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Title: Measurement and Analysis of Release Isentropes Using Proton Radiography (U)

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Form 836 (7/06)

DETAILED DESCRIPTION OF THE EXPERIMENT OR ACTIVITY

(Describe the science of engineering research being addressed, importance, and a description of how this experiment campaign will contribute to the progress of this research.)

Measurement and Analysis of Release Isentropes of Metals Using Proton Radiography (U)

Off-Hugoniot measurements are needed to further develop predictive models that accurately describe the behavior of metals undergoing phase transitions. Predictive modeling of phase transitions is essential for LANL to meet its programmatic objectives. Understanding the dynamic evolution of density as a function of time during the release process is important to developing high fidelity equation of state models. This is particularly true for metals that have a degree of complexity, such as a solid-solid phase transition. The equations-of-state (EOS) for metals with complexity are more difficult to measure and to model, and states far away from where measurements are easily made can be poorly known. Accurate density measurements can provide us with additional fundamental information that can be used to further constrain the equation of state for a material. Currently release isentrope information is obtained from shock experiments at a sample window interface using optical velocimetry. This data is highly convoluted due to wave interactions between the sample window-interface making it difficult to infer physical processes happening within the material. Proton radiography has the ability to probe the release waves *in-situ* before these wave interactions can take place. Since multiple radiographs are obtained in each experiment, pRad provides the unique capability of being able to measure both density and wave evolution within the material.[1,2] The measurement of release wave densities, however, presents new challenges for pRad since the release wave of a shocked transition is not a step function but instead a ramped wave. Previous pRad experiments have generally measured density jumps over step transitions; therefore, new analysis techniques will have to be developed to measure the ramped density change of a release isentrope. Once developed, these new analysis techniques can also be used for experiments that involve ramped compression. This kind of compression is being used to measure states close to an isentrope.

The ability analyze ramp wave data is an essential component to further the use of proton radiography to study any off-Hugoniot behavior. Wave speeds in materials depend upon the speed of sound which in turn is a function of pressure in the material. At higher pressures the sound speed is faster; at lower pressures the sound speed is slower; this is what causes shock waves to form. This same effect causes the shape of release waves to change with time. The wave will be running faster at the top and slower at the bottom, its slope steeper at the top and less at the bottom due to pressure changes. These are *unsteady waves*. WONDY simulations of these wave shape characteristics are shown in Fig. 1 for a Cu symmetric impact. We will need to look at how the shape of the wave changes over time and affects the measurement of the density as a function of time. Additionally we need to quantify the uncertainties in the spatial and density measurements as a function of ramp rate and shock strength. We will look at aluminum or copper to validate the analysis techniques that will need to be developed. Finally, we will perform shock loaded phase transition experiments on iron, zirconium, and tin using the developed analysis techniques for incorporation into predictive models. The iron (and possibly tin) experiments

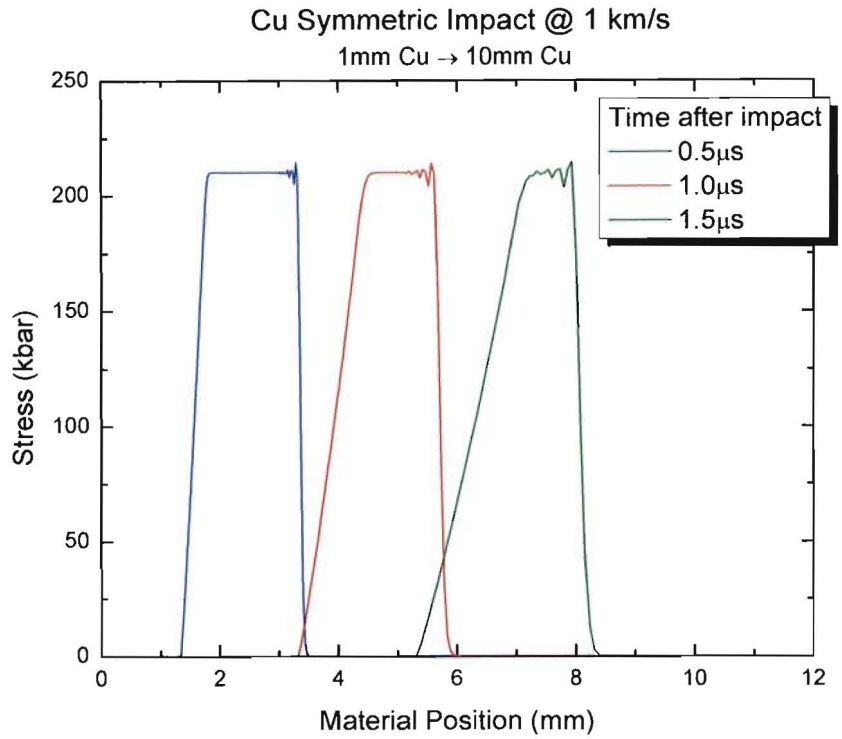

Figure 1. WONDY simulation showing the release wave shape changing over time as well as a slope variation at a specific time.

will introduce a new degree of complexity because of the existence of a rarefaction shock in the release wave.

The ability to measure release states with pRad and do accurate direct density measurements will directly benefit our understanding of the phase diagram and the transition kinetic times in release. We will choose materials according to our technical needs and our current degree of understanding:

1. Iron has been well studied both in polycrystalline and single crystal forms using time-resolved wave profile techniques. We choose it to study as a phase changing material for which a good EOS is known. Our measurements will provide direct verification that we have a good knowledge of the response of iron to dynamic release, and new evidence that the transition is not completely driven to completion in dynamic compression.
2. We then choose tin as a material for which less is known. The $\beta-\gamma$ transition has been observed experimentally in compression, but no rarefaction shock, which would indicate substantially phase reversion in release, has yet been observed. Tin may also not completely transform to the new phase in the dynamic loading process, and our measurements will serve to validate this response. Accurate density measurements in release can directly help determine which phase is present, if accuracy in density is good enough. For tin we can also reach states that are at least partially melted upon release. Partially melted release states are expected to exhibit interesting release dynamics, and density measurement may be able to shed light upon details. We say 'may', because this requires more thought on what the sensitivity to density in these states is relative to details of solid and liquid mass fractions.

3. Zirconium has been studied using time-resolved techniques, and shows interesting behavior. On shock compression a decaying P1 wave is predicted for the $\alpha-\omega$ transition. On release no rarefaction shock is observed indicating no reversion back to the alpha phase in the time scale of the experiment. This observation is consistent with recovered samples showing the presence of retained omega phase in considerable mass fraction. Proton measurements will be used to validate our ability to calculate both compression and release states for this material. Direct density measurements in deep release will be compared to shock recovered results (G. T. Gray results) for mass fraction of alpha and omega phases for a single starting material with known impurities.

We therefore propose a three part series of experiments:

1) Static objects with ramped density features to allow us to model the density
2) Dynamic experiment on Cu or Al with a well-modeled release isentrope to validate the technique
3) Dynamic series of experiments on the phase transforming materials iron, tin and zirconium as time and resources allow. This will have a direct impact on our understanding other materials of interest to the weapons program.

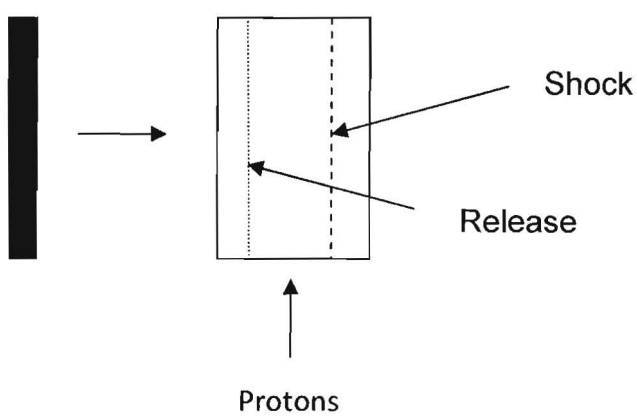

Figure 2. Experimental configuration of proposed experiments. Release will be measured off the backside of the sample.

Results of these experiments will be used to either better constrain existing EOS treatments for these metals, or drive new measurements to allow EOS's to be refined. Success on these metals will allow metals of more direct programmatic relevance to be better understood.

1. Rigg, P.A., Schwartz, C. L., Hixson, R. S., et al., "Proton radiography and accurate density measurements: A window into shock wave processes", Phys. Rev. B 77, 220101 (2001).
2. Schwartz, C.L., et al., "New Capabilities of 800 MeV Proton Radiography at Los Alamos", AIP Conf. Proc. **955**, 1135-1138 (2007).