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Title: Continued Investigation of the Solid-Solid Phase Transitions in Zirconium

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Continued Investigation of the Solid-Solid Phase Transitions in Zirconium

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Work has continued to refine and investigate differences in the Hugoniots for Zirconium with differing impurity levels. Past work has shown that interstitial oxygen inhibits the $\alpha-\omega$ phase transition but appears to have little effect on the $\omega-\beta$ phase transition. Further plate impact experiments have been carried out to determine differences in the Hugoniots for two of the three types of Zirconium samples studied in previous work.

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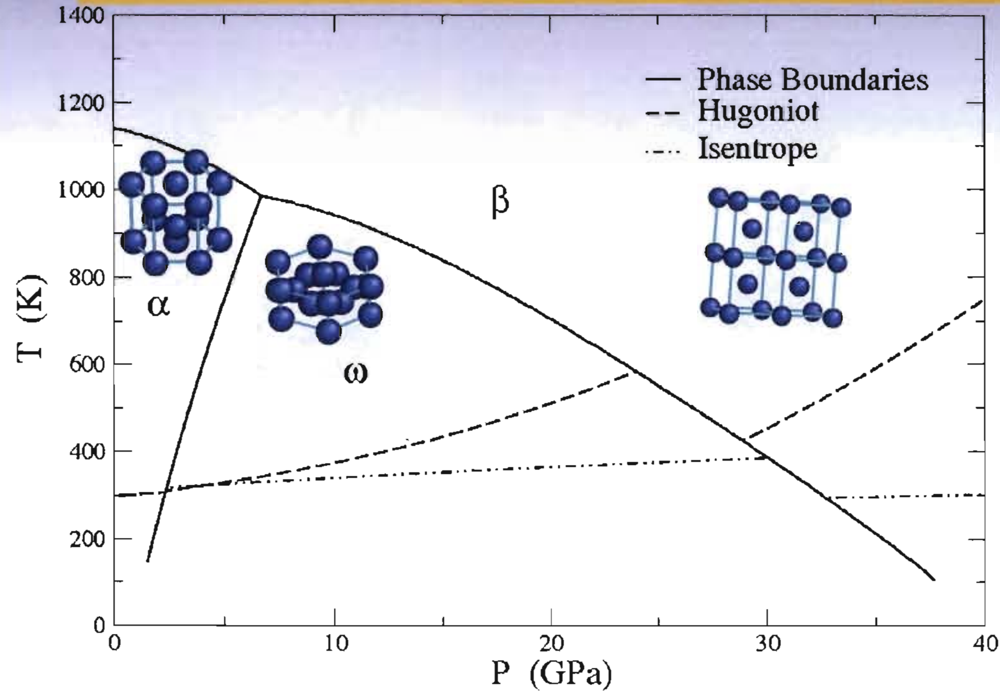
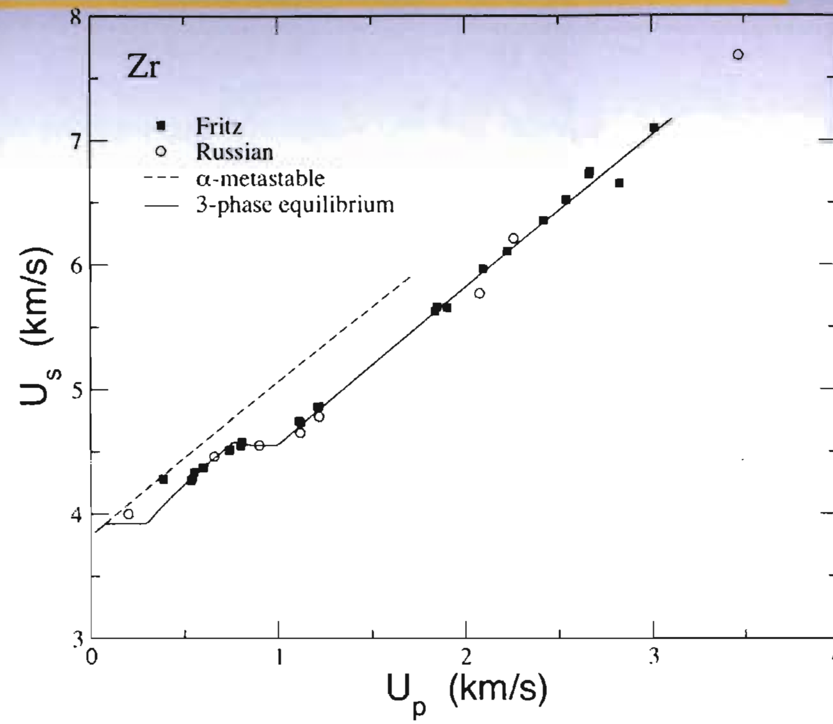
Zirconium is well suited for investigating solid-solid phase transitions under dynamic loading conditions

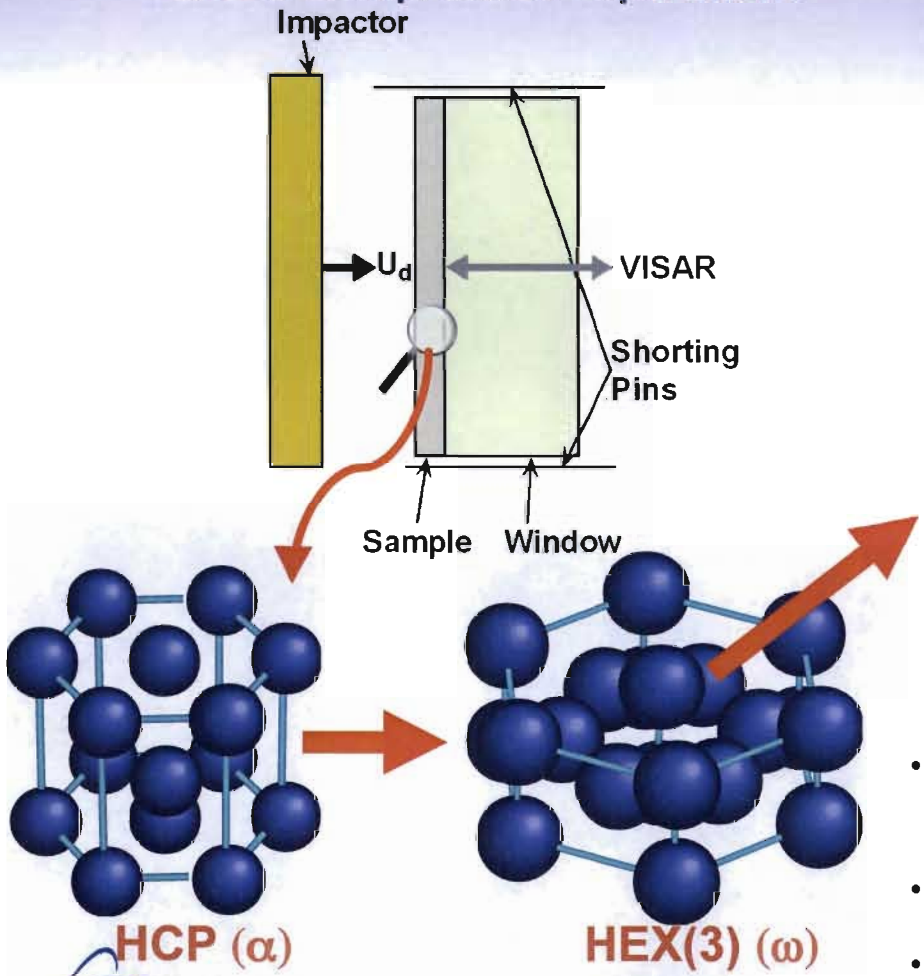




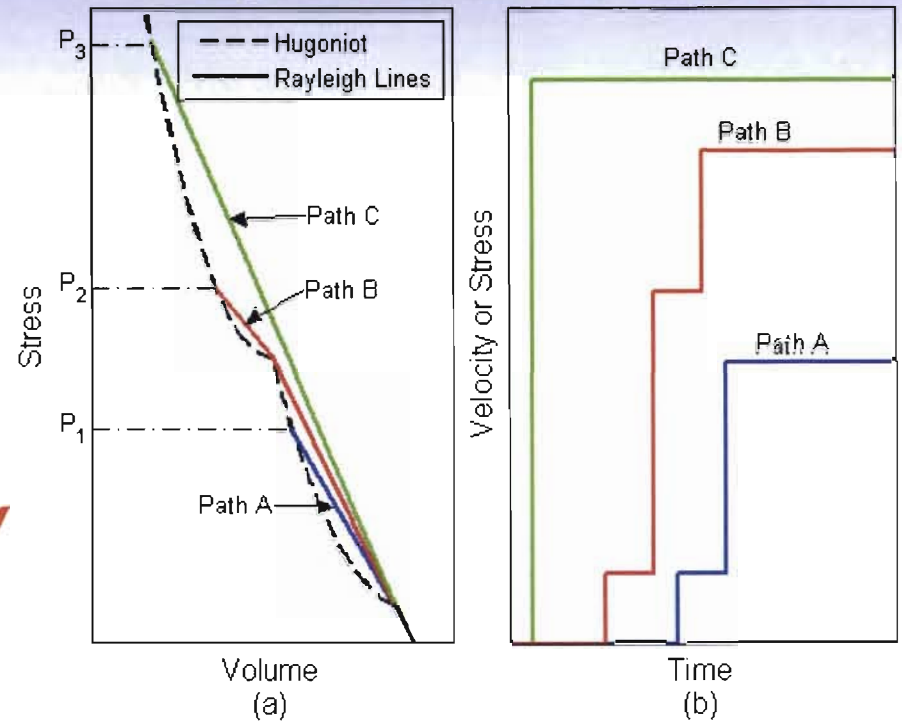
- Three solid phases exist in Zr in pressure regimes easily accessible through shock and isentropic loading.
- Kinks in legacy $U_S - U_P$ data indicate that transitions should be observable in shock compression experiments

Velocimetry is used in shock compression experiments to detect phase transitions in real time

Shock Compression Experiment

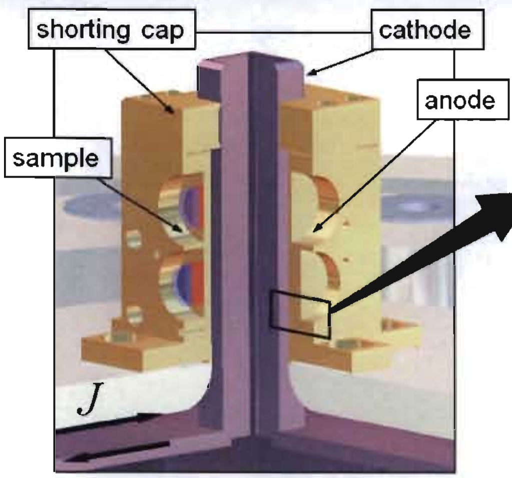


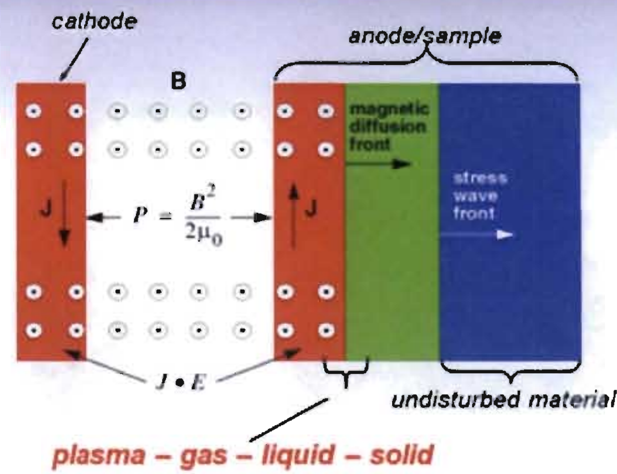
Loading Paths and Ideal Wave Profiles



- A kink in the Hugoniot indicates a change in the material:
  - Elastic-plastic deformation
  - Phase transition
- When the Rayleigh line intersects these kinks, multiple shock waves are formed (Paths A & B).
- **Path C**: Changes still occur, but with no wave profile signature – **changes are "overdriven"**.

Isentropic compression data can provide additional information about the kinetics of phase transformations

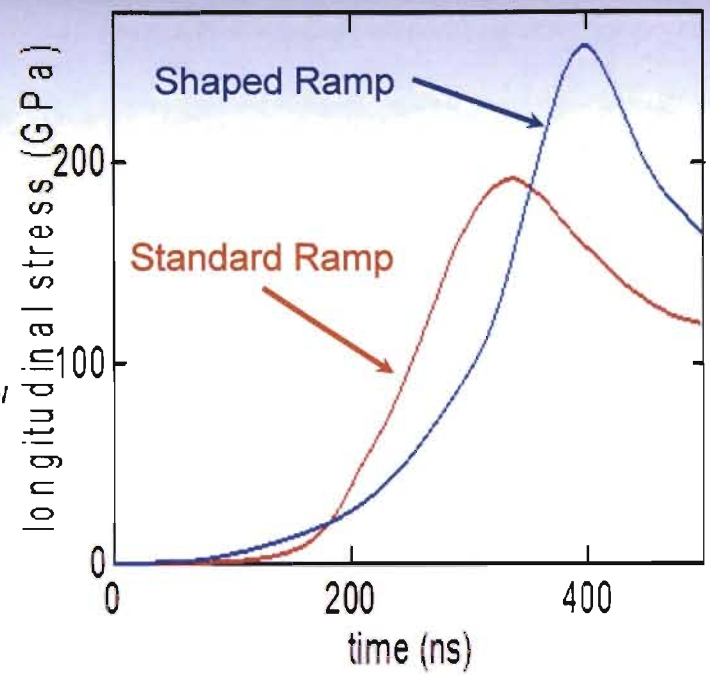




22 MJ stored energy

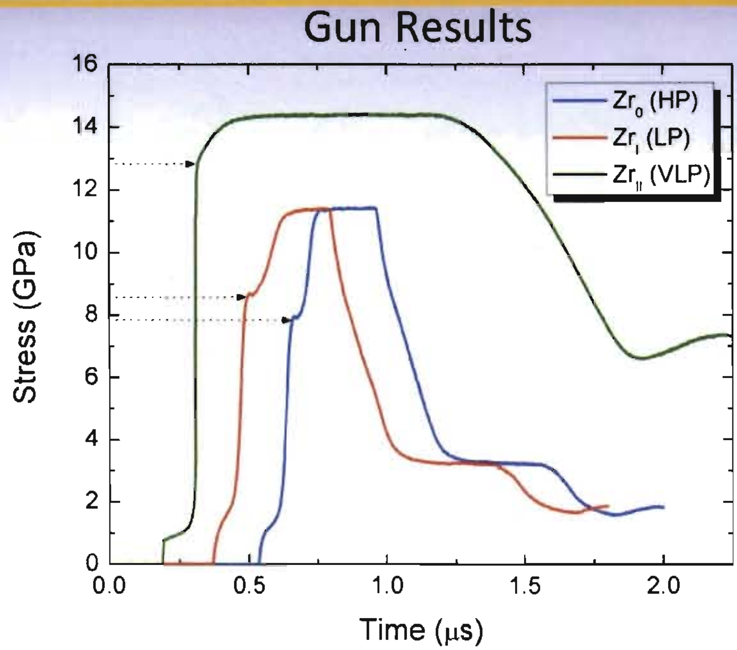
~25 MA peak current

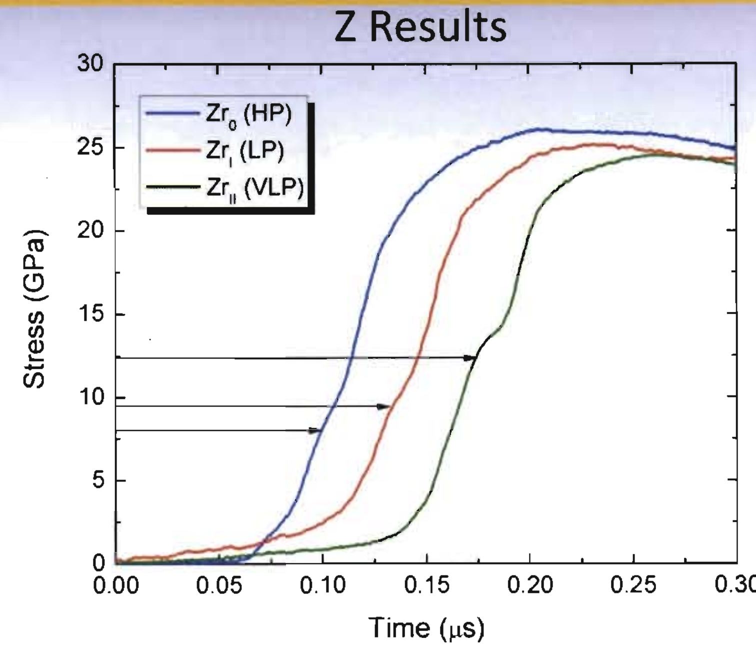
~200-600 ns rise time



- Magnetic field between anode/cathode induces pressure on the sample.
- Pressure pulse temporally follows current
  - This can be tailored by dumping capacitors sequentially
- Materials closely follow isentrope when ramp loaded.
- Isentrope will follow Hugoniot very closely for several hundred kbar.
- Same phase boundaries are accessible through shock and isentropic loading.
- Phase transition cannot be "overdriven".
- Lower strain-rates allow investigation of strain-rate effects on phase transitions.

The presence of oxygen in Zr dramatically increases the stress at which the $\alpha - \omega$ phase transition occurs

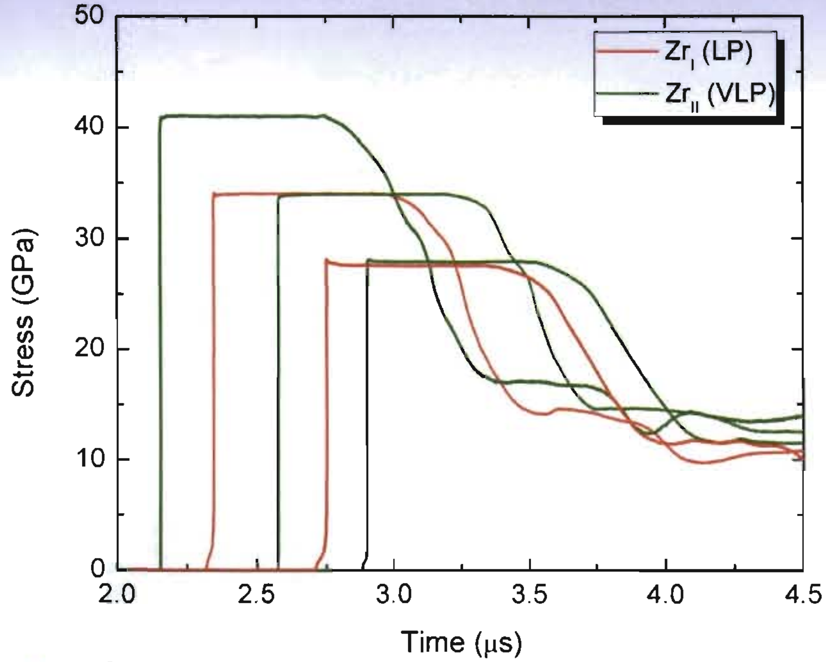




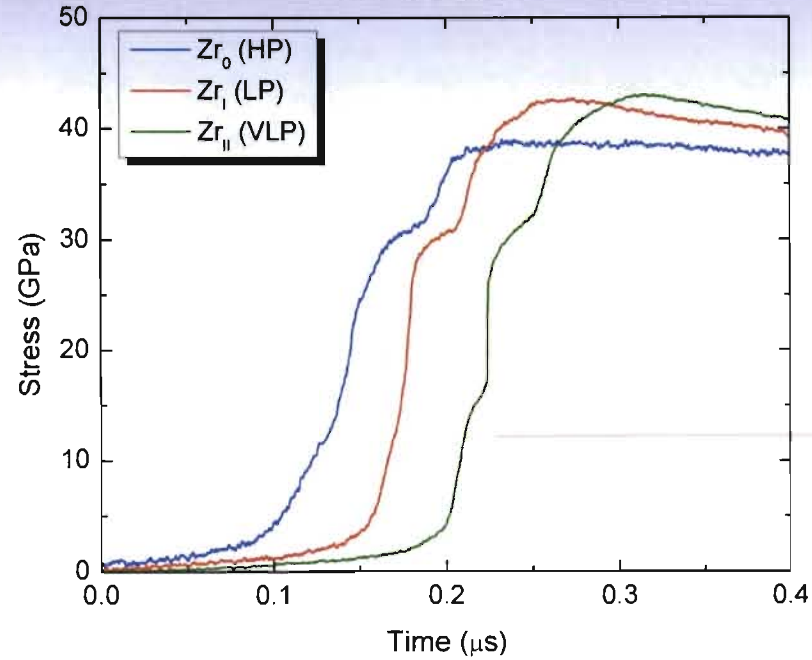
- Oxygen levels are < 50ppm for Zr_0, 390ppm for Zr_I, and 1200ppm for Zr_{II}.
- The phase transition signature is very subtle in the shocked impure sample and is overdriven just a few GPa higher.
- In contrast, the signature is more pronounced for the isentropically loaded impure sample indicating that strain rate is important.
- No rarefaction shock indicating ω phase is retained upon release.

Further experiments conducted to look for ω – β transition

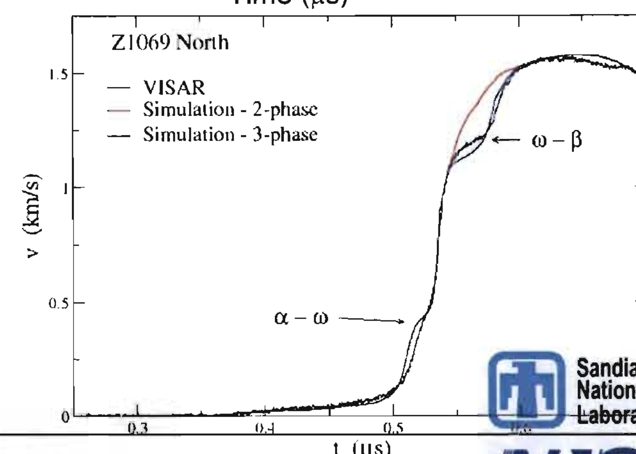
Gun Results



Z Results



- 3-wave structure not observed in gun experiments.
- Oxygen content does not affect ω – β transition stress in Z experiments.
- Model matches Z data well. Shock data not modeled



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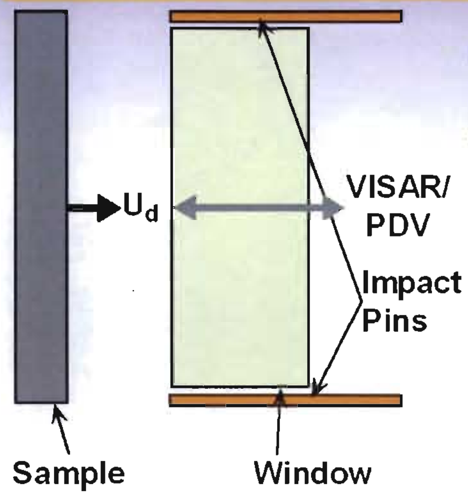
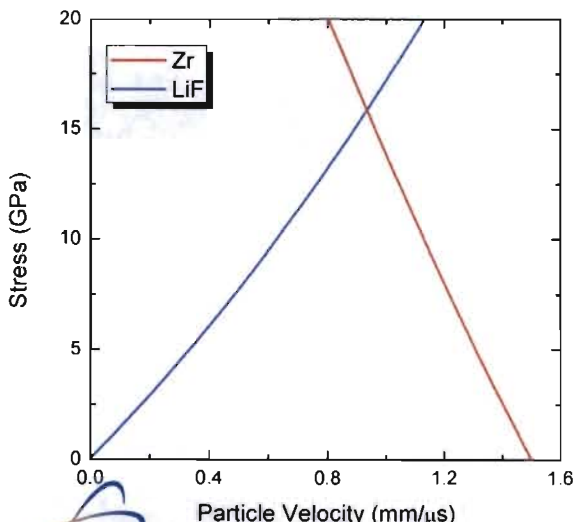
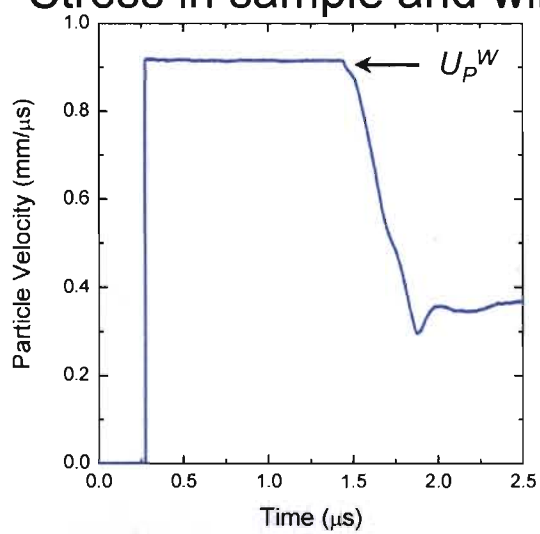
Front surface impact (FSI) experiments eliminate wave interactions due to multi-wave structure



- Sample is impacted on window directly.
- Measurement of projectile velocity, U_d, and particle velocity, U_P^W, needed to determine Hugoniot point:
  - Projectile velocity measured using shorting pins or PDV to 0.1%.
  - Particle velocity measured at impact using VISAR and PDV to ~0.5 - 1%.
- Stress in sample and window defined by window Hugoniot



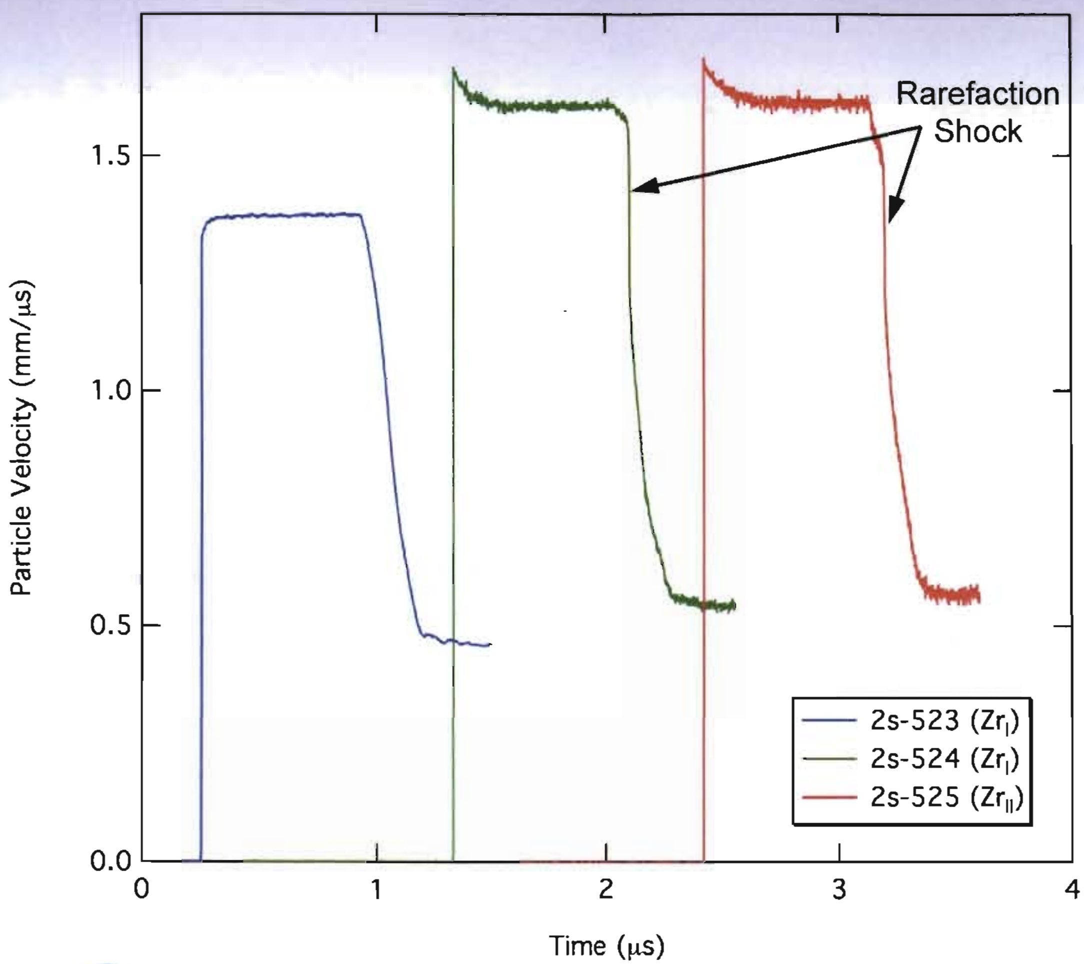


- Shock Velocity determined from R-H Jump Conditions:

$$U_S^S = \frac{P - P_1}{\rho_1 (U_d - U_P^W - U_{P1})}$$

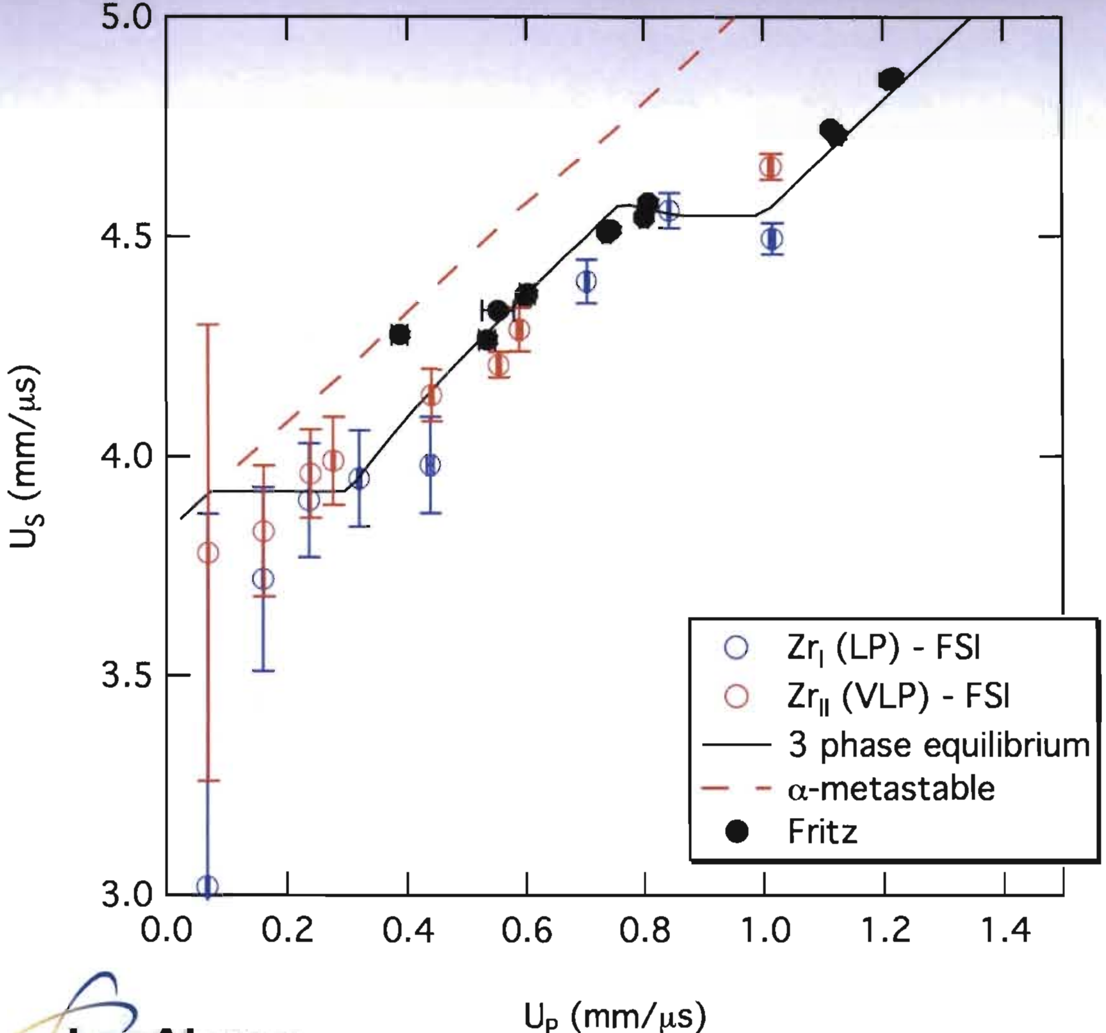
- Must know initial conditions!

FSI experiments reveal β to ω transition on release



- Experiments conducted at 25 and 31 GPa on Zr_I and 31 GPa on Zr_{II} samples.
- At 25 GPa and below – Flat-top shock with ramped release
- At 31 GPa – Overshoot and relaxation at the front followed by shock formation on release
  - ω – β boundary crossed on shock
  - Kinetics of transition observed at shock front
  - Material reverts to ω phase upon release

Calculated Hugoniot is in very good agreement with data from front surface impact experiments



- Errors are large at low stresses due to uncertainties in initial state parameters.
- Results near the $\alpha - \omega$ transition are more consistent with the calculated Hugoniot
  - Better measurement of equilibrium at transition??

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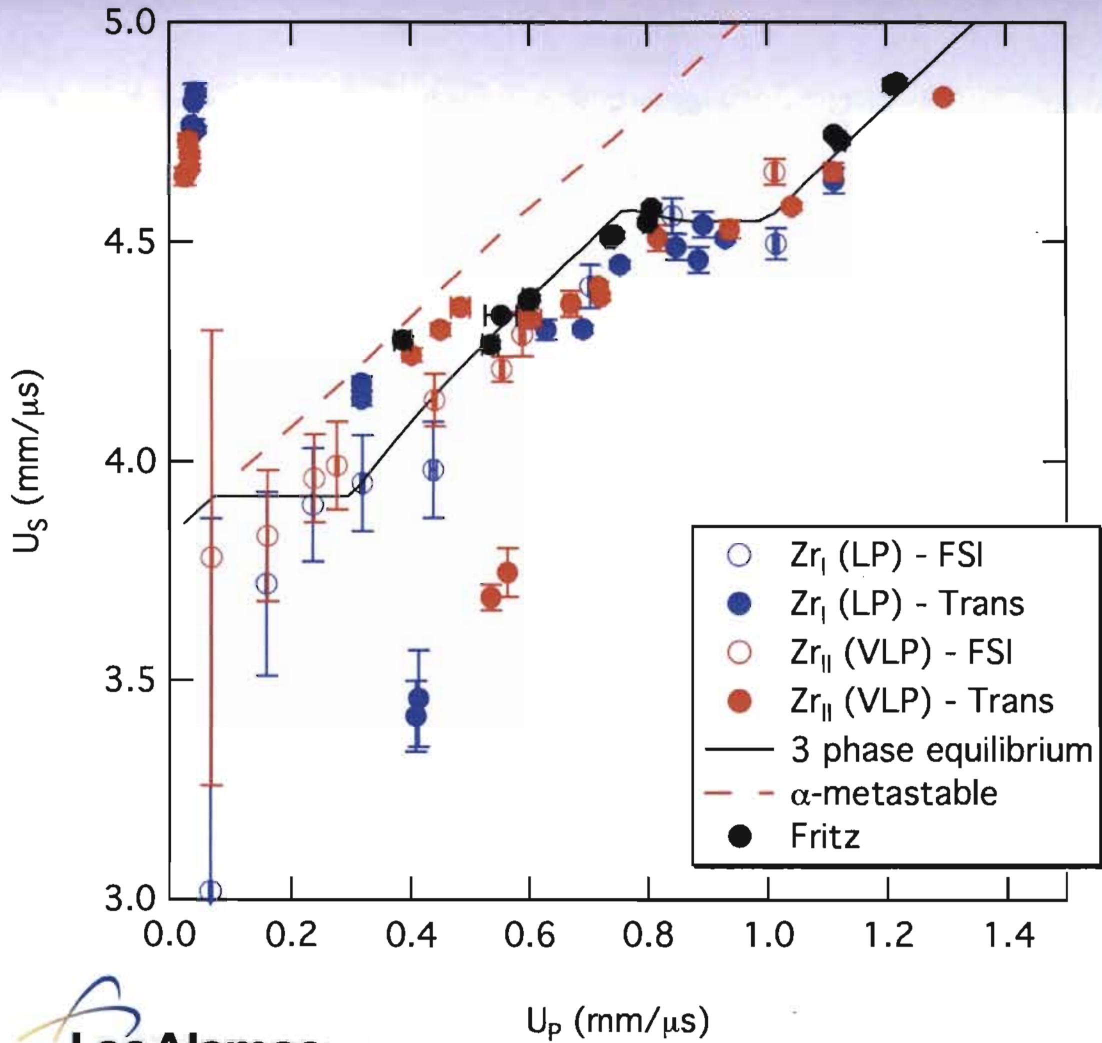

- Errors are large at low stresses due to uncertainties in initial state parameters.
- Results near the $\alpha - \omega$ transition are more consistent with the calculated Hugoniot
  - Better measurement of equilibrium at transition??
- Transmission experiments seem to be better for determining the $\omega - \beta$ transition stress, but…

Summary

- Both front surface impact and transmission experiments were performed to investigate the influence of impurities on the solid-solid phase transitions in three purities of Zr.
- Presence of interstitial O_2 dramatically changes kinetics of $\alpha - \omega$ phase transformation, but not the $\omega - \beta$ transformation.
- Differences between shock- and isentropically loaded experiments shows kinetics are also influenced by the initial loading conditions.
- Greeff Equation of State includes kinetic model which successfully captures much of the phenomena observed experimentally.
- More work needed to successfully model Zr_{II} material and simulation of gun experiments around $\omega - \beta$ transition still needs to be done.
- Combination of several experimental techniques and theory are leading to a better understanding of phase transition kinetics.