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TITLE  BROMOFORM (CHBr₃) - A VERY HIGH-PRESSURE SHOCK-WAVE ANALYZER

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BROMOFORM (CHBr₃) — A VERY HIGH-PRESSURE SHOCK-WAVE ANALYZER

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Bromoform, CHBr₃, 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. Therefore, 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 detects rarefaction waves in materials by using CHBr₃ 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 CHBr₃. 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 CHBr₃ the material of choice: 1) 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/cm³, is probably the highest of any liquid that is easily handled.

2. EXPERIMENTAL TECHNIQUES
The experiment is to impact CHBr₃ 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 CHBr₃. 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](image-url)
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 CHB\(_3\) and mylar film, was used to 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

\[
U_s = 5.29 + 1.376 U_p \quad (1)
\]

\[
U_p = 4.48 + 1.151 U_p \quad (2)
\]

Respective densities used were 2.703 and 7.93 g/cm\(^3\). Our data, along with Ramsay's\(^3\) and Sheffield's\(^3\) are shown in Fig. 3. The high pressure data are adequately described by the relationship

\[
U_s = 1.50 + 1.38 U_p \quad (3)
\]

2.2 Sound Velocity Measurements

The type of assembly used to measure the overlap position is shown in Figs. 4 and 5 and a record obtained with it in Fig. 6. The sound velocities were calculated from \( R_N \), through the equation

\[
\frac{1}{C_N} = \frac{1}{C_T} + \frac{1}{R_N} \left[ \frac{U_D}{C_D} + \frac{1}{C_K} \right] \quad (4)
\]

Here, \( C_K \) is the Lagrangian sound velocity calculated by finding where the lead characteristic of the rarefaction wave intersects the shock locus in the bromoform. \( T = 1 \) and \( D \) refer to the target and driver, respectively. The \( U_i \) 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 2**

The reservoirs for the differential shock velocity measurements were made from 6061-Al, were \( \sim 23\) 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-\( \mu \)m film.

**FIGURE 3**

Our \( U_D = U_p \) bromoform data and earlier results by Ramsay\(^3\) 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 CHB\(_3\). It can also be found independent of time. To do this, 5-\( \mu \)m-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, we have determined a small correction term to obtain the longitudinal sound velocity, \(C_L\), from the shock velocity through the equation

\[
C_L = (1.22 - 0.02 U_p)U_s.
\]

(5)

With the Hugoniot and sound velocity, the Grüneisen parameter, \(\gamma\) is obtained from

\[
\gamma = \frac{(dP/dV)_H - (dF/dV)_s)2V}{P_H + (dP/dV)_H(V_0 - V_H)}
\]

(6)

where the derivatives are along the Hugoniot, \(H\), and isentrope, \(s\). When the Hugoniot is given by the linear \(U_s - U_p\) relation and the compression, \(\eta\), by

\[
\eta = \frac{(V - V_s)}{V},
\]

(7)

the equation (6) becomes

\[
\gamma = \frac{(1 - Sn) - R^2(1 - Sn)(\rho_o/\rho)}{Sn^2},
\]

(8)

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

\[
R^* = \frac{(R + 1)/(R - 1)}{C^L/U_s}.
\]

(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 \(R\) 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 a characterstic bulk velocity instead of the longitudinal velocity. This situation does not exist for \(R\) measurements. What we believe happens is that the driver melts after impact with the CHBr3. The shock pressure is not high enough to melt the SS, although its temperature is quite hot. However, CHBr3 is extremely hot and we believe that the thermal conduction from \(\tau\) to the driver is sufficient to melt the driver. The problem now is we do not know how much of the driver melted so that the correct ratio \(\gamma\) can be calculated in the transition through the SS. We have found the best way to correct for \(\gamma\) in cases of large error is to use RHO and bromoform sound velocities. This correction provides the correct \(\gamma\) and results of the experiments are given in Table 1.

<table>
<thead>
<tr>
<th>(U_d)</th>
<th>(U_p)</th>
<th>(U_s)</th>
<th>(P)</th>
<th>(Rho)</th>
<th>(Rsys)</th>
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All velocities are in km/s, \(P\) in Gpa, Rho in g/wcc, \(C\) is the bromoform sound velocity, \(Ga\) = \(V_{OF}/DE\), 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.

\[\gamma = \frac{(dP/dV)_H - (dF/dV)_s)2V}{P_H + (dP/dV)_H(V_0 - V_H)}\]

\[\gamma = \frac{(1 - Sn) - R^2(1 - Sn)(\rho_o/\rho)}{Sn^2}\]

\[R^* = \frac{(R + 1)/(R - 1)}{C^L/U_s}\]
repetitively-pulsed xenon light source to establish the relative radiation from one experiment to the next. The one we used is called a Stroboslave, 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

\[ \frac{I}{I_{cal}} = 1.1^{-3} \left( \frac{U}{U_{cal}} \right)^{3.8} \]  

(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 (red 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 \( \mu \)m.

One additional calibration is required: that is the response of the PMT to the light stimuli. This need only be done once for each PMT system, and it can be done using the stroboscope light and neutral density filters. Thus, the voltage output on the record can be transformed to receive light intensity and the \( P \) vs \( 1/I \) function can be used to transform this to pressure as a function of time. A tabling or reference pressure must be established from some other measurement on the experiment. The details of the flow can then be obtained as described 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 \( V(dP/dE) \). Values of \( \gamma \) 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.

REFERENCES
5. Preliminary measurements of the shock-wave physics group, Los Alamos, NM.