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RADIATION TEMPERATURE IN SOLIDS UNDER SHOCK LOADING

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RADIATION TEMPERATURE IN SOLIDS UNDER SHOCK LOADING*

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ABSTRACT

This paper describes an experimental technique for measuring the temperature of a material under shock loading. Temperature measurements of shocked materials have not previously been obtainable, and therefore investigators of shock phenomena have been limited to expressing the equation of state of a shocked material in terms of the pressure, volume, and change in internal energy of the material. Temperature has been determined analytically on the basis of several theoretical assumptions. The new ability to measure temperature will not only provide a check against the theoretical determination of temperature but will also be useful in detecting melting along the shock Hugoniot and in checking the Hugoniot results against static predictions.

The new technique is based on the ability to measure the amount of thermal radiation emitted from a shock-heated surface supported by transparent material and detected by photoelectric devices capable of responding to a change that occurs within a few nanoseconds. Observations are limited to the sensitivity of the diodes which covers some of the visible and part of the near infrared energy spectrum.

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Experiments were performed on some metals near their melting region, in particular on magnesium in the pressure range 350-550 kbar which should yield temperatures between 1600 and 3000°K. Results indicate that observed temperatures of polycrystalline samples are considerably higher than temperatures estimated on the basis of equilibrium thermodynamics and depend strongly on wavelength in a time-dependent manner. A theoretical model based on nonuniform heating at high shock pressures can be used to explain the observed temperature behavior.

INTRODUCTION

The equation of state of condensed materials at high pressures and under dynamic loading is presently expressed in terms of pressure, specific volume, and change in internal energy. There has been no means of measuring the temperature of the material under these conditions, so it is evaluated theoretically in accordance with certain models and assumptions. An experimental verification of the theoretically determined temperature is considered to be of great interest not only because it will bring out the third of the three fundamental parameters for the equation of state, but also because it will provide an independent check of the theoretical assumptions.

The experimental measurement of temperature should also yield a better insight into the problem of melting under shock loading. Since the solid-liquid phase line and the shock Hugoniot in the temperature-pressure plane intersect at an appreciable angle, the two-phase region of the material should appear rather distinctly between the two abrupt changes in the slope of the Hugoniot. This should also verify the prediction of the melting region now available only from the static data at lower pressure.

Since under dynamic loading conditions the changes of state occur at an extremely fast rate, one is limited to experimental techniques that can respond to such changes with a minimum of distortion and delay. We have accordingly chosen the optical technique which can give us the absolute temperature from the measurement of the amount of thermal radiation emitted from a surface of a shock-heated sample.

When the sample material is transparent there is the advantage that its radiation may be observed through a layer of the same material which has not yet been affected by the shock. However, the transparency has a disadvantage in that one does not get the full amount of radiation corresponding to its temperature until the thickness of the compressed layer reaches the characteristic optical thickness of that material, i.e., when the shocked layer becomes opaque. This type of temperature measurement has already been done by a group of Russian investigators who reported the temperature of several alkali-halide crystals¹ and some liquid compounds.² Their results show in general a good agreement with the theory but only in and near the melting region of the material. Their deviations from theoretical predictions in other regions are attributed to the complex electronic behavior under shock compression.

When the material is not transparent then the problem becomes somewhat more difficult in that the observation is limited to the outside surface of the material which when free and unbounded is by definition never under pressure. In this case one measures the so-called residual temperature of the material, after it has been shocked and released back to zero pressure. Such measurements have been performed by Taylor³ and by King et al.⁴ and the residual temperature of Cu was found to agree within the experimental error with that predicted by the theory.

However, this information does not give shock temperature nor does it provide sufficient data to locate melting along the Hugoniot.

In order to measure temperature in the nontransparent materials under pressure one must hold that pressure by a backup transparent anvil whose own properties are such that the contribution to the amount of radiation are either nil or known. The purpose of this communication is to describe such a system and to present some results on magnesium in the range of pressures between 350 and 550 kbar.

EXPERIMENT

The shock pressures of interest in this investigation are usually obtained by a high explosive (HE) system with the aid of a flying plate. The experimental setup is illustrated in Fig. 1; the HE part is not drawn to scale because of its relative insignificance.

The pressure pulse of the detonation wave through the explosive system (1) drives the thin Monel flying plate (2) at its free surface velocity of near 3.5 mm/ μ sec through a 1-in. gap. This gives the plate ample time to reach a steady velocity before it strikes the aluminum base plate (3), generating the desired shock wave through the system.

The wave processes that take place after the impact are best illustrated in a time-space plane which is shown in Fig. 2. Here the space axis is represented by the centerline through the experimental assembly and the time axis begins with the impact of the flying plate (2) with the aluminum base plate (3). The impact results in two shock waves that propagate in opposite directions.

The forward-running wave propagates through the base plate into the sample (4) and then into the transparent anvil (5). The wave that starts back into the flying plate will reflect from its opposite side as a rarefaction wave and will follow the original shock wave at a significantly higher velocity. The geometry must be such that this reflected wave does not overtake the original shock wave before the latter reaches the interface between sample and anvil. To avoid reflections from this interface one could choose the anvil material to be of the same shock impedance as the sample, although this is not absolutely necessary if one can reasonably assess the change of state due to the reflection and in particular its contribution to the temperature. The numbers along the lines in the time-space plot indicate the velocities for a particular case where the magnesium sample was backed up by a transparent NaCl crystal and the shock velocity through Mg was measured to be 8 mm/ μ sec.

The observation of the sample surface is made by a photo detector (8) through the transparent anvil (5), through an aperture 8 mm in diameter (5a), and through a narrow-band interference filter (6) of a particular wavelength. The amount of radiation from the investigated surface is thus controlled geometrically and spectrally.

The whole system inside the sample holder (7) is placed under vacuum to eliminate a possibility of airflashes from the air bubbles trapped at the interface. Further precaution is taken to subdue the extraneous light by masking off the sidewalls of the anvil and by vapor-plating a thin film of the investigated material onto the surface of the anvil which is in contact with the sample. Both surfaces composing the interface are flat and smooth to within 1 micron.

As the shock leaves the metal the observed surface is under pressure and at a certain temperature. Being at a high temperature the surface begins to

emit thermal radiation of which a certain amount is picked up by the detector and transformed into an electrical signal on the oscilloscope. The value of the signal in volts is

$$h = B \frac{A_s A_d}{\ell^2} \times \int_{\lambda_1}^{\lambda_2} b(\lambda) \tau(\lambda) P(\lambda T) d\lambda \quad (1)$$

where

$$P(\lambda T) = c_1 \lambda^{-5} \left(e^{c_2/\lambda T} - 1 \right)^{-1}$$

is Planck's formula, with c_1 and c_2 radiation constants equal to 3.7403×10^{-5} erg-cm²/sec and 1.4387 cm-°K respectively, $b(\lambda)$ and $\tau(\lambda)$ represent the spectral response of the narrow band filter and that of the detector respectively, A_s and A_d correspond to the areas of source and detector respectively, ℓ stands for the distance between the two areas, and B is a bulk constant to convert the radiation power into the proper units of the signal. The factor χ is a geometrical factor resulting from integration of the angular response of the detector over the total area of the source.

The signal obtained during the experiment is compared with the one measured during calibration of the same detector-and-filter assembly on a standard carbon-arc light source which radiates at a known temperature $T_0 = 3800^\circ\text{K}$. The temperature of the arc has been verified with a thermopile yielding at the same time the value for the area of the source. The calibrated signal is expressed similarly by

$$h_0 = B_0 \frac{A_{s0} A_d}{\ell_0^2} \chi_0 \int_{\lambda_1}^{\lambda_2} b(\lambda) \tau(\lambda) P(\lambda T_0) d\lambda \quad (2)$$

where $\chi_0 = 1.0$.

Assuming that for a narrow spectral band one could write

$$P(\lambda T) = \alpha_{\lambda}(T) P(\lambda T_0)$$

where $\alpha_{\lambda}(T)$ is a function of temperature only, Eqs. (1) and (2) can be combined to yield

$$\frac{h}{h_0} = \alpha_{\lambda}(T) \frac{A_s}{A_{s0}} \frac{\ell_0^2}{\ell^2} \frac{B}{B_0} \chi. \quad (3)$$

Since

$$\alpha_{\lambda}(T) = \frac{P_{\lambda}(T)}{P_{\lambda}(T_0)} = \exp \left[\frac{c_2}{\lambda T_0} \left(\frac{T - T_0}{T} \right) \right] \quad (4)$$

is a function of temperature only for a particular value of λ , it can serve as a link between the oscilloscope signal and the temperature, yielding

$$T = \frac{c_2}{\lambda} \left(\frac{c_2}{\lambda T_0} + \ln \frac{h_0 \ell_0^2}{\xi} - \ln h \right)^{-1}, \quad (5)$$

where ξ is a new constant composed of geometrical, electronic, and optical factors which are determined each time for a particular set of components; it is explicitly equal to

$$\xi = \frac{B_0}{B} \frac{A_{s0}}{A_s} \frac{\ell_0^2}{\chi}. \quad (6)$$

All this of course is based on the assumption that the surface under observation is shock-heated uniformly and the emissivity of the material under these dynamic conditions is near unity or at least the same as the emissivity of the carbon arc to which these measurements are compared.

RESULTS

Typical records resulting from these experiments are shown in Fig. 3. Here the oscilloscope traces represent the signals which were obtained from a magnesium sample through an infrared filter (0.9μ) and three different anvil materials as indicated on the figure. The choice of these anvils was based on their different heat capacities and compressibilities, the combination of which should yield different shock heating of the anvil and thus enable study of the effects this had on the resulting signal from the interface.

Of main interest here is the risetime of the signal and its amplitude. In all cases the initial rise does not exceed 40 nsec, which is the risetime of the electronic circuit of the detector follower. Since it was shown previously¹ that the contribution from the shocked alkali-halide is time-dependent and does not reach its full amplitude before 0.5 or even 1.0 μ sec, the signal observed here, at the very first instant, must be that coming from the surface of the sample. The fact that the amplitude remains constant as long as the shock travels through the anvil indicates that either the anvil remains transparent or its temperature is the same as that of the investigated material.

Since the relationship between the trace amplitude and the temperature is very nonlinear, the traces of Fig. 3 were replotted on the temperature-time plot shown in Fig. 4. Here it is clearly seen that the time variation of temperature is small.

To compare the numerical values of temperature one must take into account the match of shock impedance between the anvil and sample materials and the strength of the reflected wave which is generated at this interface due to the mismatch. While NaCl is a close match to Mg and will hardly produce any

reflection, LiF and especially Al_2O_3 (sapphire) will generate a strong shock wave thus changing the pressure and temperature of the material at the observed surface. Although these additional temperatures will not amount to more than 500°K they have to be taken into account when comparison is made with the theoretical calculations behind the initial shock.

Such comparison is illustrated in Table I which lists experimental temperatures corresponding to the initial peaks in the Fig. 3 records and those theoretically expected on the basis of equilibrium thermodynamics. Numerical subscripts 1, 2, and 3 denote the state for which the temperature or pressure is determined; they correspond to the states behind the initial shock in the sample, behind the reflected shock in the sample, and behind the initial shock in the anvil, respectively.

While the LiF shot was taken at a different time, both NaCl and sapphire records were obtained simultaneously during the same experiment, illustrating the consistency of the results in that the reflected shock from the sapphire anvil raised the temperature by 20% as expected. On the other hand, since the sapphire crystal should remain below 1000°K at these pressures,⁵ the temperature we observe during the full duration of the trace must be that coming from the interface.

With the visible (0.5 μ) filter the records are somewhat different as shown in Fig. 5. Both records were taken simultaneously on the same shot with records (a) and (b) of Fig. 3. The initial temperatures here are 20% higher than those obtained with the infrared filter, but they also show time dependence, in particular the one with NaCl relaxing towards the value observed with an infrared filter. In the following section we will present some arguments which

could explain the reason for such a spectral variance in temperature; at this time we point out that it is clear the effect is real since the difference in temperature between the two records is nearly the same as that between (a) and (b) of Fig. 3, which is due to the impedance mismatch of the anvil and the sample.

In view of these observations and for the purpose of comparison with the theoretical expectations, we have taken only the results from the infrared records and plotted them on the temperature-pressure plot of Fig. 6. In this figure there are also the theoretical Hugoniot curves, with and without provisions for melting, as well as the results taken from Ref. 1, representing experimental temperatures of NaCl. The experimental points shown here are all corrected for the impedance mismatch and represent the state behind the initial shock. It is quite evident from this figure that the disagreement with theory is rather significant. However, the results are all self-consistent and follow a certain pattern which may be accepted as a real phenomenon.

INTERPRETATION OF RESULTS

The consistent but large discrepancy between the spectral temperatures measured and those estimated on the basis of thermodynamic calculations below the melting region prompted a closer look into the conditions governing the radiating interface during observation.

Since the optical depth of the metal surface from which the observed radiation is emitted is extremely small, about 100 \AA , it seems necessary to consider all possible effects on a very small scale. Such effects may be

mechanical, chemical, or thermal in character. Considering the times involved, mechanical effects should not be significant because relaxation between the sample and anvil materials is reached in less than 10^{-8} sec. Absence of chemically reactive surface effects is evidenced by the consistency of measurements through sapphire and various alkali-halide crystals. Thus only thermal effects may play a significant role in this process.

Following a virtually simultaneous shock heating of the sample and anvil materials near the interface, one can account for several thermal relaxation processes which take place at the interface. The nonuniform heating of the metal surface caused by a surface roughness of 1μ should relax in less than 10^{-9} sec and would not be observed on the time scale of the experiment. However, the difference in heat capacities and thermal conductivities between sample and anvil materials should have an effect on the value of radiating temperature. Since both materials are heated to different temperatures the heat flow is introduced in the direction of cooler material which results in a shift of the metal temperature towards that of the anvil temperature. It can be easily shown that if the thermal diffusion coefficient is independent of temperature the actual interface temperature remains steady while the temperature gradient decreases with time as $t^{-1/2}$. In this manner one finds that the difference between the initial interface temperature and the shock temperature of the anvil material is less than the difference between the two shock temperatures by a factor of $1 + \alpha$, where

$$\alpha \approx (k_2/k_1)^{1/2},$$

with k_1 and k_2 being the thermal conductivities of the metal and insulator respectively.

Within the radiating metal layer the temperature gradient due to both thermal diffusion and radiation losses at the surface will decrease to negligible values in less than 10^{-8} sec. Thus during the time of observation the sample will appear to be in thermal equilibrium at a constant corrected temperature. Russian experiments⁶ indicate that the alkali-halide anvils are also in thermal equilibrium but remain transparent in the pressure range of these experiments for at least $0.5 \mu\text{sec}$.

A rather significant uncertainty in these measurements is in the emissivity factor of the metal interface which should reduce the amount of radiation from the interface. Based on its theoretical definition the emissivity cannot exceed unity for a material in thermal equilibrium at a uniform temperature. Thus the spectral distribution of radiative energy will always fall below the ideal Planck distribution. An extrapolation of theoretical and experimental results under normal pressures to temperatures above 3000°K suggests that emissivities may vary from 0.5 to 1.0 depending on the wavelength and the surface conditions. A reliable estimate of the surface conditions cannot be made because of the insufficient knowledge of the structure of the interface after the shock has passed through it. Thus although the variation of spectral temperature with wavelength can be attributed to different spectral emissivities, the value of emissivity being less than unity would imply that the temperature of the observed interface is even higher than those determined above. In addition the time variation of spectral temperature at $\lambda = 0.5 \mu$ (see Fig. 5) also implies that emissivity may be time-dependent.

The effects described above are based on the assumption that the shock heating is uniform over the whole surface of the sample. Although some of them contribute to the discrepancy between the observed temperature and that expected

from thermodynamic calculation they do not completely explain that deviation. A qualitative explanation however may be offered by an assumption that the shock heating is not uniform across the interface. If the thermal energy is deposited nonuniformly throughout the volume of the investigated material then the portion of the area heated to a higher temperature will dominate the measurement especially at shorter wavelength. Such temperature inhomogeneity may also be expected to relax at a rate depending on the spatial scale of such nonuniformities. Since the areas at higher temperatures tend to disappear first, the relaxation time of the spectral temperatures is shorter at shorter wavelength. It is found that if regions of high temperature occupy as much as 20% of the volume with a scale of 100μ , the observed spectral effects can be roughly reproduced and are consistent with thermodynamic temperatures. Such nonuniform heating may stem from the polycrystalline structure of the investigated material. When the shock strength is such that the material is brought to a state near melting the mechanisms of compression which at lower pressure cause a large amount of twinning and work-hardening may behave in a completely different manner as a result of a greatly reduced yield strength and flow viscosity. As the shock pressure climbs above the melting line into the liquid phase, such nonuniformities should disappear as seems to be the case in the present data plotted in Fig. 6.

CONCLUSION

Although believable temperatures of the shocked solid material have not yet been determined, a sensitive and versatile method of making such measurements

at the metal-insulator interface has been demonstrated. Further investigation is needed to pin down the effect of emissivity and nonuniform heating of the sample. This will be done by varying the surface conditions at the interface and performing the experiments with single-crystal samples of the investigated material. As an example of other applications of this method it is also planned to investigate the possibility of making thermal conductivity measurements at high shock pressures through the dependence of interface temperatures on α .

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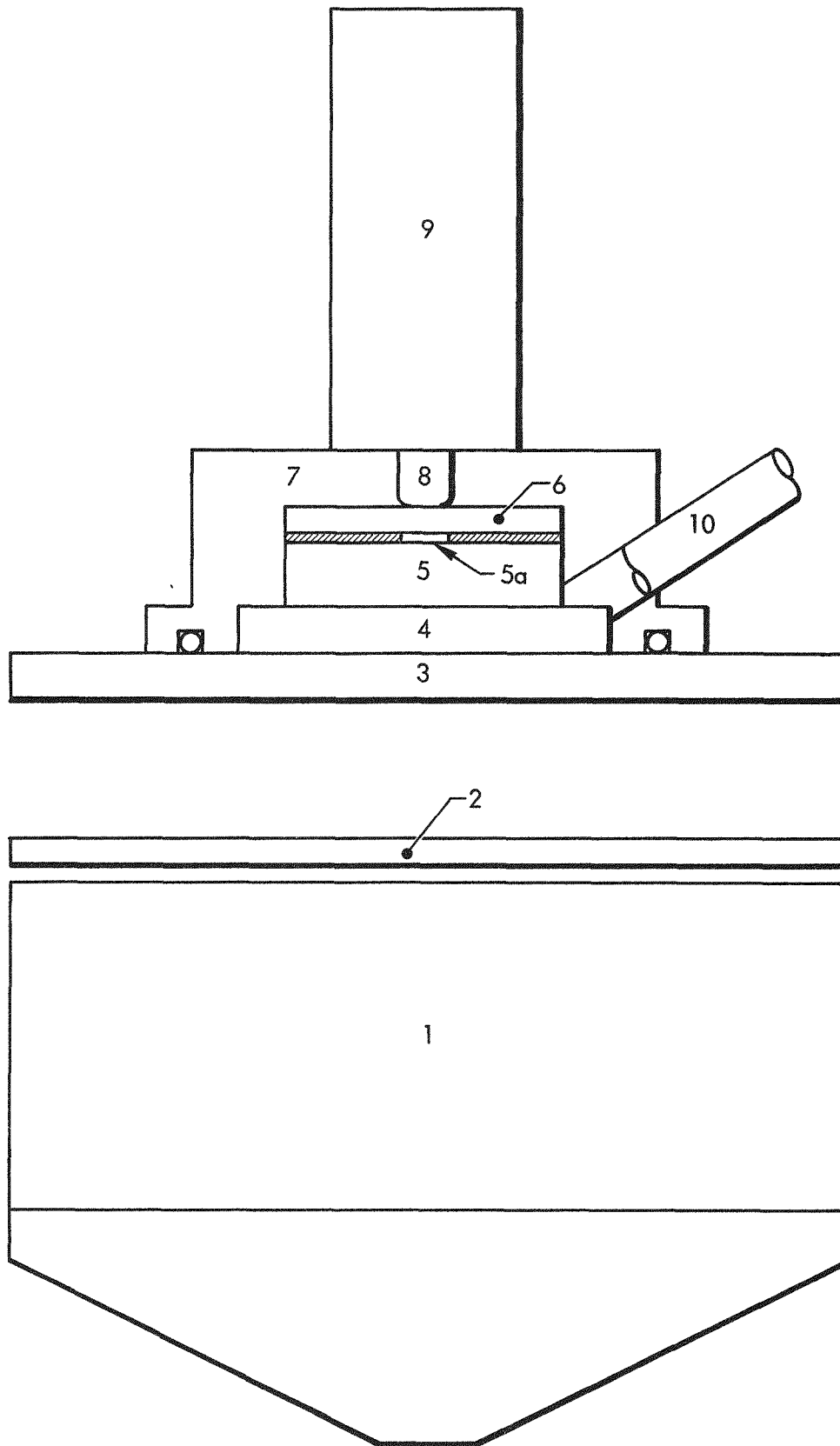
Table I. Comparison of experiment with theory, taking into account the change of state caused by the reflected wave when there is an impedance mismatch between sample and anvil materials. Sample is Mg in each case.^a

Anvil	U_s (mm/ μ sec)	P_1 (kbar)	T_1 (°K)	$P_{2,3}$ (kbar)	T_3 (°K)	T_2 (°K)	T_{expt} (°K)
NaCl	8.5	470	2440	494	2800	2520	3960
Al ₂ O ₃	8.5	470	2440	850	900	3040	4780
LiF	8.8	522	2850	660	1100	3060	3730
KCl	8.65	496	2650	486	4100	2600	4380

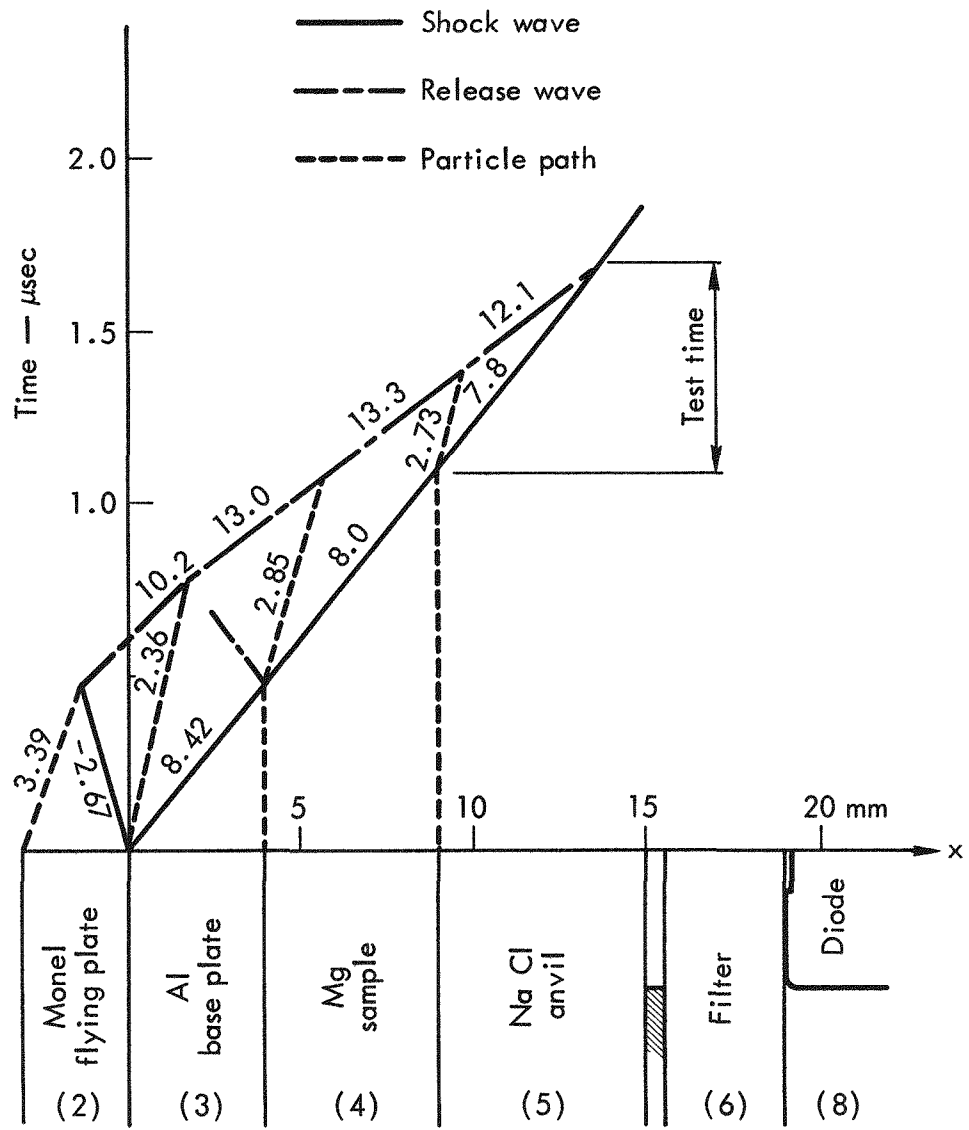
^aSubscripts: s = shock velocity; 1 = state behind the initial shock in the sample; 2 = state behind the reflected wave in the sample; 3 = state behind the initial shock in the anvil.

FIGURE CAPTIONS

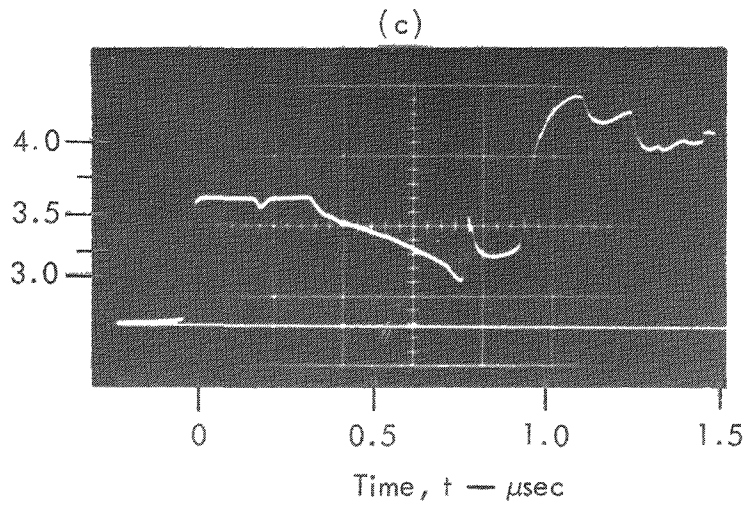
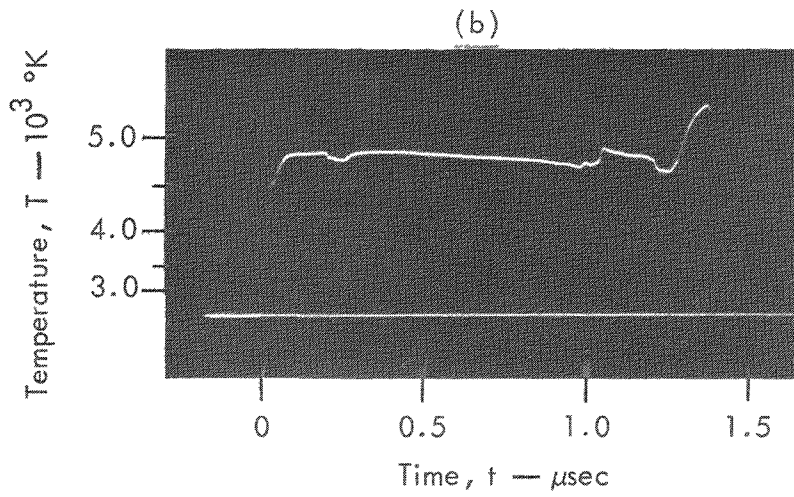
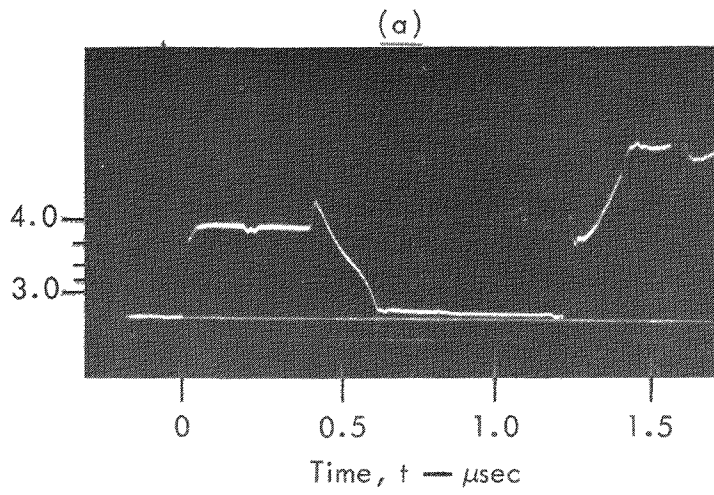
- Fig. 1. Experimental assembly. (1) High explosive system. (2) Monel flying plate. (3) Aluminum base plate. (4) Sample. (5) Transparent anvil. (5a) Aperture. (6) Interference filter. (7) Aluminum vacuum housing. (8) Photo detector. (9) Detector follower housing. (10) Vacuum pumping path.
- Fig. 2. Wave diagram in the time-space plane illustrating the events which take place during the experiment.
- Fig. 3. Experimental records taken with an infrared filter (0.9μ) and Mg sample backed by different transparent anvils: (a) NaCl, (b) sapphire, (c) LiF.
- Fig. 4. Experimental records of Fig. 3 transformed into the temperature-time plane.
- Fig. 5. Experimental records taken with a blue filter (0.5μ) and Mg sample backed by transparent anvils as follows: (a) NaCl, (b) sapphire.
- Fig. 6. Temperature-pressure plot of experimental points together with theoretical Hugoniot with and without accounting for melting. Shown also is the experimental temperature of NaCl as reported in Ref. 1.

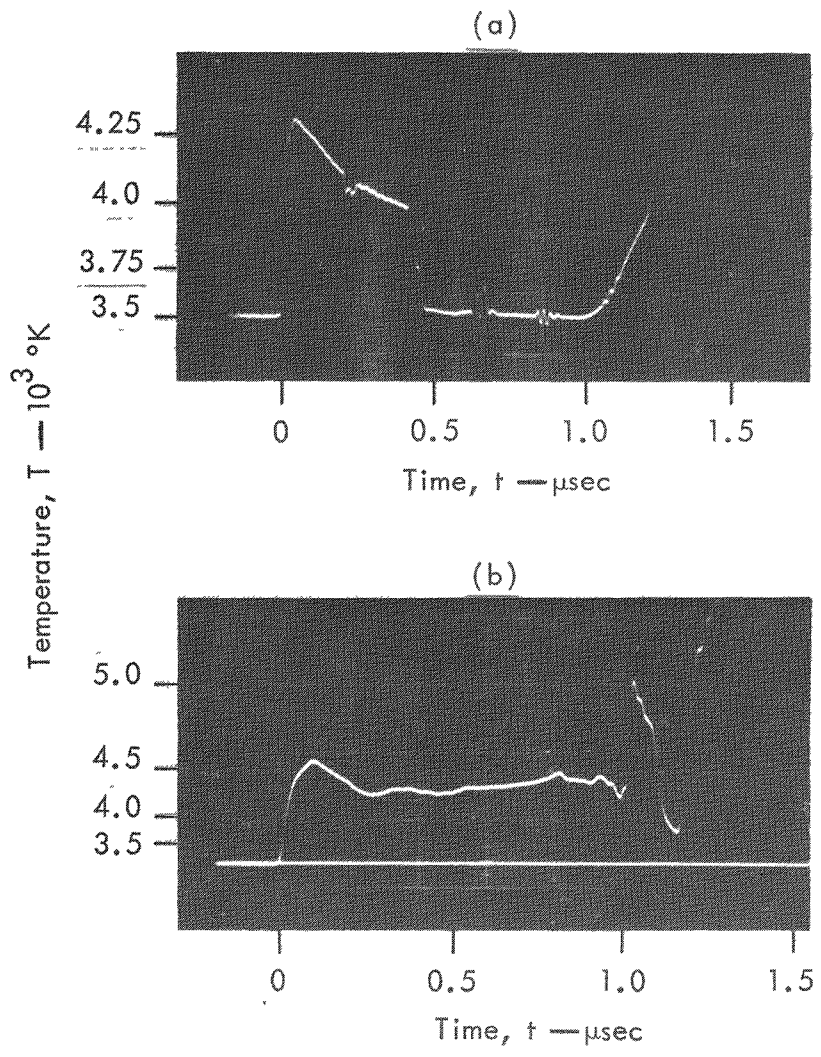


Urtiew - Fig. 1

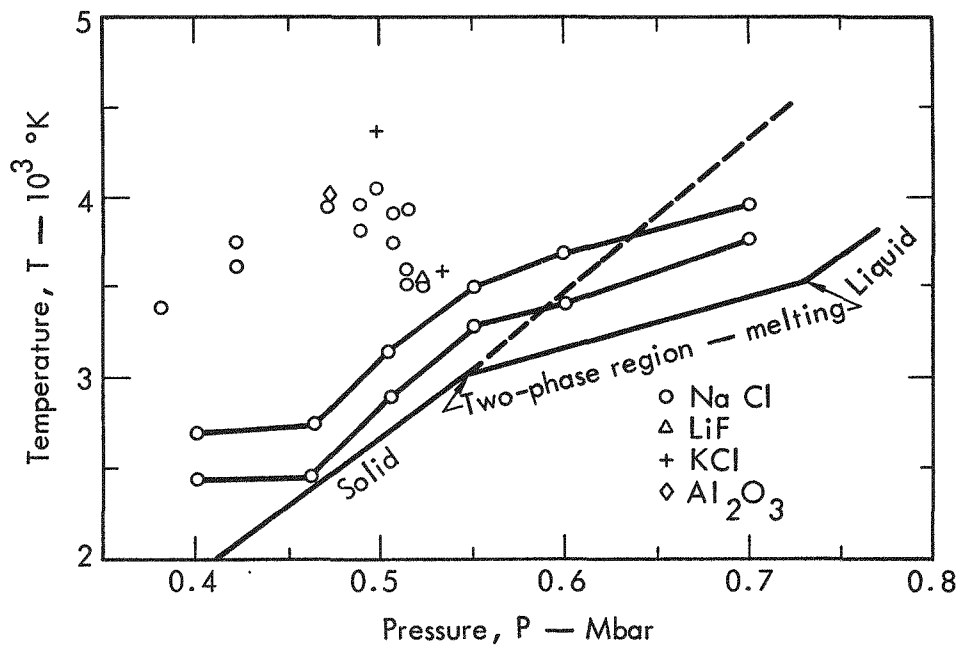


Urtiew - Fig. 2





Urtiew - Fig. 5



Urtiew - Fig. 6

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