Metallic Z-pinch method: the isentropic compression of hydrogen

V. V. Prut, V. A. Khrabrov, V. V. Matveev, and S. A. Shibaev

I. V. Kurchatov Institute of Atomic Energy
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We consider methods of using the metallic Z-pinch to obtain high (megabar) pressures, and determining the adiabatic equation of state of materials, especially hydrogen.

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The equation of state of hydrogen in the region of high pressures has been determined by a statistical method up to 25 kbar (limitation due to strength of equipment) and a shockwave method up to 40 kbar for H_2 and up to 900 kbar for D_2 (limitations due to intense heating—up to $T \approx 7000$ K). Evidently, extension of this region may be achieved only adiabatically, resulting in a very high compression at a relatively low heating. The known variants of this method[1–3] are based on the various methods of converting the detonation wave in the explosive into compression waves in the test material, and irradiation of the hydrogen target by means of the laser, electron or ion beams.

We shall analyze methods and results of the experimental generation of high

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($\sim 10^5$–10^6 bar) pressures and the determination of the equation of state in so-called metallic Z-pinch. The substance of the latter is as follows: a current pulse generated by a condenser bank flows along a metallic pipe inside which the test material (hydrogen) is placed; as a result of interaction between the current and internal magnetic field the pipe is compressed (Z-pinch) which leads to a pressure increase in the material. Moreover, two compression regimes may be achieved: quasi-static and dynamic. In the case of quasi-static compression, for which the inertial time is much less than the characteristic discharge time, and the pressure inside the material $P_H = P_M$, the pressure of the magnetic field ($P_M = \int_0^R jH dr$). The maximum possible magnetic pressure is limited by the electric explosion of the conductor; in the case of present-day "fast" condenser banks with energies $\lesssim 1 M_j$, $P_M \lesssim 1$ Mbar. Thus, in a practical sense, escalation of pressure is only possible for the case of dynamic compression to a degree which is on a par with that achieved in the compression of a plasma for the purpose of constructing a pulsed thermonuclear reactor.

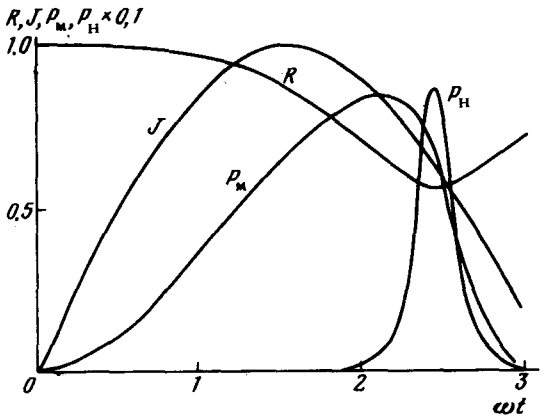

FIG. 1. Time dependence of current I, external radius R, magnetic pressure P_M and hydrogen pressure P_H.

Numerical calculations for H_2 show that in the case of dynamic compression, pressure inside a material may under normal conditions exceed the magnetic field pressure at least $\sim$10-fold. Qualitatively (see also Fig. 1), this may be explained by the fact that at first, when the magnetic pressure (allowing for a kinetic energy distribution) exceeds the pressure inside a material, the pipe is accelerated (this too is possible, for example, due to a high compressibility of hydrogen under normal conditions) and then slowed down by the still-increasing material pressure, and the kinetic energy of the pipe is converted into internal energy (pressure) of the material inside and of the pipe itself. Moreover, if the pipe moves "too rapidly," i.e., when the speed of the compression wave front exceeds the speed of sound, a shock wave is produced, otherwise the process remains quasi-isentropic. The required regime is achieved by selecting the optimal parameters of the pipe, circuit and initial state of the test material which is determined by numerical calculations.

In this work, we used a condenser bank with a current half-period of $\sim 5\,\mu$sec and a maximum magnetic pressure < 50 kbar. The hydrogen was initially in a gaseous phase and $T \approx 80$ K. We measured the radius of the external boundary in a direction

perpendicular to the pipe axis, by means of the SFR-3M high-speed photorecorder operating continuously with a bias-lighting spark, and the current—by the Rogowski band.

Inasmuch as the equation of state, in general, represents a relationship among three parameters: pressure P, specific volume V and entropy S, then assuming that one of these—S—is constant requires that we measure two independent parameters, namely pipe radius and current. Measurement of the radius almost directly determines density (in the absence of flow along the axis), and the pressure inside a material is determined by means of numerical modeling of the process as follows. A system of laws of conservation, rheological equation of state, equation of state of copper and hydrogen, and their thermophysical and electrophysical characteristics were solved at the measured current. For copper—the pipe material—we used the visco-plastic model of a continuous medium with viscosity determined experimentally. The thermodynamic functions for hydrogen were derived as zeroth-order approximation from Ref. 4, where a single functional relationship described the solid, liquid and gaseous states taking into account the free rotation of molecules and intramolecular oscillations, and the parameters were picked so that the equation of state at $T \approx 4$ K and $P \leqslant 25$ kbar, the Debye temperature and the Gruneisen coefficient at $P = 0$ coincided with known reliable experimental values.[5,6] Subsequently, in the first-order approximation, a function was introduced additively into the energy, containing the free parameter ξ which required determination in a region of pressures not attained in Ref. 5. The calculated radius R of the external pipe boundary was compared with the measured value $\tilde{R}$; the criterion which characterizes a measure of error was the functional $G = \int_{t_1}^{t_2}(R - \tilde{R})^2\, dt$

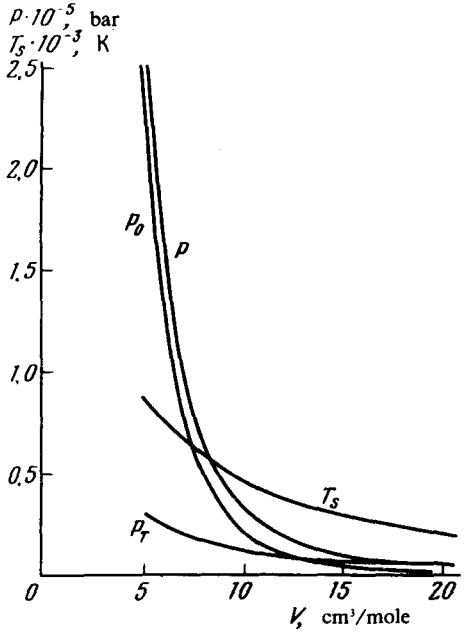

FIG. 2. Adiabatic equation of state $P(V)$, zero isotherm P_0, thermal pressure P_T and adiabatic temperature T_S.

which can be minimized with respect to R by varying the equation of state (parameter ξ) and, thus, leads to the derivation of an experimental adiabatic equation of state. Functions shown in Fig. 1 show a typical example of calculations, and in Fig. 2, the assumed equation of state of hydrogen at $\xi = 0$.

Error in the determination of density is mainly due to inaccurate measurement of the radius and equals $\Delta\rho/\rho \sim 5\%$; errors in the value of pressure are due to errors in the measurement of current, radius and the uncertainties of all the models and coefficients assumed in a model, and amount to $\Delta P/P \sim 30\%$. The maximum pressure measured was ~ 200 kbar, although the accuracy of the value is insufficient for the analysis of known theoretical equations of state of hydrogen.

The assumption that the process is quasi-isentropic is confirmed by direct numerical calculations (in which, naturally, generation of shock waves is assumed)—the difference between a mean temperature averaged over the entire volume of hydrogen and the mean adiabatic temperature did not exceed 1% and is within the margin of error for calculations by means of the difference equation.

In conclusion, we should note that the proposed method was useful in generating and measuring pressure in the megabar range and provides a relatively simple (and, evidently, real) possibility of metallization of hydrogen (see Ref. 7); the fundamental difficulty consists of enhancing (and controlling) the accuracy of measuring the pressure.

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