INTENSE COMPRESSION OF A SUBSTANCE BY MEANS OF ACCUMULATED ENERGY FROM EXPLOSIVES

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At the Institute of Plasma Physics and Laser Microsynthesis theoretical and experimental studies are carried out for different physical phenomena which occur in a substance with high energy density. The work is carried out using different experimental methods which include: a laser method, a method of intense electron beams, a system with plasma focusing, and a method using explosive substances as a source of energy. As far as the last group of methods is concerned, the high energy density is achieved with the use of explosive generators, and detonation and shock waves (SW) converging towards the axis. Mach waves of very high intensity are obtained in conical generators of detonation (shock) waves.

High velocities of metal liners are achieved in cylindrical generators. In order to accelerate liners use is made of an intermediate device. Explosive generators operating at the institute are used in order to create and compress a deuterium plasma in different systems.

The present work is a review, and therefore details connected with theoretical studies of the models used and with experimental details are not included in it.

1. Explosive Systems for Generating Powerful Mach Waves in Concentric Systems. Phenomena connected with irregular reflection and preparation of Mach waves with oblique SW collision are interesting from the point of view of energy accumulation. In plane systems an increase in pressure is observed at the front of Mach waves compared with the pressure of primary waves. Theoretical description of this phenomenon and the results of experiments have been given in [1, 2]. A more marked increase in pressure may be obtained in axisymmetrical systems in which as a result of irregular reflection a high intensity Mach wave arises in the center of the system. This phenomenon has been studied in explosive systems with cylindrical and conical specimens [3, 4] in which a pressure at the front of Mach waves from 0.2 to 1.8 TPa was recorded. Considerable energy concentration was obtained by this method and the possibility was demonstrated of an increase in dynamic pressure by a factor of 30 compared with pressure in a detonation wave. Explosive generators developed have been used in order to study solids at high pressures, and in particular in order to determine the shock adiabats for different substances.

Our experiments were carried out with the aim of demonstrating the possibility of obtaining high pressure values for smaller angles at the tip of a cone in copper compared with [4]. From theoretical studies carried out using two-dimensional numerical computation [5] it can be seen that for a cone with an aperture angle $\alpha = 30°$ it is possible to obtain pressure $p \sim 4.0$ TPa; experiments have confirmed this. Thus, it is possible to increase pressure compared with detonation pressure by a factor of 80. Experimental studies of the system were carried out with the maximum care and use of different electrical and optical diagnostics [6]. The possibility was demonstrated of using bimetallic Cu—Ni—Cu transducers for determining pressure in the powerful SW front in the range from 0.1 to 1.0 and even 3.0 TPa. Measurement of the electromotive force for the pair of metals indicates saturation with $p > 0.1$ TPa. Complete results for the measurements are contained in [6] where given as an example are the results of optical recording of Mach waves for cones with $\alpha = 30$ and 40° (Fig. 1, where 1 is a Plexiglas target, 2 is the camera).

Given in Table 1 are parameters for the Mach waves created. The maximum pressure at the Mach wave front is 4.6 TPa, and the diameter of the head is 2 mm. As a result of reaction of the wave with a Plexiglas target SW velocity in the Plexiglas reached 36.7 mm/μsec, and in argon 43.0 mm/μsec.

Since experiments gave such high SW parameters, it is tempting to use the conical system developed for generation and compression of a high-temperature plasma. Theoretical

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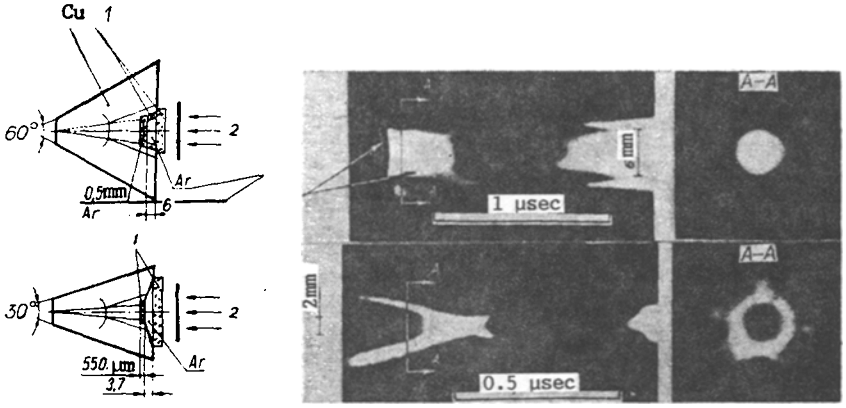

Fig. 1. (Read 0.75 µsec instead of 1 µsec, and 0.38 µsec instead of 0.5 µsec).

estimates showed that in deuterium gas it is possible to achieve a temperature of the order of 0.51 keV and a maximum compression of the order of 10^3 [7], i.e., in the system developed it might be expected that thermonuclear synthesis will be achieved with a neutron yield at the level of 10^6–$2 \cdot 10^7$ neutrons per detonation.

Additional analysis for optimization carried out by numerical methods agrees with the results of preliminary estimates given above [8]. Experiments carried out for the system represented in Fig. 2 generally confirmed the results of calculations [9] (1 is condensed explosive ($g = 1.78$, $D = 8.3$), 2 is a copper liner ($v_l \approx 5.0$ mm/µsec), 3 is a copper cone, 4 is a Mach wave, and 5 is a polyethylene plate ($v = (4-5) \cdot 10^6$ cm/sec, 6 is a gold cone, 7 is D_2 gas.

In three series of experiments for D_2 gas a thermonuclear synthesis reaction is provided with the maximum neutron yield at the level of $N = 3 \cdot 10^7$ neutrons/detonation. This result confirms achievement of high SW parameters in a copper cone ($p \approx 4.0$ TPa) and achievement of an exceptionally high concentration of energy in a small volume of D_2 gas.

The results provided stimulated a study of the so-called biconical system in which it is possible to accomplish collision of two powerful Mach waves. It was assumed that in the center of this system there should be high dynamic pressures and ultrahigh energy concentration. Analysis of the shape of primary waves indicates that the compression wave arriving at the center of the system appears to be close to spherical, which leads to an additional increase in compression parameters.

Detailed analysis of the system was carried out using Plexiglas cones. In this way it was possible to evaluate the change in angle diameter of the Mach wave, and also velocity along the cone axis [10]. For accurately prepared (in an optical sense) Plexiglas cones values were found for Mach parameters with simultaneous determination of the impact angle of the copper cone and the propagation angle for the conical incident wave. In Fig. 3 (1 are air gaps) diagrams are presented for the systems studied and there are also photographic records of the process of Mach wave propagation in the cone.

In order to consider the possibility of practical realization of biconical geometry, a series of experiments was carried with optical recording of the Mach wave trajectory from two synchronously operating conical systems. A diagram of the system is given in Fig. 4 (1

TABLE 1

Angle, deg	Pressure at the Mach wave front, TPa	Mach wave diameter, mm	SW front velocity, mm/µsec		Explosive detonation velocity, mm/µsec
	copper cone		Plexiglas target	argon	
30	3,33	1,61	31,2	38,5	7,3
36	3,0	2,0	30,0	34,0	7,3
60	1,0	6,8	18,0	22,4	7,3
36	4.60	2.1	36,7	43.0	8.3

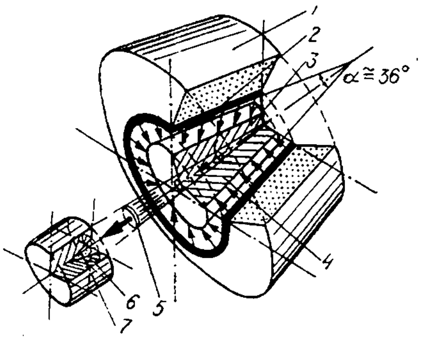

Fig. 2

is a delay circuit, 2 is a SYSTRON time meter, 3 is a 4KMS T-1201 time meter, 4 is a high-voltage system). As a result of this it was revealed that with the use of a special explosive initiation system the nonsimultaneous arrival of Mach waves may be not worse than 100 nsec [11].

Further experiments consisted of two series with "closed" biconical systems. In the initial series they were carried out in a system in which the container was loaded with D_2 gas at atmospheric pressure. Recording of the neutron yield ($N \approx 10^5$) was provided. The pulse was recorded by a diagnostic system containing a scintillation probe, an oscillograph, and also a delay system with a pulse counter. Complete description of the experiments is given in [12]. Quite good results obtained in this series confirmed the principle of operating the test system and the diagnostic system.

The second series of experiments was set up in order to estimate compression parameters for solid-state targets (UD_3 and UD_2T). Given in Fig. 5 is a sketch of the system in which simple theoretical estimates were carried out for collision of two Mach waves (1 is the Mach wave front, 2 is the incident wave, 3 is the condensed explosive, 4 is a copper liner, 5 is a copper cone, 6 is a solid state target, UD_3:UD_2T). Wave pressure was $p \approx 4.0$ TPa, and after reflection it reached 10-15 TPa, and at the same time temperature $T \approx 1.5 \cdot 10^6$°K and density $\rho \approx 16.6$ g/cm^3 ($\rho_0 = 5$ g/cm^3).

Results of these estimates and initial experiments lead to the conclusion that if in the test system parameters are achieved necessary for the occurrence of thermonuclear synthesis, then measurement of the neutron yield may be considered as a diagnostic method for these parameters. In characteristics this relates to a "closed" system where use of other diagnostics is impossible.

In basic experiments carried out with cylindrical targets of UD_3 and UD_2T of small dimensions (length 8 mm and diameter 2 mm) and initial density $\rho = 5$ g/cm^3 a neutron yield was obtained. Recorded pulses shown in Figs. 6 ($N \approx 10^5$ neutrons/detonation) and 7 ($N \approx 10^7$ neutrons/detonation) confirm that the biconical system developed achieves energy accumulation as a result of double compression of ultrahigh dynamic pressures at a level comparable with theoretical estimates.

Data connected with theoretical estimates and experiments are given in [13, 14].

TABLE 2

Number of layers	Diameter of the liner / Thickness	v, cm/μsec	$\left(\frac{v}{v_0}\right)^{1/n}$	$\frac{\varnothing_0}{\varnothing}$
1	$\frac{26{,}0}{2{,}07}$	0,56±0,02	1,46	2,90
2	$\frac{18{,}5}{1{,}12}$	0,69±0,05	1,34	2,43
3	$\frac{13.3}{0{,}61}$	0.79±0,05	1,27	1,82
6	$\frac{10{,}5}{0.10}$	1,40±0,10	1,24	2,60

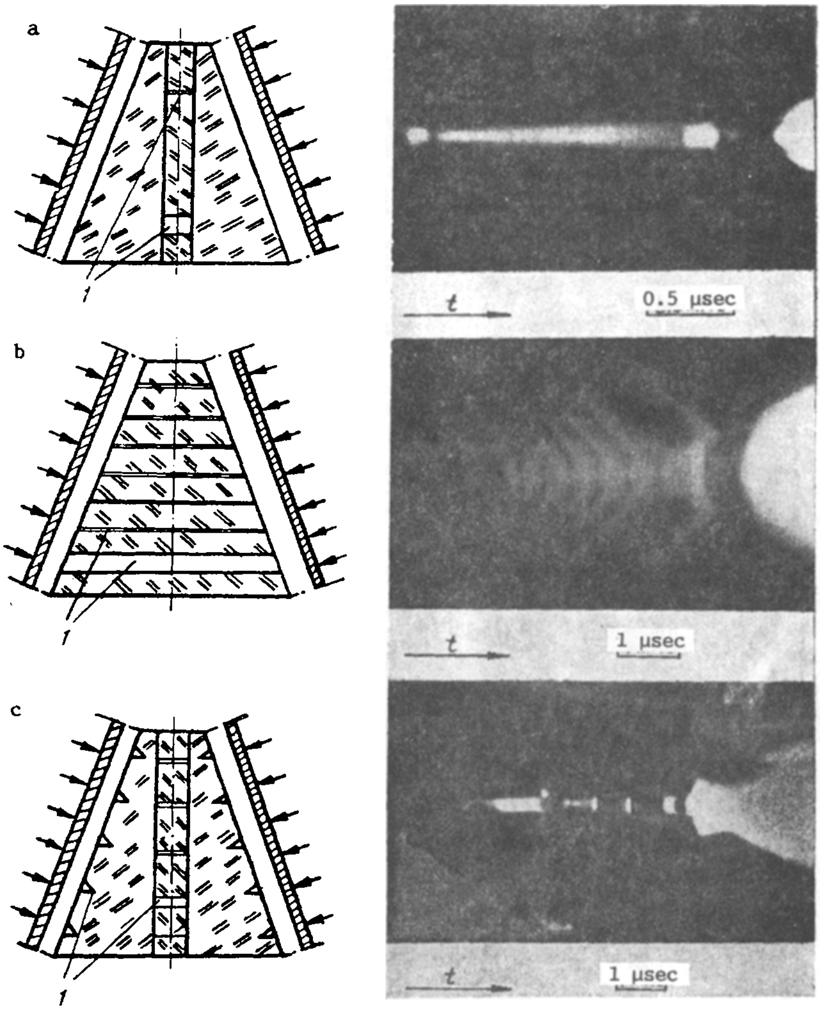

Fig. 3

2. Axially Cylindrical System of Energy Accumulation for Plasma Compression. Kaliski advanced the idea of axially cylindrical compression and production of a deuterium plasma [15]. One of the possibilities for achieving it is presented in [16] where a scheme is given for an experimental explosive system. A typical feature of it consists of initial heating of deuterium gas to high temperature as a result of axial collision of two SW of high intensity created by explosion. Initial heating should be the first phase of the process. After this in the second phase there should be adiabatic compression of deuterium by a cylindrical liner also accelerated by an explosion up to high velocity. Shown in Fig. 8 is a sketch of this system (1 is the cylindrical detonation wave, 2 is the condensed explosive, 3 is Voitenko generator, 4 is a copper liner, 5 is the D_2 gas). In it in order to obtain two ultra-high-speed jets of D_2 gas use is made of two explosive Voitenko generators, and in order to accomplish adiabatic gas compression use is made of a multilayer metal liner.

Numerical calculations are carried out on the basis of a comprehensive hydrodynamic model [17, 18] with consideration of loss by radiation, thermal conductivity, and ionization. In calculations the following data were adopted which were obtained in a real experimental system: initial cylindrical liner velocity $v_l = 1.5$ cm/μsec, initial accelerated liner radius $R_l = 0.4$ cm, liner wall thickness $g_l = 0.01$ cm, SW front velocity in D_2 along the longitudinal axis of the system $D = 6.0$ cm/μsec, initial deuterium pressure $p_0 = 0.12 \cdot 10^5$ Pa. In addition, in calculations values of T_0 and ρ_0 were adopted according to theoretical estimates for deuterium after collision of two SW at the center of the system: $T_0 = 10^5$-$2 \cdot 10^5$ K, $\rho_0 = 2 \cdot 10^{-4}$-$4 \cdot 10^{-4}$ g/cm^3.

Shown in Figs. 9 and 10 are the results of calculations for the following initial parameters: 1) $T_0 = 2 \cdot 10^5$ K, $\rho_0 = 2 \cdot 10^{-4}$ g/cm^3; 2) $T_0 = 10^5$, $\rho_0 = 4 \cdot 10^{-4}$; 3) $T_0 = 10^5$, $\rho_0 =$

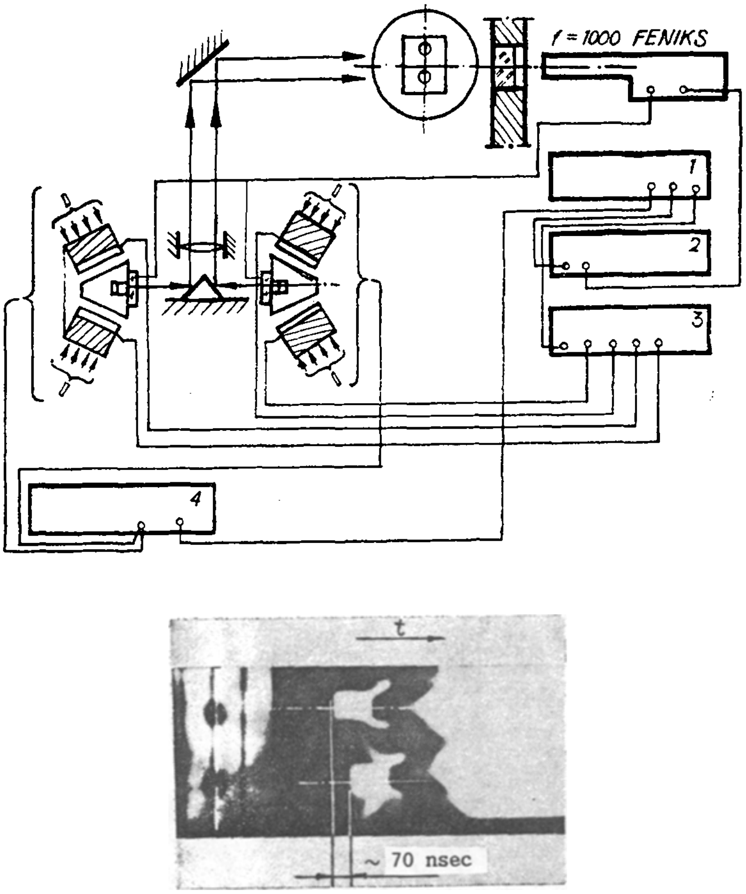

Fig. 4

$4 \cdot 10^{-4}$, $\tilde{z} = 1.5$ ($\tilde{z}$ is increased level of ionization); 4) $T_0 = 300$ K, $\rho_0 = 4 \cdot 10^{-4}$. It can be seen that initial gas heating as a result of collision of strong axial SW plays a significant role in the compression and it markedly affects the level of neutron yield. It is also very important that the measured level of emission ($\sim 10^4$) arises with quite a low level of plasma compression ($\tilde{\rho}/\rho_0 \sim 10^2$), and since this value is entirely real the situation mentioned is of considerable importance.

Accomplishment of this concept is started with detailed experiments for studying explosive systems in order to create high-speed jets of D_2 gas and cylindrical systems of metal liner acceleration to high velocities.

3. Studies of Ultrahigh-Speed Jets of D_2 Gas and Collision of Them. The experiments are described in [19] with a Voitenko generator in order to estimate tne effect of its characteristics on kinetic parameters of a D_2 gas jet. In the well-known generator scheme the effect of accelerated duralumin liner thickness on the nature of change in SW from velocity in D_2 is determined as a function of distance from the inlet hole of the compression chamber. Also found is the range of change in maximum SW front velocity. With use of a powerful explosive (RDX, D = 8.7 mm/μsec, $\rho_0 = 1.76$ g/cm³) in order to accelerate a liner to a

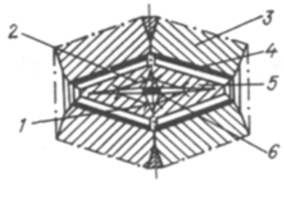

Fig. 5

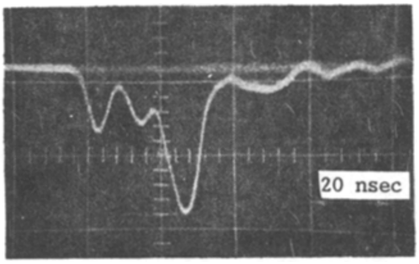

Fig. 6

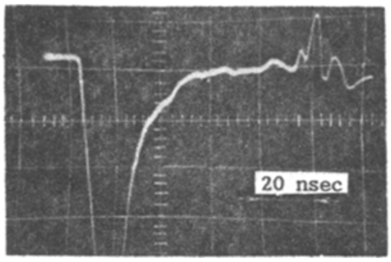

Fig. 7

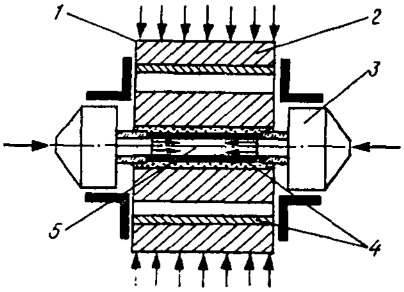

Fig. 8

velocity within the limits from 4.2 to 6.5 mm/μsec, the maximum SW velocity in deuterium was varied in a narrow range from 58 to 63 mm/μsec. The results obtained are given in Figs. 11 and 12.

For further studies one of the generator variants was selected satisfying the requirements listed above for an axisymmetrical system, and a series of experiments was carried out in which impact of two high-velocity jets of D_2 gas was accomplished. The experimental assembly is shown in Fig. 13. Experiments confirmed the results concerning kinematic parameters of a deuterium jet. In addition, optical recording of the process made it possible to obtain some information about deviation of the place of impact of the jet from the center of the system. This deviation was $\Delta x \simeq 4$ mm and it served as a basis for evaluating the possibility of synchronizing operation of the whole system. In experiments the maximum SW velocity $v_{max} \simeq 61$ mm/μsec. An example of a photographic record of the process is given in Fig. 14.

4. Multilayer Systems for Accelerating Cylindrical Liners. In order to study possibilities for achieving high energy densities use is made of explosive acceleration of metal liners, and in order to obtain the highest velocities use is made of a method of intermediate layers of light material or a system with a gradually reducing impedance [20-23]. At the Kaliski Institute these works were started with a study of the simplest plane and axisymmetrical systems for which theoretical results may be compared with measurements obtained by various methods [24-28]. Possibilities were analyzed for using electrical methods with resistance, piezoelectric, and bimetallic transducers. Similar analyses were also carried out by optical methods with different cameras. Several methods were attempted to adapt methods of energy accumulation in plane SW and methods for accelerating metal liners in multilayer systems described in [23] for the cylindrical case. The possibility was considered of high-speed acceleration of a metal cylindrical liner in the system presented in Fig. 15 (1 is copper liner, 2 is light layer). For this it was possible to make a simple evaluation of parameters and to compare some of the initial experiments. The optimum number of layers in the system was determined for the simplest model of elastic impact and a constant mass ratio for the neighboring heavy liners. In calculations use was made of the so-called impact elasticity coefficients which were determined by comparing liner velocities calculated in the elastic model and measured for one pair of layers. More real situations were analyzed in [30, 31] where numerical calculations were given for a copper liner and light layers of different materials. Results of the calculations are shown in Fig. 16 where 1 is Plexiglas, 2 is elastic impact, 3 is lithium, 4 is magnesium oxide, Plexiglas, 5 is aluminum, broken curves relate to a plane system, and broken-dotted curves to an axisymmetrical system. It was

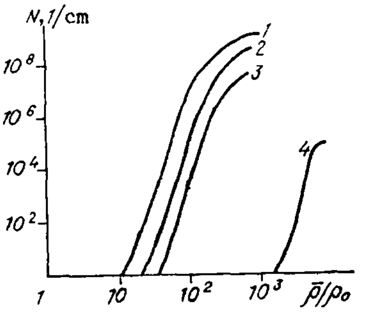

Fig. 9

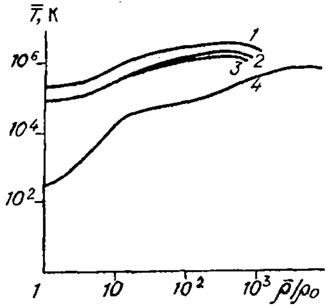

Fig. 10

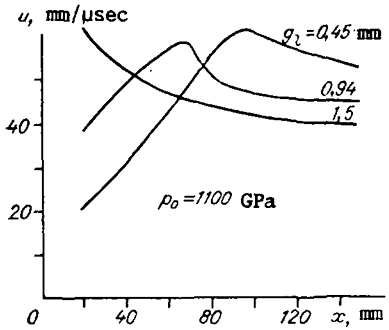

Fig. 11

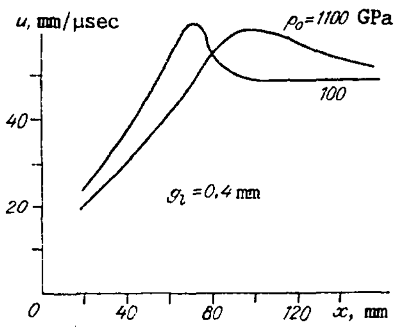

Fig. 12

established that under real conditions an accelerated liner acquires 85-96% of the velocity corresponding to that calculated by the elastic impact model. Simultaneously calculations have shown that in the axisymmetrical case for real conditions it is possible to achieve higher values of velocity than in the case of elastic impact and plane geometry. On the basis of the primary analysis carried out it is possible to adopt the following basic characteristics for a multilayer cylindrical system with a capacity to provide achievement of "internal" linear velocity of the order of 15 mm/μsec: six pairs of Plexiglas—copper layers; mass ratio for the liners $m_6/m_0 = 0.007$; impact elasticity coefficient $k = 0.95$; ratio of copper liner thicknesses $g_{n+1}/g_n = 0.543$; ratio of the plexiglas layer thickness to that of the copper liner $g_{ln}/g_n = 1.462$; diameter and thickness of the first liner made of copper $\varnothing = 70$ mm, $g_0 = 2$ mm; diameter and thickness of the next liner made of copper $\varnothing = 10.4$ mm, $g_N = 0.1$ mm.

Explosive systems prepared in accordance with the characteristics given were subjected to experimental testing. Four series of tests were carried out for 1, 2, 3, and 6 pairs of layers. The aim of the experiments was determination of the velocity and shape of internally accelerated liners. A diagram of experiments and the recording system is given in Fig. 17 where M is a beam splitter; M1, M2, M3 are mirrors; SNEF IV is a frame-by-frame camera; FENIKS II is a slit camera, 1 is a cylindrical multilayer system, 2 is a He—Ne laser, 3 is a dye laser, 4 is a supply system. Experimental conditions and some characteristics of explosive generators have been described in detail in [29]. Shown in Fig. 18a, b is movement recorded in an experiment for an accelerated linear, and also its form for a three-layer system of copper—Plexiglas, pairs (*a* is a slit record of liner movement by camera FENIKS II, b is a frame-by frame record by a SNEF IV camera, frame exposure time was 40 nsec, initial liner diameter was 13.3 mm, and its thickness was 0.61 mm). It follows from the experiment that the liner retains a symmetrical shape and it has an almost constant velocity immediately after the start of movement. Given in Table 2 are average values for all experiments. The greatest velocity of an accelerated liner v = 1.4 cm/μsec was obtained for a system with six pairs of layers. A velocity of value $v/v_0 = 3.6 \pm 0.09$ was achieved with an initial velocity $v_0 = 0.382$ cm/μsec. The value of velocity recorded in a single pair of layers decreases with an increase in the number of these pairs. In the system considered for the last experiment its value was 1.24, and for one pair it was 1.46.

A value of impact elasticity coefficient $k = 0.957$ was determined from experiments. In design for the system $k = 0.95$ was adopted, whereas from numerical calculation $k = 0.988$.

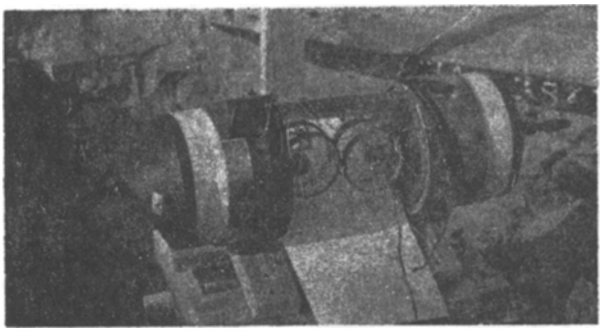

Fig. 13

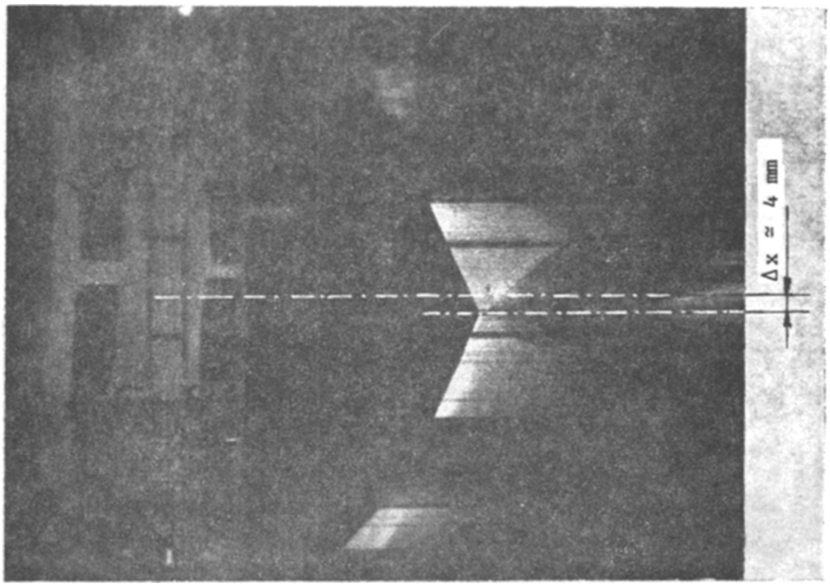

Fig. 14

This points to good agreement between estimates of k and those values obtained in an experiment, and about the possibility of using in practice the methodological selection of characteristics for the system. It is noted that liner velocity in the last stage of acceleration appeared to be (1.4 ± 0.1) cm/μsec, which is also comparable with previous estimates.

In the test problem of energy accumulation in individual systems the possibility was considered of obtaining results equivalent to those set forth above in other so-called cylindrical multilayer systems with a heavy SW concentrator. A scheme of this type is given in Fig. 19. In this system the copper liner 4 accelerated by detonation products impacts with a thick copper concentrator 3 in which the SW is created and accelerated. The loading pulse then passes through a layer of light material 2 and it accelerates the inner liner 1 to high velocity.

The following parameters were obtained by numerical analysis [32] for this system: $g_0 = 0.38$ cm, $g_{k+b} = 1.08$ cm, $g = 0.01$ cm, and $R_0 = 1.6$ cm, liner velocity at the instant of impact with the concentrator 0.385 cm/μsec. Analysis was carried out in a unidimensional nonsteady-state model using an experimental—theoretical equation of state [31].

Shown in Fig. 20 is free surface velocity of the inner layer v_{fs} in relation to layer thickness of the light material (Plexiglas) for different distances between this surface and the axis of the system r_{fs} (lines 1-3 correspond to $r_{fs} = 0.7 \cdot 10^{-3}$; $1.5 \cdot 10^{-3}$; $2.0 \cdot 10^{-3}$ m). From the curves it follows that liner velocity has a maximum for a certain layer thickness of light material, which relates to a Plexiglas layer thickness of about 2 mm with a change of r_{fs} within the limits of practical interest. For the case selected with a layer thickness of light material $g_b = 2.8$ mm given in Fig. 21 is the change in free and outer v_{es}

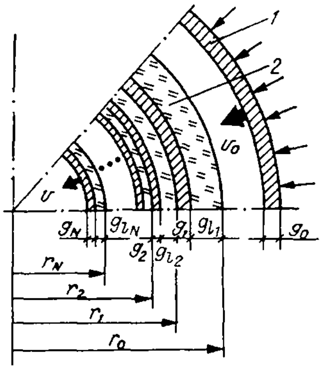

Fig. 15

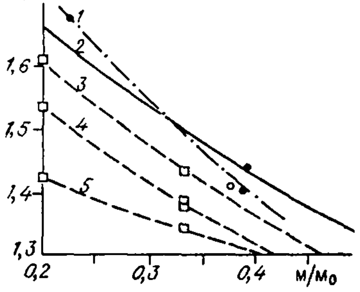

Fig. 16

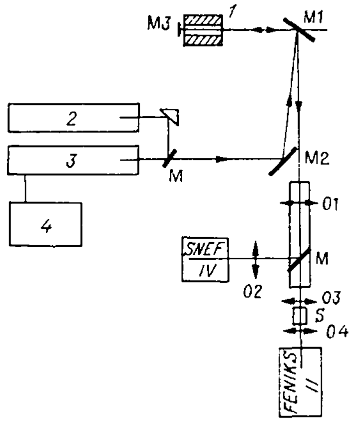

Fig. 17

surface velocities for an accelerated liner in relation to the distance to the axis of the system.

A preliminary experiment for the system shown in Fig. 19 was carried out. However, in it the layer of light material was not the optimum size; its thickness was 1 mm and density 0.2 g/cm^3. As a result of this experiment an average velocity v_l = 1.1 cm/µsec was obtained for a liner 0.1 mm thick. This value is applied to a diagram (Fig. 20) by point A and it relates to the results of numerical calculations [32].

Comparison of characteristics for both of the cylindrical systems presented points to their equivalence from the point of view of efficiency, velocity, and the energy of accelerated liners. Experiments also showed that the velocity for a copper liner is of the order of 1.4-1.6 cm/µsec is realistic and entirely achievable under laboratory conditions.

The main results of experiments for obtaining high dynamic pressures and high cylindrical metal liner velocities are as follows.

1. Pressure at the front of a strong Mach wave in conical explosive systems reached 3.3-4.6 TPa. These results confirm the hypothesis formulated that in axisymmetrical (conical or cylindrical) systems irregular reflection and an intense Mach wave form with lower values of angle of incidence than in plane systems.

2. Experiments showed the possibility of using conical and biconical systems in order to obtain a high-temperature plasma of considerable density.

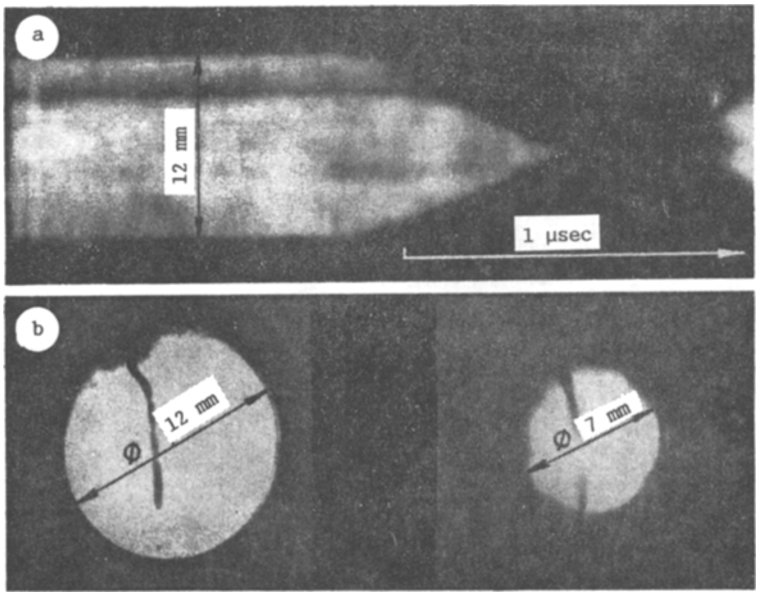

Fig. 18

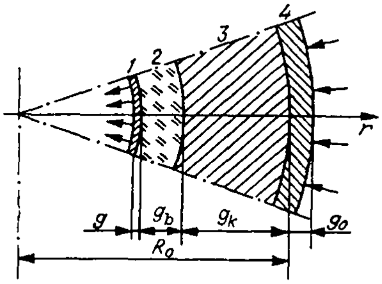

Fig. 19

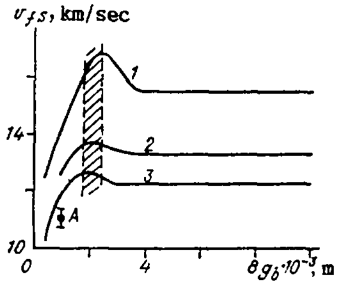

Fig. 20

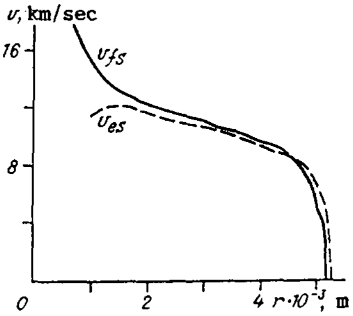

Fig. 21

3. In studying explosive multilayer cylindrical systems a high velocity is found for a copper liner (v_l = 1.4 cm/μsec). The study of these systems continues. There is hope of achieving a higher velocity in similar cylindrical systems.

4. From the point of view of the physics of high energy densities a theoretical and experimental study of the use of explosive substance energy is very justified, and it is necessary to continue it. The fact that with low cost (cheap source of energy) and comparatively simple technology it is possible to achieve ultrahigh dynamic pressures and high flows of energy confirms this conclusion. It is possible to strengthen pressure by almost a factor 100 compared with pressure at the detonation front, and also to create a power of the order of 10^3 W/cm^2 comparable with that achieved in high pulsed laser systems. In the so-called closed systems these values may be increased.

The small series of systems developed and prepared may be applied for fundamental studies in a plasma and various phenomena in different materials at high pressures. The first problem is of interest while a study of plasma is justified by the purely dynamic nature of the phenomena observed and the relative simplicity of interpreting experimental results. The second problem is connected with the fact that explosive methods currently provided may find application in solid physics where as a source of energy use is made of underground atomic explosions.

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STRUCTURE AND BRIGHTNESS OF NONSTEADY-STATE SUPERCRITICAL SHOCK WAVES IN AIR OF REDUCED DENSITY

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Basic ideas about the quasisteady structure of intensely emitting shock waves (SW) which were given in [1-3] have made it possible to make qualitative estimates of the thickness of a heated layer and peak behind the SW front approximating a gray gas, and also to estimate SW brightness at different velocities in air of normal density [3-5]. Numerical calculations for the nonsteady-state radiation-gas dynamic problem of SW propagation in air with velocities up to 50-70 km/sec have been carried out for densities of 0.1-0.03 of normal density [6-9]. The emission spectrum of an air plasma (up to 500 spectral intervals have been introduced in order to describe it) has been considered in detail, and detailed tables of thermodynamic [10] and optical [11] properties of air have been used. In order to reduce the volume of computations a special method has been used for averaging equations of emission transfer [12, 13]. Calculations have made it possible to determine the dependence of the brightness temperature of emission on its wavelength with different wave velocities and air densities, and also the time for emergence of parameters into their steady-state values.

Numerical calculations [6-9] have confirmed the validity of the basic qualitative ideas [1-5], and made it possible to define quantitative characteristics for emitting SW. However, new qualitative features of these SW were detected, i.e., occurrence of a two-region structure for the heated layer ahead of the wave front. Analysis of emission spectra and the nature of change in group and integral (according to spectrum) one-sided emission flows has shown that the reason for occurrence of a two-region structure is the difference in behavior of absorption coefficients in different parts of the spectrum with a change in temperature. The drop in absorption coefficient for fronts with energies of 6.5-11 eV at temperatures of 0.7-0.9 eV, connected with dissociation of the air molecules, leads to occurrence of a heating wave and brightening. High energy quanta, which have a capacity for photo-ionization, form a hot region adjacent to the SW front. Between the ionization and dissociation waves an extended, comparatively cold zone arises whose existence has not previously been noted.

The role of radiation processes may be characterized by the parameter $\chi = q_r/q_h$, where q_r is radiation flux density; q_h is hydrodynamic radiation flux $\left(q_h = \frac{1}{2}\rho_0 D_s u_s^2\right)$, ρ_0 is gas density ahead of the SW front; D_s is SW velocity; u_s is gas velocity behind the SW front. If the plasma behind the SW front is optically thick and uniformly heated, then $q_r = q_b = \sigma T_s^4$

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