SAND2013-5545C

30 Seconds? Read this!

Novel Experimental Technique: We developed a new technique to determine the density on the liquid-vapor dome and the entropy on the Hugoniot. The technique will work for nearly any material.

Equation of State: The liquid-vapor dome and the entropy on the Hugoniot provide extremely sensitive constraints on the equation of state surface in the warm dense matter region.

Planetary Collisions: Significantly more iron is vaporized during planetary collisions than previously thought.

Multi-Mbar Shock and Release Experiments on Iron: Entropy on the Hugoniot and Density on the Liquid-Vapor Dome

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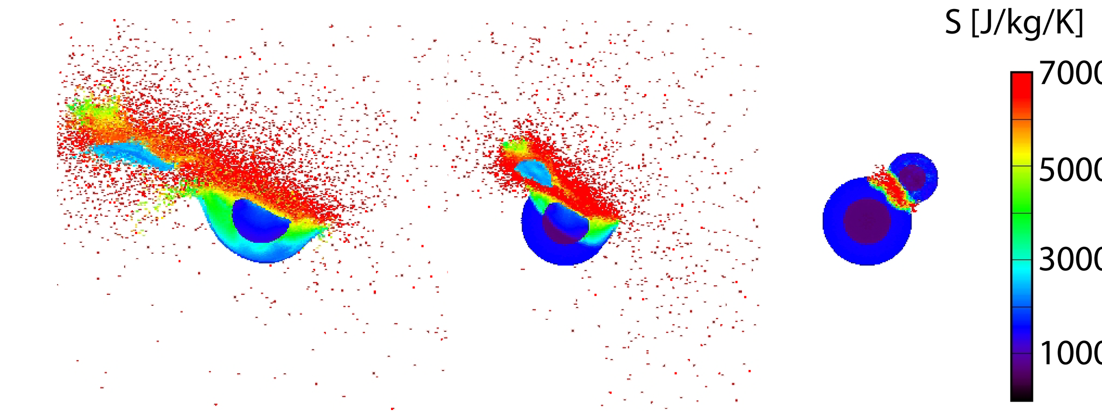
Experiments Conducted under the Sandia Z Fundamental Science Program



Impact of a 0.4 Mercury mass object onto a proto-Mercury at 25 km/s and 37 degrees.

Multi-Mbar Shock Waves to Study the EOS of Iron

The high-pressure region of the liquid-vapor curve of many materials is almost impossible to reach using static techniques. We have developed a novel shock and release technique to determine the density on the liquid-vapor dome. The entropy on the Hugoniot is then obtained by linking the Hugoniot state to a state of known entropy on the liquid-vapor dome via the release isentrope.

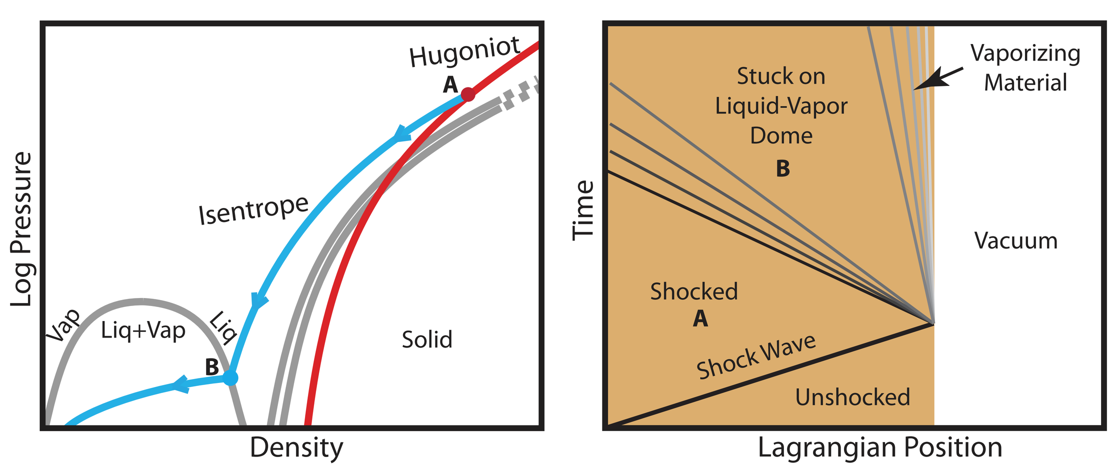


Figure 1: Schematic pressure density phase diagram (left) and characteristics diagram (right). Starting as a solid, a shock takes the material to state **A** on the Hugoniot (red line). Upon decompression, the material follows an isentropic path (blue line). Upon intersection of the isentrope with the liquid-vapor dome at state **B,** there is a discontinuous decrease in sound velocity. Upon breakout of a shock wave at a free surface, this discontinuity in the sound velocity creates a plateau of material stuck on the liquid-vapor dome (at state **B**). The density at state **B** is determined by stagnating the released liquid onto a standard window (Figure 5), which is similar to a reverse impact experiment.

Entropy on the Iron Hugoniot

Shock temperature measurements on opaque solids are difficult, here we determine entropy

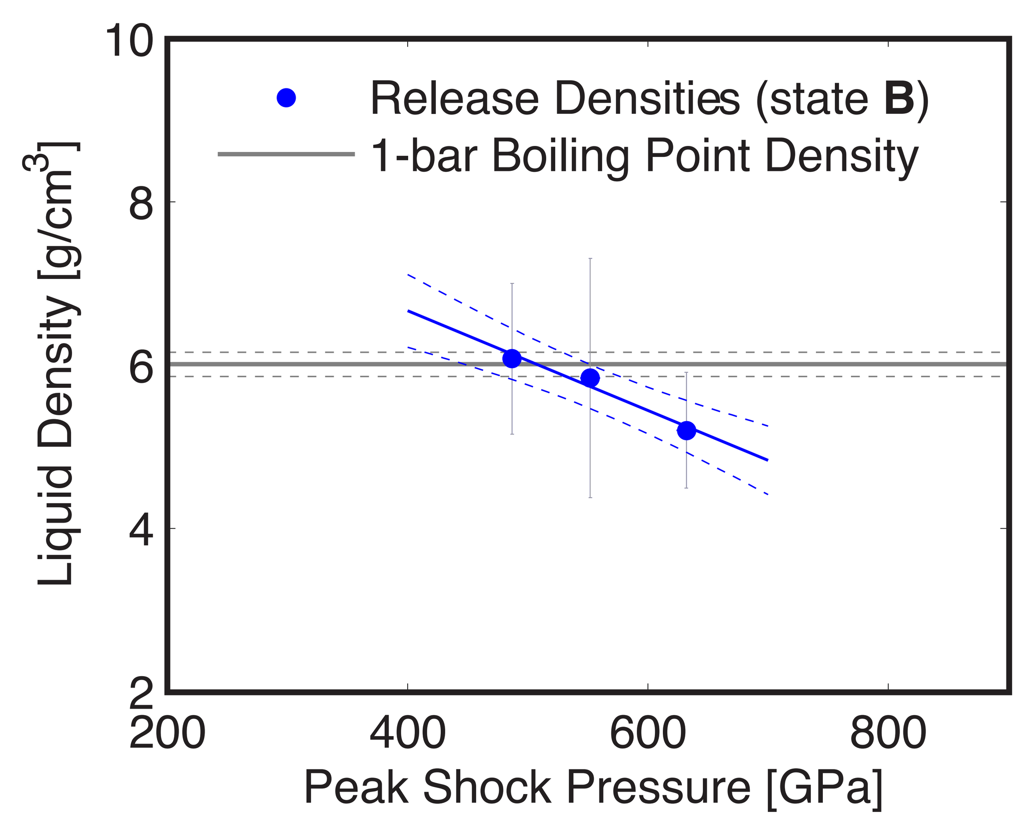


Figure 2: Iron density at the intersection of the release isentrope with the liquid branch of the liquid-vapor dome as a function of shock pressure (points) and the density of liquid iron at the 1-bar boiling point [1,2,3] (horizontal line) with 1-σ confidence interval (dashed lines). The intersection between the release densities and the density at the boiling point determines the critical shock pressure required to release to the liquid branch of the liquid-vapor dome at the 1-bar boiling point. Figured modified from [3].

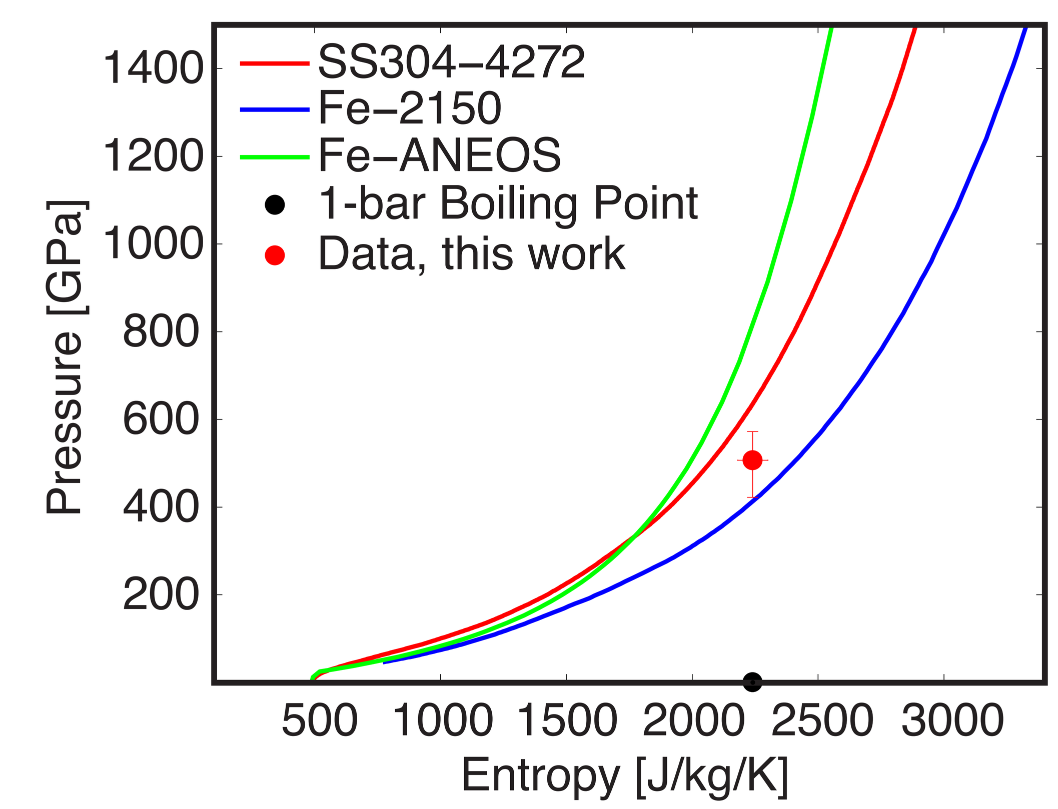


Figure 3: Comparison of the SESAME 4272 EOS for stainless steel, the SESAME 2150 EOS for iron [4], the ANEOS EOS for iron [5], and our data point for the entropy on the iron Hugoniot. Also shown is the entropy at the 1-bar boiling point [6]. The entropy on the ANEOS Hugoniot has been shifted to agree with the SESAME 2150 EOS at ambient conditions. The largest differences result from the different electronic EOS models, the ANEOS model utilizes an average atom ionization model, the SESAME 4272 model uses the TFD electronic EOS, and the SESAME 2150 model uses the INFERNO code.

Phase Diagram of Iron

Presented in an uncommon phase space

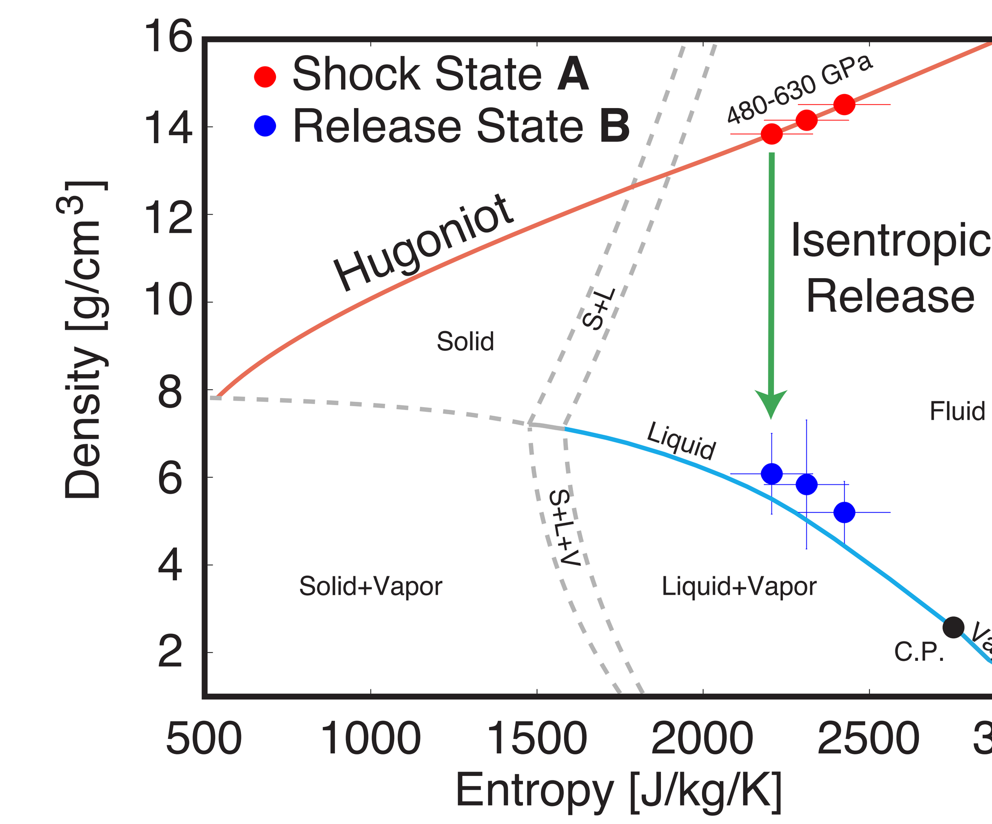


Figure 4: Density-Entropy phase diagram for Fe. Samples of Fe were shocked to states of high density and entropy (red circles) and decompressed to states on the liquid-vapor curve (blue circles). The entropy change along the Fe Hugoniot is from the SESAME 2150 EOS, fixed to the reference entropy we determined in Figure 3. We assume release from the Hugoniot state to be isentropic. The blue liquid-vapor curve is from the SESAME 4272 EOS. C.P. denotes the critical point. Gray dashed phase boundaries are schematic.

Sandia Z Experiments

Flyer plates are magnetically accelerated to velocities of up to 40 km/s.

At impact up to 300 microns of the aluminum flyer is still solid, allowing for millimeter scale targets.

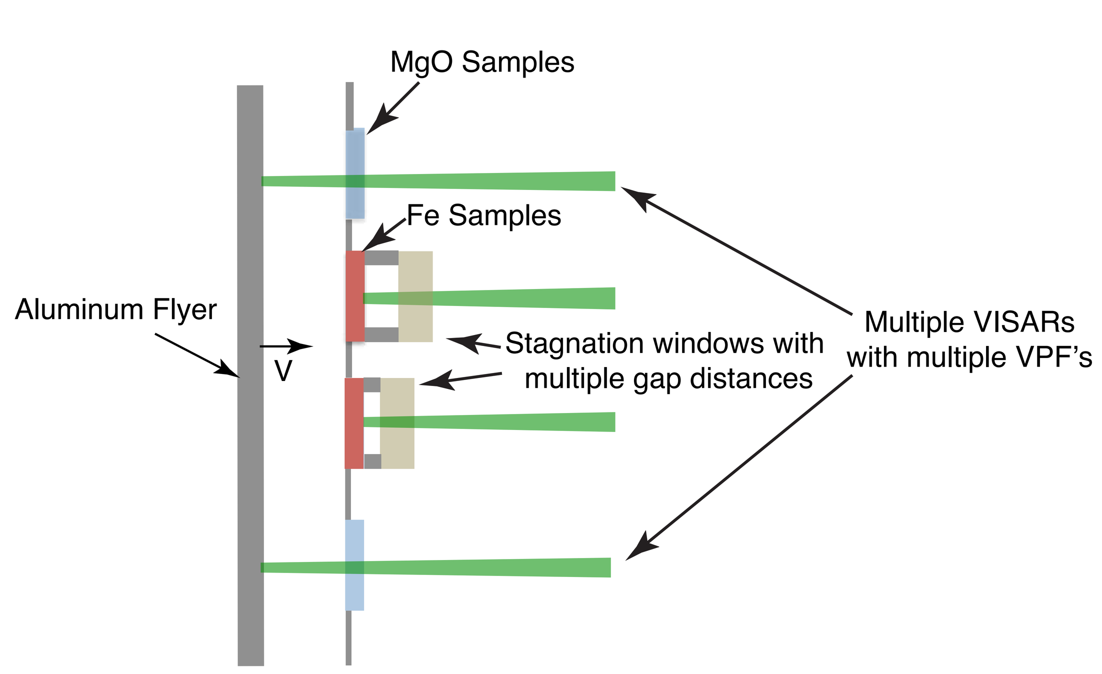


Figure 5: Experimental schematic of a target panel immediately prior to impact. Up to 10 samples can be placed on each panel for a dedicated experiment or data can be obtained from a single stagnation sample on a ride-along experiment. The flyer velocity is measured at multiple points along the target panel using the VISAR diagnostic. Multiple gap distances are used to accurately determine the liquid impact velocity.

Stagnation Experiments

We measure the impact velocity, the release velocity of the liquid across the gap, and the induced shock velocity in the standard window (Qtz. or TPX).

After the impact of the leading vapor, the material stuck on the liquid-vapor dome impacts and generates a steady shock wave in the window. The steady shock is followed by an increase in shock velocity (~57 ns) related to wave reflections from the higher density partially released fluid Fe.

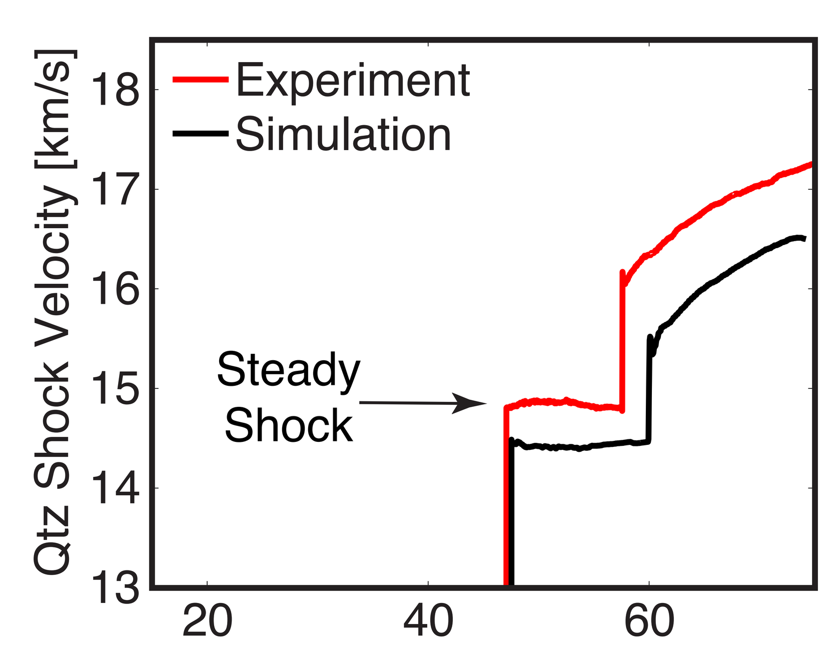


Figure 6: Comparison of experimental and simulated shock velocity profiles in a quartz window after stagnation of Fe that was impacted at 17.5 km/s. Iron was modeled using ANEOS [5] and simulations were performed in CTH.

Determining Liquid Density

To determine the post-shock density we impedance match the stagnating fluid with the window material, similar to a "reverse" impact experiment.

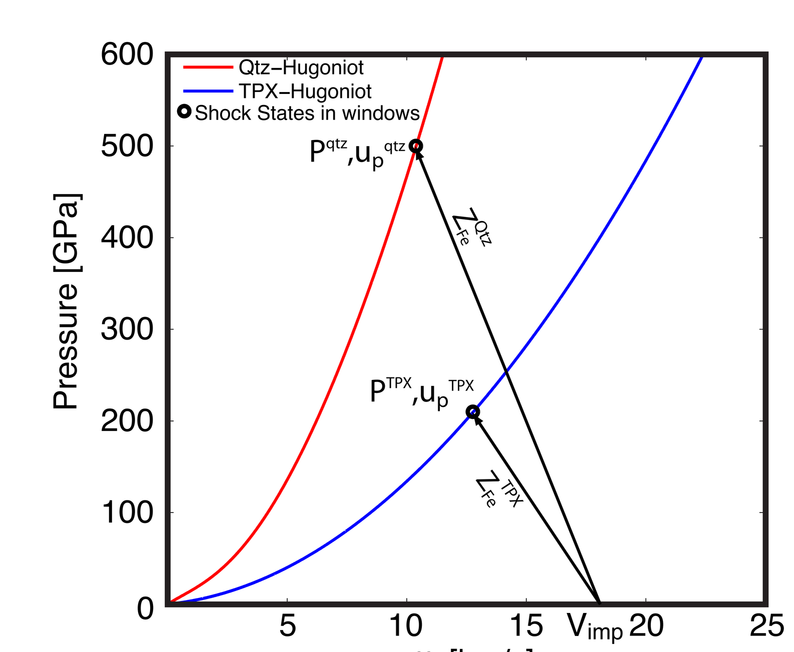


Figure 7: P-u_p diagram illustrating the states achieved during stagnation of fluid Fe at a velocity V_{imp}.

Single Window: For single window measurements, we must assume a re-shock U_s-u_p relation to obtain the density from the measured shock impedance. We use the large amount of porous Hugoniot data on iron to constrain a Mie-Gruneisen equation of state and obtain a U_s-u_p relation for the re-shocked fluid iron.

TPX and Qtz windows: With two types of windows, you reduce the systematic error in the U_s-u_p relation by taking the difference in the shock impedances, although the random errors are significantly larger.

Conclusions

Equation of State
We determined the entropy on the Hugoniot of iron at ~500 GPa.

We measured the density on the liquid branch of the liquid-vapor dome.

Planetary Science
We experimentally determined the criteria for impact induced vaporization of iron and find that significantly more iron is vaporized during the giant impact stage of planet formation than previously thought. Our lower criteria for impact vaporization of iron has significant implications for understanding how the Earth's core formed and the fate of planetesimals during the end stages of accretion.

Novel Technique Development
Here we present a new technique to determine the density along the liquid-vapor dome up to the critical point of the most refractory materials.

This technique, coupled with thermodynamic information at the boiling point, allows us to determine the entropy on the Hugoniot at multi-Mbar pressures.

REFERENCES: 1) Beutl, M., G. Pottlacher, H. Jager, International Journal of Thermophysics 15, 1323 (1994). DOI:10.1007/BF01458840. 2) Hixson, R.S., M. A. Winkler, M. L. Hodgdon, Physical Review B 42, 6485 (1990). DOI:10.1103/PhysRevB.42.6485. 3) Kraus, R.G., et al., Shock Thermodynamics of Iron and Impact Vaporization of Planetesimal Cores, submitted to Nature, 2013. 4) Kerley, G.I., Multiphase equation of state for iron, Tech. Rep. SAND93-0027, Sandia National Laboratories, Albuquerque, NM (1993). 5)Thompson, S.L., H. S. Lausen, Improvements in the CHARTD radiation-hydrodynamic code III: Revised analytic equation of state, Tech. Rep. SC-RR-710714, Sandia National Laboratories, Albuquerque, NM (1972). 6) M. W. Chase, NIST-JANAF thermochemical tables, Monograph No. 9 (American Institute of Physics, Washington, DC, 1998).

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