Measurement of sound velocities and shear strength of cerium under shock compression

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Abstract. Sound velocity in shock-compressed cerium was measured over the pressure range of 35-140 GPa using the rarefaction overtake technique. Indicator liquids carbogal and tetrachloromethane were used. The samples were loaded with planar shock wave generators using powerful high explosives (HE). Luminescence of the liquid indicators was recorded by optical gauges based on photodiode “FD 256”. For the pressure range of 13-35 GPa, sound velocity was measured in cerium samples using the counter release method with manganin-based piezoresistive gauges. From the measured longitudinal and bulk sound velocities, Poisson’s ratio and shear strength of cerium were determined. The melting boundary on the shock Hugoniot was estimated. Experimental data is compared with calculation results.

1. Introduction
In addition to the basic parameters included in an equation of state, (pressure $P$, volume $V$ or density $\rho$, temperature $T$ and entropy $S$), the need often arises for information concerning the sound velocity $C_s$. Sound velocity is one of the values that characterizes the behavior of the substance under shock compression followed by release. In addition to the sound velocity, when creating a constitutive model for the deviator, knowledge of the shear strength of the material, or its resistance to plastic deformation, is required.

Interest in studying cerium is prompted by its very complicated phase diagram [1]. Because of its large volume collapse (occurs during the $\gamma$-$\alpha$ isomorphic phase transformation), it is expected that cerium will melt at very low pressures under shock compression. Therefore, one of the purposes of the work is to determine the melt boundary of cerium on the shock adiabat.

Upon melting, a substance will lose its allotropic properties. Thus, in an experiment, by recording the presence (or absence) of a difference between the elastic $C_l$ and plastic $C_s$ sound velocities over the shock wave (SW) pressure region where a material is expected to melt, it is possible to determine the lower and upper pressure boundaries of melting. As the difference between $C_l$ and $C_s$ is reduced, the Poisson’s ratio approaches a value of 0.5, which is typical of melting.

2. Indicator method of sound velocity measurement
Optical measurements of sound velocities were performed using the overtake method in conjunction with indicator liquids. The method is described in detail in [2]. To form shock waves in cerium
samples, SW generators were used. The SW generators used the explosion products from cylindrical HE charges (with a variety of power outputs) to accelerate thin impactors.

After the fast-flying thin plate impacts a baseplate, upon which resides a stepped sample of cerium, a rarefaction wave is formed from the “back side” of the impactor. The rarefaction wave passes through the impactor, baseplate, cerium sample, and into the indicator liquid. One objective of the experiment is a determination of the sample location, $X_{MAX}$, where the rarefaction wave overtakes the shock wave front. For a target with thickness $x$ less than $X_{MAX}$, a constant intensity of radiation will be recorded by the indicator liquid up to the moment that the first indication of the rarefaction wave appears. Afterwards, radiation intensity will begin to drop.

The indicator liquids carbogal ($C_8F_{16}$) or tetrachloromethane ($CCl_4$) were used. They have an initial density, $\rho_0$, of 1.86 and 1.58 g/cm$^3$, respectively. The luminescence of the indicator liquid (produced as a result of shock wave passage) was collected by 400 μm quartz-fiber light guides located above each sample step and recorded by optical signal transducers based on photodiode “FD 256.” The signals were recorded by oscillographs of the types Agilent (54642D, 54624A) and Tektronix (TDS 3054). Accuracy of time measurements for the arrival of the shock wave front in the indicator was no worse than ±2 ns. Knowing the thickness of each cerium sample step, it was possible to determine the shock wave velocity in each experiment.

Sound velocity in cerium was calculated by the formula:

$$C_r = X_{MAX} \left( \sigma \cdot (t_{SW} - t_{RW} + \frac{X_{MAX}}{D}) \right)^{-1}$$

where $\sigma$ is compression, $t_{SW}$ is shock wave arrival time at the surface of the sample, $t_{RW}$ is rarefaction wave arrival time at the surface of the sample, $D$ is the shock velocity in cerium, $X_{MAX}$ is thickness of the step when overtake occurs at the cerium-indicator interface.

Typical oscillograms obtained in experiments involving the measurement of sound velocity in a four-step cerium sample are presented in figure 1. Arrows mark the shock wave arrival times at the cerium-indicator liquid (carbogal) ($t_1$) interface and “overtake” ($t_2$) of the shock wave front by rarefaction.

Figure 2 presents a graph for determining the velocity of the isentropic wave of rarefaction in cerium. The graph plotted in figure 2 was based on the data presented in figure 1.

Calculations of the x-t diagrams simulating shock wave motion and rarefaction waves in impactor, baseplate and the cerium sample for determination of $t_{SW}$ and $t_{RW}$ in (1) were performed with using a hydrodynamic computer program produced by VNIIEF. The shock adiabat determined for cerium from [3] was used in the calculations. For the impactors and baseplates made of steel and aluminum, the authors used the standard EOS applied at VNIIEF.

**Figure 1.** Oscillograms of irradiation of shock wave front in $C_8F_{16}$ at $P_{Ce} = 96.5$ GPa behind cerium steps having thicknesses: a) 1.99 mm; b) 2.27 mm; c) 3.00 mm; d) 3.38 mm.
Table 1 presents the experimental data on the sound velocity in cerium obtained by the optical method. At pressures less than 40 GPa in cerium, the temperature of luminescence of the shock-compressed liquid indicator is close to the sensitivity limit of recording photodiodes. This limit is equal to about 2000 K. It is for this reason that the manganin pressure gauge method was used in determining sound velocities in cerium for pressures less than 40 GPa.

**Table 1.** Experimental data on measurement of sound velocity in cerium by optical method.

| Parameters of shock waves in cerium |
|------------------------------------|
| $D$, km/s | $U$, km/s | $P$, GPa | $\sigma$ | $C$, km/s |
|----------|----------|---------|---------|----------|
| 6.46 | 3.23 | 141.2 | 2.00 | 6.09 ± 0.31 |
| 6.46 | 3.23 | 141.2 | 2.00 | 6.02 ± 0.25 |
| 5.92 | 2.89 | 115.5 | 1.95 | 5.49 ± 0.21 |
| 5.85 | 2.82 | 111.3 | 1.93 | 5.59 ± 0.25 |
| 5.50 | 2.60 | 96.5  | 1.90 | 5.11 ± 0.17 |
| 5.37 | 2.52 | 91.3  | 1.88 | 5.23 ± 0.27 |
| 5.02 | 2.32 | 79.7  | 1.86 | 4.94 ± 0.18 |
| 4.21 | 1.80 | 51.1  | 1.75 | 4.26 ± 0.16 |
| 4.19 | 1.79 | 50.8  | 1.75 | 4.40 ± 0.26 |
| 3.65 | 1.47 | 36.2  | 1.68 | 3.94 ± 0.11 |

3. **Manganin pressure gauge method**

The experimental method used for measuring the sound velocities $C_L$ and $C_S$ in shock-compressed cerium is similar to that used in [4]. Cerium samples ~2 mm thick and 40 mm in diameter were made. They were mounted on a copper baseplate. Three manganin gauges were placed between the baseplate and the cerium sample. An HE charge formed a quasi-stationary shock wave profile with front dissymmetry of 0.05 μs or less over a diameter of ~ 70 mm in the baseplate. The manganin gauges recorded profiles of the direct shock wave and the rarefaction wave formed by the free surface of the sample. In order to measure timing of the direct shock wave motion and the reflected rarefaction wave in the sample, an electrocontact gauge was mounted on the free surface of the sample.
As illustration, figure 3 presents one of the oscillograms obtained from a recording of the stress profile in cerium.

![Oscillogram](image)

**Figure 3.** Oscillogram, which was obtained in experiment with recording of profiles of waves of loading and release in cerium. $\Delta P_{EL}$ is pressure jump in elastic wave of release.

The pressure profile “$P$” was calculated using a calibration of the electrical resistivity of manganin to the stress of shock compression.

Concurrent processing of the oscillograms recorded by pressure gauges and by electrocontact gauges, enabled a determination of the elastic and bulk sound velocities. Small corrections were made during the calculations. These corrections accounted for the thickness of the pressure gauge and the thickness of its insulation. Accuracy of the pressure measurements was $\pm 3\%$.

Poisson’s ratio $\nu$ can be determined from knowledge of the elastic wave velocity $C_L$ and plastic wave velocity $C_S$, and is given by the following relation:

$$\nu = \frac{3-(C_L/C_S)^2}{3+(C_L/C_S)^2}$$  (2)

Based on the experimentally-measured values of $C_L$, $C_S$ and $\Delta P_{EL}$, the values of dynamic yield strength $Y_g$ (shear strength) of cerium were determined using the following formula:

$$Y_g = \frac{1-2\nu}{2(1-\nu)} \Delta P_{EL}$$  (3)

Results of the experiments with determination of sound velocities in cerium using manganin gauges are shown in table 2. The experimental dependence of sound velocity in cerium on pressure is presented in figure 4.

| Baseplate | Ce sample |
|-----------|-----------|
| Material  | $U_f$, km/s | $P_f$, GPa | $P_s$, GPa | $\Delta P_{EL}$, GPa | $D_s$, km/s | $\rho_s$, g/cm³ | $C_L$, km/s | $C_S$, km/s | Poisson’s ratio, $\nu$ | $Y_g$, GPa |
| Cu        | 0.58       | 24.94     | 12.7      | 3.03 | 2.49 | 9.66 | 3.10 | 3.73 | 0.398 | 0.55 |
| Al        | 1.12       | 20.79     | 21.3      | 4.28 | 2.98 | 10.46 | 3.50 | 3.10 | 0.390 | 0.77 |
| Al        | 1.12       | 20.79     | 21.6      | -    | 3.00 | 10.48 | 3.71 | -   | -    | -    |
| Al        | 1.45       | 28.69     | 27.0      | 6.20 | 3.26 | 10.84 | 4.18 | 3.53 | 0.363 | 1.33 |
| Al        | 1.40       | 27.43     | 28.3      | 3.88 | 3.41 | 10.55 | 3.99 | 3.69 | 0.438 | 0.43 |
| Al        | 1.46       | 28.93     | 31.5      | -    | 3.45 | 11.09 | -   | 3.74 | -    | -    |
| Al        | 1.49       | 29.69     | 32.4      | -    | 3.49 | 11.14 | -   | 3.85 | -    | -    |
This figure also presents a calculation of isentropic sound velocity determined using the VNIIEF equation of state, as well as the zero pressure values of the longitudinal \( C_L = 2.40 \text{ km/s} \) and plastic (volume) \( C_S = 1.90 \text{ km/s} \) sound velocities obtained using the ultrasound method.

As one can see in the graph, the experimental data are in agreement with the calculation to within the measurement error. Based on the obtained data, the probable cerium melt phase transition occurs below a pressure of \( \sim 32 \text{ GPa} \). Additional experiments are needed to determine more accurately melt transition on the Hugoniot.

4. Conclusion
The optical analyzer technique at pressures of 35 GPa and greater showed a one-wave structure in the rarefaction behavior recorded in measuring the sound velocity in cerium. Comparing the rarefaction wave structure obtained by the optical method and the manganin gauge method, indicates that the upper boundary for cerium melting on the Hugoniot is below 32 GPa. Additional experiments are needed in order to obtain a more accurate determination of the cerium melt transition on the Hugoniot.

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6. References
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