0.9	42.3	19.1	29.8
Lead	48.8 ± 1.5	39.3	21.7	58.0
Copper	55.9 ± 0.8	40.8	20.4	33.0
Titanium	62.3 ± 2.5	48.6	13.6	20.5

Table 8.

Metal	ρ_0/g cm^{-3}	C_0/km s^{-1}	D'_U	Range of measurements D/km s^{-1}
Iron	7.85	7.0	1.19	20–46
Lead	11.34	3.4	1.15	12–50
Titanium	4.51	4.5	1.20	4.5–65
Copper	8.93	6.1	1.21	16–55
Molybdenum	10.20	5.0	1.26	5–20
Aluminium	2.71	5.9	1.19	10–40

It should be pointed out that the data in Table 7 agree almost completely with all the previous measurements and can therefore be regarded as their continuation. Table 8 gives the corresponding linear relationships obtained for the investigated metals at high pressures. The slopes D'_U of the adiabats of all the metals are approximately the same (on the average they are equal to 1.2) and they agree with the values deduced from the dependences calculated on the basis of the TFQC model. Moreover, the calculated (on the basis of the same model) parameters of the shock waves in Fe, Cu, Pb, and Ti (for which the range of the experimental wave velocities is widest) practically coincide with the experimental data. For example, the velocities of the wave transmitted by iron, $D_{Fe} = 57.4$ km s^{-1}, calculated on the basis of the TFQC model are as follows:

$$D_{Ti} = 62.81 \text{ km s}^{-1}, \quad D_{exp} = 62.3,$$

$$D_{Cu} = 55.80 \text{ km s}^{-1}, \quad D_{exp} = 55.9,$$

$$D_{Pb} = 49.59 \text{ km s}^{-1}, \quad D_{exp} = 48.8,$$

i.e. the maximum deviation in the case of lead amounts to 1.5%, which is naturally within the expected range of the experimental errors.

Fig. 25 gives the experimental data for these metals both in the range of the laboratory measurements and at high pressures obtained under the conditions of underground explosions. We can see that on the whole the agreement between the results is satisfactory. The reasons for the deviations of some of the data, particularly the results reported in Ref. [57], have been discussed earlier.

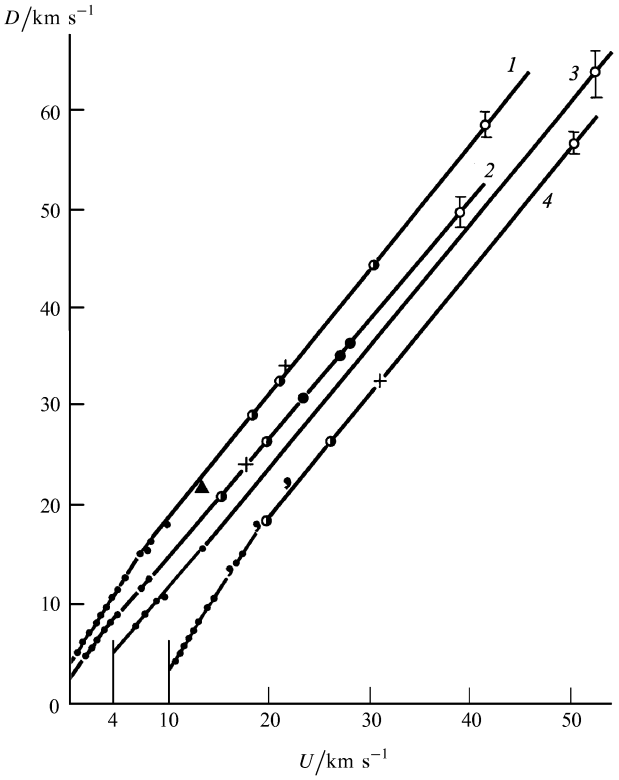

Figure 25. $D-U$ diagrams of Fe, Pb, Ti, and Cu at ultrahigh pressures: (*1*) Fe; (*2*) Pb; (*3*) Ti, $U+4$; (*4*) Cu, $U+10$.

5. Conclusions

We shall conclude this analysis of the compressibility data found in the course of nuclear test explosions by summarising them as follows.

1. The compressibility of iron has been determined by the absolute methods at pressures of 4.3, 5.5, and 10 TPa, which are 8–10 times higher than the pressures reached in the laboratory. The results have given the position of the shock adiabat of iron in this range of pressures and have thus made it possible to replace the relative with the absolute measurements for a whole range of elements, including copper, lead, molybdenum, and cadmium.

2. The compressibility of aluminium has been measured by the absolute methods up to maximum pressures of 2.0 TPa. The results taken as a whole have made it possible to determine the shock adiabat of aluminium and to obtain the absolute compressibilities of a number of light compounds, including α-quartz (of different initial densities), water, polymethyl methacrylate, and also of porous metals (copper, iron, and tungsten).

3. In comparable ranges of pressures the results of the Chelyabinsk Nuclear Centre and laboratories abroad have been found to agree with our results within the limits of the mutual error in determining the parameters of shock waves.

4. The comparative compressibilities of iron (used as a standard), lead, copper, and titanium have been obtained at pressures of 15–20 TPa. They have been compared with the results of the Chelyabinsk Nuclear Centre obtained for the iron–lead system at gigantic pressures (hundreds of terapascals). They are found to be in mutual agreement (in a comparable range of compressions) and are also consistent with the laboratory experiments carried out at

lower pressures. An analysis has been made of the results in the form of the $D-D$ dependences.

5. Estimates have been obtained of the average values of the Gruneisen coefficient of quartz and aluminium, and of the electron analogue of this coefficient in the case of copper, iron and tungsten. The results obtained are close to the limiting values.

6. A comparison of the experimental and calculated adiabats for standard metals (iron and aluminium) demonstrates the advantage of the description of these adiabats by the Thomas–Fermi model with the quantum and exchange corrections, which takes into account the non-ideal nature of the interaction between the nuclei (TFQC model).

7. In the investigated range of pressures tackled by the absolute methods (up to 10 Tpa for iron, 5–7 TPa for copper, lead, and tungsten, and 3 TPa for aluminium and quartz) the shock adiabats are smooth dependences without obvious deviations from monotonic behaviour which might be associated with oscillatory effects.

8. The shock adiabats are not affected by the scaling up of the experiments (involving an increase in the duration of application of pressure to a material) or by changes in the dimensions of the particles which are constituents of porous samples.

The results obtained do not however give answers to a range of questions which continuously arise in the process of tackling various tasks. Without attempting any comprehensive list of the unsolved problems, I shall list some of them.

First of all, it is essential to investigate the compressibility of ultraporous metals (with an initial density less than 0.5 g cm^{-3}) at terapascal pressures. The parameters found in experiments of this type make it possible to obtain test data for checking the 'transparent' models of the equations of state of materials in the parts of the phase diagrams not investigated so far and located between the known solutions for gases and solids (models of the Saha and TFQC type, and the corresponding experiments on gases and condensed matter). In this part of the phase diagram (more exactly at the minimum parameters of the states) the first data have been obtained for samples of superporous nickel (laboratory measurements [64]), which, however, cannot be extrapolated over large parts of the phase diagram because of the limited capabilities of the laboratory experiments. The only way of tackling this problem is to carry out measurements with strong shock waves under the conditions of underground explosions.

The second and related task is the acquisition of extensive information on the range of states under discussion. It involves determination of the expansion adiabats with initial states on the shock compression curves of ultraporous metals. Experiments of this type are in a sense equivalent to those involving variation of the initial densities.

One of the important tasks is to develop a method for direct investigations of the oscillatory effects in the compression of materials by ultrashort shock waves. The present approach to the problem of oscillations of the shock adiabats depends, strictly speaking, on the precision of determination of the parameters of shock waves in the absolute measurements of the compressibility. When the kinematic parameters are measured with errors not exceeding 0.5% – 0.7%, it will become possible to record these oscillatory effects. Such high precision is not yet attainable. Moreover, studies of the effects at pressures above 10 TPa have been carried out by the comparative methods, which presumes that there are no oscillations or that there are only small oscillations in one of the standard elements (used as a shield), which is not always fully justified.

The next task is the determination of the states in the $P-\rho$ diagram in the region between the $T = 0$ K isotherm and the shock adiabat. This region can be investigated by measurements in which the entropy of the investigated system is less than the entropy corresponding to the shock adiabat. These conditions are satisfied in particular by the multiple compression adiabats, isentropic compression curves, and some other dependences. The simplest to implement (at least in the case of light elements) is the process of consecutive compression of matter by several shock waves (one example of such measurements is described in the present review). Measurements of this kind give the thermal characteristics of materials and can sometimes give unexpected results, particularly near the limiting states.

One should mention also the possibility of additional experimental calibration of wide-range equations of state. This is based on a comparison of the calculated and experimental parameters of the metal expansion adiabats (with the initial states on the adiabats of continuous metals at pressures above 1 TPa) in the range of relatively low pressures (below 0.1 TPa), where the deviations of the positions of the expansion curves plotted on the basis of different equations of state are the largest.

This is a far from complete list of problems that have to be solved. Unfortunately, the tackling of these problems in practice does not depend only on the investigators.

Acknowledgements. The present review summarises the results of a major effort made by a team of researchers at the Russian Nuclear Centre. Studies of the compressibility of materials in strong shock waves under the conditions of underground nuclear explosions had been started by us in cooperation with L V Al'tshuler, who in the initial stages understood better than others the importance and the need to develop such work. Subsequently, the greatest contribution to this work had been made by M A Podurets, G V Simakov, L V Popov, B N Moiseev, and many of their colleagues. I record with gratitude their creative and selfless work, without which it would have been impossible to acquire and analyse the experimental results reported above.

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