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SHOCK-INDUCED VAPORIZATION OF ZINC— EXPERIMENTS AND NUMERICAL SIMULATIONS

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Record-high impact speeds achieved using the Sandia HyperVelocity Launcher have permitted a systematic study of shock-induced full vaporization of zinc. Pressures up to 5.5 Mbar and temperatures as high as 39000 K (~ 3.4 eV) are induced in a thin zinc plate by impacting it with a tantalum flier at speeds up to 10.1 km/s. Such high pressures produce essentially full vaporization of the zinc because the thermodynamic release isentropes pass into the vapor dome near the critical point. To characterize vapor flow, the velocity history produced by stagnation of the zinc expansion products against a witness plate is measured with velocity interferometry. For each experiment, the time-resolved experimental interferometer record is compared with wavecode calculations using an analytical equation of state, called ANEOS, that is known to have performed quite well at lower impact speeds (less than ~ 7 km/s) where vaporization is negligible. Significant discrepancies between experiment and calculation are shown to exist under conditions of the more recent higher impact speeds in excess of 7 km/s where the release isentrope appears to pass near the critical point.

MASTER

INTRODUCTION

Prediction of the interaction between expanded vaporized debris and target materials for applications such as meteorite impact on space vehicles, ballistic penetration of armors, debris shield design, *etc.* demands an accurate treatment of the melting and vaporization process and the kinetics of liquid-vapor propagation. Historically, experimental efforts to understand high-pressure melting and vaporization have been hindered by unavailability of experimental launchers that are capable of speeds needed to induce vaporized states.^[1] This problem has been circumvented to some extent by studying materials such as lead, cadmium, and zinc, which have relatively low melting and boiling points.^[2,3,4] For materials of greater programmatic interest (such as aluminum), an alternative is to shock *porous* samples for which irreversible pore collapse enhances heating of the matrix material.^[5,6]

In this paper, we describe our achievement of record-high impact speeds and resultant vapor concentrations from initially solid zinc. Using the new Sandia HyperVelocity Launcher,^[7,8] a tantalum flier plate was launched to speeds from 8 km/s to 10.1 km/s. The flier impacted a thin target plate of zinc, producing computed shock pressures of up to ~ 5.5 Mbar, and temperatures as high as 39000 K. The release isentropes computed from these states pass near zinc's thermodynamic critical point, and it is therefore believed that significant — perhaps *full* — vaporization of the zinc target occurs. To characterize the vapor states, the velocity history produced by stagnation of the expansion products against a witness plate is measured using velocity interferometry. The amount by which peak witness-plate velocity decreases for increasing distance between the zinc target and witness plate is an indicator of the degree of vaporization. Zinc was chosen for this study because the zinc liquid-vapor co-existence diagram, discussed later,

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suggests the feasibility of approaching the critical region using our state-of-the-art impact technology. Furthermore, the commonly-used ANEOS equation of state^[9] represents earlier lower-speed lower-pressure experiments^[6] for zinc remarkably well.

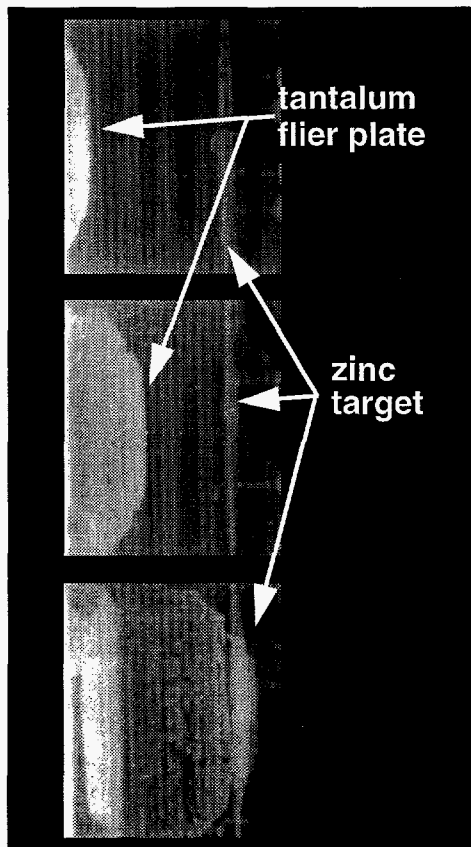
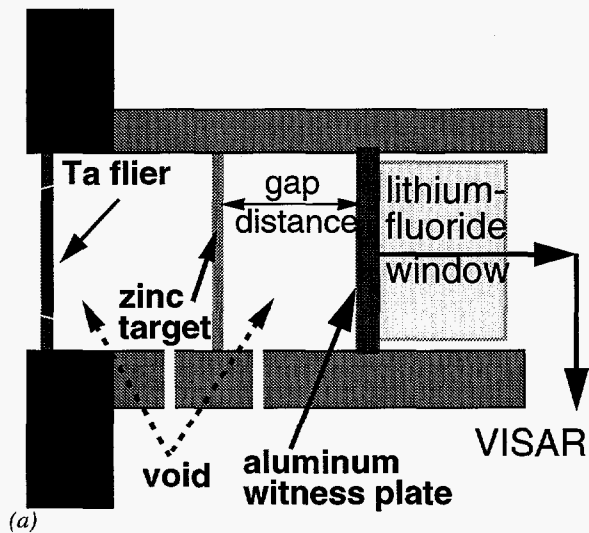


FIGURE 1. (a) Experimental configuration.^[11] The thicknesses of the Ta flier, zinc target, and Al buffer are ~0.20mm, 0.18mm, and 1.99mm, respectively. (b) Radiograph: tantalum flier traverses 40 mm prior to impacting the thin zinc plate at 9.1 km/s in the final frame.

The purposes of this paper are (1) to summarize experimental results for essentially full vaporization of zinc and (2) to use these experiments to evaluate the predictions of the ANEOS equation-of-state. Because ANEOS is rather well-established (and therefore commonly used), it is important to report any results that limit its range of applicability. ANEOS-based calculations have been shown in previous studies^[6] to match data for sub-critical shock release of zinc. However, lacking a critical point model^[10] and boiling kinetics, ANEOS fails to adequately match the new near-critical data. These results highlight the risk of inaccurate predictions resulting from extrapolating equation-of-state models into pressure/temperature regimes for which they have not been validated.

EXPERIMENTAL TECHNIQUE

The new experiments were performed using the Sandia HyperVelocity Launcher,^[7,8,9] which is based on the principle that a structured shockless pressure pulse is required to *ramp* a flier plate up to the desired final velocity to avoid premature melting or fracturing. Flash X-rays (Fig. 1b) were taken to determine the velocity of the flier and also to verify its integrity and flatness upon impacting the zinc. Impact of the flier against the zinc plate then produced a debris cloud of rarefied liquid-vapor zinc which was permitted to traverse a *gap* (Fig. 1a) of known dimensions before stagnating against an aluminum witness plate. The subsequent particle velocity history at the witness-plate/window interface was measured using a velocity interferometer, commonly referred to as VISAR.^[12] In the experiments, the gap size was varied from 0 to 20 mm and the tantalum flier speed was varied from 8.1 to 10.1 km/s. More details are in [13].

NUMERICAL MODEL DESCRIPTION

The Sandia wave propagation code CTH^[14] was used to simulate the experiments. The thermomechanical response of the materials was modeled using the ANEOS analytical equation-of-state package,^[15,16] which handles solid, liquid, vapor and mixed phases in a complete thermodynamically consistent semi-empirical manner. ANEOS was selected because it is known to agree well with experimental data for zinc at lower impact speeds.^[6]

The current experiments correspond to zinc release isentropes that pass close to the critical point (Fig. 2). Had the target been a higher melt/vapor material such as tantalum or aluminum, the release isentrope would not pass so near the critical point.^[13]

EXPERIMENTAL AND COMPUTATIONAL RESULTS

Table 1 and Figures 3 and 4 show both the computational and experimental results for flier-plate impact velocities ranging from 8.2 km/s to 10.1 km/s and gap sizes ranging from ~5 to ~10mm. A much more detailed report of these results may be found in [13]. There is no time fiducial: the time scales of the experimental records are adjusted to overlap the calculated records at the mid-range point on the initial rise. For all calculations, "time zero" is when the tantalum flier plate impacts the zinc target

Table 1: Peak Velocity Measurements

Gap distance (mm)	Impact velocity, V (km/s)	Peak velocity, u_{wp} (km/s)	Zero-gap velocity ^a , U_{max} (km/s)	u_{wp}/U_{max}
9.99	8.22	4.14	6.3	0.657
9.90	9.03	3.81	6.55	0.591
9.98	9.1	3.61	6.45	0.560
20.09	9.1	1.67	6.45	0.256
5.04	10.1	2.50	6.85	0.365
5.01	10.1	2.32	6.85	0.339
9.94	10.1	1.22	6.85	0.178
10.02	10.1	0.50	6.85	0.073
20.05	10.1	0.90	6.85	0.131
19.99	10.1	0.34	6.85	0.050

a. Based on calculations.

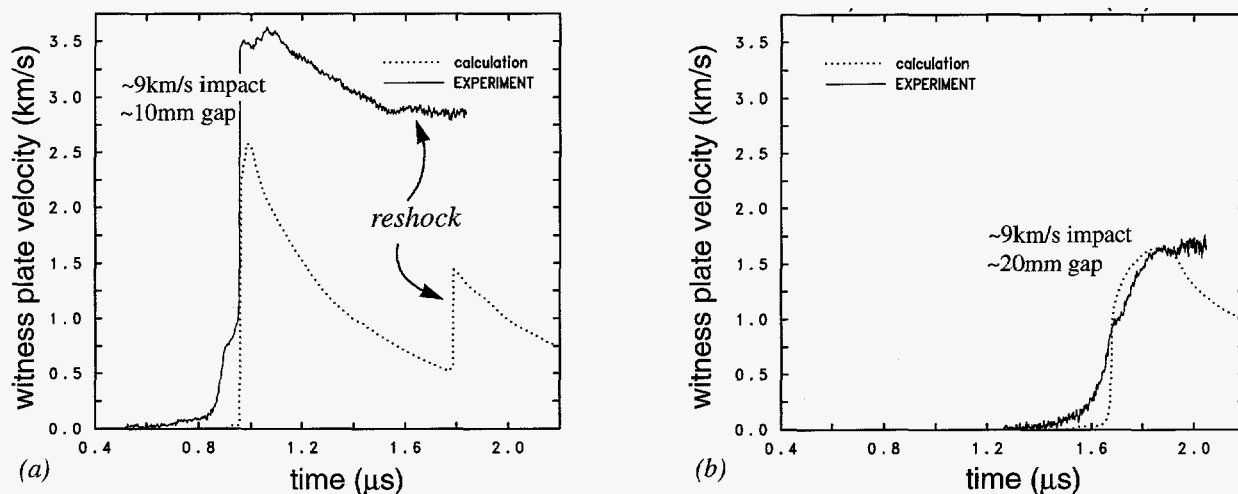


FIGURE 3. Measured and calculated VISAR particle velocities for experiments conducted at approximately 9.1 km/s.

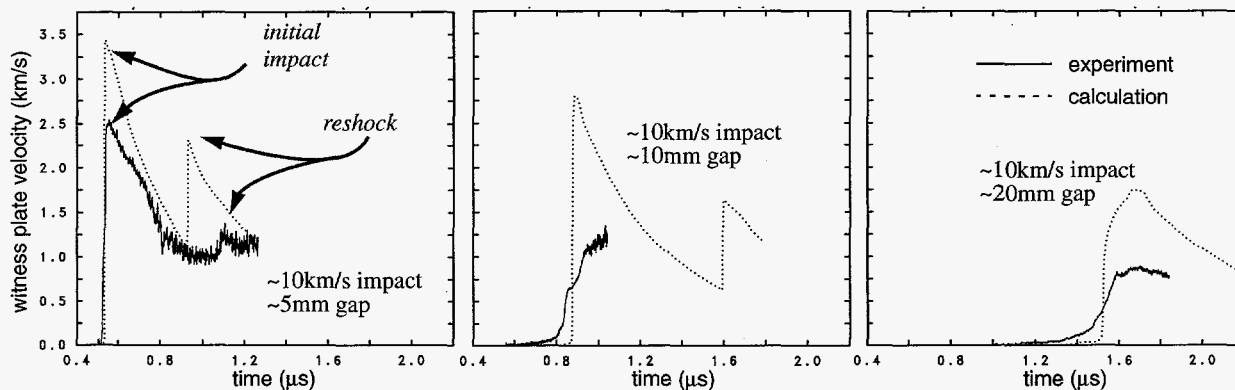


FIGURE 4. Measured and calculated VISAR particle velocities for experiments conducted at approximately 10.1 km/s.

Computational Predictions of Peak State

Immediately following impact of the tantalum flier at ~ 9.1 km/s, the zinc is shocked to a computed stress of ~ 4.7 Mbar, a temperature of 31000 K, and a dilatation (natural log of initial to final density) of -0.69 . At ~ 10.1 km/s, the zinc is shocked up to a computed ~ 5.5 Mbar, 39000 K and a dilatation of -0.71 . It is from these highly compressed states that the zinc expands upon release, following a path along an isentrope illustrated in Figure 2. These shocked states of the zinc appear to be at pressures and temperatures high enough to expect liquid/vapor (or perhaps aerosol) states upon release.

Variation of Velocity Measurements with Propagation Distance/Gap Size and Impact Speed

Assuming the zinc does indeed vaporize upon release from its highly compressed shocked state, then it will naturally tend to expand across the entire propagation gap until it stagnates against the witness plate (Fig. 1). Therefore, at high impact speeds where vaporization is expected, the *rate* of mass deposition on the witness plate should decrease with increasing gap size. By contrast, at lower speeds where vaporization is *not* expected, the zinc propagates across the gap as a coherent, comparatively non-expanding liquid/solid unit, and the mass deposition rate upon arrival at the witness plate would be about the same for any gap size. Mass deposition rate is indicated by the velocities measured at the back of the witness plate.

Similar investigations^[6] were previously performed at impact speeds of ~ 5.9 km/s and 6.8 km/s, where the zinc sample was shocked to ~ 2.3 Mbar and 2.9 Mbar, and the release products were allowed to traverse a gap of 10 mm before stagnating against an aluminum witness plate backed by a lithium-fluoride window. Shocks were observed at the interferometer window, and the velocity profile showed only moderate change with gap size, suggesting that very little vapor had been produced.

By contrast, the higher speed experimental records in Figures 3 and 4 show that the peak velocities decrease and the rise times (and pulse widths) increase with increasing gap size. As explained above, these features indicate that the zinc has at least partially vaporized in the higher-speed experiments.

The *experiments* show a pronounced decrease in peak velocity as flier impact speed is increased, which is evidence (though not conclusive) of increased vapor/aerosol states at higher impact speeds.

Specific Volume

Figure 5 shows a plot of numerically predicted specific volume vs. time for seven Lagrangian points distributed evenly throughout the zinc target material for the 10.1 km/s calculations. The linear increase in volume with respect to time is consistent with free expansion of a vapor. Note also that the region of least expansion lies in the target interior about one fourth of the plate thickness from the free surface. Similar behavior has been speculated *for lead*.^[3,17]

COMPARISON WITH CALCULATIONS

Previous studies^[6] indicate that the current ANEOS model is quite accurate for lower impact speed events where the material does not vaporize. At the higher impact speeds used in our study

(and unlike previous studies of lead^[3]) the ANEOS numerical predictions underestimate witness-plate velocity (overestimate vaporization) for the slightly sub-critical experiments at ~9 km/s and overestimate witness-plate velocity (underestimate vaporization) for the slightly super-critical experiments at ~10 km/s.

Since reductions in witness plate velocity with gap size indicate vaporization, the quantity $(1 - u_{wp}/U_{max})$ may serve as a measure of the degree of vaporization. For both the ~9 and ~10 km/s impact speeds, *the vaporization errors decrease in magnitude with increasing gap size*, suggesting there may be a vaporization delay (such as a superheating at very early times) in the experiments not captured in the ANEOS model. The vaporization errors are lower in the 10 km/s experiments, indicating that boiling kinetics may not play so strong a role above the vapor dome.

TARGET SURVIVAL

The aluminum witness-plate/lithium-fluoride window may be regarded as a target with which the liquid/vapor debris cloud interacts. The peak velocity measurement u_{wp} is an indicator of the maximum stress resulting from this interaction. The measured peak velocities were *higher* for the *lower-speed* 9.1 km/s shots (Fig. 3) than for the corresponding 10.1 km/s shots (Fig. 4), which suggests that greater vaporization occurred in the 10.1 km/s shots. Fig. 6 (which summarizes experimental data in Table 1 and Figures 3 and 4) shows that the peak witness-plate velocity u_{wp} and, therefore, the target/debris interaction stress decrease with increasing propagation distance (gap). All curves in Figure 6 must — in theory — asymptote to some constant value as gap size is increased. When such a curve asymptotes to *zero*, the sample must have vaporized completely. When a curve asymptotes to some non-zero value, the sample must have only partially vaporized. When a curve is *constant*, no vaporization must have occurred and the maximum target/debris interaction stress must be independent of gap size. The lowest speed experiment exhibits negligible expansion (*i.e.*, the zinc target remains essentially intact as it crosses the gap). By contrast, the highest speed experiment shows considerable expansion of the zinc, which corresponds to a much

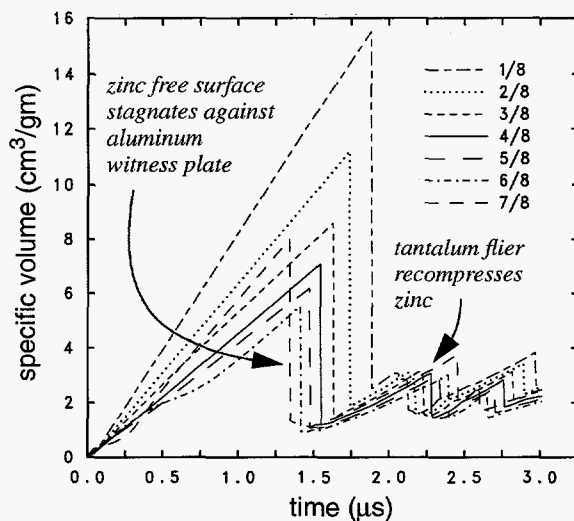


FIGURE 5. Specific volume vs. time for several Lagrangian points in the zinc target. A legend label $n/8$ refers to a point that is $n/8$ ths of the zinc target plate thickness away from the impact side.

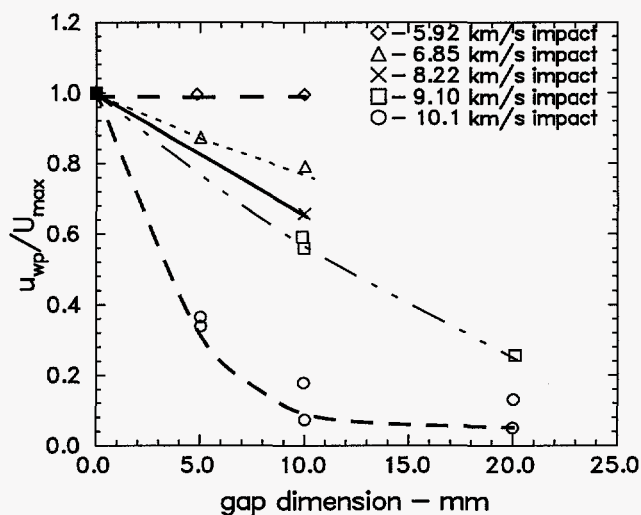


FIGURE 6. Witness-plate peak velocity (normalized by the computed zero-gap peak velocity U_{max} , which depends on tantalum impact speed and experiment geometry) vs. propagation distance (i.e., gap size).

lower stress on the witness plate than the lower-speed lower-vaporization experiments. (Of course, the survivability of any target depends on many other parameters, including the duration of the pressure pulse, the thickness of the target, and the yield and fracture strength of the target.) For zinc, the rapid approach to an asymptotic limit suggests that boiling occurs more rapidly from super-critical states. Further applications and extensions of this work are discussed in [13].

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