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Title: Ejecta Research: Perspectives, Model Development and Validation

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Form 836 (7/06)

Ejecta Research: Perspectives, Model Development and Validation

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I present a brief history of experimental ejecta physics and contrast the early approaches to ejecta physics with our recent successes. Our successes in model development at LANL intrinsically link to a basic application of the scientific method to ejecta phenomena where we control the variables to look for correlations in the measurements. The observations imply that ejecta form as a special limiting case of a Richtmyer-Meshkov (RM) instability. I present an RM based Mikaelian model and compare its predictions to simple experiments. I also show how ejecta physics are being implemented in the FLAG hydrodynamics code.

Ejecta Research: Perspectives, Model Development and Validation

W. T. Buttler

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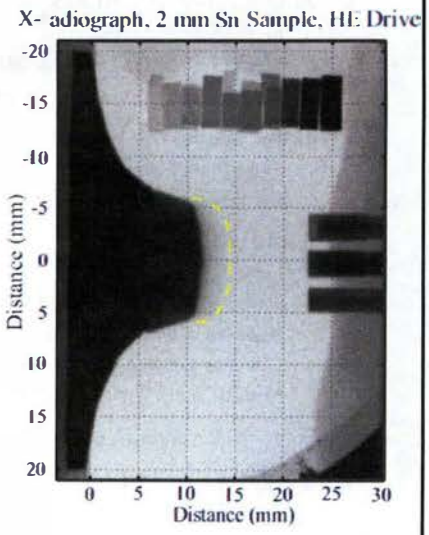
January 10, 2012

Ejecta are Important Because…

- **It is well known that when a Shockwave Interacts with a Metal-Vacuum Interface the Metal will "Eject" Liquid/Solid Metal Fragments: Ejecta**
  - Known as Source Term
    - → Mass-Velocity Distribution
    - → Size-Velocity Distribution
    - → Temperature and Phase
    - → Bulk Material Phase
- **If a Gas is Present the Ejecta will Interact with the Gas**
  - Transport
    - → Drag (Reynolds: Viscous -- Laminar)
    - → Breakup (Weber: Surface Tension -- Turbulent)
    - → Other Processes?



Current Experimental efforts are motivated to Develop and Validate Physics Based Ejecta Source and Transport Models for Inclusion in FLAG

- **Source Term Assumption: Ejecta Form as a Limiting Case (A = -1) of a Richtmyer-Meshkov Instability (RMI).**
  - ⇒ Implies Wavelength and Amplitudes of Perturbations are Important
- **Transport is ballistic with drag (kinematic or ???)**
- **Immediate Goal is to provide modeling contraints on:**
  - ⇒ Total amount of mass ejected
  - ⇒ Velocity of the bulk mass (mass-velocity distribution)
  - ⇒ Fundamental conditions under which ejecta form (solid or liquid material)
  - ⇒ Discover regimes of drag on transport

A Brief Ejecta History…

- **James Asay: Pb, Al Ejecta Formation Measurements**
  - Flyer Plate Experiments
  - Ejecta Formation Linked to Material Phase: Solid or Liquid
  - Ejecta Mass a Function of Defect Volume
- **In the 1980s, the French became involved: Sn, Ta**
  - Flyer Plate Experiments
  - Ejecta Formation Linked to Micro-jetting
- **Some work at**
  - LLNL
  - Particle Sizes: LLNL and LANL in 1990s and 2000s
  - Russian Work in 2000s (Not well published, SCCM-2011)
  - Chinese Work in 2000s (SCCM-2011)
  - English Work Over Similar Periods.
- **Some M-Division Reports from the 1980s**
- **AWE, LANL and LLNL Pu Experiments in 1990s, 2000s**

A Brief Ejecta History…

J. R. Asay, L. P. Mix, and F. C. Perry, Appl. Phys. Lett. 29, 284 (1976).

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Zellner, M. B., Grover, M., Hammerberg, J. E., Hixson, R. S., Iverson, A. J., Macrum, G. S., Morley, K. B., Obst, A. W., Olson, R. T., Payton, J. R., Rigg, P. A., Rourley, N., Stevens, G. D., Turley, W. D., Veeser, L. & Buttler, W. T. 2007 Effects of shock breakout pressure on ejection of material from shocked tin surfaces. *J. Appl. Phys.* **102**, 013522.

Zellner, M. B., Vogan-McNeil, W., Gray, G. T., III, Hooks, D. C., Kenz, N. S. P., Neal, G. E., Valentine, S. J., Payton, J. R., Robin, J., Stevens, G. D., Turley, W. D. & Buttler, W. T. 2008 Surface preparation methods to enhance dynamic surface property measurements of shocked metal surfaces. *J. Appl. Phys.* **103**, 083521.

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Zellner, M. B. & Buttler, W. T. 2008 Exploring Richtmyer-Meshkov instability phenomena and ejecta cloud physics. *Appl. Phys. Lett.* **93**, 111902.

IMPACT STRESS MEASUREMENT USING PIEZOELECTRIC PROBES WITH PZT AND LITHIUM NIOBATE ELEMENTS
CP1195, *Shock Compression of Condensed Matter - 2009*
A. Mears, N. R. Rourley and P. A. Kendall

G. Dimonte, et al., "Use of Richtmyer-Meshkov Instability to Infer Yield Strength," Accepted for Publication in Phys. Rev. Lett. (2011).
W. T. Buttler, et al., "Unstable Richtmyer-Meshkov Growth of Solid and Liquid Metals in Vacuum," Submitted to J. Fluid Mech. (2011), in Revision.

Many Conference Proceedings by LANL and LLNL.

Many NEDPC publications by LANL and LLNL.

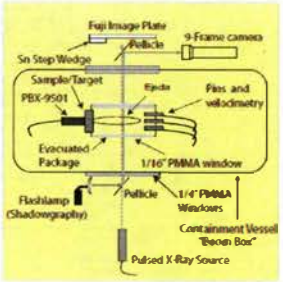
Many Red Publications.

Scientific Method: Question Accepted Conclusions

- **We asked: How much, how fast, under what conditions?**
  - Do Ejecta Production Link to Surface Perturbations?
    - Accepted position was yes
  - Do Ejecta Link to Loading-Pressures?
    - Accepted position was only material phase
  - Do Ejecta Link to Shockwave Loading Profile?
    - Accepted position was only peak stress mattered
  - Can We Cause Ejecta From Solids?
    - Accepted position was only material phase mattered
- **We are now investigating**
  - Sensitivity to First Shock? Sensitivity to Second Shock?
  - Sweeping Shockwaves Link to Ejecta Production
  - Size Versus Wavelength and Amplitude

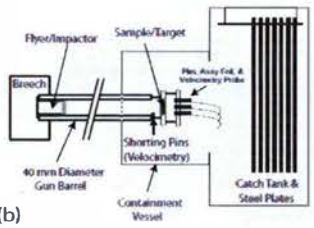
LANL 2000s: Basic Experiments

Explosive



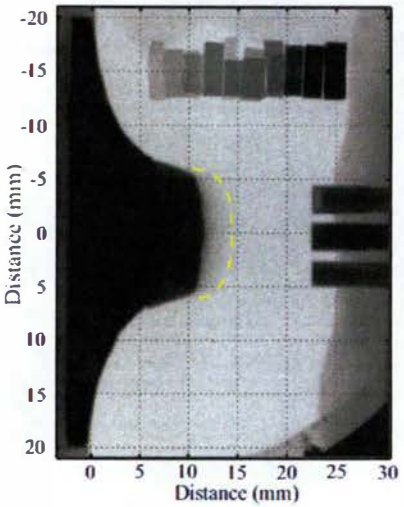
(a)

Gun



(b)

X-radiograph, 2 mm Sn Sample, HE Drive



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LANL 2000s

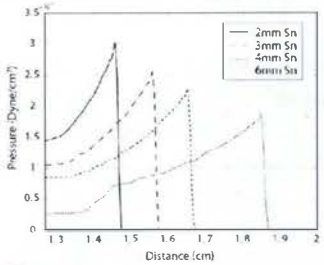
- **Ejecta Measurements: Mostly from Sn**
  - Control Variables: Material, Perturbations, Driving Conditions
    - Fix Loading Pressure, Vary Finish (Perturbations)
    - Fix Finish, Vary Pressure
      - Pressure Varied Two Ways:
        - Flyer Plate (Supported Shockwave)
        - High Explosive (Taylor, or Unsupported Shockwave)

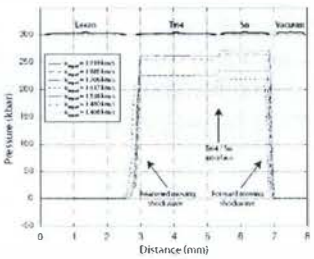
⇒ Look for Correlations to Build a Model

Calculated Taylor Profiles for varying Sn thicknesses

Calculated supported profiles for varying Sn impactor velocities

Taylor





Square

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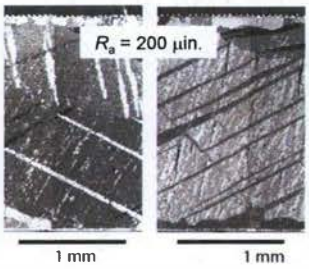
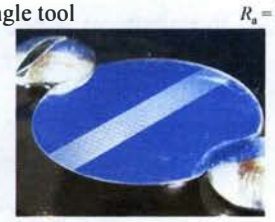
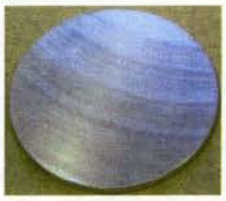
Control Variables (2000s)

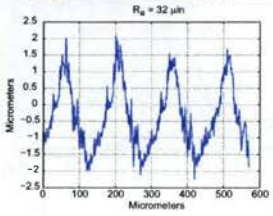
- Pressure and Loading Profiles
- Sn (ESPI, 0.99995 purity)
- Machine Finishes (Fly-Cut grooves, R_a = 16 to 250 µin.)
  - Same rotation angle/feed rate/fly-cut radius, rake angle
  - Most experiments done with a single tool
  - Same machine and tool holder
  - Felix—Machinist with MST-7

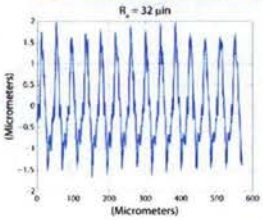


R_a = 32 µin.









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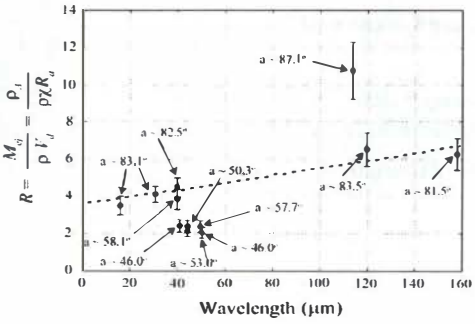
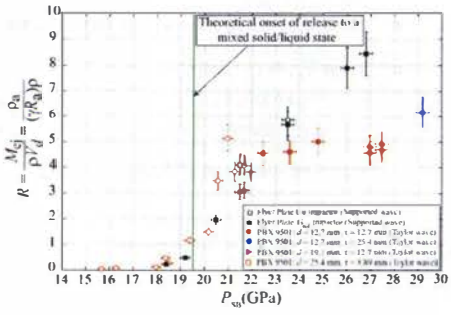
LANL Historical Sn Data (2002 – 2010)

Fixed Pressure: P_{SB} = 27 Gpa
Varied Finish



Fixed Finish
Varied Pressure: P_{SB}



These data show marked consistency, and begin to reveal trends that imply we can find correlations and develop a model.

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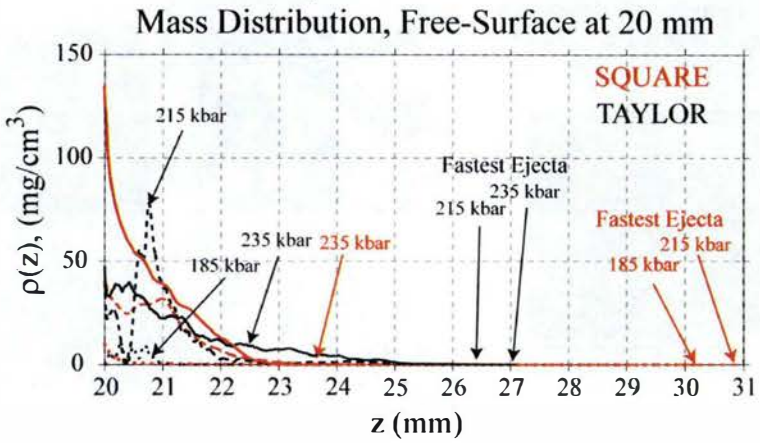
Mass Distributions

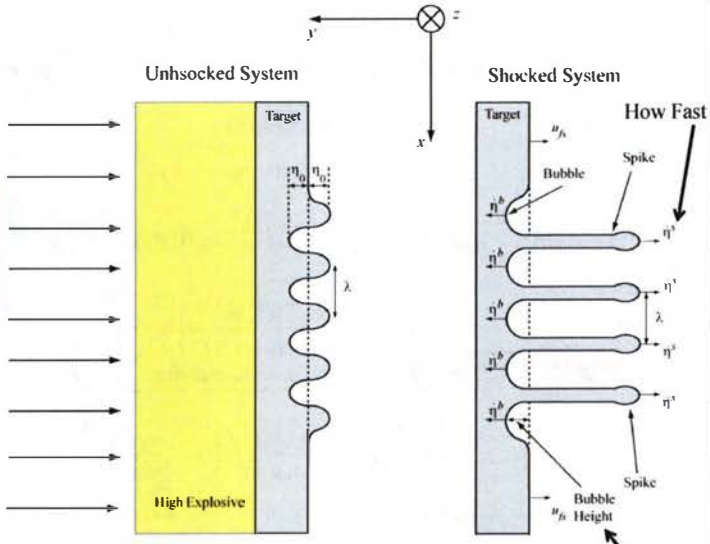
- Square vs. Taylor Loading Differences:
  - Mass vs. Velocity Distributions
  - Total Mass
  - Fastest Ejecta



- **Results Imply Mass and Distributions are Linked to RM Instability**
- **Gun Experiments**
  - Total Mass Increases Linearly with Increasing Pressure
  - Mass Distribution is Nearer to the Free-Surface than Taylor Wave Loading

⇒ **Implies we Should Focus on HE Driven Experiments**

A *Fluid* Source Model



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Bubble and Spike Model, High-Strain, High-Strain Rate Model

Setting $g = \eta_0 k = 0$ in Eq. 5a in Mikaelian (1998), gives

$$\frac{\dot{\eta}}{\dot{\eta}_0} = \frac{Y_0}{Y} = \sqrt{\frac{3}{2}}\frac{1}{Y} = \sqrt{\frac{3}{2}}\frac{1}{\sqrt{\dot{\eta}_0 k + 1/2}} \quad (1)$$

Integrating (1) gives (applies to bubbles and spikes)

$$\dot{\eta}_0 k\, t = \frac{2\sqrt{2}}{3\sqrt{3}}Y - \frac{2}{3} + \frac{1}{3\sqrt{3}}\ln\left[\frac{(\sqrt{3}+1)(\sqrt{2}Y-1)}{(\sqrt{3}-1)(\sqrt{2}Y+1)}\right]$$

$$= \frac{2\sqrt{2}}{3\sqrt{3}}Y - \frac{2}{3} + \frac{\eta k}{\sqrt{3}} + \frac{1}{3\sqrt{3}}\ln\left[\frac{\sqrt{3}+1}{(\sqrt{3}-1)(\sqrt{2}Y+1)^2}\right]$$

Asymptotic Spike Velocity from (1): $\lim_{\eta\to-\infty} \dot{\eta}(\eta) = \sqrt{3}\dot{\eta}_0^s$

Mikaelian (1998) Gives an approximation to the bubble velocity:

$$\dot{\eta}_0^b = \frac{2\dot{\eta}_0^b}{2 + 3\dot{\eta}_0^b k t}$$

$$\Rightarrow \dot{\eta}_\infty^b \equiv \lim_{t\to\infty}\dot{\eta}_0^b = \frac{2}{3kt}$$

Equations (1) to (3) requir the impulse:

$$\dot{\eta}_0^b = -\dot{\eta}_0^s = \eta_0 k u_{fs}$$

COMPRESSIBILITY

Meyer-Blewett (1972) found that A = −1 requires an average of the pre- and post-shock amplitudes:

$$F_{cmp} = 1 - \frac{u_{fs}}{2u_{sh}}$$

NON-LINEAR REGIME

For spikes, Dimonte and Ramaprabhu (2010) fit simulations in Velikovich and Dimonte (1992) and found:

$$F_{nl}^s = \frac{1}{1 + (\frac{\eta_0 k}{2})^2}$$

For bubbles a similar fit to simulations in Velikovich and Dimonte (1992) gives:

$$F_{nl}^b = \frac{1}{1 + \frac{\eta_0 k}{6}}$$

Assuming Compressible and non-linear effects are independent we find:

$$|\dot{\eta}_0^{b,s}| = F_{cmp}F_{nl}^{b,s}|\eta_0 k u_{fs}|$$

Mikaelian, K. O. 1998 Analytical approach to nonlinear Rayleigh-Taylor and Richtmyer-Meshkov instabilities. *Phys. Rev. Lett.* 80, 508–511.

Meyer, K. A. & Blewett, P. J. 1972 Numerical investigation of the stability of a shock-accelerated interface between two fluids. *Phys. Fluids* 15, 753–759.

Dimonte, G. & Ramaprabhu, R. 2010 Simulations and model of the nonlinear Richtmyer-Meshkov instability. *Phys. Fluids* 22, 014104.

Velikovich, A. L. & Dimonte, G. 1996 Nonlinear perturbation theory of the incompressible Richtmyer-Meshkov instability. *Phys. Rev. Lett.* 76, 3112–3115.

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A High Strain, High Strain Rate Strength Model (What Conditions)

$$\xi_m - \xi_0 = 0.29\frac{\rho\dot{\xi}_0^2}{kY}$$

ξ_m is the height the spike reaches after inversion, growth and arrest

$$\dot{\xi}_0 \equiv k\xi_i u_p$$

when $A = -1$, $u_p \mapsto u_{fs}$

$$(\eta_\infty^s - \eta_0)k \approx \mu\eta_0\frac{\rho_0(\eta_0 k u_{fs})^2}{Y} \approx 0.29\eta_0\frac{\rho_0(\eta_0 k u_{fs})^2}{Y}$$

$$\mu = 0.29$$

Meyer-Blewett (1972)

In Piriz (2008), for RT, $A = 1$, for RMI, $A = -1$, implying

Richtmyer (1972)

$$\mu' \approx \mu \times \left[\left(1 - \frac{u_{fs}}{2u_{sh}}\right)\Big/\left(1 - \frac{u_{fs}}{u_{sh}}\right)\right]^2$$

Piriz, A. R., Lopez-Cela, J. J., Tahir, N. A., & Hoffmann, D. H. H. 2008 Richtmyer-Meshkov instability in elastic-plastic media. *Phys. Rev. E* **78**, 056401.

Piriz, A. R., Lopez-Cela, J. J. & Tahir, N. A. 2009 Richtmyer-Meshkov instability as a tool for evaluating material strength under extreme conditions. *Nucl. Instrum. Meth. Phys. Res. A* **606**, 139–141.

Richtmyer, R. D. 1960 Taylor instability in shock acceleration of compressible fluids. *Commun. Pure Appl. Math* **13**, 297–319.

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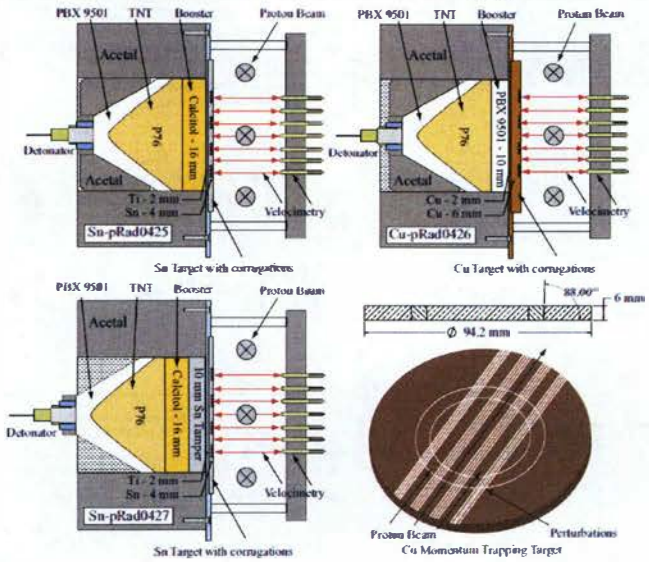
FY10 pRad Experiments: Model Validation

Unstable Richtmyer-Meshkov growth of solid and liquid metals in vacuum 9



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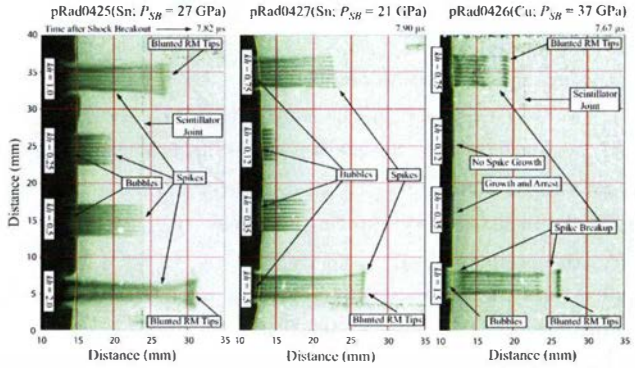
FY10 Results: Model Validation

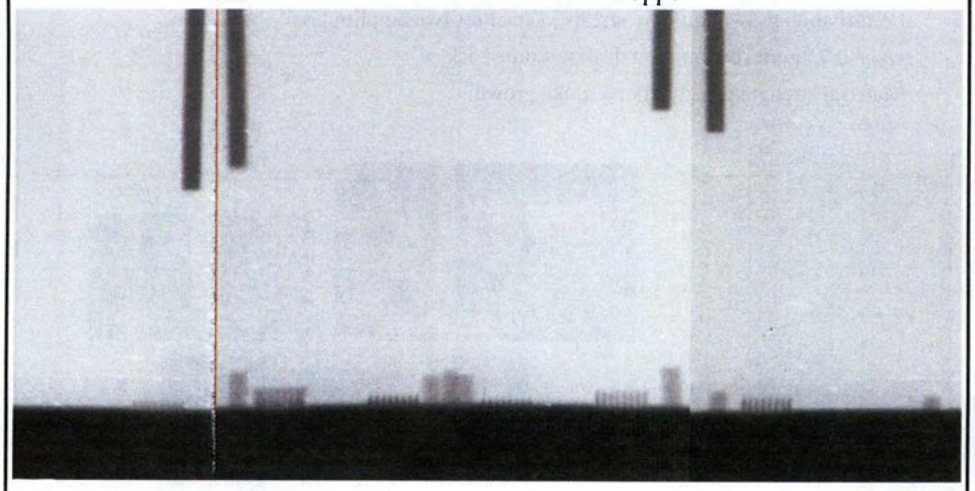
- Large drive, improved target design ⇒ minimal curvature.
- Sn targets liquefied, Cu target solid.
- Non-arrested spike growth in Cu dependent on wavenumber-amplitude product.
- Spike breakup evident in Cu.

- FY10 work studied on/off mechanism of ejecta production :
→ Piriz, et al. found that yield strength saturates the RM amplitude

$$(\eta_\infty^* - \eta_0)k \approx \mu\eta_0 \frac{\rho_0(\eta_0 k u_{fs})^2}{Y}$$



Selected FY10 pRad Movies



Sn Bubble and Spike Velocity Comparisons

	$\eta_0 k$	η_0 (μm)	τ^s_{bo} (μs)	τ^s_{rt} (μs)	$\dot{\eta}^{b,m}_{t=0.3\ \mu s}$ (mm/μs)	$\dot{\eta}^{b}_{t=0.3\ \mu s}$ (mm/μs)	$\dot{\eta}^{s,m}_{\infty}$ (mm/μs)	$\dot{\eta}^{s}_{\infty}$ (mm/μs)
Sn-pRad0425	0.25	22	−0.012	< 0.14	−0.07	−0.12	0.63	0.61
$P_{SB} = 26.7$ GPa	0.5	44	−0.023	< 0.13	−0.15	−0.15	1.14	1.16
$\langle u^{\infty}_{fs} \rangle = 1.85$ (mm/μs)	1.0	88	−0.023	< 0.21	−0.14	−0.17	1.60	1.97
$u_{sh} = 3.97$ (mm/μs)	2.0	175	−0.088	< 0.34	−0.26	−0.18	2.10	2.46
Sn-pRad0427	0.12	11	+0.010	< 0.11	0.00	−0.08	0.31	0.26
$P_{SB} = 21.9$ GPa	0.35	31	−0.013	< 0.09	−0.02	−0.13	0.81	0.74
$\langle u^{\infty}_{fs} \rangle = 1.59$ (mm/μs)	0.75	66	−0.026	< 0.08	−0.09	−0.16	1.26	1.43
$u_{sh} = 3.77$ (mm/μs)	1.5	131	−0.073	< 0.22	−0.06	−0.17	1.78	2.09

$\lambda = 0.55$ mm

η_0: initial perturbation amplitude

τ^s_{bo}: time the spikes began to compress and invert

τ^s_{rt}: time over which the spikes rise to 90% of their maximum velocity

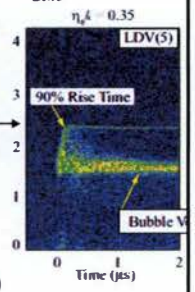
$\dot{\eta}^{b,m}_{t=0.3\ \mu s}$: bubble velocity relative to u_{fs} at $t = 0.3\ \mu s$

$\dot{\eta}^{s,m}_{\infty}$ the measured asymptotic spike velocity

$\dot{\eta}^{s}_{\infty}$: the pre icte spike velocity.

uncertainty in *all* measured velocities is of $O(0.01$ to 0.02 mm/μs)

uncertainties in τ^s_{bo} is of $O(0.005\ \mu s)$



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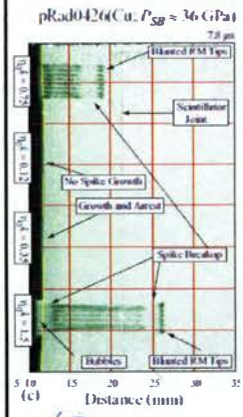
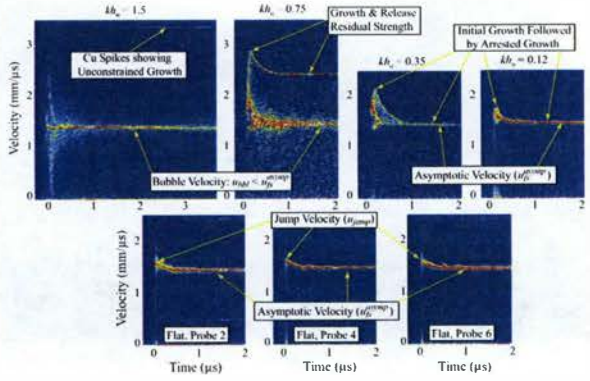
LA-UR-11-03785

Cu Strength Velocimetry

- Evidence of initial growth in all perturbation regions
- Perturbation growth quickly arrests in smallest two amplitudes.
- $kh_0 = 0.75$ perturbation growth shows pull-back.
- Material strength clearly affects spike growth.





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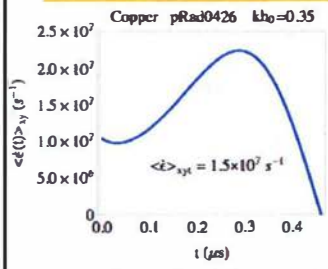
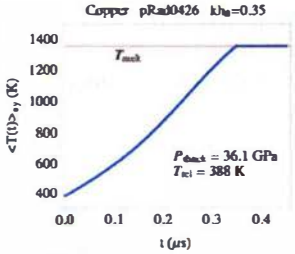
LA-UR-11-03785

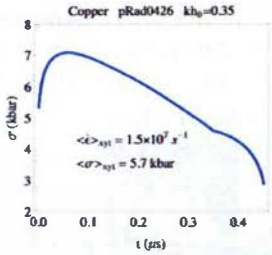
Preliminary analysis by Preston of Cu kh_0 = 0.35 w/ PTW



Mean plastic strain rate in the spikes vs. time



Mean spike temperature vs. time. <*T*> reaches T_{melt} at 0.35 μs, but the Cu remains solid until growth arrests. Plastic work while <*T*> = T_{melt} results in ~25% of heat required to melt Cu.



Mean stress in the spikes vs time. Growth becomes plastically unstable at 0.06 μs, which corresponds to a strain of approximately 60%.

Piriz machinery says:
$Y(\mu'=0.29)$ = 0.37 Gpa

$$\mu' \approx \mu \times \left[\left(1-\frac{u_{fe}}{2\alpha_{eh}}\right)\Big/\left(1-\frac{u_{fe}}{\alpha_{eh}}\right)\right]^2$$

Y = 0.52 GPa

The simple constitutive relation chosen by Piriz et al., namely elastic-perfectly plastic, is a poor approximation. In order to extract high strain rate flow stresses from ejecta data it will be necessary to generalize above equation using a more realistic constitutive relation.

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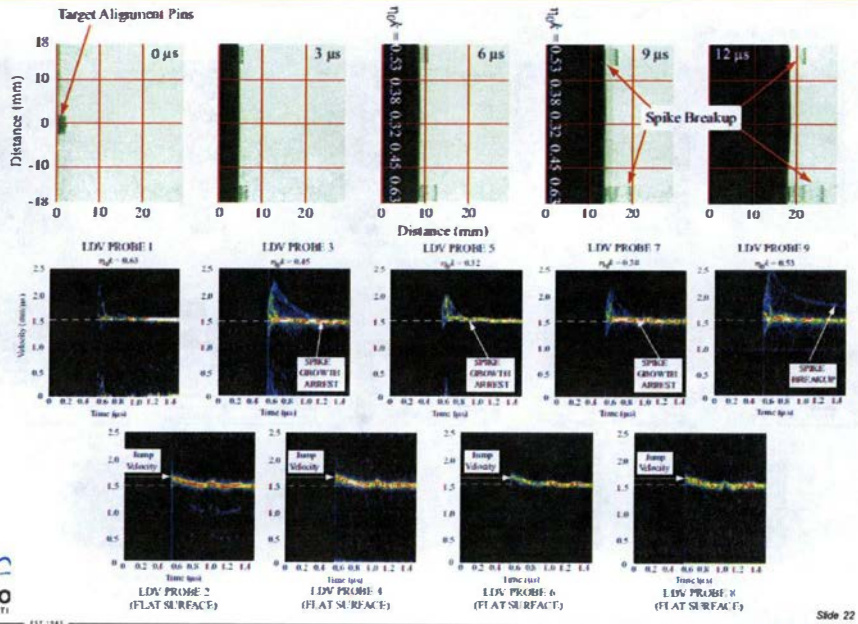
FY11 Campaign 1: Cu Strength – Stastics



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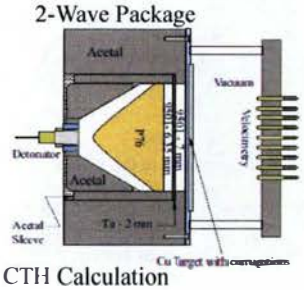
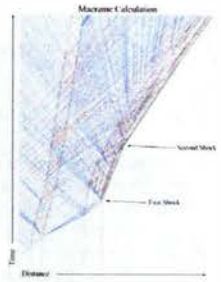
High on our List: Two-Shockwave Uniaxial Strain Physics

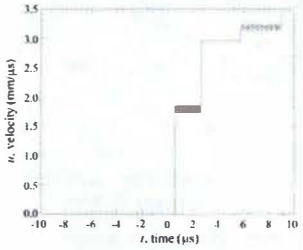
- **Results Cross Campaigns**
  - 2-wave Drive Developed and Tested Under C2
  - 2-Wave Drive Used to Support C1 Physics Topics

2-Wave Package





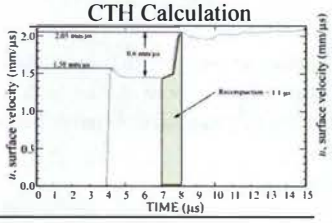
Macrame Calculation



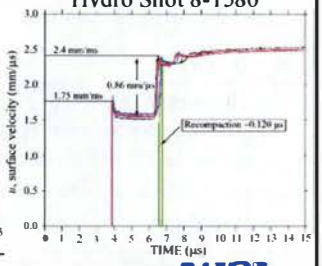
CTH Calculation

- Elastic Plastic
  - o Steinberg Guinan
- Strength
  - o Pmin (16 kbar)
- Interval Time
  - o CTH: 3.6 ms
  - o Hydro: 2.5 ms

CTH Calculation



Hydro Shot 8-1580



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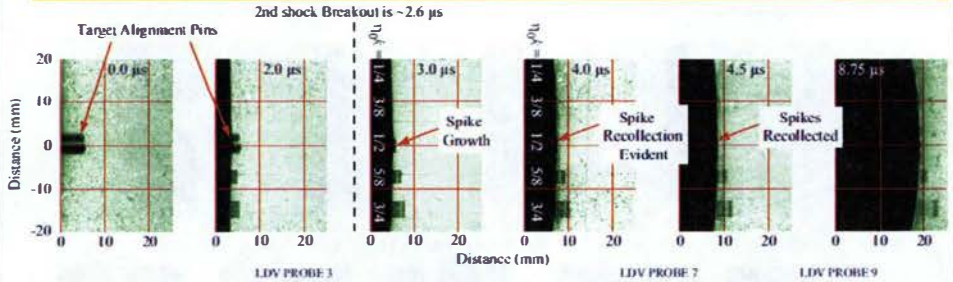
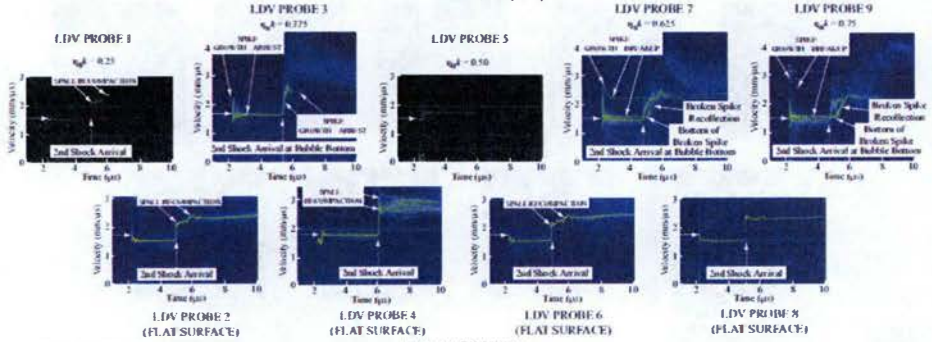
FY11 Campaign 1 Two-Wave Experiments





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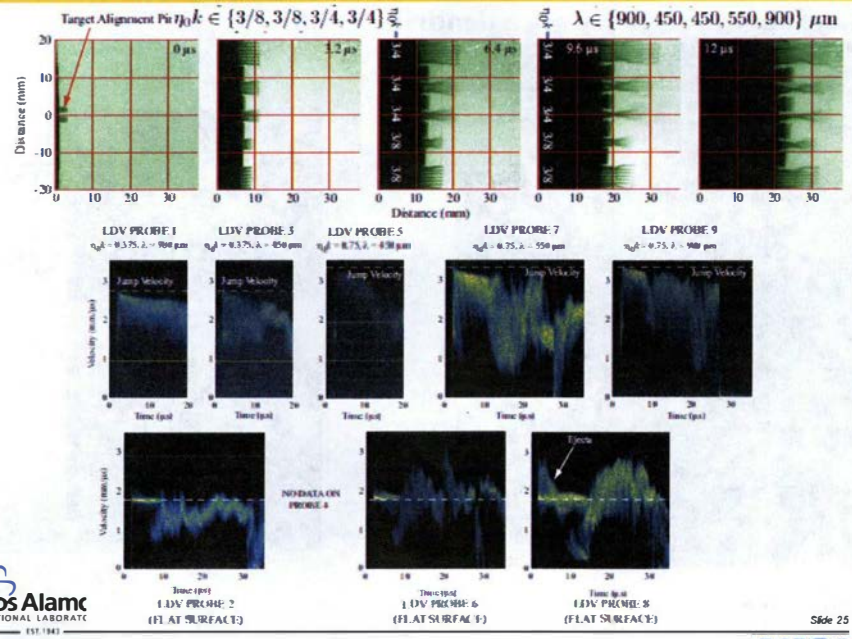
FY-11 Transport(Sn): 2.5 Atm Ne



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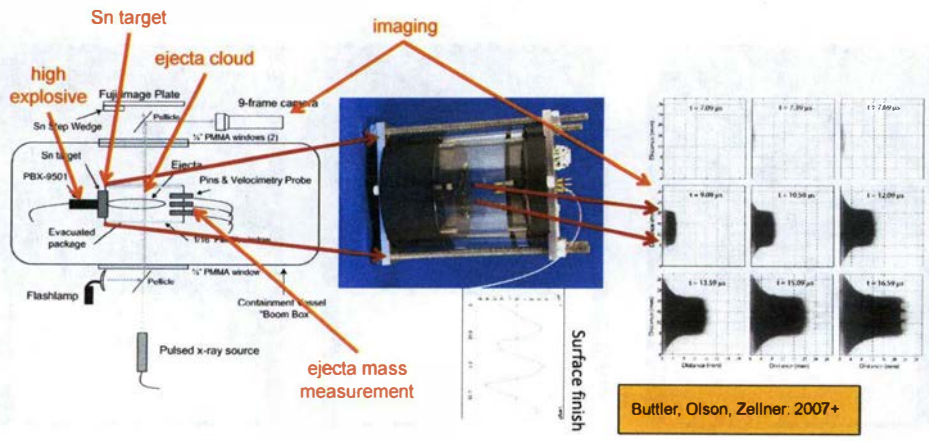
Slide 25

Implementation: Modeling Experiments

- **W. Buttler and colleagues at LANL have made extensive ejecta measurements in tin.**



Buttler, Olson, Zellner: 2007+

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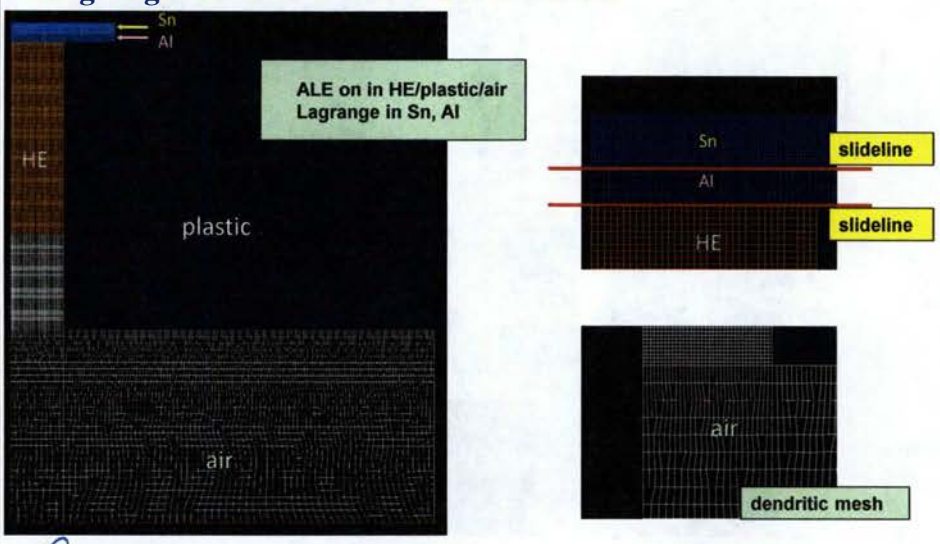
The general setup for the experiment applies slidelines, Lagrange and ALE over a dendritic mesh.



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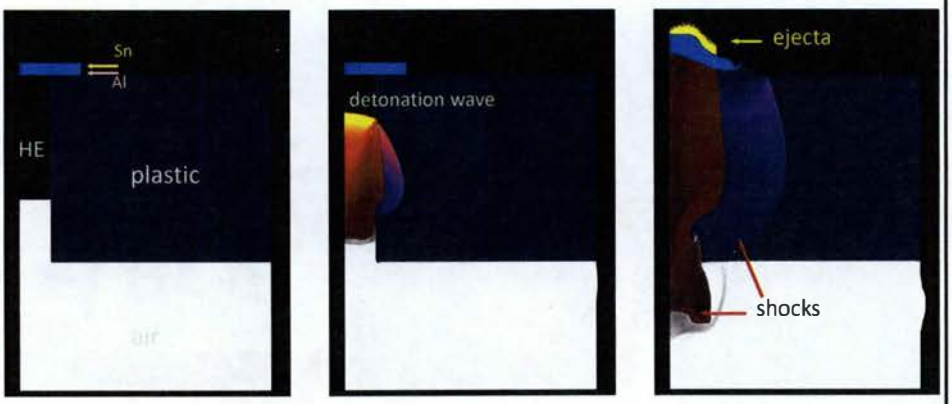
FLAG captures the general hydrodynamics of the Al-Sn experiment.



0 microseconds 2 microseconds 6 microseconds

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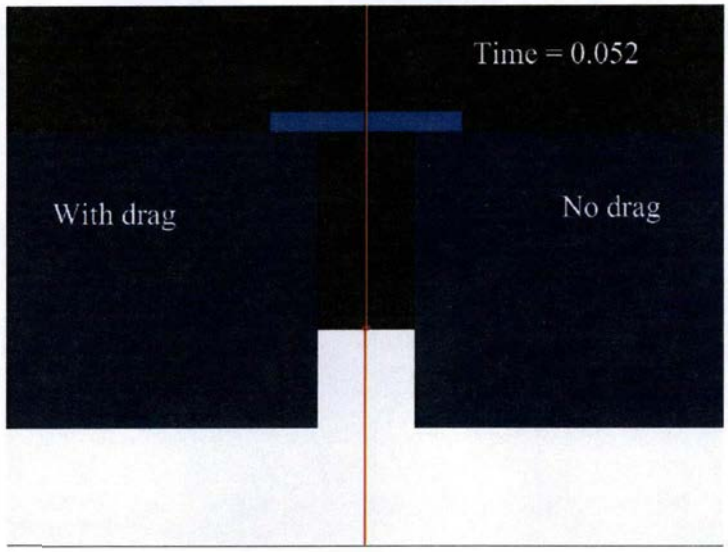

- **We have demonstrated the conditions under which ejecta form from solids and liquids.**
- **We are predicting bulk ejecta velocity.**
- **Work remains on total mass, but some success here as well.**
- **FY12:**
  - One Sn: 10 Atm Helium
  - Two Sn Two-Wave experiments – Into vacuum into Gas
  - Ta Strength?