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TITLE BROMOFORM ($CHBr_3$) - A VERY HIGH-PRESSURE SHOCK-WAVE ANALYZER

AUTHOR(S) R. G. MCQUEEN
D. G. ISAAK

SUBMITTED TO 1989 APS TOPICAL CONFERENCE ON SHOCK COMPRESSION OF CONDENSED MATTER, 14-17 AUGUST 1989, ALBUQUERQUE, nm

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

BROMOFORM ($CHBr_3$) -- A VERY HIGH-PRESSURE SHOCK-WAVE ANALYZER*

R.G. MCQUEEN and D.G. ISAAK

Los Alamos National Laboratory, Los Alamos, NM 87545 USA

Bromoform, $CHBr_3$, appears to radiate like a black body. This means that the amount of radiation emitted from the shock front is extremely sensitive to temperature and hence even more sensitive to pressure. This feature has been exploited to locate overtake waves in impact experiments. Heretofore, bromoform was used only for making timing measurements. However, if its P, V, E, and T EOS are known it could be used as a high-pressure analyzer. Measurements to determine the Hugoniot, the Grüneisen parameter, γ, and its optical radiation characteristics are described, and preliminary data are presented.

1. INTRODUCTION

Experiments to determine rarefaction wave velocities in opaque materials using optical detectors have been done for several years. The technique[1] detects rarefaction waves in materials by using $CHBr_3$ or some other transparent material placed in front of them that radiates when shocked. The material of interest is made several thicknesses so that the rarefaction catchup wave occurs at different levels in the analyzer. Since the location where the shock and rarefaction both reach the material-bromoform interface at the same time, giving the overtake ratios for the material, the EOS of the analyzer is immaterial.

However, the records of the radiation history obtained in these experiments contain considerable information on the elastic-plastic flow behavior of materials at pressures not possible to record with currently available gauges. To date, this technique has been used successfully on materials shocked into the multi-megabar regime. At low pressure there are several techniques that can resolve the rheology of small-amplitude stress waves. However, there are some low-pressure, a few 10s of GPa, experiments that require the time resolution available in these optical experiments. An example of this is the record shown in Fig. 1 where the detonation wave in 9404 HE interacts with $CHBr_3$. A replica of the reaction zone and Taylor wave can clearly be seen. If a more complete EOS of the analyzer were known a Lagrangian 1-D hydrocode could be used to model the reaction zone in the explosive.

There are many materials that could be used as an analyzer. Two features make $CHBr_3$ the material of choice: 1) it is a liquid, which means that it will exhibit hydrodynamic behavior, free from elastic-plastic behavior of its own; and 2) its density, 2.87 g/cm^3, is probably the highest of any liquid that is easily handled.

*This work was supported by the US Department of Energy

2. EXPERIMENTAL TECHNIQUES

The experiment is to impact $CHBr_3$ with a metal driver and to measure the location where the rarefaction from the back surface of the driver overtakes the shock wave in the $CHBr_3$. To do this it is necessary to hold the target plate horizontal and impact it from above without any intervening material, which would detract from the inherent precision. This also allows us to make the measurements over as long a distance in the target as possible. Because it is very compressible, the driver, D, to target, T, catchup ratios, R_a = D/T, of the systems, are quite small, as

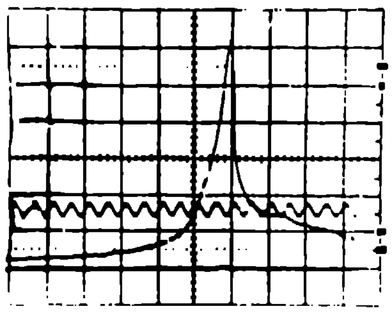

FIGURE 1
An oscilloscope record of the radiation coming from 9404 HE and bromoform. The initial increase in the radiation comes from the shine through in the translucent HE. The decay represents a replica of the reaction zone of the HE. Excellent time resolution (~1 ns) can be obtained in these measurements because there are no perturbations introduced by the gauges, but they must be analyzed through the behavior of the $CHBr_3$.

are the target thicknesses in the higher pressure experiments. The experiments to be described are Hugoniot, sound velocity, and radiation measurements.

2.1 Hugoniot Measurements

A cross-sectional view of the assembly used to determine the particle velocity, U_p, and shock-wave velocity, U_s, velocities is shown in Fig. 2. A similar system, without the $CHBr_3$ and mylar film, was used to

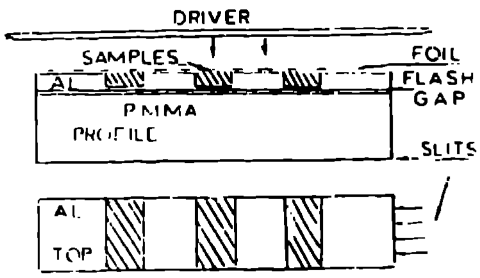

FIGURE 2

The reservoirs for the differential shock velocity measurements were made from 6061-Al, were ~25-mm wide, and were held flat on the Plexiglas block with double stick tape and glue. The grooves were from 2.5 to 5.0-mm deep and covered with a 5-μm film.

determine the driver velocity, U_D. The shock arrivals were recorded with a sweeping image camera. The Hugoniots of 316-SS and 6061 Al used to calculate the Hugoniot data and sound velocities were

$$U_s = 5.29 + 1.376\ U_p \tag{1}$$

$$U_s = 4.48 + 1.151\ U_p \tag{2}$$

Respective densities used were 2.703 and 7.93 gm/cc. Our data, along with Ramsay's[2] and Sheffield's,[3] are shown in Fig. 3. The high pressure data are adequately described by the relationship

$$U_s = 1.50 + 1.38\ U_p \quad . \tag{3}$$

2.2 Sound Velocity Measurements

The type of assembly used to measure the overtake position is shown in Figs. 4 and 5 and a record obtained with it in Fig. 6. The sound velocities were calculated from R_s, through the equation[1]

$$\frac{1}{C_T^L} = \frac{1}{U_T} - \frac{1}{R_S}\left[\frac{1}{U_D} + \frac{1}{C_D^L}\right] \quad . \tag{4}$$

Here, C^L ... the Lagrangian sound velocity calculated by finding where the lead characteristic of the rarefaction wave intersects the shock locus in the bromoform. T and D refer to the target and driver, respectively. The U's are the shock wave velocities. The sound velocity of the SS and Al needed for this analysis were based on other overtake experiments.[4,5]

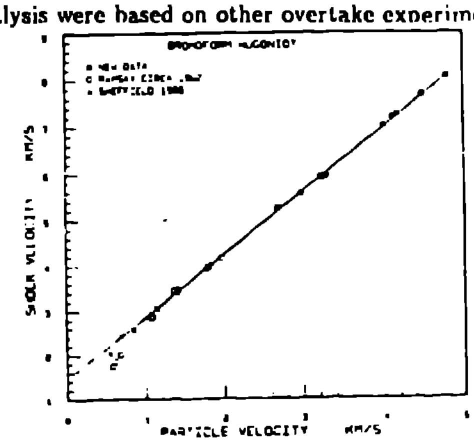

FIGURE 3

Our U_s-U_p bromoform data and earlier results by Ramsay[2] and more recently, Sheffield.[3] Ramsay observed a loss of transparency below 10 GPa. The kink in this curve occurs at ~13.5 GPa.

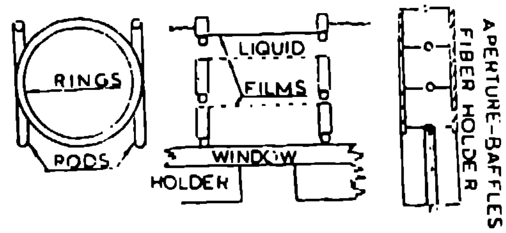

FIGURE 4

An assembly used for obtaining the sound velocity. In principle, the position where the rarefaction wave caught the shock wave could be calculated from the shock velocity in $CHBr_3$. It can also be found independent of time. To do this, 5-μm-thick mylar films with a partial light-absorbing deposition were placed in the liquid. Each rod-ring-mylar assembly was glued together separately and measured. The mylar was first stretched and the rings glued to it and then the rods to the rings. The rods not only allow the bromoform to fill the system but offer the minimum bearing surface for optimum precision support of the rings. These subassemblies were then glued in sequence from the transparent window upward. The total thickness from the bottom of the window to the top of the rods was recorded at each step. The top ring, which holds the opaque film, prevents the bromoform in the reservoir from coming on to the film. Because of the problem of the bromoform bulging the upper mylar, the upper subassembly was made as thin as possible thus making the spacing between it and the next film as large as possible. This large separation was used to establish the distance reference. The radiation falls on light pipes that transmit it to PMTs.

Since for metals the sound velocity on the Hugoniot is nearly equal to the shock velocity,[6] we have determined a small correction term to obtain the longitudinal sound velocity, C_L, from the shock velocity through the equation

$$C_L = [1.22 - 0.02\, U_P] U_s \quad . \tag{5}$$

With the Hugoniot and sound velocity, the Grüneissen parameter, γ is obtained from

$$\gamma = \frac{\{(dP/dV)_H - (dF/dV)_s\} 2V}{P_H + (dP/dV)_H (V_o - V_H)} \tag{6}$$

where the derivatives are along the Hugoniot, H, and isentrope, s.[7] When the Hugoniot is given by the linear U_s-U_p relation and the compression, η, by

$$\eta = (V_o - V)/V_o \quad . \tag{7}$$

equation (6) becomes

$$\gamma = \frac{[(1 - S\eta) - R^{*2}(1 - S\eta)](\rho_o/\rho)}{S\eta^2} \quad . \tag{8}$$

R^* in the above, Eq. 8 is defined as

$$R^* = (R + 1)/(R - 1) = C^L/U_s \quad . \tag{9}$$

R in Eq. (9) is the catchup ratio in bromoform for a symmetrical impact. An unexpected complication was encountered in the higher pressure experiments. The R_s increased from ~2.5 to something over. This behavior is typical when shocking a metal over its melting point where the head of the rarefaction wave then travels at its characteristic bulk velocity instead of the longitudinal velocity. This situation does not exist for our measurements. What we believe happens is that the driver melts after impact with the $CHBr_3$. The shock pressure is not high enough to melt the SS although its temperature is quite hot. However, $CHBr_3$ is extremely [illegible] and we believe that the thermal conduction from it to the driver is sufficient to melt the driver. The problem now is we do not know how much of the driver [illegible] melted so that the correct [illegible] [illegible] velocity [illegible] be calculated on the transm[illegible] through the [illegible]. We have [illegible] the bulk [illegible] for SS [illegible] the R*BROM [illegible] those experiments [illegible] [illegible] provide [illegible] upper bound [illegible] results of the [illegible] experiments are given in Table I.

TABLE I.

Ud	Up	Us	P	RHO	Rsys	Rbrom	C	Ga
-4.63	2.69	5.24	40.5	5.90	2.09	2.90	5.24	0.63
-5.12	2.98	5.55	47.5	6.20	2.94	4.39	4.09	1.26
-5.60	3.22	5.91	54.6	6.31	2.14	2.86	5.59	0.75
-6.00	3.29	5.94	56.1	6.43				
-6.00	3.26	5.91	55.3	6.40				
-7.13	4.01	7.00	80.6	6.72	2.26	2.92	6.11	0.85
5.68	4.12	7.18	84.9	6.73	2.73	2.15	8.37	0.74
5.77	4.18	7.24	86.9	6.79	2.80	2.23	8.03	0.83
6.25	4.50	7.77	100.3	6.82	3.00	2.36	8.06	0.92
6.70	4.80	8.04	110.8	7.12	2.90	2.26	8.39	0.93

All velocties are in km/s, P in Gpa, Rho in gm/cc,
C is the bromoform sound velocity. Ga=V(DP/DE)v.
the - means the driver was 6061Al,all others 316SS.

2.3. Radiation Calibration Measurements

The radiation calibration can be as involved as measuring the temperature along the Hugoniot, which then could be used to determine the radiation properties of the bromoform, or one can just specify the radiation behavior relative to some standard as a function of pressure or some other Hugoniot parameter, e.g., U_p. The former case would be a major effort, but the latter procedure can be done with a minimum of equipment and only a bit more effort than doing an overtake measurement.

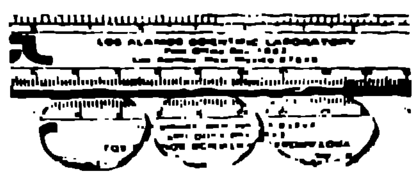

FIGURE 5
Photograph of a set of opaque films mounted on their support ring. This set is of very high quality as can be seen from their mirror quality. The measurement of the location of these films is the largest source of errors, and is estimated to cause ~2% uncertainty in any one determination of the overtake ratio.

With reference to Fig. 4, it can be seen that the optical components are quite simple. The holder is made so that only the radiation from the shock front passes through an aperture, 0.5–2.0 mm in diameter, to the fiber ~20 mm away. Thus, depending on the size of the apertures, which is determined by the amount of radiation expected, the signal is obtained from a relatively small area 1–3 mm in diameter. Since the radiation to be recorded is very sensitive to pressure, there must be some way to calibrate the system so that records can be obtained. We have used an inexpensive repetitively-pulsed xenon light source to establish the relative radiation from one experiment to the next. The one we used is called a Stroboslave,[8] which when coupled with an elliptical reflector, generates a pulse ~5-ms long every 10 ms with enough radiation to calibrate the most energetic experiments. In designing and setting oscilloscopes for an experiment it is necessary to estimate the amount of radiation to be expected. We have found it convenient to use the ratio of the radiation measured on the experiment to that measured from the light calibrator, see Fig. 7. Thus knowing the velocity of the driver, the relative amount of radiation to be expected is given by

$$I/I_{cal} = 10^{-3} \, | U_D^2 |^{3.8} \quad . \qquad (10)$$

As a calibration curve is established the pressure in the bromoform as a function of the relative radiation can also be determined.

FIGURE 6
Oscilloscope record showing the increase in radiation as the shock wave passes the thin films. A sharp decrease in radiation is observed before the rise because of the decrease in pressure or light transmission when the shock wave passes through the film. The decrease in radiation when the rarefaction overtakes the shock front is also easily identified. The marks clearly establish the distance (based on the assembly record) and the break gives the location of the overtake. The drivers were from 1 to 2 mm thick and were known to 3 μm.

One additional calibration is required; that is the response of the PMT to the light stimuli. This need only be done once for each PM system, and it can be done using the strobe light and neutral density filters. Thus, the voltage output on the record can be transformed to relative light intensity and the P vs I/I_{cal} function can be used to transform this to pressure as a function of time. A starting or reference pressure must be established from some other measurement on the experiment. The details of the flow can then be obtained as [illegible] above.

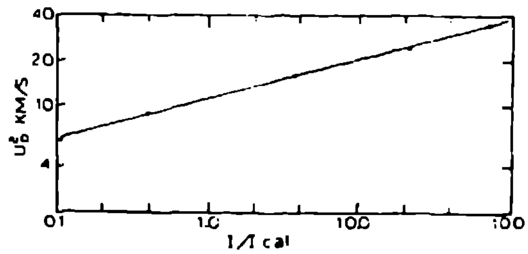

FIGURE 7
LOG-LOG plot of the square of the SS driver velocity vs the ratio of the voltage signals from the experiment and the calibrator.

SUMMARY

The Hugoniot of bromoform and the sound velocity on the Hugoniot are presented along with the calculated thermophysical parameter $V(dP/dE)_V$. Values of γ are good to about 10%. A rather simple procedure is described that can be used to make optical measurements with bromoform for elastic-plastic studies at very high pressure.

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