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Shock Compression Measurements at Pressures >1 TPa*

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ABSTRACT

A nuclear explosive generated planar shock has been used to perform impedance-matching experiments relative to a molybdenum standard. Shock velocities were measured with accuracies of 1.5% to 2.5%, thus providing Hugoniot data for samples of Al, quartz, Fe, Mo, and low-density Mo at pressures from 2 to 5 TPa.

INTRODUCTION

In the past few years, we have developed several techniques[1-4] for obtaining ultrahigh pressure equation-of-state (EOS) data using underground nuclear explosions. In an absolute measurement at the beginning of the program, we determined[1,2] a Hugoniot point for molybdenum at 2.0 TPa. The calculated Hugoniot based on the SESAME EOS library[5] agreed with the measurement, thus providing increased confidence in the theoretical molybdenum EOS. In a subsequent impedance-matching experiment,[3,4] we used a planar, stable shock to obtain a Hugoniot point for uranium at 6.7 TPa relative to the molybdenum standard; differences from predictions[5] stimulated improved theoretical treatments.[6] The present experiment was fielded to utilize this previously demonstrated[3,4] technique in order to obtain ultrahigh pressure Hugoniot data for a variety of sample materials: a similar experimental setup with several improvements was used.

EXPERIMENTAL SETUP AND RESULTS

The sample arrangement is shown in Fig. 1. The shock passed from the lead base plate through the molybdenum standard and into seven sample stacks. This package was located $\sim$3 m from the nuclear explosive, and detailed Monte Carlo calculations were used to optimize the shielding to reduce the neutron and gamma radiation.

An array of 75 electrical contact pins[3,4] was used to determine shock-arrival times. Sixteen pins were embedded in the molybdenum standard, three to five pins were embedded in each of the small samples, and four pins were embedded in the lead driver. The pins were separated by 1 to 3 mm in the vertical direction and were positioned horizontally to avoid rarefactions. Five pins were multiplexed onto each cable, and different decay times were used to provide a unique signature pulse for each pin. The signals were recorded on sets of oscilloscopes that provided coverage for 2 to 3 µs with a 100-MHz sine-wave time base. The signal quality for 25 of the pins was excellent, and shock-arrival times were determined with ±1-ns uncertainties. The remaining pins produced lower quality signals and uncertainties of 3 to 10 ns were assigned to the closure times.

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DATA ANALYSIS AND CONCLUSIONS

The data analysis procedure involved a sequence of several hundred least squares fits of the function $t = t(x,y,z)$ to the pin coordinates and closure times using different functional forms for t. The results of these fits indicated that the shock velocity was decreasing slightly with z and that the shock front was curved. The effective radius of curvature was $\sim$2 m, and the corresponding outer-sample tile angle was $\sim 1^{\circ}$. Additional fits indicated that nonplanar effects were purely radial and that asymmetry about the z-axis introduced <6-ns variation in arrival time along a radius.

These results supported our procedure for determining shock velocities for different portions of the shock front by fitting various subsets of the pins. The results of these fits gave small values (consistent with zero) for the decrease in the shock velocities. In the previous experiment,[3,4] the shock velocities changed by <1% over 10 mm. We assumed a similar variation in this experiment and used changes of ±0.5% about the shock velocities at the centers of the samples. The resulting shock velocities[7] at the appropriate interface or sample center are summarized in Table I, which lists in columns one and two the sample materials (lower first) and the experimental shock velocities. For the molybdenum standard, an overall error of 1.5% that includes systematic effects has been assigned to the measured upper-surface value of 27.16 km/s. For the small samples discussed in this paper (except iron), the errors in the shock velocities from the fits were $\sim$1%; however, overall uncertainties of ±2% have been assigned to each of these velocities to include systematic effects. For the iron sample, an uncertainty of ±2.5% have been assigned to the measured shock velocity.

These measured velocities were used to obtain Hugoniot points based on impedance-matching analyses for each possible pair of samples. For the lower samples, the measured velocity at the upper surface of the molybdenum standard was used in the analysis. For each upper sample, the responding lower sample was treated as the standard material. For the molybdenum atop the aluminum, the measured shock velocity at the upper aluminum surface was used to determine a Hugoniot point. For the quartz and low-density molybdenum, the initial state in the corresponding lower

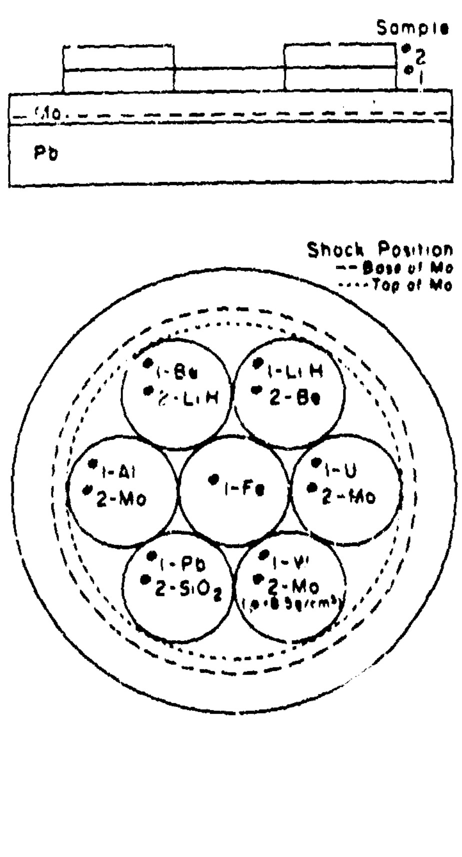

Fig. 1. Schematic drawing of the sample package showing the 180-mm-diameter by 12-mm-thick molybdenum standard, the 25-mm-thick lead driver, and the thirteen 10-mm-thick samples. These samples consisted of the indicated materials.

Table I. Comparison of Experimental and Calculated Results

Material	Shock Velocity (km/s) Experiment[b]	Difference[c](%) Old[d]	New[d]	Hugoniot Point[a] Pressure (TPa)	Particle Velocity (km/s)
Mo Std	27.16[+]	---	---	4.900(3.5)	17.67(2.0)
Al	34.39[*]	1.63	0.55	2.226(3.8)	23.89(2.7)
Mo	24.64[*]	-0.13	1.90	4.034(4.5)	16.05(4.3)
Pb	23.79[e]		---	4.723(--)	17.51(--)
Quartz	31.95[*]	6.66		1.693(4.3)	24.04(3.0)
W	22.12[e]	---	---	6.351(--)	14.87(--)
Mo[f]	24.28[*]	9.85	9.77	3.693(4.4)	18.35(3.4)
Mo Std	28.02	---	---		
Fe	30.48	-1.92	-3.48	---	---

[a]Based on measured shock velocities and the improved molybdenum EOS; percent errors in parentheses.

[b]Corrected for variation of $\pm 0.5\%$ across each sample: + = upper surface, * = lower surface. Uncertainties = 1.5 - 2.5% (see text).

[c]$(D_{th} - D_{exp})/D_{exp}$.

[d]Calculated results, "Old" from Ref. 5, "New" from Ref. 6.

[e]Calculated velocity for 1% lower velocity in the Mo standard.

[f]$\rho_0 = 8.29\ g\text{-}cm^{-3}$.

sample was calculated from the pressure in the molybdenum standard. In this calculation, the measured shock velocity of 27.16 km/s was decreased by 1% to account for the decay across the lower sample. These analyses were based on the SESAME EOS library[5] and on both the original and improved[6] molybdenum EOS (when appropriate). In addition, the shock velocity in each sample was calculated based on these theoretical EOSs; columns three and four give the differences (in %) between these calculated results and the experimental values.

For the aluminum-molybdenum pair and the iron sample, the differences between calculation and experiment are small; the improved molybdenum EOS gives slightly better agreement, but for either, the EOSs for these samples from the SESAME library[5] are in good agreement with experiment. The calculated and experimental results for the quartz and low-density molybdenum samples differ by more than the experimental uncertainties.

Table I also gives the experimental Hugoniot points and percent errors for the samples. The appropriate shock velocities were used to determine the intersection point in the P-u plane of the straight line $P = (\rho_0 D)u$ with the reflected shock (RS) Hugoniot or the release isentrope (RI) of the lower standard material. The initial state of the standard was determined as described above, and the upper-sample results are based on the assumption that the SESAME EOSs for the lower samples are correct. The errors in parentheses correspond to the quoted uncertainties in the shock velocities. Both the original and improved EOSs for molybdenum were used in this analysis; however, the results given in the table are for the improved molybdenum EOS.

Details of the analysis are illustrated in Figs. 2 through 4. For each sample, the region of interest is shown on an expanded scale with a circle around the experimental point and a large dot (●) indicating the theoretical point. The regions of uncertainty are not indicated in the figures, but errors are given in Table I.

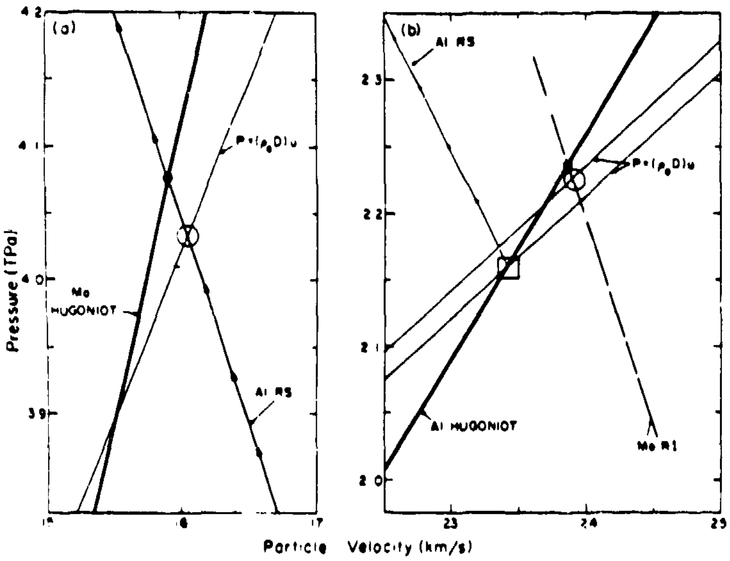

Fig. 2. Plots in the P-u plane comparing the theoretical Hugoniots (heavy curves) for (a) Mo and (b) Al with the experimental points (circled) for the Al-Mo stack. For Al (b) this point occurs at the intersection of the Mo release isentrope (RI, large dashes) with the upper line labeled $P = (\rho_0 D)u$. The theoretical point is indicated by the large dot (●). The two lines labeled $P = (\rho_0 D)u$ correspond to $\pm 0.5\%$ variations of the shock velocity across the sample (see text). The initial state in the Al is enclosed in the box, and the reflected shock (RS) Hugoniot from this point is indicated by arrows (→). The Hugoniot point for the Mo sample occurs in (a) at the intersection of this RS Hugoniot with the line labeled $P = (\rho_0 D)u$.

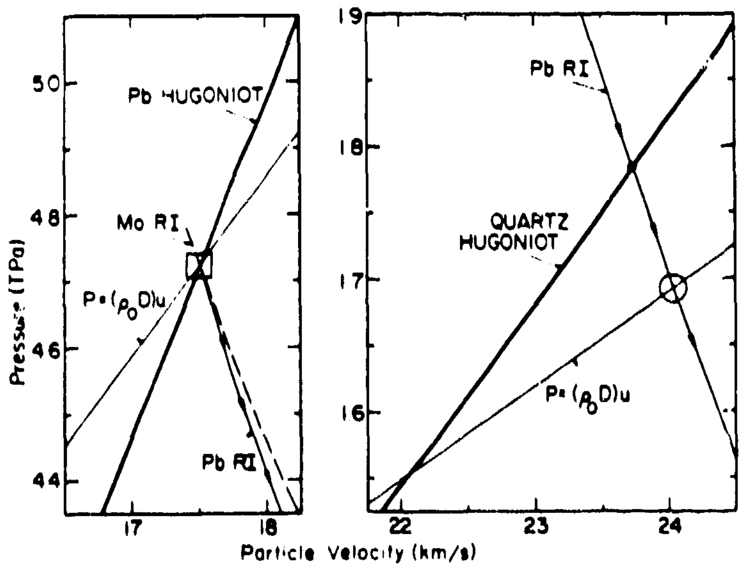

Fig. 3. Hugoniot point for the quartz atop the lead sample (see Fig. 2 for notation). a) The initial state in the lead was calculated using SESAME (see text), and the RI from this point determines a Hugoniot point (circled) for quartz in (b) that is 5.1% lower in pressure than that predicted by SESAME (large dot).

This experiment provides Hugoniot data that can be used as bench marks for checking the consistency of theoretical EOS calculations. The theoretical EOSs for aluminum, iron, and molybdenum in the SESAME library[5] are in good agreement with these data. The discrepancies for the quartz and low-density molybdenum are larger than the experimental errors and indicate the need for improved theoretical treatments. Such improved theories should provide additional insight into the physics at these extreme conditions.

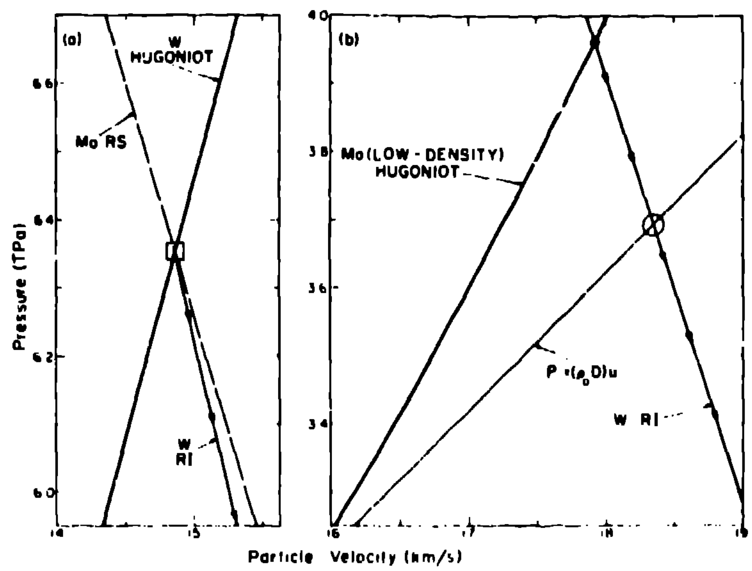

Fig. 4. Hugoniot point for the low-density molybdenum (ρ_0 = 8.29 g-cm^{3}) atop the tungsten. The initial state in the tungsten (a) was calculated using SESAME (see text). b) The derived Hugoniot point (circled) for the low-density molybdenum lies ~6.5% lower in pressure than the SESAME, value (large dot).

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