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Extreme states of metals: investigation using shock wave techniques

R F Trunin

1. Introduction

The beginning of the research reviewed here dates back to 1947, when the gasdynamics scientists of KB-11 [presently the Russian Federal Nuclear Center — All-Russian Research Institute of Experimental Physics (RFNC–VNIIEF)] were given the task of investigating the shock wave properties of the substances used in the design of the atomic bomb developed in the USSR. These properties were required to select its design on the basis of calculations, because the properties-based equation of state, i.e., the relation between pressure, density, and energy, closed the system of equations of motion and thereby allowed estimating the parameters of compression of the active and other substances.

Our pioneers of experimental investigations in this area were L V Al'tshuler, K K Krupnikov, V A Tsukerman, B N Ledenev, V I Zhuchikhin, S B Kormer, and their collaborators. Scientists of the theoretical divisions, Ya B Zel'dovich, E I Zababakhin, G M Gandel'man, N A Dmitriev, V P Kopyshev, and others, actively participated in the development of research methods and the interpretation of the data obtained. The contribution of Yu B Khariton was inestimable as regards the scientific organizational aspects.

The techniques proposed for determining the parameters of shock-compressed substances enabled making the first measurements of their characteristics already in 1947.

The first substance whose properties had to be known to ensure the success of a bomb test was the explosive that was part of the bomb. Many are familiar with the epic work to obtain the detonation parameters of this explosive (see, e.g., Ref. [1]), and I do not therefore enlarge on this issue. I merely mention that only owing to Zel'dovich was it possible to eliminate the existing discrepancies between detonation parameters and thereby resolve the burning problem of the bomb test.

Uranium became the first metal investigated in 1947; its compression was studied at pressures up to 500 kbar.

The measurements were initially made using the spall technique; owing to its low precision, it soon gave way to the absolute method of 'deceleration' [2] and the method of 'reflection' [3] based on its principles.

The majority of measurements whose results are partially outlined in Sections 3–5 were carried out using the last two techniques. According to them, two kinematic parameters are determined from experiments: the shock velocity D in a sample and the velocity of motion of the substance behind the front, the so-called particle velocity U.

The shock velocity is easily determined in both techniques: all that has to be done is, in the path of wave propagation, to place sensors of an arbitrary type that react to the high pressures of the front and to record the time of wave passage between them.

Special methods were introduced for determining the particle velocity, permitting indirect determination of this parameter. The reader can become familiarized with them using source materials [2, 3]. Here, I only recall that according to the deceleration method proposed by Al'tshuler, the velocity W of a striker (liner) approaching a target is precisely equal to the doubled value of the particle velocity U in the target (when the liner and the target consist of the same material). Applications of the reflection method (Al'tshuler, Krupnikov, and Gandel'man) require the knowledge of the equation of state of the material of the screen that covers the samples on the side of the approaching shock wave and the parameters of this wave in the screen. The particle velocity U in the substance under investigation is found by considering the decay of an arbitrary discontinuity in the pressure–particle velocity diagram.

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The thermodynamic parameters of the compressed substance — the pressure, density, and energy of shock compression — are determined via these kinematic quantities from the conservation laws for momentum $P - P_0 = DU/V_0$, mass $V/V_0 = (D - U)/D$, and energy $E - E_0 = 0.5(P + P_0)(V_0 - V)$. Here, P, V, and E are the pressure, the specific volume, and the internal energy; the subscript '0' pertains to the initial values of these quantities. The temperature of shock-compressed substances is not measured directly but obtained from the equation of state (EoS) constructed on the basis of these parameters.

The conservation equations underlie the so-called Hugoniot adiabat — the adiabat $P_{\mathrm{H}} = P_{\mathrm{H}}(V, P_0, V_0)$ of the material under investigation, which is the continuum of thermodynamic states resulting from the shock compression of the material that was initially in the state with P_0 and V_0.

The Hugoniot adiabat is the main source of experimental information that underlies the determination of other matter equations of state. Other shock wave characteristics of material — sound velocities behind the shock front, expansion and twofold compression adiabats, shock compression temperatures, and so on — are directly related to the shock adiabat and are largely determined by it. This is the reason why emphasis is placed on the investigation of shock adiabats in the determination of matter equations of state.

A remarkable property of shock adiabats is that they are approximated by linear or nearly linear dependences in the $D-U$ coordinates in a wide range of these parameters. This rule — the linearity of $D(U)$ — was experimentally shown over a wide range of D and U in several hundred cases of investigation of different materials, from gaseous to initially solid. Of course, this representation is some approximation to reality, because real 'perturbations' exist on the linear $D(U)$ representations arising from physical processes that occur under shock compression: melting, evaporation, dissociation, and so on. This gives rise to deviations from linearity; however, they are not large enough to invalidate the general tendency rule, the linearity of adiabats in the $D-U$ diagrams.

Another property of shock adiabats demonstrated in experiments must also be mentioned. For high shock parameters ($D > 10-15$ km s^{-1}), the shock adiabats exhibit a universal slope $D'_U \approx 1.2$, which is characteristic both of different substances and of materials with different initial densities.

To determine the kinematic parameters D and U, two types of measuring devices are primarily used at VNIIEF: 'planar' devices [4], which produce a plane stationary shock wave in the samples under investigation, and spherical (to be more precise, hemispherical) [5], which form a spherical shock wave converging to the center of the system.

Almost until the end of the past century, a third source of shock waves also existed, which was far superior to the first two. The case in point is the high-power shock waves in rock induced by underground nuclear explosions, which could be used as an instrument for solving research problems [6].

This brings up the question: why should we aspire to increase the pressure at all? The pressure 0.5 Mbar in uranium was achieved back in 1947! Can we stay with that figure? But in the operation of a nuclear charge, the compression of its constituent materials proceeds at different pressures, including those that far exceed the value specified above. That is why these states had to be studied. This was the subject of active research in our laboratory during the subsequent period.

2. Measuring devices

The hemispherical measuring charge proposed by Al'tshuler, Zababakhin, Zel'dovich, and Krupnikov in 1948 is a universal measuring device for determining the shock compression of materials. Its structure has been repeatedly conceptualized in many papers (see, e.g., Refs [5, 7, 8]), and is therefore not reproduced here. I only recall that the charge is a hemisphere of a high-power explosive, which is simultaneously initiated over its entire outer surface. Inserted into the inner (also hemispherical) cavity of the charge is a steel hemisphere — the striker — which is accelerated to the center of the system by the explosion products of a converging detonation wave and strikes the target samples at the radius selected for the investigation and imparts the converging shock wave to them. The first measuring devices of this kind had several disadvantages (insufficiently high symmetry of the converging shock wave, ambiguity in the inclusion of the wave nonstationarity, the density nonuniformity of the explosive, and so on). The devices were improved [5, 7, 8] in the 1960s so as to minimize these and some other disadvantages: higher-power explosives with a higher density stability were used and the focusing system was replaced with a higher-performance one. This resulted in a significant improvement in wave symmetry, which in turn permitted decreasing the thickness of the samples and made the inclusion of nonstationarity less ambiguous. An air gap was introduced between the striker and the explosive, which softened the pressure of the first wave arriving at the striker. These and some other alterations served to stabilize the initial discharge parameters. The shell velocity measured at different radii in its motion ranges from 7 km s^{-1} at 'high' radii to 23 km s^{-1} at 'deep' radii.

The modern theory of the charge was elaborated by L V Al'tshuler, A A Bakanova, N V Panov, and the author.

3. Growth dynamics of the pressures investigated

I next consider the dynamics of pressure growth in the compressive investigation of one of the main structural materials, iron (a similar picture is also observed for uranium and other substances). The corresponding diagram is given in Fig. 1. Of course, our attention is drawn to the rapid progress as regards the increase in pressures attained. Even in 1951, we obtained pressures above 10 Mbar in iron. These measurements were made by Al'tshuler, Krupnikov, Ledenev, and M I Brazhnik. The dashed vertical segments in Fig. 1 signify that at that time, the authors of these data had some slight doubts about the accuracy of the high points achieved. More recently, the position of these points was confirmed using modern measuring devices with improved characteristics. Therefore, these doubts were removed. It is pertinent to note that similar values for the parameters in iron were obtained in the USA more than 30 years later.

The highest parameters that we obtained in the investigation of the compressibility of iron in laboratory facilities are equal to 18 Mbar; even higher values (25 Mbar) were recorded in the investigation of tantalum [8–10].

Is it possible to obtain even higher pressures with spherical systems? Yes, it is. But these systems would be so expensive that the pros and cons should be weighed when considering the expediency of their implementation. Furthermore, even the values already attained permit us to accurately select the theoretical model suitable for calculating our structures, including those for significantly higher pressures than the experimentally attained ones.

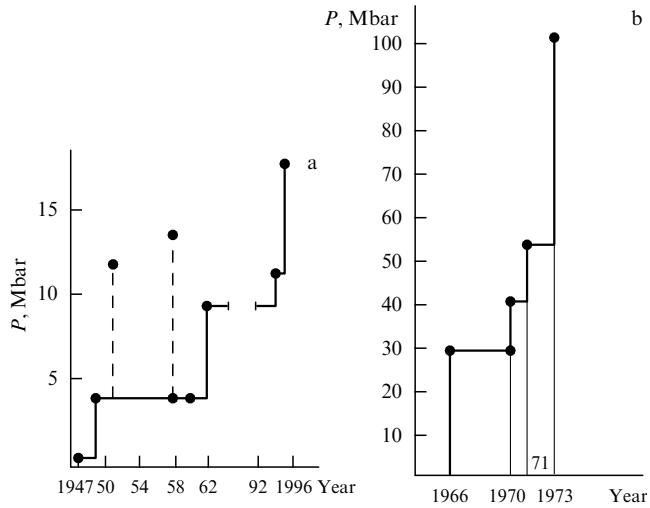

Figure 1. Temporal diagrams of pressure growth in the investigation of shock wave compression of iron: (a) laboratory research, (b) investigations involving underground nuclear explosions.

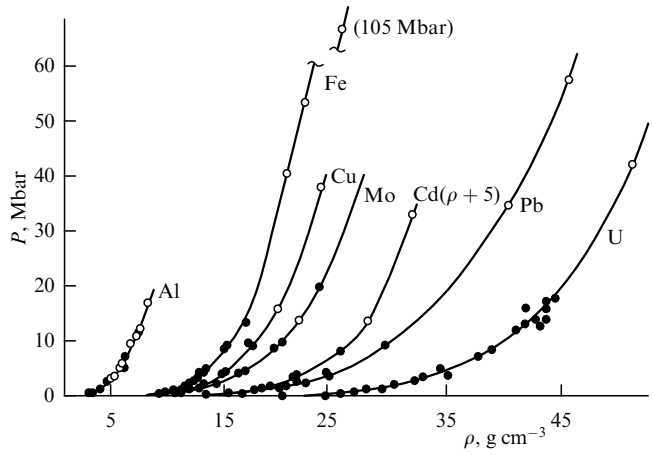

Figure 2. Shock adiabats of metals investigated in laboratory conditions (dark circles) and in underground nuclear explosions (empty circles). The inscription 'Cd $(\rho + 5)$' signifies that all density values for the corresponding adiabat are shifted along the horizontal axis by 5 g cm^{-3} for convenience of representation.

Figure 1b shows the growth in pressures (also for iron) under conditions of nuclear test explosions.

I briefly recall the setup of these experiments [6]. In a tunnel, near the nuclear charge to be tested, a technological site was made directly in the rock, the center of the site area being perpendicular to the direction to the charge center. The site accommodated a measuring device, which comprised a steel striker-plate and a steel target located at the optimal distance from the plate (optimal from the standpoint of attaining a constant plate flight velocity). The design of the measuring device ensured a lowering of the shock wave load on the striker and the suppression of perturbations propagating in front of the striker toward the recording system.

Because iron plays an important role in the method of reflections as the reference material, several measurements of iron compression were performed by the absolute method of deceleration [2], whereby measurements were simultaneously made of the velocity of the impinging steel striker-plate and the velocity of the shock wave in the target (steel-3).

These measurements turned out to be effective in three experiments. Their data have been widely discussed in the scientific literature, at conferences, and so on (see, e.g., Refs [6, 11, 12]), and I therefore only mention the main results.

The following parameters were obtained:

— the pressures 41.3, 54.2, and 105.0 Mbar in three iron specimens;

— the respective compressed sample densities 21.7, 23.00, and 26.5 g cm^{-3};

— the respective impinging striker velocities 36.5, 42.7, and 60.8 km s^{-1}.

Under similar conditions and much later, our colleagues in the USA attained a pressure of only 20 Mbar (with molybdenum).

The resultant data points defined the position of the shock adiabat of iron throughout the range of pressure investigated, up to 105 Mbar, thereby opening the way to the pursuance of material compression measurements both in laboratory conditions and in conditions of underground nuclear tests under ultrahigh pressures (reflection method, iron screen).

The same data provided the answer to the question about the selection of the material behavior model in the ultrahigh pressure domain that was most adequate for the experiment.

Figure 2 shows our metal compression curves obtained both in laboratory investigations and with underground nuclear explosions. Attention is drawn to the fact that underground nuclear test and laboratory pressure data for Mo and especially for Al overlap and are mutually consistent. Similar agreement is supposedly observed for other elements. This is supported by the agreement of similar data for complex compounds like plexiglass and rock salt [13, 14]. Furthermore, a reasonable interpolation of the data pertaining to different pressures suggests that laboratory and nuclear test data are mutually consistent for other metals as well.

I now consider how the resultant experimental data correspond to the theoretical dependence in our use. For example, Fig. 3 shows the data on iron and lead. The dashed line is the adiabat calculated by the Thomas–Fermi model with the inclusion of nuclear interaction (TFCK, an acronym for 'the Thomas–Fermi model + corrections due to Kalitkin and Kopyshev'). At pressures of the order of 100 Mbar, the calculated and experimental adiabats are virtually coincident, as are their derivatives.

Much the same picture also occurs for other metals [6, 7]. Also noteworthy is the fact that other theoretical models are in a much poorer agreement with experiment [6].

The experimental verification of the TFCK model opened the door to an extension of research into the compressibility of different materials to the ultrahigh-pressure domain. And these opportunities were rather amply used.

To summarize, the shock compression of more than 250 substances was studied in our laboratory. These include virtually all metals of the periodic system, including hydrogen isotopes and several transuranium elements, metal alloys, oxides, metal hydrides and nitrides, the majority of representatives of organic compounds, and liquids. To this may be added more than a hundred shock adiabats of surface rocks [15].

4. Compression of porous metals

I next consider the investigation of the shock compression of porous metals, i.e., metals with an artificially lowered initial

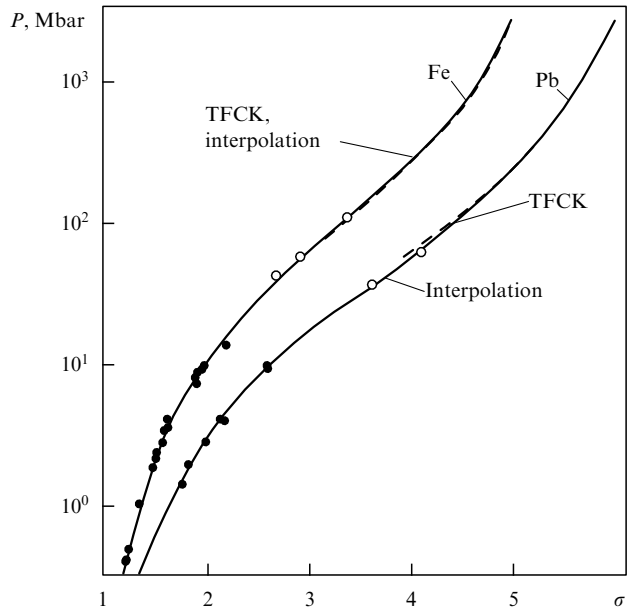

Figure 3. Interpolative shock adiabats of iron and lead: ● — laboratory measurements, ○ — underground nuclear explosion measurements, dashed curves — TFCK model calculations, solid curves — interpolation.

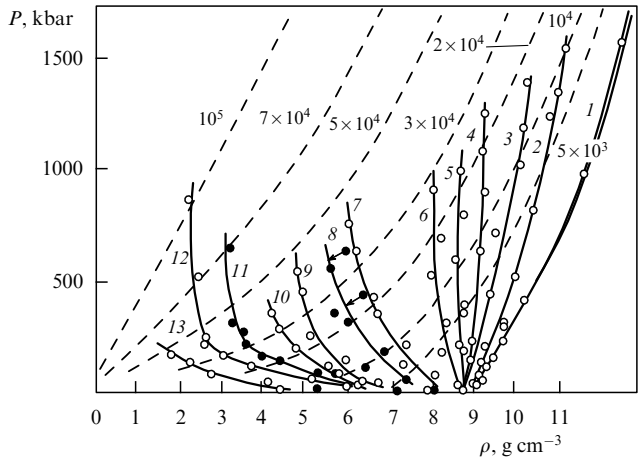

Figure 4. A $P-\rho$ diagram of nickel. Laboratory measurements. The numbers by the adiabats (*1–13*) correspond to the degree of porosity $m = \rho_0/\rho_{00} = 1.1, 1.41, 1.72, 2.0, 2.3, 2.7, 4.55, 5.5, 7.2, 10, 15, 20, 28$. The dashed curves are the isotherms calculated based on Refs [28, 29], the figures by the isotherms indicate temperature values.

density, when the average sample density is $\rho_{00} = \rho_0/m$ (m is the degree of porosity). The necessity of investigating these systems was first emphasized by Zel'dovich in the late 1940s. The interest in these systems is primarily due to their significance in selecting and substantiating the models of matter equations of state, in particular, the thermal constituents of these equations [16]. Indeed, in the $P(\rho)$ diagram, the shock adiabats of porous materials occupy the main part of the area to the left of the adiabat with the initial crystal density ρ_0. Furthermore, they are characterized by substantially higher sample-heating temperatures in comparison with the temperature on the adiabat of a material with the initial density ρ_0. That is why investigations of porous materials yield a broad field of different states for testing model parameters.

The first compressibility measurements of porous iron samples date back to the late 1940s [3].

In the investigation of tungsten, a paradoxical effect was first discovered in [17]: for initial densities below some critical density ρ_{00}, applying pressures of even several megabars to the sample did not compress it to the initial density of crystalline tungsten.

Measurements on four metals (iron, lead, aluminum, and copper) were performed in [18]. The pressure ceiling was substantially increased to 9 Mbar. In Ref. [18], an interpolative equation of state was first proposed, based of the data of investigations of the shock adiabats of porous and continuous metals.

The general properties of the compression of porous metals and different compounds (for a wide variety of initial densities) were investigated in considerably greater detail in Refs [19–25]. For instance, 13 (!) 'porous' adiabats were obtained for nickel alone.

All these investigations used the 'reflection' method.

In the acquisition of experimental data, much attention was devoted to methodical issues arising from the specific character of sintered samples and its effect on the resultant data.

The effects of the particle size, of the air, and of humidity of the samples on the parameters of shock waves were studied. The corresponding measurements were made both in laboratory experiments and in underground tests [26, 27]. These investigations allowed the following general conclusion: for a reasonable variation of the parameters involved, they exert no effect on the characteristics of the shock waves. Of course, this conclusion holds for the presently existing technical recording capabilities and experimental uncertainties. At the same time, this conclusion permitted treating the shock wave regimes in the compression of porous specimens as being close to equilibrium, which reduced the formulation of experiments to the conventional one and substantially simplified the interpretation of resultant data.

The compressibility of 16 metals in total was investigated in [15]. Apart from nickel, these were copper (9 adiabats) and molybdenum (8); magnesium was studied less than other metals (one 'porous' adiabat). From 8 to 12 experimental points were obtained for each adiabat. For example, the data on the compressibility of nickel are given in Fig. 4. The shock adiabats of other metals exhibit the same behavior.

We see that porous shock adiabats occupy almost the whole $P-\rho$ plane on the left of the adiabat with $m = 1$. The highest porosity (the lowest initial density) corresponds to the leftmost adiabat. Its initial density is 0.32 g cm^{-3}.

The adiabats exhibit the following characteristic features.

(1) Each adiabat contains two parts with different slopes. The first, mildly sloping part, 'creeps' along the abscissa and terminates at a density close to the normal metal density. The pressures in the adiabats of this part almost coincide with one another (on the scale of the drawing) and are close to the abscissa. They are not shown in Fig. 4.

The second part begins with an abrupt change (with a change of sign in the derivative $\mathrm{d}P/\mathrm{d}\rho$) in the slope in the adiabat. The pressure at which it occurs ranges from several kilobars to several tens of kilobars. This is the so-called 'packing pressure' — the minimal experimental value that results in the density of compressed material closest to the normal density. Each porosity corresponds to its own 'packing pressure.'

(2) The second parts are steep, 'poorly compressible' branches, characterized by different slopes: for $m < 2$, the

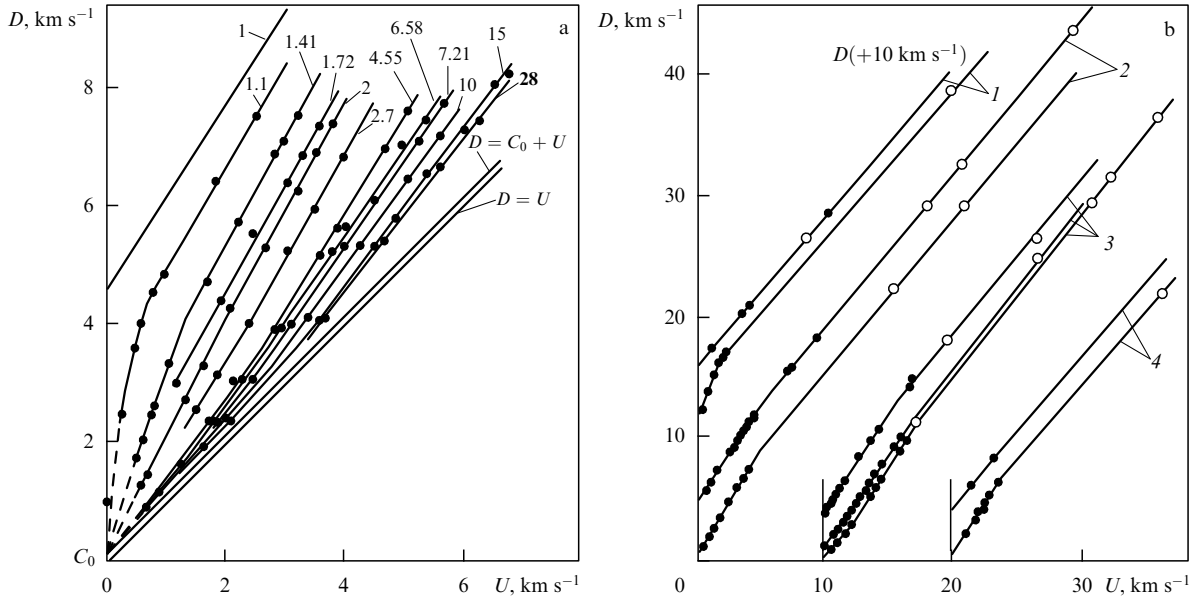

Figure 5. (a) A $D-U$ diagram of nickel. Laboratory measurements. The figures by the adiabats indicate the corresponding values of porosity. (b) $D-U$ diagrams of 'continuous' and 'porous' metals: *1* — molybdenum ($m = 1.0$, 1.23), *2* — iron ($m = 1.0$, 3.3), *3* — copper ($m = 1.0$, 3.1, 4.0), *4* — tungsten ($m = 1.0$, 3.1); ● — laboratory data, ○ — measurements for underground explosions. (For clarity, all velocities in the shock adiabat of Mo (adiabat *1*) are shifted upwards by 10 km s^{-1} along the ordinate axis.)

slope $\mathrm{d}P/\mathrm{d}\rho > 0$; in the interval $2 < m < 3$, $\mathrm{d}P/\mathrm{d}\rho \sim \infty$; and lastly, for $m > 3$, the slope $\mathrm{d}P/\mathrm{d}\rho < 0$.

The highest temperature calculated from the EoS [28, 29] corresponds to the porous nickel adiabat with the initial density 0.45 g cm^{-3} and is equal to 110,000 degrees for the pressure 0.9 Mbar. For comparison, on the 'continuous' adiabat, the same temperature is attained for the pressure about 16 Mbar.

Finally, we must consider at least a couple of shock adiabats plotted in the primary coordinates, i.e., those in which our experimental data are acquired.

Figure 5a gives the same data on nickel. We see that the adiabats of porous samples occupy the domain between the adiabat of the 'continuum' material ($m = 1$) and the straight line $D = C_0 + U$, which is shifted relative to the bisecting line $D = U$ by a value C_0 ($C_0 \geqslant 0.1$ km s^{-1} is the minimal value of D of all the values obtained in the extrapolation of porous shock adiabats to the ordinate axis).

Investigation of kinematic parameters is restricted to the region in the $D-U$ plane located to the left of this straight line: conservation laws forbid going beyond this curve to the right of it. A natural restriction on the low-m side is the position of the adiabat with $m = 1$. Similar situations also occur for other metals.

It is evident from Fig. 5 that we have closely approached the limiting straight line and that there is little point in a further increase in porosity, i.e., the acquisition of adiabats for initial densities even lower than 0.32 g cm^{-3}. Worth noting is the characteristic form of porous adiabats, which originate from the neighborhood of the common initial point and adjust to the run of the normal-density adiabat.

Lastly, in the same coordinates, Fig. 5b shows the data acquired in the laboratory and in underground nuclear tests. What is noteworthy in this case? For some velocities, the shock adiabats corresponding to different m turn into straight lines that are approximately parallel to each other and have about the same slope $\mathrm{d}D/\mathrm{d}U \approx 1.2$. This testifies to equalization of their dynamic properties. Under these conditions, incidentally, the adiabats themselves and their slope correspond to the parameters calculated by the TFCK model.

5. Compression of hydrogen isotopes

To conclude, we give our recent data on shock compression of the hydrogen isotopes protium and deuterium. One of the objectives of this research was to verify the results obtained by American researchers from the Lawrence Livermore National Laboratory: at pressures above 400 kbar, with the use of the Nova laser facility, they discovered an anomalous increase in compression of liquid deuterium, its density increasing from 0.6 g cm^{-3} to ≈ 0.9 g cm^{-3} [30, 31]. By its character, the adiabat at these pressures resembled a dependence corresponding to a first-order phase transition with a large density step (Fig. 6).

These data were doubted both in our country and abroad. That is why we set ourselves the task of verifying the American data at the explosion facilities of our institute in a comparable density domain. For greater rigor, our measurements were carried out not only on deuterium (initially in the liquid and solid phases), but also on protium (solid phase). Simultaneously, researchers of the Sandia National Laboratory verified the results of their colleagues (with liquid deuterium) [32, 33].

Of course, the aim of our investigations was not only to verify the American data but also, and most importantly, to obtain the test data required to determine the parameters of the equations of state for hydrogen isotopes.

The resultant data are plotted in $P-\rho$ coordinates in Fig. 6. It follows that the data obtained at the Nova facility in Livermore are at variance with our data, as well as with the data of the Sandia Laboratory. The mutual uncertainties of the approximating curves arising from the aggregate inaccuracy of our data and those of the Sandia Laboratory do not overlap with the data obtained at the Nova facility.

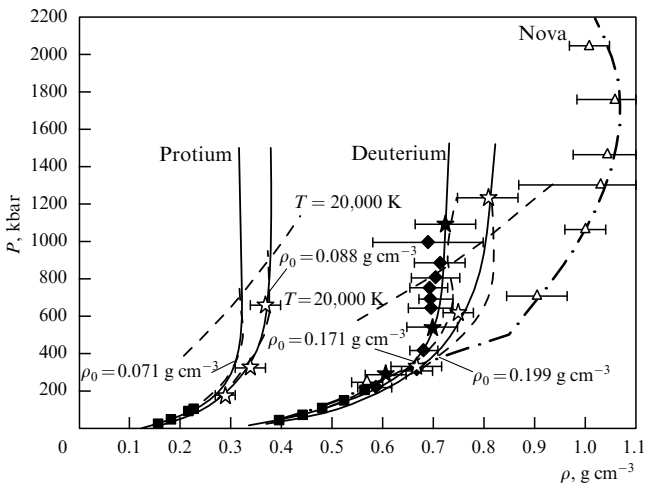

Figure 6. Shock adiabats of hydrogen isotopes: ■ — measurements at low pressures (American data), ◆ — the data in Refs [32, 33], △ — the data in Refs [30, 31], ★, ☆ — VNIIEF measurements (liquid and solid initial states, respectively).

This formally demonstrates the fallaciousness of the Nova results. In essence, the internal consistency of the data in Refs [34–36], which were obtained with a technique repeatedly borne out in several hundred independent experiments (with gas guns and explosion systems involving high explosives) is by itself an indication that the Nova results are fallacious.

Apart from elucidation of the issue about the stepwise change of the liquid deuterium density, we obtained data on the shock compression of initially solid phases of deuterium and protium. There are no publications on this issue in the literature.

It is worthy of mention that V E Fortov has proposed to verify the data of the Livermore researchers and that the work itself was actively supported by R I Il'kaev.

6. Conclusions

In this brief report, I have not touched upon the results of measurements of other material properties: isentropic and double compression, sound velocities, phase transformations, and so on. The reader is referred to the reports on these investigations that have appeared in numerous publications in scientific journals.

I add several words about equations of state. Efforts have been repeatedly mounted, both in our country and abroad, to obtain the equations of metal state in a wide range of thermodynamic parameters without recourse to experimental data in the relevant domain of states of matter. These attempts are being made even nowadays. Incidentally, one of the first endeavors was made precisely at VNIIEF (Gandel'man). But none of these attempts has met with success from the standpoint of the requirements that we impose on these equations. It is valid to say that as regards the applied problems facing VNIIEF (and not only it), preference was given to semiempirical models rather than a priori ones.

There are several semiempirical models. The widest acceptance has been gained by versions of the so-called equations with thermal lattice and electronic terms. These equations typically rely on solid-state notions, although some of the versions include the properties of liquids as well. One of the disadvantages of these models is that they do not take the evaporation of liquids into account.

This disadvantage is not inherent in another type of equation, the modified van der Waals model, whose applicability extends to the domain of higher fluid compression. The model takes the difference between the solid and fluid properties into account, as well as the evaporation of the fluid and ionization. The modified van der Waals model equation offers several advantages over other model equations as regards breadth in describing metals in different states of the phase diagram.

Generally, the equations of state are of course a major subject on their own, which invites special consideration. In this connection, I have the pleasure to refer the reader to the recently published book by Kopyshev [37].

And, finally, I cannot help recalling the pathfinders and those who provided crucial services to the formation and development of high energy density physics. These are, first and foremost, L V Al'tshuler, E I Zababakhin, Ya B Zel'dovich, S B Kormer, K K Krupnikov, and Yu B Khariton — the organizers and supervisors of the research carried out on this subject at the Nuclear Center of the Soviet Union. Their closest colleagues and supervisors of research in separate areas at VNIIEF are A A Bakanova, M I Brazhnik, F V Grigor'ev, N A Dmitriev, M V Zhernokletov, V N Zubarev, A G Ivanov, V P Kopyshev, B N Ledenev, A B Medvedev, V N Mineev, S A Novikov, M N Pavlovskii, M A Podurets, A M Podurets, G V Simakov, M V Sinitsin, V D Urlin, A I Funtikov, K B Yushko, and many others.

This brief report deals with only a small fraction of the results obtained in our laboratory at VNIIEF. At the same time, many interesting and important investigations have been carried out at the second Russian Nuclear Center — Zababakhin All-Russian Scientific Research Institute of Technical Physics (E N Avrorin), Moscow institutes (V E Fortov), the Siberian Branch of the RAS (V M Titov), and several other organizations.

However, it is we, not they, who are 65 today.

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Explosive magnetic generators and their application in scientific experiments

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1. Introduction

The quest for energy sources that approach high explosives (HEs) in energy reserves inevitably brings up the idea of using electric or magnetic fields. But the store of specific energy in dielectrics ($\varepsilon_0 \varepsilon E^2/2$) and magnets ($\mu_0 \mu H^2/2$) is ordinarily moderate, of the order of 100 J l^{-1}.

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As a consequence, it turns out that making capacitor banks capable of storing energy in the range of several dozen megajoules is a highly intricate and expensive task. For HEs, the specific energy is $\rho D^2/16 \approx 10$ MJ l^{-1} (where ρ is the HE density and D is the speed of the detonation wave). An endeavor can be made to convert this energy into the energy of a magnetic field and simultaneously increase the energy density. This idea was first expressed by Andrei Sakharov [1] in 1951. As he pointed out, by rapidly decreasing the inductance of the current-carrying circuit with the magnetic flux conserved and drawing the conductors carrying oppositely directed currents closer with the aid of an explosion, the HE energy can be converted into the magnetic field energy. The greater the field energy is in comparison with the Joule heat, the higher the conversion efficiency.

Sakharov proposed two types of generators implementing magnetic cumulation: field generators and energy generators [2]. There are two main limitations imposed on the rate of magnetic flux compression. First, the compression should be fast enough so as to satisfy the condition $\mathrm{d}L/\mathrm{d}t \gg R$ and prevent load damage by the action of ponderomotive forces. Second, because a fast variation of the flux Φ gives rise to a high electric voltage $U = -L\,\mathrm{d}I/\mathrm{d}t$, it is necessary to provide sufficiently strong electric insulation to guard against electric breakdowns. For efficient generator operation, the voltage should be kept constant at the maximum permissible level. In the absence of flux losses, this may be achieved for an exponential law of the inductance reduction.

2. Operating principle and main characteristics of a disk explosive magnetic generator

Figure 1 is a schematic representation of a disk explosive magnetic generator (DEMG). When the magnetic flux in the generator attains the desired magnitude, the generator circuit closes, thereby trapping the introduced magnetic flux. At the same instant, with the aid of an initiation system, the HE charges along the axis are exploded in a synchronous mode. As the current-carrying plates draw closer together under the action of explosion products, they compress the magnetic flux simultaneously in all cavities and force it out of the compression cavities to the load via a transmission line. The shape of the current-carrying plates is selected such that the compression obeys the exponential law.

We outline the test results in [3] for one of the first DEMGs, 400 mm in diameter, which was made according to the diagram in Fig. 1. The device consisted of a two-stage

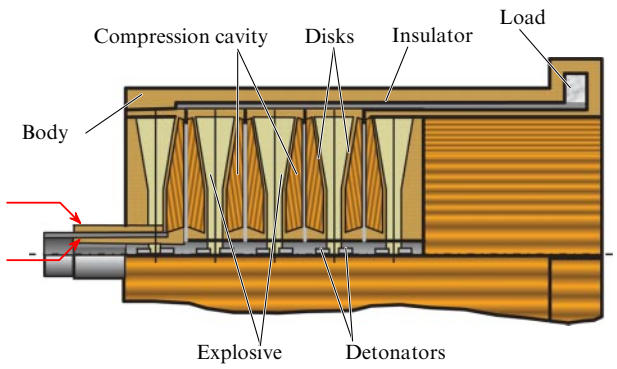

Figure 1. Disk explosive magnetic generator.