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MASTER

URANIUM SHOCK PROPERTIES

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Work Done By:
Group GMX-6

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I Low Pressure Shock Properties of Uranium - J. W. Taylor.

Some further work has been done on the low pressure hydrodynamic behavior of uranium. Three shots have been fired in addition to the ones reported last month in GMX-6-510 and, where possible, all records have been analyzed for rarefaction sound speed data. Table I is a recapitulation of Table I of GMX-6-510, p. 74 plus the new data.

Figure 1 is a set of plots of target free-surface velocity versus time for three shots in which the target thickness was constant but the pressure was radically different. It may be seen that the "elastic" precursor has a very poorly defined starting point and that the free-surface velocity rises very gradually as the plastic shock approaches. Figure 2 is a similar set of curves for a thicker set of targets. It will be noted that the stronger shocks appear to "leak" forward into the elastic-plastic transition zone with the result that the slope of the curve behind the arrival of the elastic front depends on the magnitude of the following plastic shock.

This sort of behavior supports the general phenomenological stress-relaxation-with-viscosity model which appears to fit most metals if parameters are properly chosen. The general features of this model were reported in some detail by R. G. McQueen in GMX-6-484.

Figure 3 is a complete record from shot 56146, in which one can see the free-surface deceleration which ultimately results when the

TABLE I

Shot No.	Projectile Velocity (mm/ μ sec)	Target Thickness (inches)	C_L (mm/ μ sec)	U_s (mm/ μ sec)	U_{fs} (Final) (mm/ μ sec)
56142	0.317	1.003	3.45	2.54 ± 0.02	0.110 ± 0.010
56144	0.390	1.0029	3.54	2.80 ± 0.02	0.395 ± 0.005
56145	0.105	1.0038	3.48	2.60 ± 0.02	0.099 ± 0.001
56146	0.525	0.5035*	3.52	2.91 ± 0.02	0.520 ± 0.010
50148	0.660	0.5050	3.54	3.05 ± 0.02	**
56150	0.849	0.5034	3.4	3.1 ± 0.02	0.855 ± 0.010
56151	0.152	0.5055	3.43	2.50 ± 0.02	0.130 ± 0.005
56152	0.267	1.0032	3.32	2.71 ± 0.02	0.270 ± 0.010

*Note error in GMX-6-510

**Record not suitable to quantitatively determine the free-surface velocity.

shock in the uranium driver is released into the Duralumin projectile. The deceleration is followed by a second gradual acceleration which must result from spalling of the target plate in the rarefaction interaction zone. This spalling is almost certainly not equivalent to the "ultimate yield" spalling reported for copper by McQueen and Marsh (J. Appl. Phys., 33, 654 (1962)). It is more probably produced by the "imperfection induced brittle fracture" discussed briefly by them and reported in some detail by authors quoted by them. Recent work (J.H. Smith, "The Three Low Pressure Spall Thresholds in Copper", ASTM Meeting in Albuquerque, N.M., Sept. 28, 1962) indicates that this brittle fracture in copper obeys a sort of tension-time "reciprocity law" wherein specimens subjected to greater tension require less time to spall. It is probably significant that the net decrease in target free-surface velocity after the arrival of the second compression wave is essentially independent of the initial shock pressure and amounts to about 0.02 to 0.03 mm/ μ sec.

Rarefaction sound speeds can be obtained from records similar to Fig. 3 by choosing the first instant of observable deceleration of the free surface and then doing a numerical or graphical construction of the position-time history of waves in the target and driver.

The analysis for the velocity of the leading disturbance depends primarily on an assumed velocity for dilational waves at zero pressure and is inexact only to the rather trivial extent that the complete details

of the interaction of two rarefaction characteristic fans are not known. Figure 4 is a sketch of the analysis for shot 56146. The results of the analyses (Fig. 5) are in complete general agreement with the findings of Al'tshuler, et al., for lead, iron, aluminum and copper (J. E. T. P. (U. S. S. R.) 38, 1061-1073 (1960)). The leading disturbance is propagated at a velocity, C_R , consistent with the formula

$$C_R^2 = C_B^2 + \frac{4}{3} \mu V$$

where $C_B^2 = \left(\frac{\partial P}{\partial \rho} \right)_S$ from the hydrostatic equation of state deduced by McQueen and Marsh from the high pressure data (GMX-6-401, R. G. McQueen and S. P. Marsh), μ is the Lamé rigidity modulus, and V is the specific volume at the pressure of interest. This relationship has been derived by Walsh (GMX-6-443), Al'tshuler, et al. The present data indicate that for our samples, μ may be regarded as a constant up to 250 kilobars at least. Unhappily, the elastic-plastic transition zone cannot be observed in this type of experiment, primarily because the metal apparently spalls and ceases to propagate tension waves before the "bulk" rarefaction waves have a chance to interact. The gradual rise of the free surface velocity profiles at very low pressures may readily be responsible for the otherwise inexplicably low rarefaction-sound-speed data obtained below 50 kilobars, and it should be interesting to know whether such a condition prevails when a fifteen or twenty kilobar shock is driven into a material which is already at two or three hundred kilobars pressure.

A new type of experiment which will be attempted in the near future is to measure the velocity of a weak reflected shock rather than a rarefaction. The shock will be reflected from a sintered tungsten plate which will back up the uranium driver plate on the projectile. Tungsten appears to be sufficiently stiffer than uranium that we may expect an additional fifteen or twenty kilobar shock at two hundred and fifty kilobars initial shock pressure in the uranium. It is hoped that the results of this experiment will contribute to the understanding of a (stress-strain) relaxation model for uranium.

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Fig. 1. Free-surface velocity versus time for three shots with half-inch targets.

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Fig. 2. Free-surface velocity versus time for three shots with one-inch targets.

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mm/ μ sec

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Fig. 3. Free-surface velocity versus time for shot 56146. The arrow shows the time chosen as the arrival of the first rarefaction signal.

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SHOT 56146

cas π / mm

0.6

0.4

0.2

0

3

4

5

TIME (μ sec)

6

7

8

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Fig. 4. Graphical solution for the rarefaction wave velocity in shot 56146. The target-projectile thickness ratio was two to one. The ordinate of the graph is time measured from collision time. The abscissa is Eulerian position coordinate. The projectile velocity (slope (1-2) is known, as are the free-surface velocity (3-5) and the shock velocities (0-2), (0-3) and the rarefaction velocity in the zero pressure medium (4-5). The tail C-characteristic, (3-4) is assumed to coincide with the low pressure extrapolation of McQueen and Marsh's high pressure data, and it is known that the rarefaction signal from the uranium-dural interface must begin at (2) and end at (4). One does not know much about its behavior between (4) and (6) but evidently a straight line is not a bad assumption. The rarefaction sound speed is the slope of the line (2-6) minus the shock particle velocity.

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Fig. 5. Rarefaction sound speed versus shock pressure. The dotted curve was computed by McQueen and Marsh (GMX-6-401). The solid curve was computed from the dotted curve, the zero pressure elastic wave velocity, and the assumption that μ is constant. The lowest pressure data points do not have large apparent uncertainties but are inconsistent with the low pressure compressive elastic wave velocity. This is probably due to smearing of the actual initial wave beyond recognition.

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II Reflected Shocks in Uranium - J. W. Taylor.

An experiment has been performed with the 6-1/2 inch diameter cannon, using the capacitor technique, to observe a reflected shock in uranium. The essential features of the experimental geometry are shown in Fig. 1. A one-inch thick uranium target was impacted at a velocity of 0.385 mm/ μ sec

Fig. 1

by a one-half-inch thick uranium plate backed up by a one-quarter-inch tungsten plate. This projectile velocity is sufficient to produce a 100 kbar shock in uranium. The hydrodynamic impedance of tungsten is sufficiently higher than that of uranium that a 100 kbar shock in uranium should reflect a 125 kbar shock.

It has been shown by us at low pressures and by Al'tshuler et al. at high pressures (Soviet Physics JETP, 11 766 (1960)) that rarefaction waves into compressed metals consist of a fast moving small amplitude component which travels at a "high pressure longitudinal sound speed" and a slower component which corresponds essentially to a "rarefaction fan" of characteristics with sound speed given by $(\partial P / \partial \rho)_s^{1/2}$. It is not obvious, however, that a differential compressive disturbance will have a high-velocity component. Fowles (Poulter Laboratories Tech. Rept. 011-60) argues on the basis of

his data for 2024 Duralumin that this material appears to exhibit no time dependent effects and behaves as if the Hugoniot at low pressures were offset by a constant yield stress from a true hydrostatic curve (see Fig. 2). If this were true for uranium it would imply that no compressive signal could be propagated at longitudinal sound speed, whereas a rarefaction could. If, on the other hand, the metal behind the first shock has relaxed to a state very close to hydrostatic equilibrium, one knows from such facts as the existence of a high longitudinal sound speed in the Earth's mantle that an additional compressive disturbance may be propagated faster than bulk sound speed. The situation is represented schematically in Fig. 2.

The free-surface velocity of the uranium target measured on the shot is shown in Fig. 3. The first elastic wave arrives at point C. The portion of the plastic front which corresponds to a shock velocity of 2.82 mm/ μ sec (measured independently on the same shot with pins) is point E. The first reflected disturbance from the tungsten arrives at point J and the "center" of the main secondary disturbance arrives at point K.

The data represented by these points, together with implied points at the uranium-tungsten interface in the driver assembly and the conclusions to be drawn therefrom are shown in the Eulerian x-t plot of Fig. 4. Admittedly the shocks are by no means sharp in the real experiment, nor are the rarefaction waves centered simple waves.

It can readily be seen, however, that a more accurate consideration of the facts will not materially affect conclusions about the first disturbance. The details of the analysis are given in the figure caption. The conclusion is that a signal from the tungsten-uranium interface must have traveled at approximately $3.54 \text{ mm}/\mu\text{sec}$ relative to the shocked uranium in order to reach the free surface at time J. This is to be compared with the calculated "bulk" hydrodynamic sound speed of $2.90 \text{ mm}/\mu\text{sec}$ in uranium at 100 kbars. We conclude therefore that the uranium Hugoniot is not displaced from the hydrostatic curve by the ultimately tolerable one dimensional stress.

The first shock front is so wide that it is no doubt useless to speculate on the meaning of the shape of the differential pressure-pulse, but the similarity of the whole pulse to the very low pressure data published in GMX-6-514 raises a suspicion that the whole yielding process must be undergone all over again. This raises various questions such as whether a series of successively higher shock pressures would ever actually steepen into a single shock as predicted by simple theory.

It may be worth noting that the peak differential velocity amplitude in the reflected pulse is slightly less than that expected from an impedance match solution at the uranium-tungsten interface. This is reasonable since the rarefaction from the back of the tungsten has begun to cut down the shock.

Fig. 2. Schematic of alternate hypotheses concerning the behavior in the P,V plane of a shocked material. In the time independent model any shock of strength greater than A, the Hugoniot elastic limit, would send the metal to a state such as B which is above the hydrostatic curve OD by the dynamic yield stress. Any subsequent compressive disturbance would be forced along line BE, parallel to OD at that point and would propagate at the high pressure bulk adiabatic sound speed $(\partial P / \partial \rho)_s$. A dilatational disturbance would have at least a component along line BC propagated at a high pressure longitudinal sound speed.

According to the relaxation model, the material when shocked to state B would relax to some point such as D on the hydrostatic curve. Subsequent compressive and dilatational disturbances will be propagated along line EF, both initially at longitudinal sound speed.

P

Fig. 2

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Fig. 3. Free-surface velocity record from Shot 56-167. The points labeled with letters correspond to the same labeled points of Fig. 4.

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Fig. 3

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Fig. 4. Analysis of data from Shot 56167. The x-t plot is in Eulerian coordinates. The uranium collision interface is indicated by a dotted line. The important regions of different mass velocity are so labeled. The target is in the left, the warhead backed up to tungsten on the right. Lines AC, AB are "elastic" waves. Lines AE, AD are the plastic shocks. Note that in fact the shock is somewhat smeared but that the resultant family of arrival time rays would be relatively small in this diagram. Line CFG is the "elastic rarefaction" which is known to exist from data obtained previously (GMX-6-514). The rarefaction from the bulk shock is treated as a centered simple wave although in fact it should be uncentered with the tail C^+ characteristic occurring near point J. Neglect of this fact is also within other experimental uncertainties. The first reflected disturbance to arrive at the free surface is seen at point J and is required to have passed through point H because we know the maximum possible signal speed in the uncompressed medium. We now ask at what speed a signal must have propagated from B to H. The result is 3.54 mm/ μ sec and this definitely establishes its essentially longitudinal character, since the bulk sound speed $(\partial P / \partial \rho)_s^{1/2}$ is 2.9 mm/ μ sec. Note the line JH and BH are so nearly colinear that errors in the nature of the rarefaction wave due to shock dispersion are quite trivial.

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Figure 1 is a graph showing the time t (in μsec) versus distance x (in mm) for the propagation of a shock wave in a tungsten-uranium system. The graph includes several curves labeled "TAIL C^+ " and "LEAD C^+ ", and a dashed line labeled "SLOPE = 3.73 (3.54 + 0.19) $\text{mm}/\mu\text{sec}$ ". The graph is divided into regions labeled "P=0" and "P=100".

Key points and labels on the graph include:

- Y-axis:** t (μsec) with major ticks at 0, 5, 10, and 15.
- X-axis:** x (mm) with major ticks at 30, 20, 10, 0, and 10.
- Regions:**
 - $P=0$, $U_p=0$ (bottom left)
 - $P=100$, $U_p=0.192$ (middle)
 - $P=125$, $U_p=0.24$ (top right)
 - $P=0$, $U_p=0.384$ (bottom right)
- Curves:**
 - "TAIL C^+ " (upper set of curves)
 - "LEAD C^+ " (lower set of curves)
 - A dashed line with slope 3.73 (3.54 + 0.19) $\text{mm}/\mu\text{sec}$
- Points:** A, B, C, D, E, F, G, H, J.
- Material Labels:** "TUNGSTEN" (top right) and "URANIUM" (bottom right).
- Units:** "P (kilobars)" and " U_p ($\text{mm}/\mu\text{sec}$)".

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