CALCULATION OF THE COMPRESSION OF A DT MIXTURE BY AN ELECTRICALLY EXPLODED CYLINDRICAL SHELL

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A possible path to the solution of the problem of controlled thermonuclear fusion consists of heating up a target containing a DT mixture by compressing it with a dense shell accelerated to velocities $\gtrsim 10^7$ cm/sec [1]. One of the methods for achieving such compression is the use of megagauss magnetic fields [2]. This method is attractive due to the possibility of obtaining a comparatively high ($\gtrsim$ 1%) transfer coefficient of the initially stored energy to the shell. An accumulation of kinetic energy occurs both due to the pressure of the magnetic field and due to the dispersion of material from the shell surface. Both acceleration mechanisms operate when the shell is subject to an electrical explosion (EE) by a strong current pulse. A calculation of the electrical explosion of a thin cylindrical shell upon the discharge of a megajoule capacitor bank into it is performed in [3]. Compression rates up to 3×10^7 cm/sec are obtained in the calculation; however, the comparatively low rates of current growth provided by a capacitor bank have led to the necessity of choosing a very small initial relative shell thickness $\sim 10^{-5}$. The heating of the gas filling the shell and the conditions for the occurrence of thermonuclear reactions were not considered in this research.

The results of a numerical calculation of the compression and thermonuclear burning of a DT mixture upon its compression by a cylindrical shell are given in [4]. The calculations show that burning of DT with a positive energy yield is possible with a constant power liberated in the shell of $\gtrsim 3 \times 10^{14}$ W. The possibility of an electrodynamic means of power liberation is mentioned; however, this process has not been considered in more detail, and the magnetohydrodynamic effects in the shell and the plasma were not discussed.

This paper is an attempt at a computational estimate of the possibility of producing thermonuclear fusion by electrically exploded shell compression. The processes in the electrical circuit of the device, magnetohydrodynamic processes in the target, and the occurrence of fusion reactions are taken into account. The shell compression is assumed to be ideally symmetric. Questions of the stability of the compression [5] are not considered in this paper.

An analysis of electrophysical devices from the viewpoint of their possibilities for creating an energy density $\sim$MJ/g in a conductor upon its being electrically exploded has been performed in [6]. It is shown that such a possibility may be realized if lines with distributed parameters connected in parallel are discharged into the load, which is a cylindrical shell. Therefore we will restrict ourselves in what follows to a discussion of the EE of copper cylindrical shells located at the center of a disk collector to which a system of lines is connected in parallel.

The system of one-dimensional equations of magnetohydrodynamics (MHD) with thermal conductivity, where the latter was taken into account in the diffusion approximation, was used to describe the EE of cylindrical shells. The thermal conductivity coefficient was taken to be proportional to the 5/2 power of the temperature, i.e., it was assumed that heat transfer was accompanied by electrons. If a gas was inside the shell, then the energy of the bremsstrahlung arising upon compression of the gas was not returned to the shell but extracted from the load with the help of the appropriate heat discharge function. The energy of α-particles of thermonuclear origin absorbed in the gas was also not taken into account.

Similarly to [7], an interpolation equation of state [8] describing the evaporation of copper and the region of a mixture of vapor and liquid was used in connection with the calculations of processes in copper. The dependence of the electric conductivity of copper on density and thermal energy was also described similarly to [7]. The electric conductivity was chosen on the basis of experiments on the electrical explosion of conductors in the region of temperatures up to several electron volts and densities greater than 0.1 g/cm^3. We note that the accuracy of the description of the electric conductivity in this region of states determines the initial phase of the process – explosion of the shell – and has a significant effect during the entire compression. In the region of densities lower than 0.01 g/cm^3 and temperatures of 10-100 eV the data on the electric conductivity were taken from [9], where it was calculated from the Saha and Boltzmann equations with screening taken into account. The electric conductivity was interpolated between the computational-experimental values and the data of [9] in a certain region of states of copper, and in individual cases it was extrapolated to temperatures exceeding those considered in [9]. The accuracy of the interpolation and extrapolation naturally requires experimental checking. However, the calculations show that such states of copper are achieved only in the last phases of the compression; errors in the description of the electric conductivity even by two orders of magnitude do not result in a significant change in the compression process. The equation of state of an ideal gas with $\gamma = 5/3$ was used for the calculation of D_2 or DT gases

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contained in the shell. If the DT mixture was frozen, it was calculated with the following equation of state:

$$p = p_c + p_W = \frac{\rho_0 c_0^2}{n}(\delta^n - 1) + \Gamma \rho_0 \delta \varepsilon_W$$

$$\varepsilon = \varepsilon_c + \varepsilon_W \quad \varepsilon_c = -\int_{v_0}^{v} p_c dv,$$

$$n = \begin{cases} n_1, & \text{if} \quad \delta < \delta_1, \\ n_2, & \text{if} \quad \delta_1 \leqslant \delta \leqslant \delta_2, \\ 5/3, & \text{if} \quad \delta > \delta_2, \end{cases} \quad \Gamma = \begin{cases} \left(1 - \frac{\varepsilon_W}{Q}\right)\Gamma_n + \frac{2}{3}\frac{\varepsilon_W}{Q}, & \text{if} \quad \varepsilon_W < Q, \\ 2/3, & \text{if} \quad \varepsilon_W \geqslant Q, \end{cases}$$

where ρ_0 and c_0 are the initial density and speed of sound, δ is the relative density, p is the pressure, ϵ is the specific energy density, and v is the specific volume. In accordance with the experimental data given in [10], the constants in this equation of state were set equal to the following values:

$$\rho_0 = 0.2\ \text{g/cm}^3,\ c_0 = 1.73\ \text{km/sec},\ n_1 = 3,\ n_2 = 2,$$
$$\delta_1 = 10,\ \ \delta_2 = 100,\ \ \Gamma_n = 2/3,\ \ Q = 0.27\ \text{kJ/g}.$$

The gas compressed inside the shell was assumed to be conducting. Its heating both due to the work of the completed shell and due to the Joule heat liberated upon passage of the current were taken into account. The electric conductivity of the gas was determined from the formulas for the electric conductivity of a completely ionized hydrogen plasma from [11]. The possibility of individual channels of electrical breakdown arising was not taken into consideration in the calculations.

The system of MHD equations for calculation of the load was solved on a computer simultaneously with the system of equations of the electrical circuit. The length and the energy supply in the lines were determined after conclusion of the calculation of the process in terms of its time. The collector of the device was considered in the form of a disk line with a characteristic impedance dependent on the radius.

If the propagation time of a wave through the collector is much less than the propagation time of a wave through the main lines, then the current in the line–collector–load system (with a constant load resistance R_L) varies exponentially from the value $U_0/(R_c + R_L)$ to $U_0/(R_L + R_0)$, where U_0 is the voltage to which the lines are charged, R_0 is the characteristic impedance of the system of coaxial lines, and R_c is the circuit resistance, i.e., the sum of R_0 and the collector resistance. Therefore the circuit in Fig. 1 is a sufficiently good approximation to the equivalent circuit of the device. The quantity

$$R_{eq} = R_0 + (R_c - R_0)e^{-\frac{t}{\tau}},$$

where τ is the time for a wave to pass through the collector, is taken as R_{eq}.

The series of calculations carried out have confirmed the validity of the dependences derived in [6]. MHD calculations have shown that the dependence of the dispersal velocity of an exploding copper shell and the energy contributed to it on the voltage U_0 is comparatively weak. As U_0 increases from 0.75 to 2 MV, a small decrease occurs in the convergence time of the shell along with an increase in the energy contributed to it. Further increase of U_0 has practically no effect on these quantities, but it should evidently lead to a complication in the construction of the device. A decrease in the value of R_0 increases the rate of increase of the current in the load, and consequently the rate of energy contribution to it. The latter is the decisive moment for producing thermonuclear fusion. Unfortunately, there exists a limit to R_0, below which it is impossible to achieve an increase in the energy contribution rate. The load resistance R_L, which starts to determine the energy contribution rate to the conductor at $R_0 < R_L$, is such a limit. It is unreasonable to reduce R_0 below R_L from the standpoint of energy costs, because the energy stored in the lines for fixed U_0 and process time Θ is inversely proportional to the values of R_0, and the energy contribution process is determined by the quantity R_L.

One can decrease R_L only by either decreasing the length of the cylindrical conductor or increasing its radius. An increase in the shell radius is especially significant for the process. It results in an increase in the acceleration (due to an increase in the rate of current growth) upon acceleration of the shell by the magnetic field, an increase in the base line of shell acceleration (with conservation of mass it is constant), a sharp increase in the maximum flight velocity of the shell (due to the first two factors), and a decrease in the thermal losses in the gas (due to shortening of its compression time). The totality of these factors creates a nonlinear increase of the maximum temperature of the compressed gas upon an increase in radius and a decrease in the relative thickness of the copper shell.

It followed from the calculations that, other fixed parameters being the same, the value of the maximum temperature of the compressed gas depends in the most essential way on its initial density ρ_0. In order to produce temperatures in the gas of the order of several kiloelectron volts which are necessary for the onset of a thermonuclear reaction, it was necessary to fill the conductor with a gas at a pressure of the order of or less than atmospheric, i.e., $\rho_0 \lessapprox 0.0002$. An increase of ρ_0 by two orders of magnitude resulted in practice in cold compression of the gas.

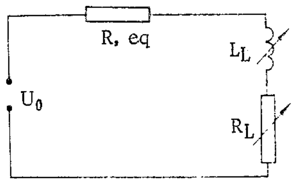

Fig. 1

As the computational results show, one can choose the length of the lines in such a way that double the passage time of the wave over the lines is somewhat less than the compression time of the shell. The second part (in time) of the process takes place with a somewhat smaller voltage in the lines, but this has a weak effect on the final result, since the greater portion of the energy consumed by the load is already located in its magnetic field.

The calculations performed were of an exploratory nature and were not designed to optimize the load in this or the other device. The principal task of the calculations consisted of exhibiting the regularities of the process of compression of matter upon the EE of a cylindrical shell and showing the possibilities of this method from the standpoint of producing thermonuclear fusion. Several versions of calculations of different systems are given below.

Version 1. A copper shell with a length of 1 cm and a thickness of 0.01 cm with an exterior radius $r_e = 1.25$ cm is filled with a gaseous DT mixture having initial density $\rho_0 = 3 \times 10^{-5}$ g/cm³. The shell is connected through a collector to a system of lines charged to $U_0 = 2$ MV with an overall characteristic impedance $R_0 = 0.005\ \Omega$

A preliminary calculation showed that maximum compression of the gas occurs at time t = 0.33 μsec. Based on this, the length of the lines was selected equal to 280 cm, which corresponds to an energy reserve of 34 MJ in them. At time t = 0.17 μsec the voltage in the lines was lowered to 1.8 MV. It follows from the calculation that the maximum velocity of the shell was attained at its inner boundary and was 20 cm/μsec. Plots of the time dependence of the inner radius r_i of the shell and the average temperature of the gas T_{avg} are presented in Fig. 2. The distributions of the temperature T and density ρ in the shell--gas system which are given in Fig. 3 refer to an instant of time close to the time of maximum compression of the gas. The temperature and density in the gas are practically constant. Since the thermal conductivity in copper drops off sharply as the density increases, the high density peak near the inner boundary of the copper sharply reduces the heat transfer from the gas. The rapid decline of the temperature in the narrow copper layer adjacent to the boundary is explained by this circumstance. The position of the gas–shell boundary is noted in Fig. 2.

Energies of 10 and 0.06 MJ, respectively, were imparted to the shell and the gas. The maximum energy in the shell was equal to 20 MJ/g. The neutron yield of the system was 6×10^{17} neutrons, and the energy of the α-particles absorbed in the gas exceeded by a factor of three the energy of the gas imparted to it by the shell. However, it is impossible to expect here any kind of intense thermonuclear flash (see [12]), since the maximum $\int \rho dr$ in the gas was equal to 0.03 g/cm².

Version 2. The mass in the copper shell is reduced in comparison with Version 1. Its external radius is increased to 2 cm with a shell thickness of 0.001 cm, and the shell length was left equal to 1 cm. DT gas with a density of 10^{-4} g/cm³ is placed inside the shell out to a radius of r = 0.17 surrounded by a cold layer of DT ($0.17 \leqslant r \leqslant 0.2$) having a density of 0.2 g/cm³. A gap filled with a gas having the low density $\rho = 2 \times 10^{-6}$ g/cm³ is left between this layer and the shell. The voltage in the lines was taken as 2 MV, and the characteristic impedance of the lines was $R_0 = 0.0075\ \Omega$. The voltage was reduced to 1.71 MV at time t = 0.135 μsec.

The time dependences of the external r_e and inner r_i radii of the shell and also of the external r_{DTe} and inner r_{DTi} radii of the frozen layer of DT are presented in Fig. 4. After the impact of the shell with the DT layer the velocity of their common boundary was 37 cm/μsec, and the inner surface of the layer was accelerated to 42 cm/μsec. In 3 nsec after the impact, compression of the gas to $r_{DTi} = 4.3 \times 10^{-5}$ cm occurs, and its average temperature rises to 8.5 keV. Somewhat before this time the temperature and density in the DT layer have the distributions presented in Fig. 5. We note that in 0.4 nsec the DT layer is compressed, the distributions in it become equal, and the average values of the density and temperature are 40 g/cm³ and 0.6 keV. Energies of 7 and 1 MJ out of the 21 MJ of the initial reserve in the lines are imparted to the shell and the DT, respectively. The maximum values of the internal energy in the copper near its inner boundary reach 70 MJ/g. The energy of the α-particles absorbed in the gas exceeded by a factor of 7 the energy from compression of the gas by the shell, the quantity $\int \rho dr$ amounted to 0.4 g/cm², and the neutron yield was of the order of 10^{17}; one-half of it goes into the DT gas, and the other half goes into the initially frozen layer of DT.

Version 3. DT gas with a density $\rho_0 = 0.07$ g/cm³ is enclosed in a copper cylindrical shell 0.012 cm in thickness with an external radius $r_e = 1.2$ cm. The shell length is 3 cm. A system of lines with voltage $U_0 = 2$ MV and characteristic impedance $R_0 = 0.03\ \Omega$ is discharged into the shell. The problem was considered with the goal of clarifying what the compression of a gas of high initial density will lead to.

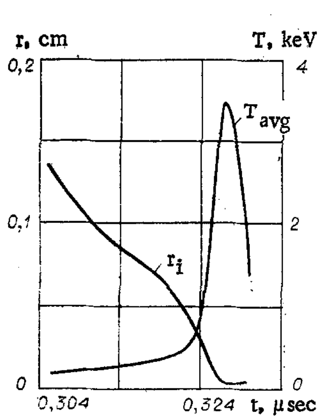

Fig. 2

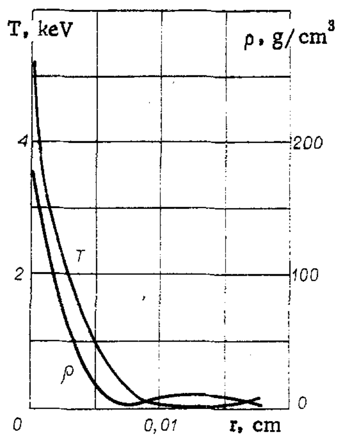

Fig. 3

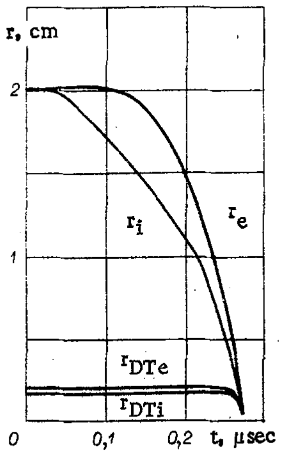

Fig. 4

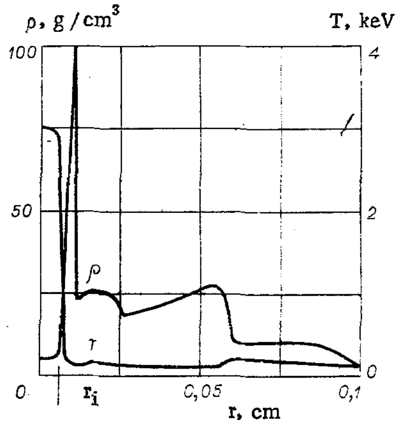

Fig. 5

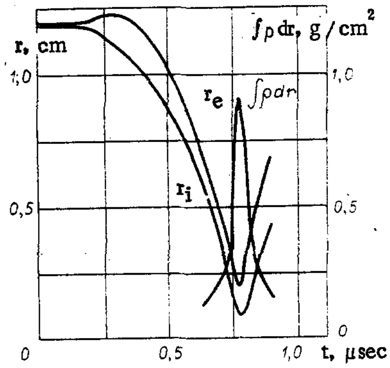

Fig. 6

The compression process occurred comparatively slowly: The flight velocity of the shell did not exceed 4 cm/μsec. The maximum compression was 220 in all. The gas was practically unheated. Up to the instant of maximum compression the gas was a thin filament of cold matter of high density. The quantity $\int \rho dr$ rose to 0.92 g/cm^2. Plots of the time dependence of the external r_e and inner r_i radii of the shell and of the quantity $\int \rho dr$ are presented in Fig. 6. It follows from the calculation that out of the 26 MJ of initial energy reserve 21 MJ goes into the system shell + gas. Of this 4.2 MJ constitutes the shell energy, and 3.5 MJ the energy of the gas, and the remaining energy is in the magnetic field of the system. One should note that the required initial energy reserve in the lines depends significantly on the maximum value of the quantity $\int \rho dr$. Thus in order to obtain a value of 0.67 for this quantity, 12 MJ of initial energy reserve is necessary in all.

Common to all the calculations is the fact that a large portion of the energy stored in the lines goes into the load and its magnetic field upon sufficiently good agreement in the calculations between the load and line impedances. This portion was higher than 90% in connection with the calculation of one of the systems with an energy reserve of 2.5 MJ. Naturally, the energy of the load exceeded 30% of this reserve. We note that one should not expect self-heating of the gas for this system due to a thermonuclear reaction; however, the neutron yield obtained in the calculation proved to be sufficiently high: $\sim 10^{15}$.

It is interesting to note the characteristic peculiarity of gas compression upon EE of a shell which is related to variation of the distribution of the conductivity in the conductor during the EE process. In the initial stage the maximum value of the current density is necessary for the region of the conductor adjacent to its outer boundary due to the skin effect. The magnetic field prevents the conductor from flying apart; however, a small decrease in the density and the contribution of Joule heating nevertheless result in a decline in the conductivity of the outer part of the conductor by approximately two orders of magnitude. This situation amplifies the process of the penetration of the magnetic field and the maximum density of the current within the conductor. The magnetic field rises with a large gradient towards the inner boundary of the copper shell. A rapid increase in the magnetic and hydrodynamic (due to the large current density and the liberation of Joule heat) pressures leads to a sharp acceleration and unloading of the inner part of the shell. Gas with low density and pressure located inside the shell does not impede this motion. As the density of the inner part of the conductor decreases, its conductivity decreases and becomes a minimum (over the cross section). The current density curve falls steeply as the radius decreases. The density distribution (and conductivity distribution as well) declining from the outer boundary to the inner one which has been established in the shell facilitates this. Approximately from this moment the inner layers of the shell continue to fly by inertia; the outer layers, and gradually the entire mass of the shell, start to be accelerated by the magnetic field. This is what happends until the inner layers start to be decelerated due to resistance by the compressed gas. After this, equalization of the densities, and consequently the conductivity and current density, occurs over the cross section of the conductor. A large gradient of the current density remains only in a narrow neighborhood of the inner boundary of the conductor. It creates an additional shock through the gas near the moment of maximum compression. Figure 2, in which it is evident that the inner radius of the shell produces an additional acceleration inwards near the moment of its stopping, can serve as an illustration of what has been said.

Let us dwell on the question of the effect of a current flowing through the gas and the process of compression of the gas by the shell. The pattern of the process was one and the same in all the calculations. A remarkable conductivity appeared in the gas at times close to the time of the limiting compression of the gas, when its temperature rose to a value of 1 keV. The conductivity of the gas increased rapidly and became greater by several orders of magnitude than the conductivity of the copper as the gas was compressed further. A flow of current began through the gas, but notwithstanding the difference indicated above between the conductivity of the materials, the value of the current density in the gas was comparable to the values of the current density flowing through the copper due to the small radii, and consequently the large inductive impedance. And since the cross-sectional area of the gas at these times was several orders of magnitude smaller than the cross-sectional area of the copper, practically the entire current flowed through the copper conductor. The difference between the maximum temperatures attained in the gas with and without its conductivity taken into account did not exceed several percent.

The efficiency of the devices may turn out to be comparatively high. For example, in order to obtain in version 2 an overall efficiency (with respect to the initial energy reserve in the lines) greater than unity, it is sufficient that a comparatively small portion of the DT (about 1%) react.

Assumptions which simplify the conduct of the calculations are: one-dimensional approximation, taking thermal conductivity into account in the diffusion approximation, a single temperature for the plasma, and others; they make the results described idealized. Therefore the calculations only illustrate the maximum possibilities of the systems considered. Taking more complete account of the physical phenomena which occur upon the EE of cylindrical shells may introduce significant corrections both to the computational results and to the choice of the parameters of the systems. However, the data obtained by computational means as well as those in [1-5] indicate the advisability of further investigation of the compression processes upon EE of cylindrical shells.

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CUMULATIVE BEHAVIOR OF CONVERGENT SHOCKS WITH DISSIPATION EFFECTS

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1. One-dimensional (spherically or cylindrically symmetric) converging shock waves represent a familiar example of cumulative gasdynamical processes, which play so vital a part in nature and technology [1]. Asymptotic solutions of the converging shock-wave problem in the neighborhood of the center of axis of symmetry are found in the well-known self-similar solutions indicated independently by Guderley [2] and Landau and Stanyukovich [3]. The domain of validity of these solutions depends on the initial and boundary conditions (the simplest of which occur for a cold stationary gas with constant density ρ_0 and a constant-velocity piston), but a self-similar solution is almost always realized in a sufficiently close neighborhood [4]. In this solution, at the instant of "cumulation" of the shock front (usually taken as t = 0) and strictly at the center or axis of symmetry, the velocity of the front ("shock velocity") as well as the pressure and temperature at the front increase without bound: $\dot{r}_f \sim (-t)^{1/k-1} \sim r_f^{1-k} (r_f^k \sim -t)$; $p_f \sim T_f \sim (-t)^{2\left(\frac{1}{k}-1\right)} \sim r_f^{2(1-k)}$, where the self-similarity index $k = k(\gamma) \geqslant 1$ for an isentropic exponent of the gas $\gamma \geqslant 1$ [4, 5]. The self-similar variable, on which depend all the unknown functions of the self-similar solution, has the form $\xi = r/r_f = \xi_0 r^k/(-t)$ in this case, where at the shock front $\xi = 1$ and $r_f = (-t/\xi_0)^{\frac{1}{k}}$. The only arbitrary constant in the self-similar solution has dimensions $cm^{-k}s$ and quantitatively characterizes the "strength" of the initial impulse. The self-similar solution admits continuation in the reflected-shock stage. The cumulative buildup of energy between the shock front $\xi = 1$ and an arbitrary value of the variable $\xi^* > 1$ behind the front (ξ^* normally coincides with a singular ξ-line that nowhere intersects the C-characteristics directed toward the shock front) is characterized by the following dependence on the radius of the shock front: $E_a \sim r_f^{5-2k}$ (spherical case) or $E_a \sim r_f^{4-2k}$ (cylindrical case) [4]. As a result of the cumulative process, the energy of this region decreases as $r_f \to 0$ more slowly than r_f^3 (spherical case) or r_f^2 (cylindrical case), because the self-similarity index $k > 1$ (or $\gamma > 1$).

In this article we investigate the constraints imposed on the "cumulation" parameters of the self-similar solution (with inclusion of the reflected-shock stage) due to dissipation effects. These effects clearly become significant when the effective mean free path of the investigated gas particles is commensurate with the radius of the shock front, $l_s \sim r_f$. The allowance for dissipation effects, first of all, shows that all the hydrodynamic and thermodynamic variables are bounded and, second, yields very general expressions for the maximum cumulation parameters, which are determined simultaneously with the characteristics of the self-similar solution and dissipation effects. Of course, the cumulation parameters can actually also be affected by the deviations of the motion of the gas from one-dimensionality in connection with the singularities due to the well-known instability of converging shock waves [6, 7]. We realize that these deviations are rendered inconsequential by the sufficiently symmetric initial and boundary conditions of the problem. Accordingly, violations of the one-dimensional symmetry of the motion can not only attenuate the cumulation parameters, but can amplify them as well, as shown by the examples of two-dimensional cumulative motions in the case of a plasma focus and a current sheet [8, 9].

For sufficiently strong converging shock waves, in general, the most interesting case is a fully ionized plasma. If a high-temperature plasma generated in a cumulation zone has a sufficiently high density, its motion is described by the system of two-temperature gasdynamic equations with well-known dissipation effects, which in this case are associated with

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