

TABLE II. Results of data analysis.

Shot No.	Resistance ratio $\frac{R}{R_0}$	Resistivity ratio $\left(\frac{\rho}{\rho_0}\right)_{\text{expt}}$	Temperature rise ΔT_H (°C)	Thermal resistivity change $\frac{\Delta \rho_T}{\rho_0}$	Isothermal resistivity ratio $\frac{\rho(V, T_0)}{\rho(V_0, T_0)}$	Defect resistivity $\frac{\Delta \rho_D}{\rho_0}$
72-065	1.051	0.992	~ 51	0.16	0.83	...
72-068	1.170	1.086	~ 74	0.21	0.88	...
72-069	1.073	0.995	71.6	0.190	0.797	0.072
73-009	1.049	0.982	58.6	0.160	0.813	0.058
73-010	1.058	0.990	58.9	0.161	0.820	0.066
73-011	1.022	0.974	39.3	0.113	0.853	0.039
73-013	1.000	0.977	17.6	0.052	0.917	0.013
73-027	1.120	1.031	81.8	0.211	0.810	0.106
73-028	1.035	0.995	31.3	0.094	0.895	0.052
73-029	1.032	0.990	33.4	0.099	0.884	0.049
73-034	1.087	1.014	63.1	0.170	0.834	0.090
73-036	1.122	1.050	59.4	0.162	0.879	0.126
73-040	1.037	0.987	40.8	0.117	0.862	0.053
73-044	1.111	1.039	59.9	0.170	0.870	0.120
73-047	1.149 ± .013	1.071	63.7	0.178	0.894	0.152
73-050	1.185	1.09	82.5	0.220	0.872	0.170
73-059	1.139	1.045	84.0	0.219	0.821	0.122

cut from the same 3×5-cm foil, the resistance change was significantly larger using ceramic anvils; apparently the ceramic anvils cause extraneous deformation of the foil. The remaining experiments used polished single-crystal Al_2O_3 anvils.

To test whether observed shock-induced changes in voltage drop across a foil were due to resistance change or to artifacts, two experiments were carried out monitoring foils with no current flowing through them. No appreciable signal was observed without current flow, confirming the resistive source for voltage signals observed in the remaining experiments.

Table II presents the results of shot data analysis according to Fig. 5. The experimental resistance ratio (column 1) $R/R_0 = E/E_0$ is converted to resistivity (column 2) by

$$\frac{\rho}{\rho_0} = \frac{R}{R_0} \frac{V}{V_0}.$$

The shock temperature rise ΔT_H in column 3 is calculated as described in Sec. III C, and columns 4 and 5 give the resistivity change due to temperature rise and isothermal shock resistivity calculated from the results of Sec. III A. The last column gives the resistivity deviation between isothermal shock resistivity and calculated hydrostatic resistivity (Sec. IV D).

B. Error analysis

Contribution to errors in the analysis are found in (i) determination of the shocked state (P, V, T), (ii) recording and reading of foil resistance, and (iii) assumptions for the model describing the temperature coefficient of resistivity α as a function of volume.

Errors in determination of the shock P - V state originate in the empirical Hugoniot curve and in projectile speed. Hugoniot data for silver do not exist below 200 kbar. Hence, the portion of the curve used is an interpolation between the ambient state and data from 200 to 500 kbar. The Hugoniot curve used was from the

Zharkov and Kalinen equation-of-state fit to shock data and to Bridgman's hydrostatic P - V data. Disagreement with the fit of Rice, McQueen, and Walsh²⁴ was 0.0005 and 0.002 in V/V_0 at 40 and 120 kbar, respectively. Uncertainties in the projectile speed are about ± 0.002 mm/ μ sec. This uncertainty implies random uncertainty in the sapphire longitudinal stress state of ± 1 kbar.

The sapphire Hugoniot itself is well established below 120 kbar and should be accurate to within ± 0.5 kbar below 60 kbar and within ± 1 kbar in the 60–120-kbar range. A fit by Ingram and Graham²⁵ for the sapphire Hugoniot, $P_x = 444 \mu + 13.6 \mu^2$, was used (μ in mm/ μ sec, P_x in kbar). (The Hugoniot data are for 0°, 60°, and 90° orientations relative to the c axis.)

So the final pressure state in silver is accurate to within ± 1 kbar random errors and ± 0.5 to 1 kbar systematic errors. The compressed volume state could be subject to a random error of ± 0.001 in V/V_0 and a systematic error of up to ± 0.003 .

The ratio of shocked foil resistance to unshocked resistance is subject to errors in calibrating the voltage drop across the foil. The principal error source arises from recording and reading of oscilloscope traces that define the voltage. The reference voltage level E_0 should be accurate within 0.5%. Considering all elements of measurement, ΔE is accurate to about 5% and

$$\frac{E}{E_0} = 1 + \frac{\Delta E}{E_0} = \frac{R}{R_0}$$

is accurate within 0.8% for the range studied.

Calculation of temperatures in the shocked state is subject to systematic uncertainty. The thermodynamic calculation is generally accepted as valid for compressions less than 20%. However, there has been no accurate experimental confirmation of temperatures. Systematic uncertainties arise because the equation of state is fit to Hugoniot and hydrostatic compression curves; the fit is insensitive to thermal parameters. One can understand this by realizing that it would require a large temperature change to cause a 1% in-

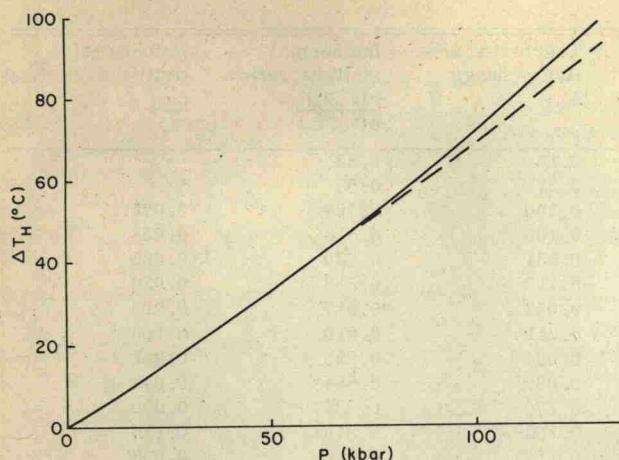


FIG. 6. Hugoniot temperature rise vs pressure. Solid line, from Zharkov and Kalinen equation of state; dashed line, from Rice, McQueen, and Walsh (Ref. 24).

crease in volume at a given pressure; for silver it would take about a 200 °K temperature change from ambient conditions. Rice, McQueen, and Walsh²⁴ state that calculated temperature increases should be accurate within 10%. In fact, Rice, McQueen, and Walsh's calculated temperatures agree with those from the Zharkov-Kalinen equation of state to 60 kbar and diverge to a difference of 6% at 120 kbar (Fig. 6).

The temperature coefficient of resistivity $\alpha(V)$ [Eq. (1)] and the hydrostatic pressure-resistivity curve [Eq. (5)] are calculated quantities subject to error. There are experimental data on the temperature coefficient of resistivity as a function of pressure for iron.²⁶ Calculated approximate coefficients,

$$\frac{\alpha}{\alpha_0} \approx \left(\frac{\theta}{\theta_0}\right)^{-2} \approx \exp\left[2\gamma_0 \left(\frac{V}{V_0} - 1\right)\right],$$

(here we assumed $\gamma/V = \text{const}$) are 0.4% higher at 50 kbar and 2.9% higher at 100 kbar than experimental results. (The iron data extend over a temperature range of 1000 °C.) Bridgman has also measured temperature coefficients of resistance as a function of pressure, but there are contradictions in his work. In one set of experiments he measured resistance as a function of temperature at constant pressure and in a second set he made measurements as a function of pressure at constant temperature. In the first set he measured resistance changes in noble metals over a 100 °C temperature range at constant pressure in the range 0–12 kbar.²⁷ The measured temperature coefficient of resistance is independent of pressure within $\frac{1}{4}\%$ ($\alpha/\alpha_0 = 1.00$). Assuming $\rho = \alpha(V)T$, this work is inconsistent with Bridgman's other work on pressure dependence of resistance at constant temperature (30 °C), where $\rho/\rho_0 = 0.956$ at 12 kbar.²⁸ That is to say, in the first work he found $\alpha/\alpha_0 = 1.00$ at 12 kbar, in the latter work $\alpha/\alpha_0 = 0.956$ [from Eq. (4), $\alpha/\alpha_0 = 0.96$]. This inconsistency remains if one uses Eq. (5) for relating ρ/ρ_0 and α/α_0 . Based on the above discussions, accuracy of the calculated volume dependence of resistivity for silver is not well known but may be about 3% over the pressure range studied here. Until isothermal electrical resistivity and

its temperature coefficient are reliably measured for silver up to 120 kbar, there remains the possibility that this part of the analysis is in serious error.

C. Voltage-time profiles

Examples of oscilloscope records of the profiles are shown in Fig. 4. The foils remain under uniaxial compression for 0.5 μsec before a rarefaction wave from the rear sapphire-epoxy interface (Fig. 2) arrives at the foil; within another 0.5 μsec rarefactions from the sapphire lateral edges also arrive. The shock-induced signal rise time is about 0.035 μsec . During the next 0.5 μsec the voltage level shows time-dependent structure. Structure depends on pressure level, silver purity, and state of anneal. That the structure is not random noise can be seen by comparing the profiles of shots 73-036 and 73-044 (Fig. 7). The two shots had the same pressure level and were the same foil type. Over-all shapes of the profiles do match roughly. The two shots were done two weeks apart, and the silver foils used were polished, photoetched, and annealed at different times. While one cannot rule out the agreement as due to reproducible artifacts of the experiment, it is tempting to ascribe the structure as due to time-dependent behavior of the silver resistivity.

Observed signal rise times range from 0.019 to 0.085 μsec , 0.035 μsec being typical. Aside from the time it takes for foil resistance to change in response to the shock transition, there are a number of experimental conditions which also affect rise time. These conditions include shock-impedance mismatch between silver and sapphire, impact misalignment, and the low-impedance epoxy layer adjacent to the foil edges. The foil reaches pressure equilibrium in about three shock transits across the foil (Sec. III. C); this takes 0.015 μsec . A typical impact misalignment of 0.3 mrad would mean a time as long as 0.013 μsec for the shock front to cross the foil. These two time effects are additive. The pressure equilibration time of about 0.05 μsec for the epoxy adjacent to the foil edges will also degrade signal rise time. The above conditions are sufficient to account for observed rise time; intrinsic response time of the resistance change is probably obscured.

D. Isothermal results

Because the shock process raises the silver tempera-

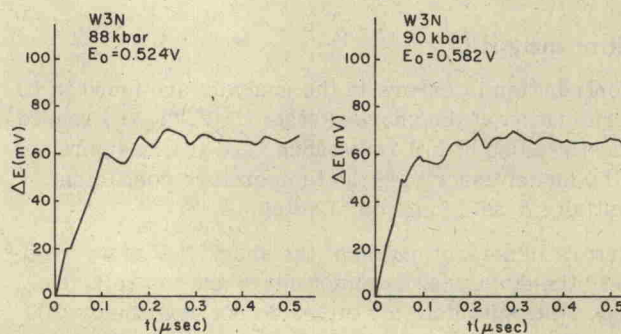


FIG. 7. Voltage-time profiles for two nearly identical shock experiments on W3N silver foils.