Isentropic expansion of shock-compressed lead

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Results are presented of experiments aimed at registering the isentrope of the expansion of porous lead previously compressed and heated in the front of a shock wave.

To analyze physical phenomena caused by rapid energy release in a condensed phase (laser heating, evaporation of the skin layer of pinch liners, magnetocumulative generators, etc.), a decisive role is played by information on the equation of state of a metal in a wide range of parameters, from the strongly compressed state all the way to the ideal gas, including the region of nonideal plasma in the vicinity of the critical point. No reliable theory has been developed to date for the description of this range of parameters,[1] and the available experimental methods do not make measurements possible at extremely high temperatures and pressures.

We use here, for the investigation of the equation of state of a metal, a dynamic method based on the generation of the necessary states by isentropic expansion of the condensed matter which has been compressed beforehand and irreversibly heated in the front of a powerful shock wave. The variation and registration of the hydrodynamic parameters that are produced in the relaxation wave were carried out by expanding the shock-compressed matter to a partition having a lower dynamic rigidity and known thermodynamic properties.[2,3] In this case the measurement of the shock-wave velocity D in the partition makes it possible to determine the pressure P and the mass velocity u of the shock-compressed matter, which by virtue of the condition on the contact discontinuity are equal to the pressure and mass velocity of the investigated metal in the rarefaction wave. By performing experiments with partitions having different dynamic rigidities we can determine in this manner the expansion isentrope of the metal in the $P-u$ plane from the state P_H, V_H, E_H on the shock adiabat to lower pressures and temperatures. The conversion from the hydrodynamic variables P and u to the thermodynamic variables E, P, and V is effected by calculating from the experimentally known function $u=u(P)$ the Riemann integrals[4] that express the conservation laws for a centered rarefaction wave:

$$V = V_H + \int_P^{P_H} \left(\frac{du}{dP}\right)^2 dP, \qquad E = E_H - \int_P^{P_H} P\left(\frac{du}{dP}\right)^2 dP. \tag{1}$$

This procedure was used to determine the isentrope of the expansion of lead with initial porosity $m=1.25$. We used in the experiments an explosive generator of rectangular square waves, the explosion products of which accelerated uniformly an aluminum plate to a velocity 5.92×10^5 cm/sec. The collision of this plate with the porous lead target led to the production of a shock wave with amplitude 0.94×10^{12} dyn/cm^2 and a calculated entropy $S=0.8\times10^7$ erg/g deg. The partitions used at high dynamic pressures were made of aluminum, magnesium, Plexiglas, and polystyrene of varying density and of experimentally known shock adiabats.[2] At lower dynamic pressures the partitions were compressed gases, the thermodynamic properties of which were calculated with allowance for the electron excitation, ionization, and plasma nonideality.[5] The velocity of the shock waves in the sample and the partition was measured by a system of six electric-contact pickups arranged in such a way as to take into account the possible tilting of the shock wave. The measurement base was chosen to satisfy the conditions of stationarity of the flow on the basis of hydrodynamic calculations of shock waves and of the distorting relaxation waves.

The results of the experiments are shown in Fig. 1.

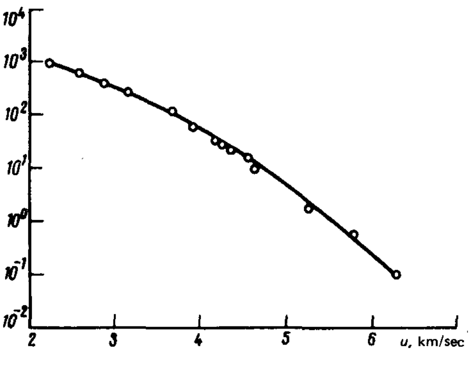

FIG. 1. Expansion isentrope in pressure (P) and mass velocity (u) coordinates.

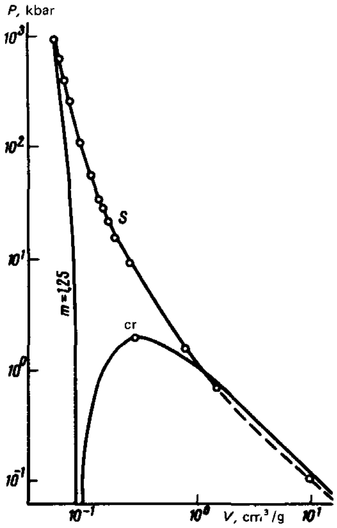

FIG. 2. Phase diagram of lead: H—shock adiabat, $m=1.25$, S—relaxation isentrope, cr—estimate for the critical point.

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Each point was obtained by averaging over 3–5 experiments, with two independent records obtained in each experiment. The accuracy with which D, P, and u were determined was on the order of 1%, 2%, and 1.5%, respectively. Figure 2 shows the obtained isentrope of lead, together with the two-phase liquid-vapor transition region, estimated in analogy with[6] by the principle of corresponding states. The accuracy with which the thermodynamic parameters were calculated from (1) was determined by the Monte Carlo method by simulating, with a computer, the probability structure of the measurement process,[7] and its values were $\delta V/V \sim 15\%$ and $\delta E/E \sim 25\%$. It was difficult to measure the temperature T simultaneously with the other parameters in this experiment. Estimates of T for the upper point of the isentrope S yield $T \sim 12.5 \times 10^3\,^\circ\mathrm{K}$ and $T \sim 2.5 \times 10^3\,^\circ\mathrm{K}$ for the lower.

The results of the isentrope reduction have shown that in the case of isentropic expansion the properties of the metal change with decreasing pressure from those of a condensed and strongly compressed metal [effective adiabatic exponent $\gamma = (\partial \ln P/\partial \ln V)_S \approx 2.4$] to those of an ideal gas state ($\gamma \approx 1.7$); in the lower part of the isentrope, lead appears to be in a two-phase state (dashed curve in Fig. 2). It is interesting that it is possible to cover in one series of experiments a sufficiently wide range of parameters, in which the degeneracy of the electronic component is lifted and the region of a strongly compressed metallic liquid and of a strongly nonideal plasma is realized. We note that the experiment has revealed no noticeable breaks[8] located on the expansion isentrope outside the region of the "liquid–gas" transition and capable of being interpreted as the specific first-order phase transitions discussed in[9] in connection with the "metal–dielectric" transition and in[10] in connection with the phase transition in a strongly nonideal plasma. In the investigated range of parameters, the phase diagram of lead seems to have the usual form with one critical point corresponding to the "liquid–gas" phase transition.

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