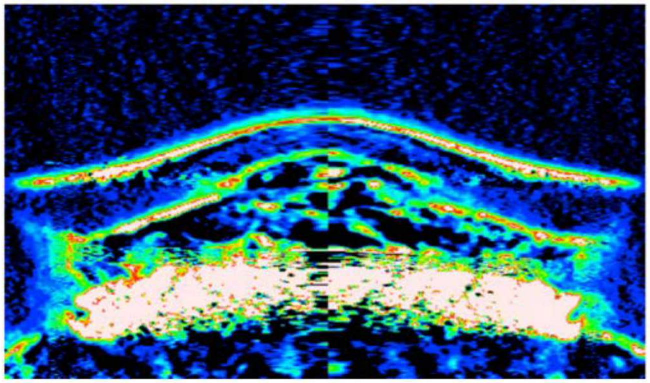
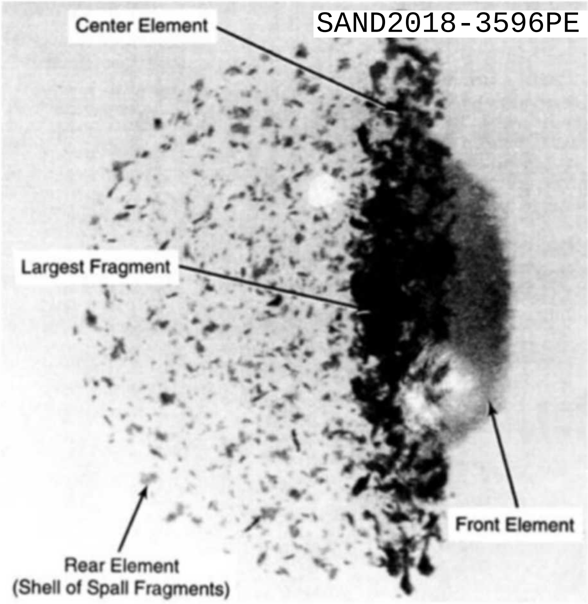
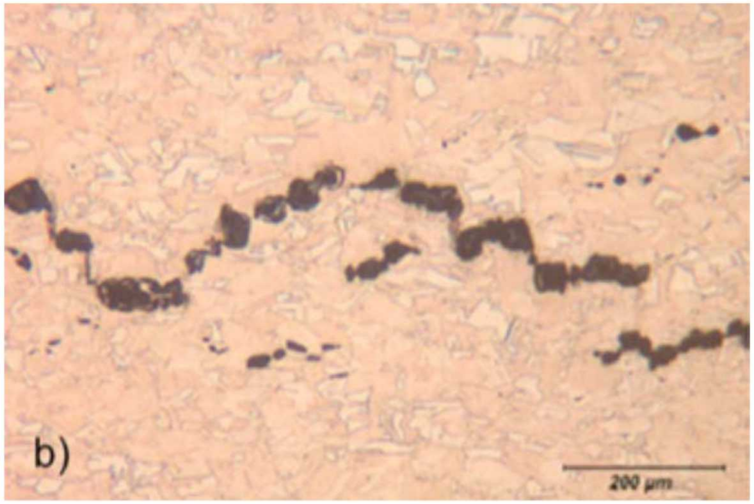
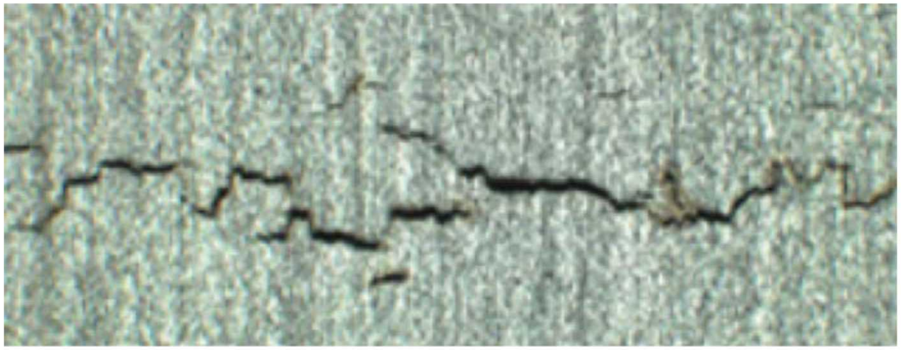




Spall and Fragmentation

Tracy Vogler
Department 8256, Mechanics of Materials
Sandia National Laboratories, Livermore CA





National Nuclear Security Administration

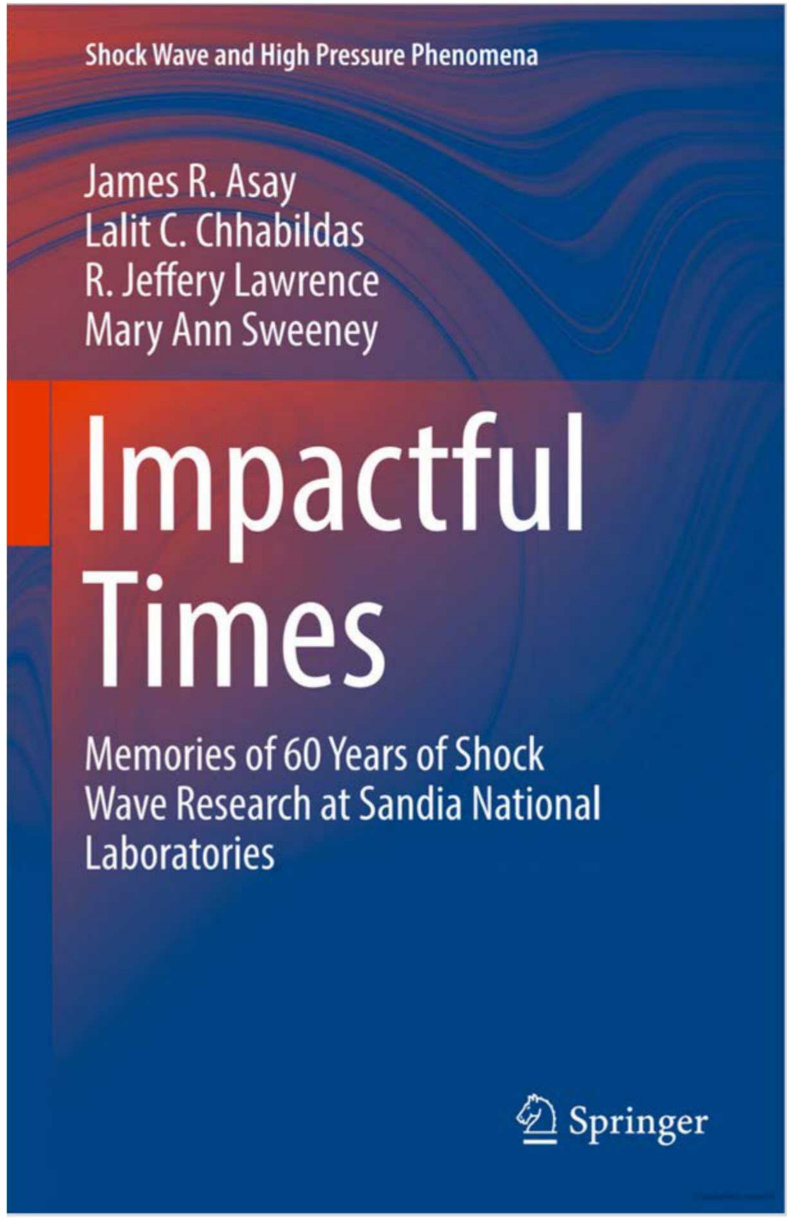
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories

- Brief Introduction to Shock Physics
- Spall
- Fragmentation
- Closure and Acknowledgements

Shock Physics at Sandia

Sandia National Laboratories



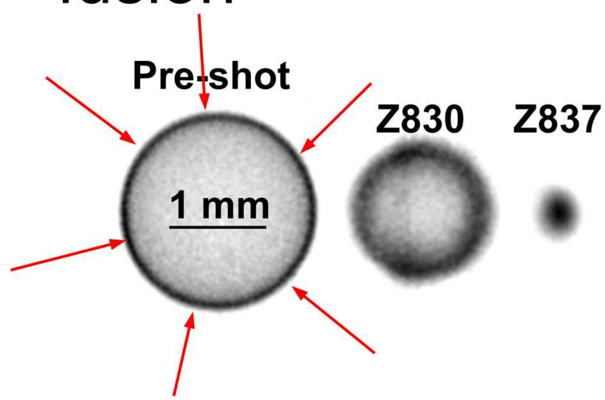
Why Do We Need To Know the Behavior of Materials Under Extreme Conditions?

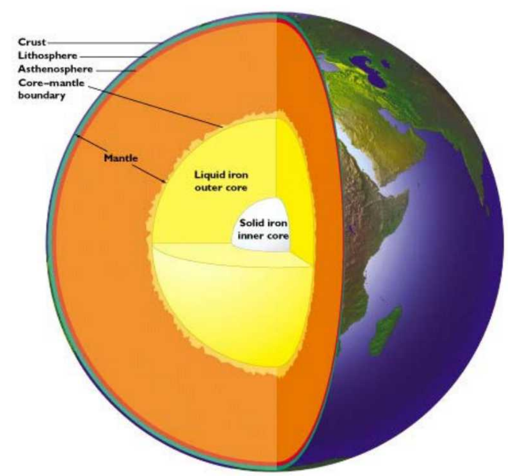
Sandia National Laboratories

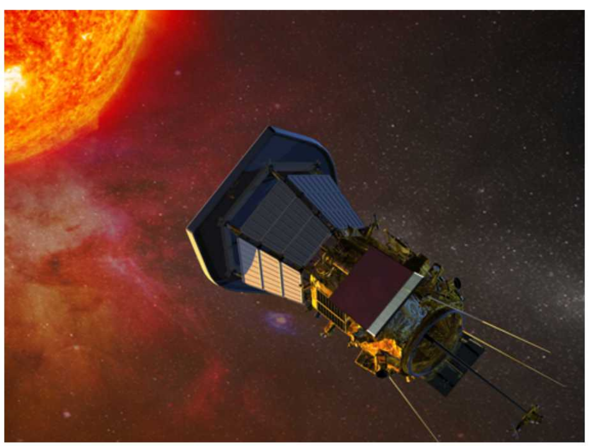
- weapons applications (warheads, armor, etc.)

- explosives behavior and applications

- inertial confinement fusion





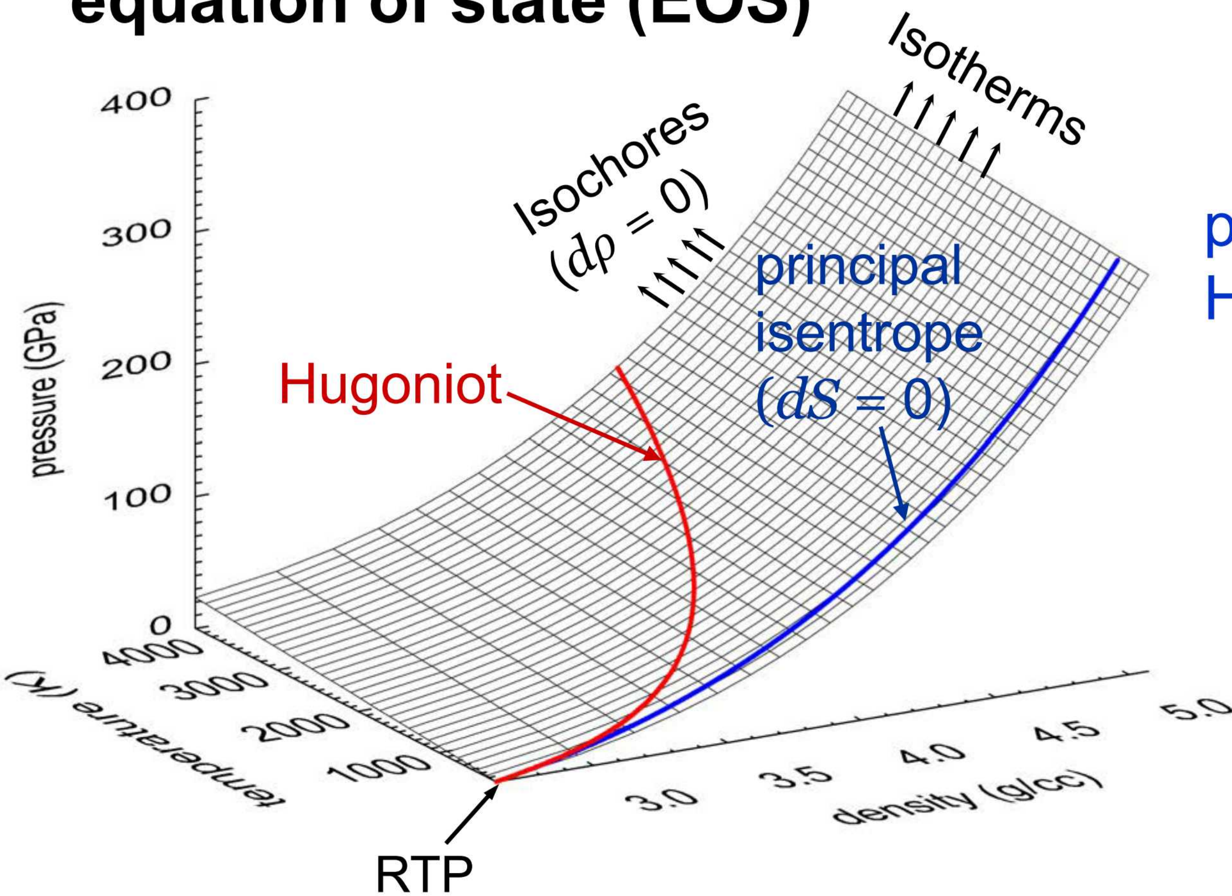


- solar probe
  - 100 μm particles
  - up to 300 km/s velocities
  - P_{max} ~ 100 TPa, T_{max} ~10^6 K

- planetary science (P~360 GPa, T~7000 K)

Material Behavior: EOS & Constitutive Aspects

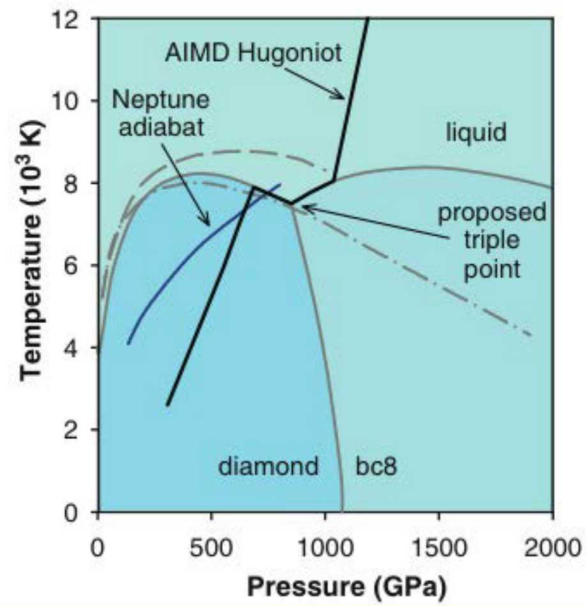
equation of state (EOS)



one thermodynamic state variable as a function of two others:

pressure $P = P(\rho,T)$

Helmholtz energy $f = f(v,T)$

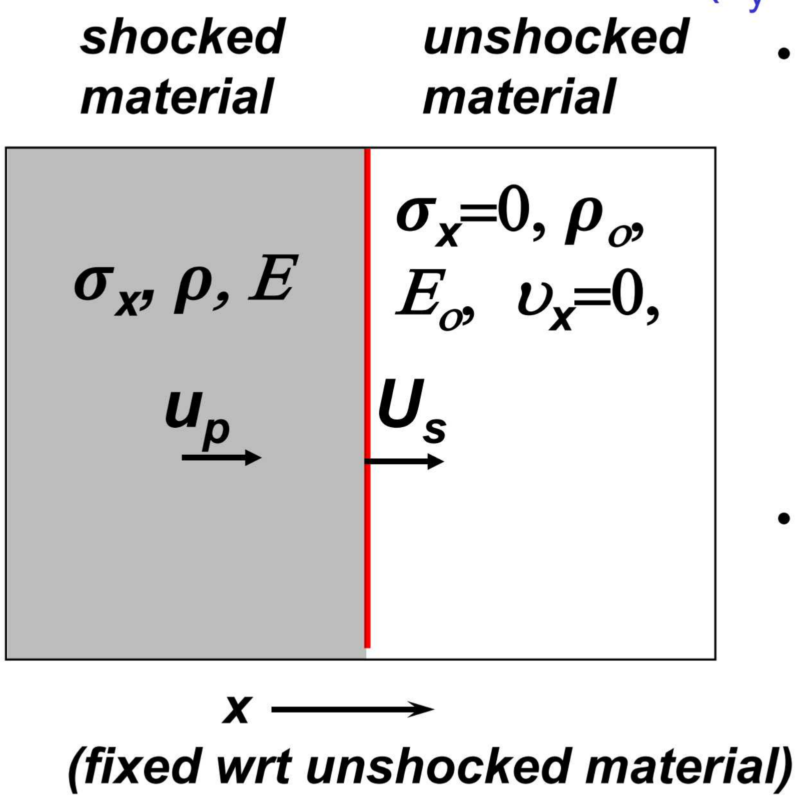


Knudson, M. D., M. P. Desjarlais and D. H. Dolan (2008). "Shock-wave exploration of the high-pressure phases of carbon." *Science* **322**: 1822-1825.

Also: strength, damage, spall, compaction

What is a Shock Wave?

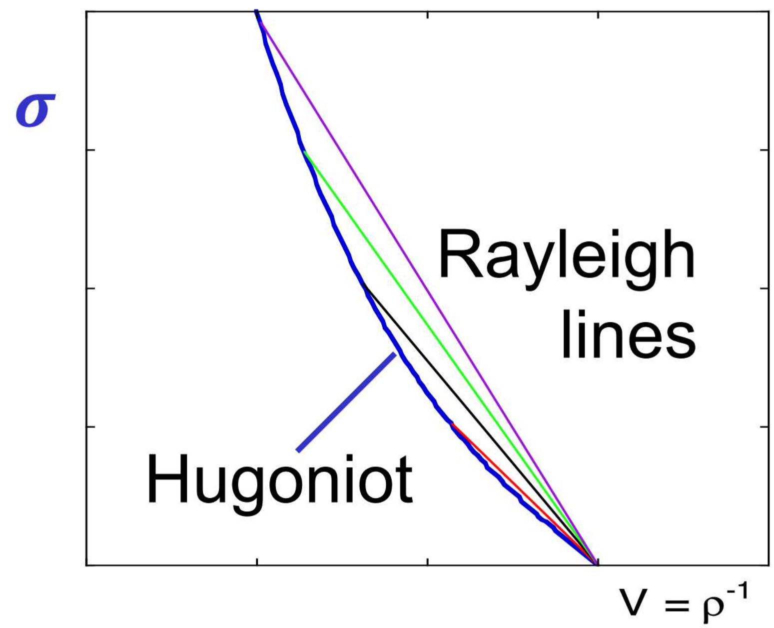
- A “discontinuous” wave that moves at a fixed velocity (if steady)
  - wave front moves at speed U_s *(shock velocity)*
  - shocked material moves at speed u_p *(particle or mass velocity)*
  - uniaxial strain condition ($\varepsilon_y=\varepsilon_z=\varepsilon_{xy}=\varepsilon_{yz}=\varepsilon_{xz}=0$)



- States ahead and behind shock *assumed* to be in thermodynamic equilibrium
  - well defined temperature in each state
  - described by equilibrium thermodynamics
- Shock compression is adiabatic
  - often very fast process (< 1 ns)
  - irreversible (i.e. NOT isentropic)
  - temperature *typically* increases

Conservation Equations and the Shock Hugoniot

- Five variables: $\boldsymbol{\sigma}_x$, $\boldsymbol{u_p}$, $\boldsymbol{U_s}$, $\boldsymbol{\rho}$, and $\boldsymbol{E}$
- Three conservation relationships (Rankine-Hugoniot jump conditions)
  - By measuring two variables (typically $\boldsymbol{\sigma}_x$, $\boldsymbol{u_p}$, or $\boldsymbol{U_s}$), the other three can be determined



<u>conservation of</u>

mass: $\rho_o U_s = \rho\,(U_s - u_p)$

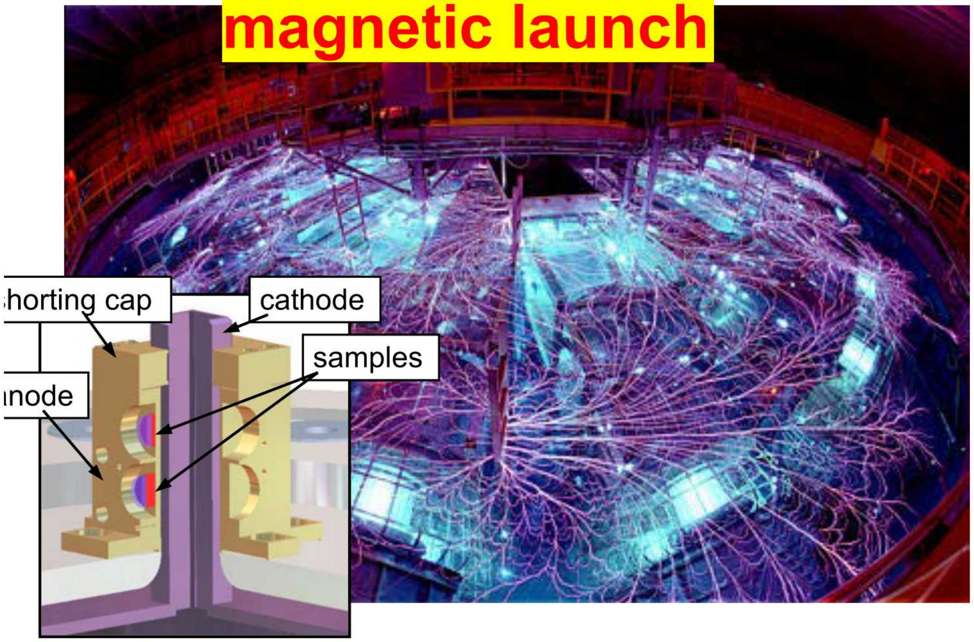
momentum: $\boldsymbol{\sigma}_x = \rho_o U_s u_p$

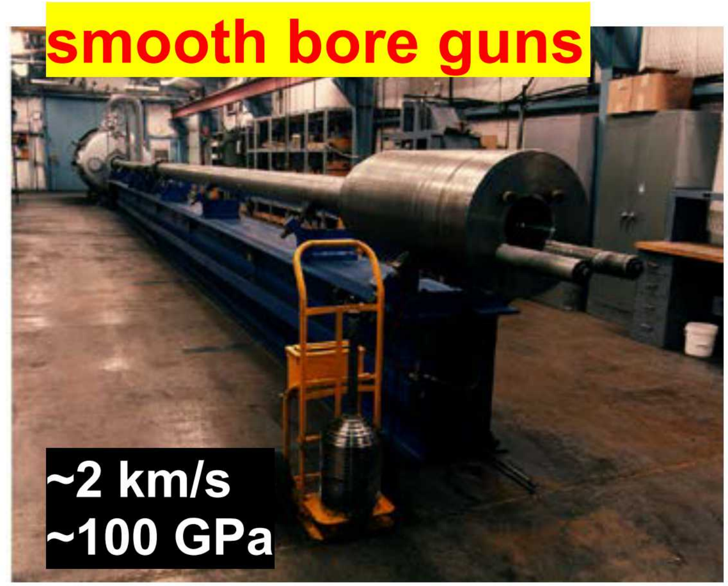
energy: $E - E_o = 0.5\boldsymbol{\sigma}_x\,(V_o - V)$

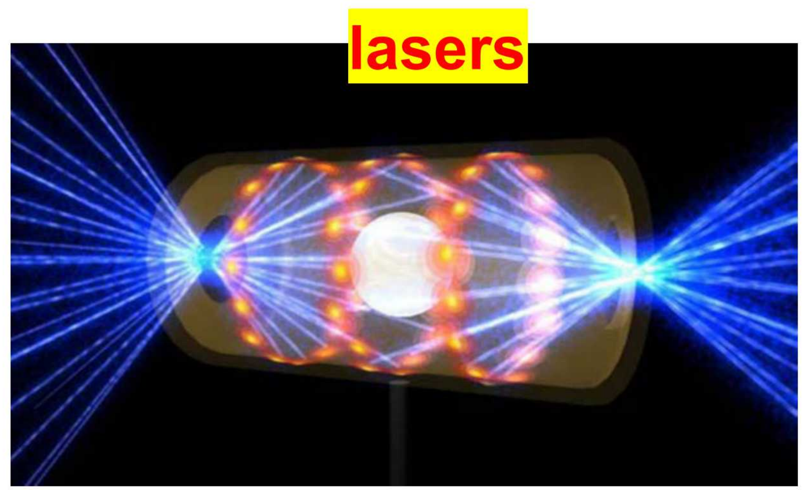
material loads along the Rayleigh line, so the Hugoniot is a <u>collection of end states</u>, not a material response curve

the Hugoniot is not a complete equation of state (EOS)!

Techniques for Shock Loading

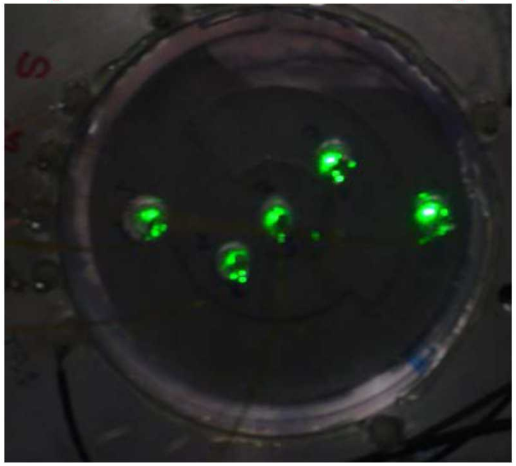




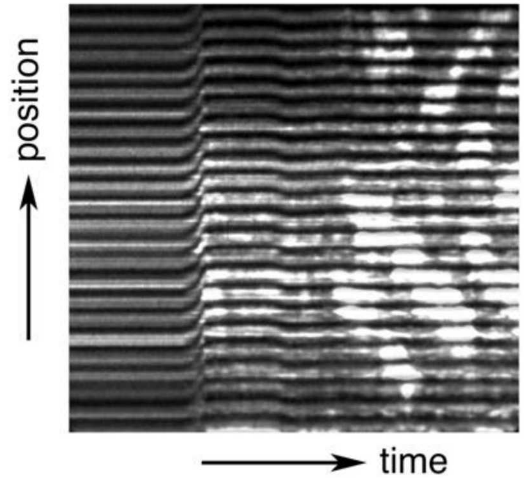


Shock Physics Diagnostics

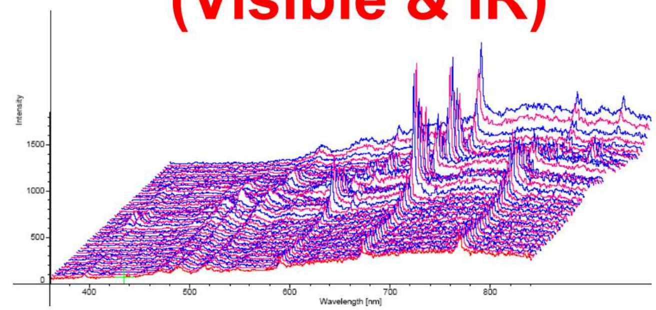
Velocity Interferometry (VISAR & PDV)



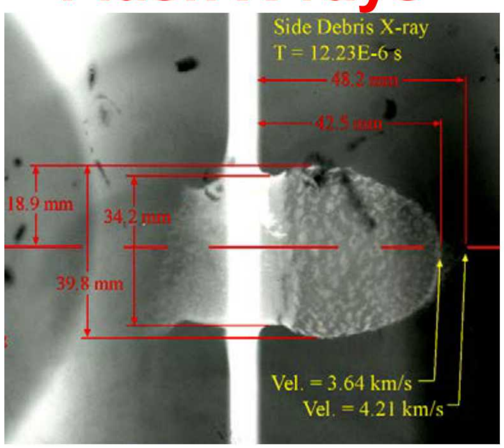
Line-VISAR



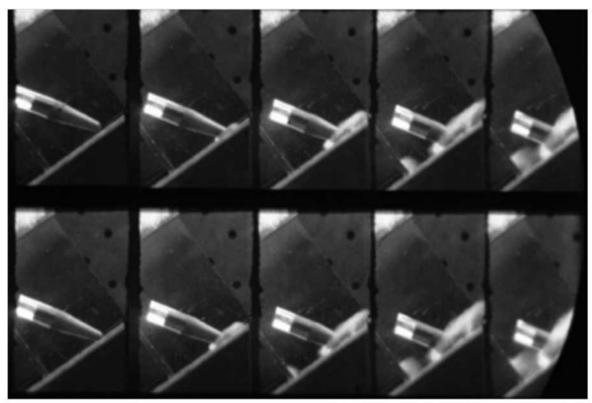
Time-Resolved Spectroscopy (Visible & IR)



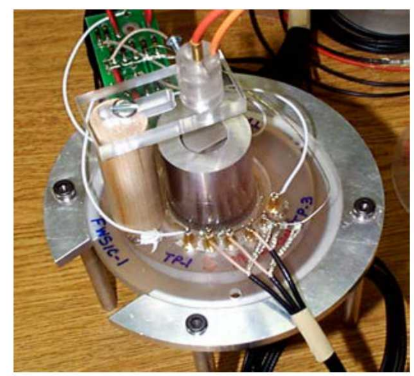
Flash X-rays



High-Speed Photography



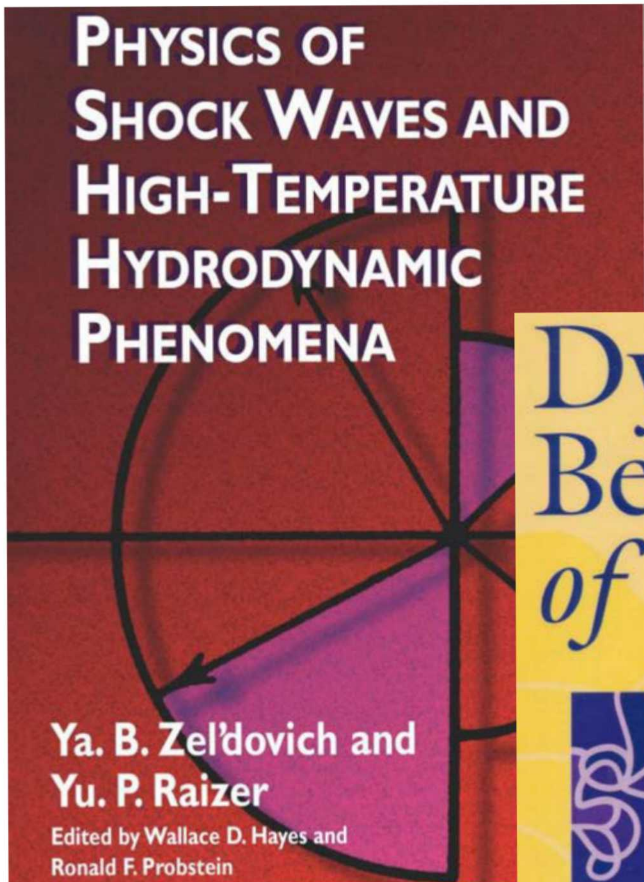
Pressure Gauges



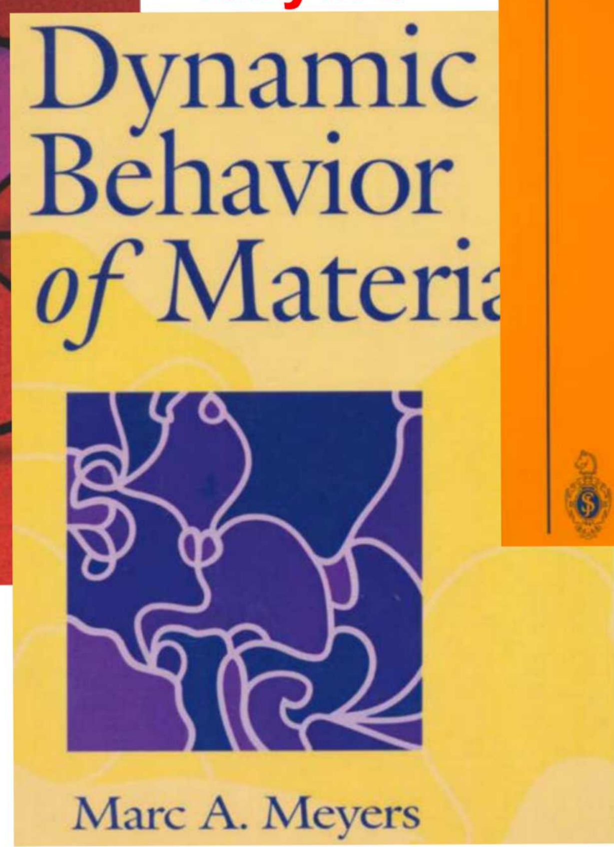
Advanced Diagnostics: pRad, synchrotron (DCS), etc.

Some References

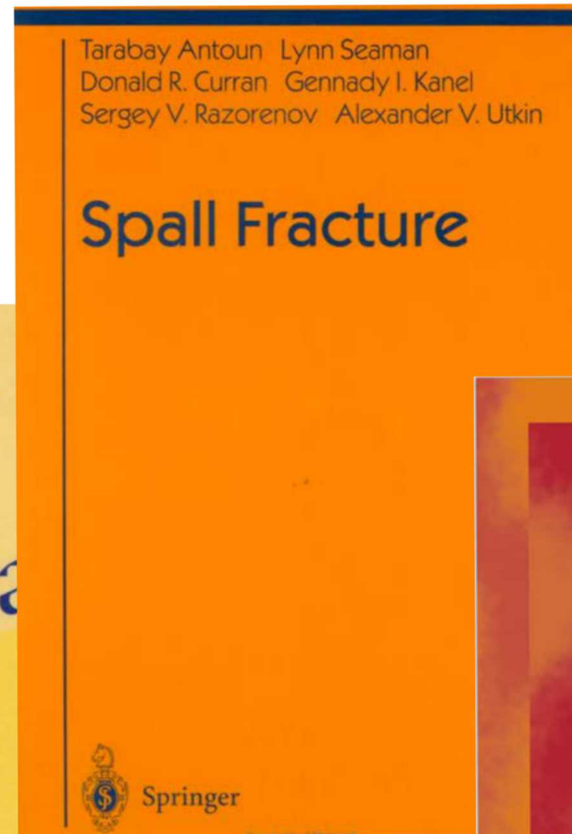
Zel'dovich & Raizer



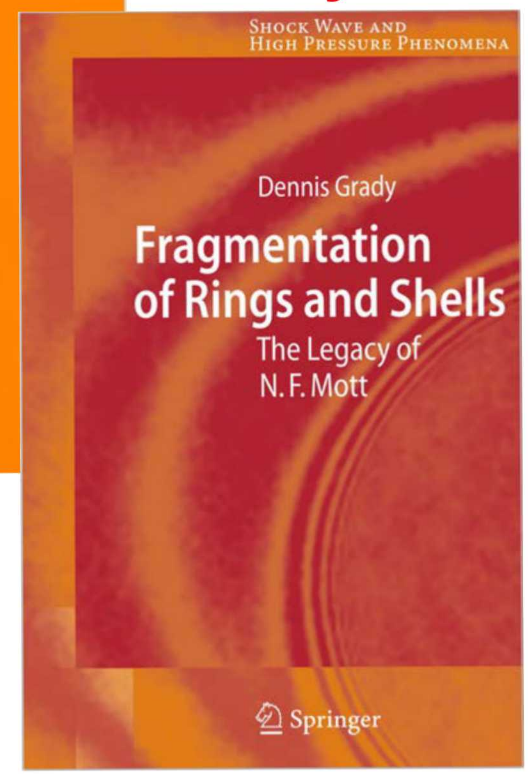
Meyers



Antoun et al.



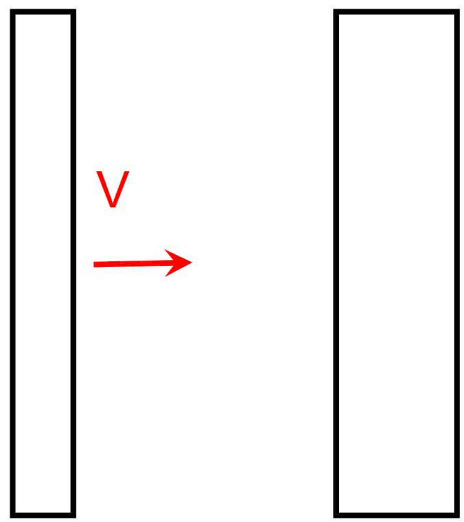
Grady



- Brief Introduction to Shock Physics
- Spall
- Fragmentation
- Closure and Acknowledgements

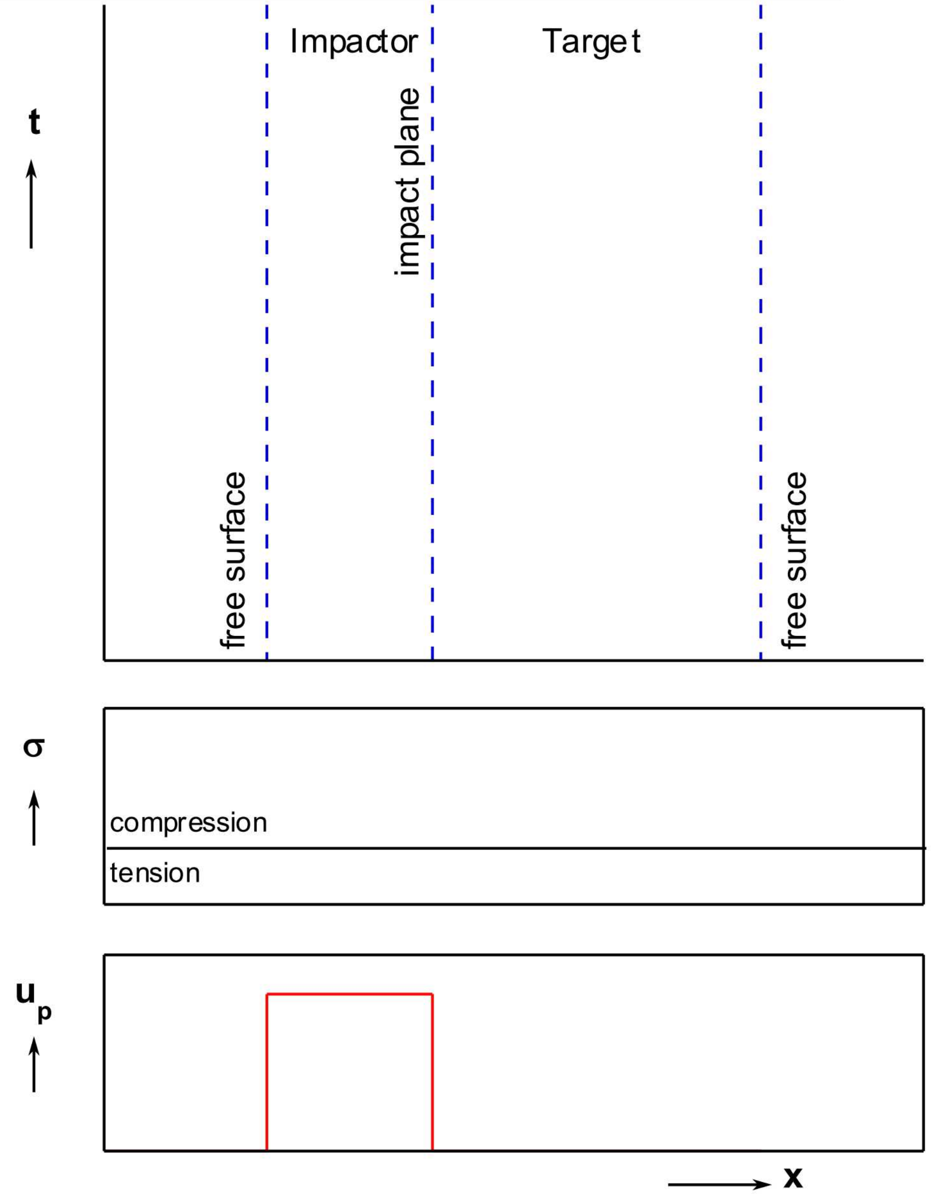
What is Spall?

- spall is dynamic tensile failure of a material due to interactions of waves
- failure initiates at internal flaws (triple points, voids, inclusions, etc.) rather than surface flaws
- spall strengths are typically much higher than tensile strengths measured in quasi-static experiments
- spall experiments typically involve plate impact experiments with dimensions of 1:2 for impactor and target



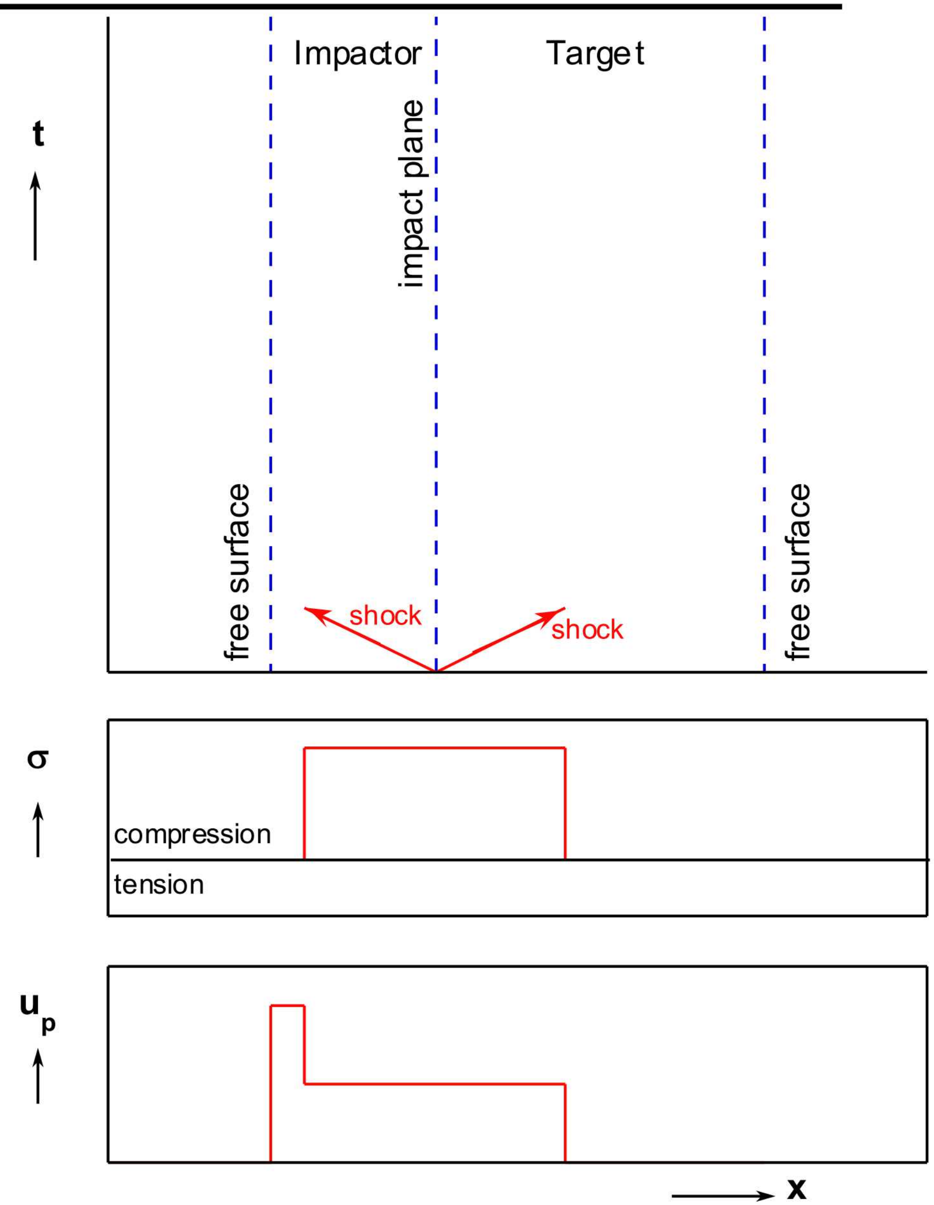
The Canonical Spall Experiment

- impactor hits stationary target at t = 0



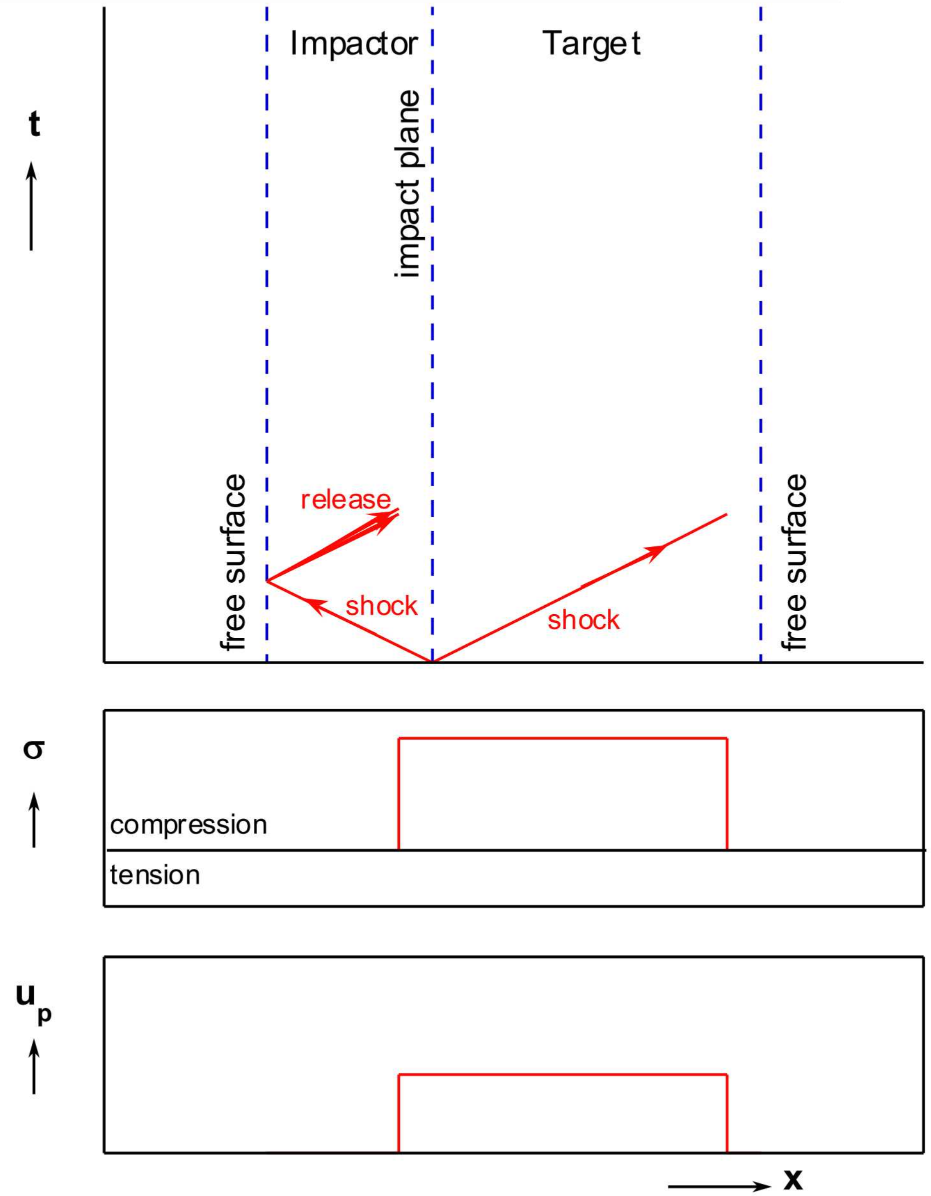
The Canonical Spall Experiment

- impactor hits stationary target at t = 0
- shocks travel into impactor and target



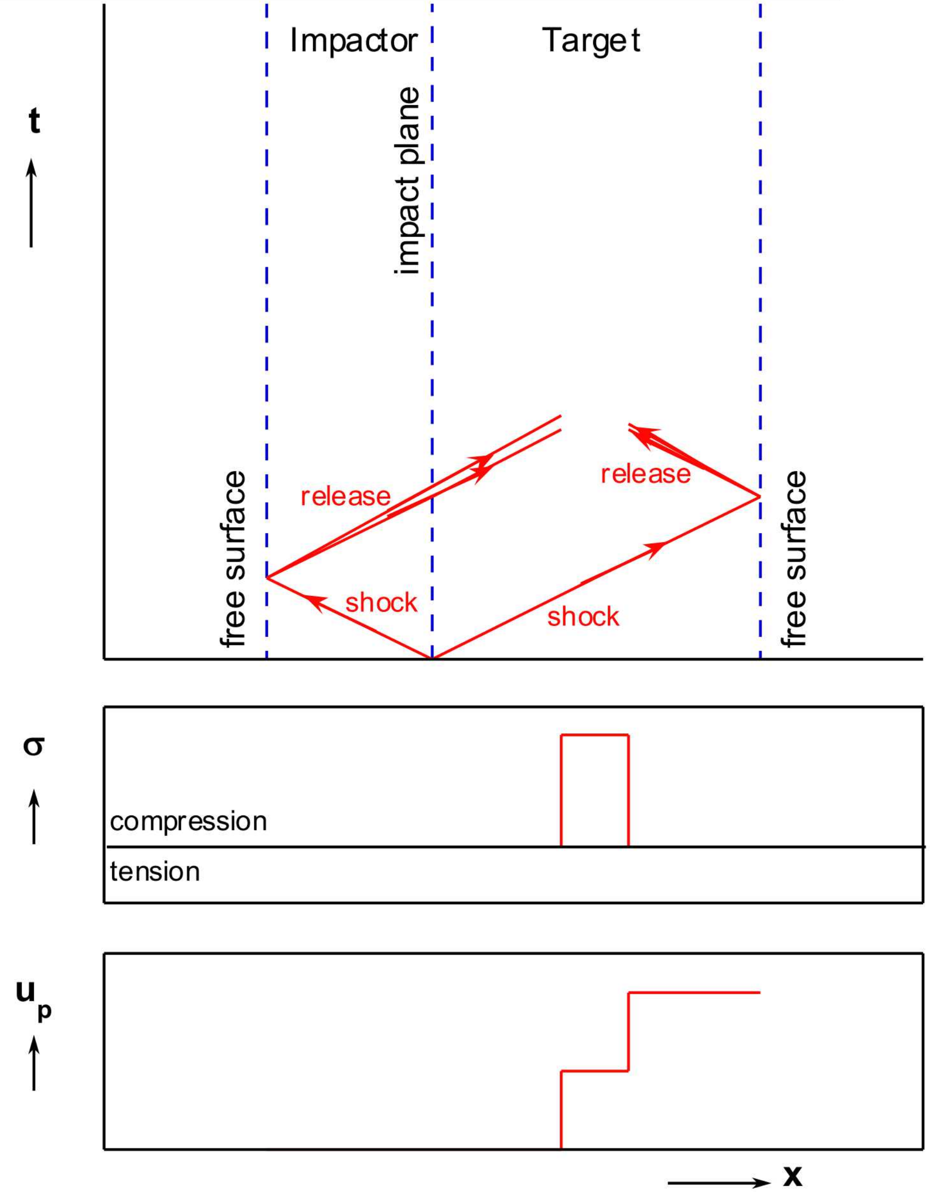
The Canonical Spall Experiment

- impactor hits stationary target at t = 0
- shocks travel into impactor and target
- shock in impactor reflects from free surface as release (unloading) wave (rarefaction fan)



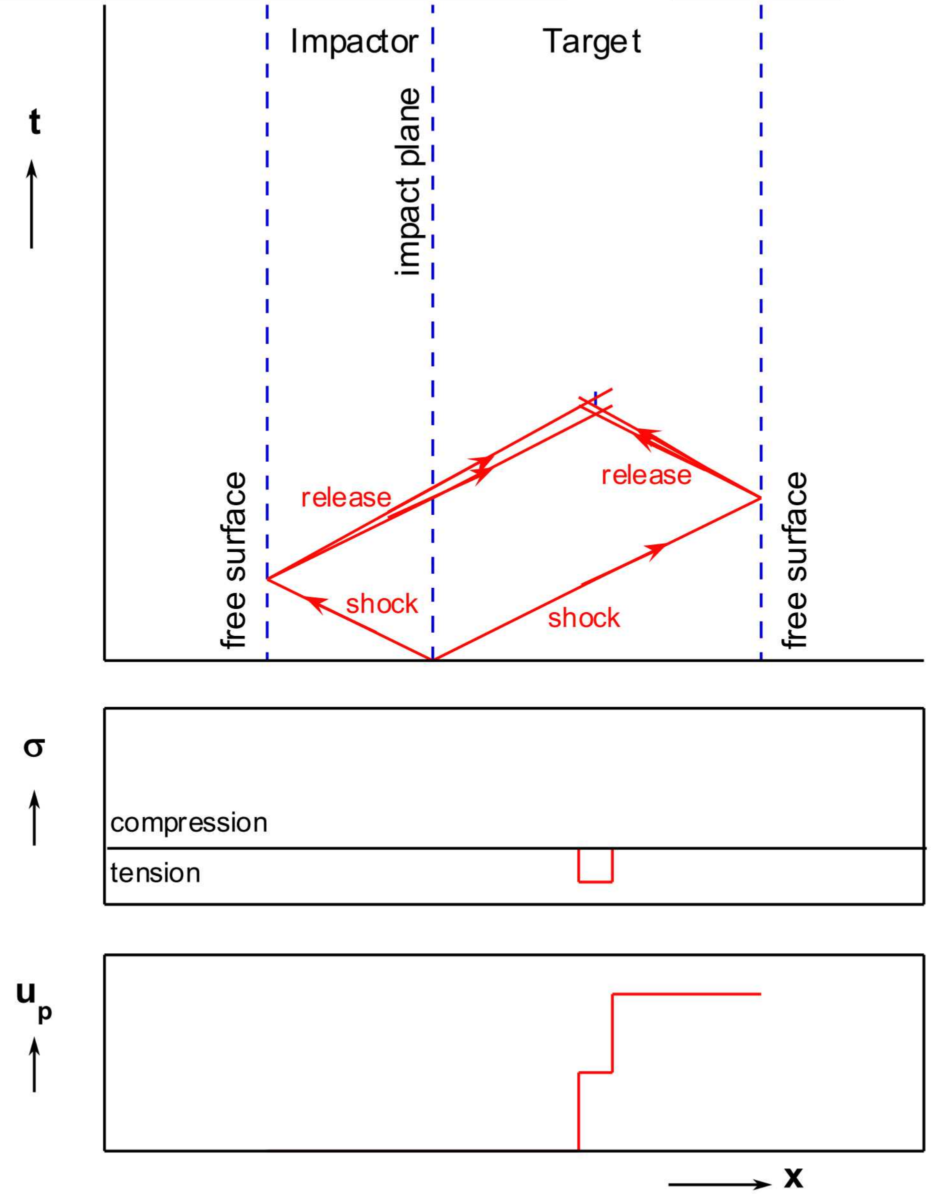
The Canonical Spall Experiment

- impactor hits stationary target at t = 0
- shocks travel into impactor and target
- shock in impactor reflects from free surface as release (unloading) wave (rarefaction fan)
- same thing happens in target



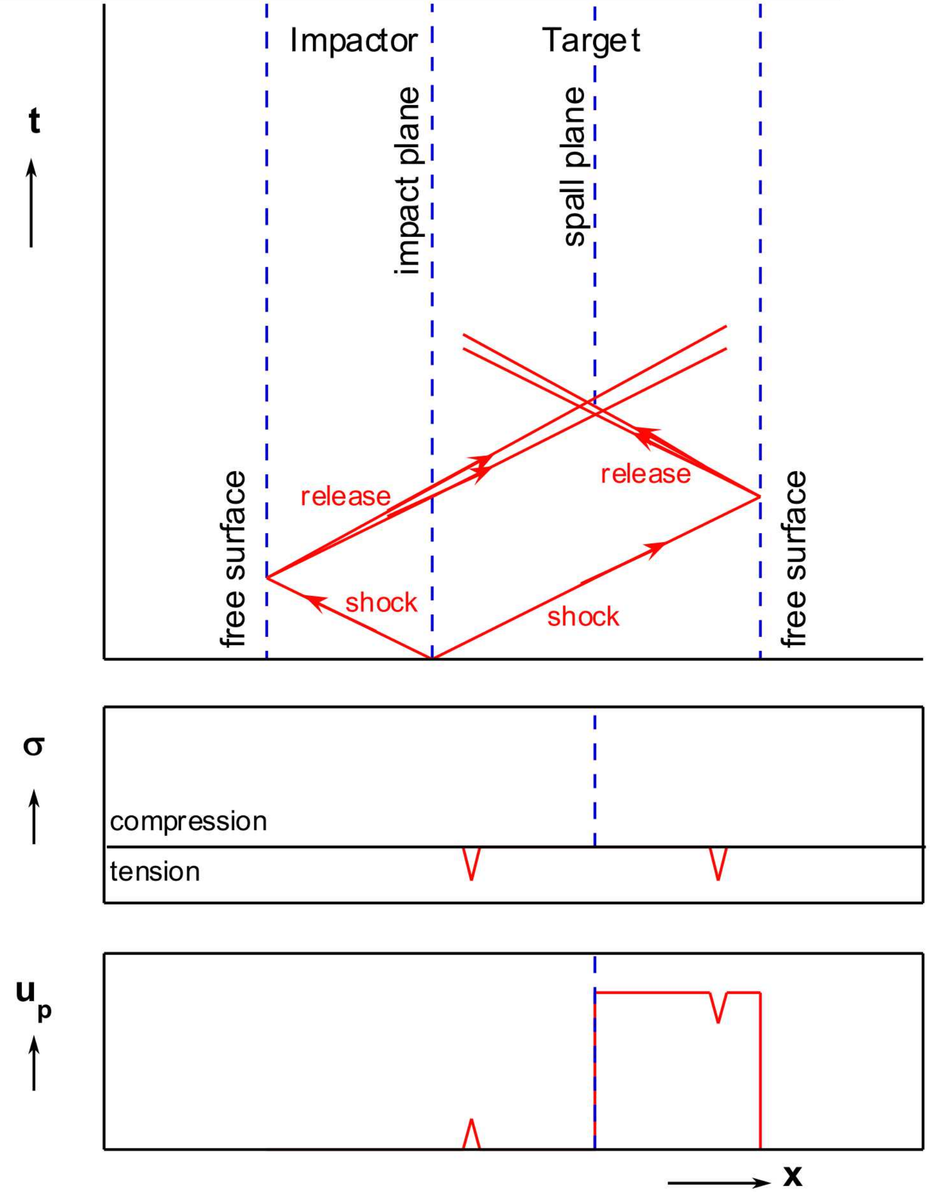
The Canonical Spall Experiment

- impactor hits stationary target at t = 0
- shocks travel into impactor and target
- shock in impactor reflects from free surface as release (unloading) wave (rarefaction fan)
- same thing happens in target
- release waves intersect at mid-plane and cause tensile stresses to build



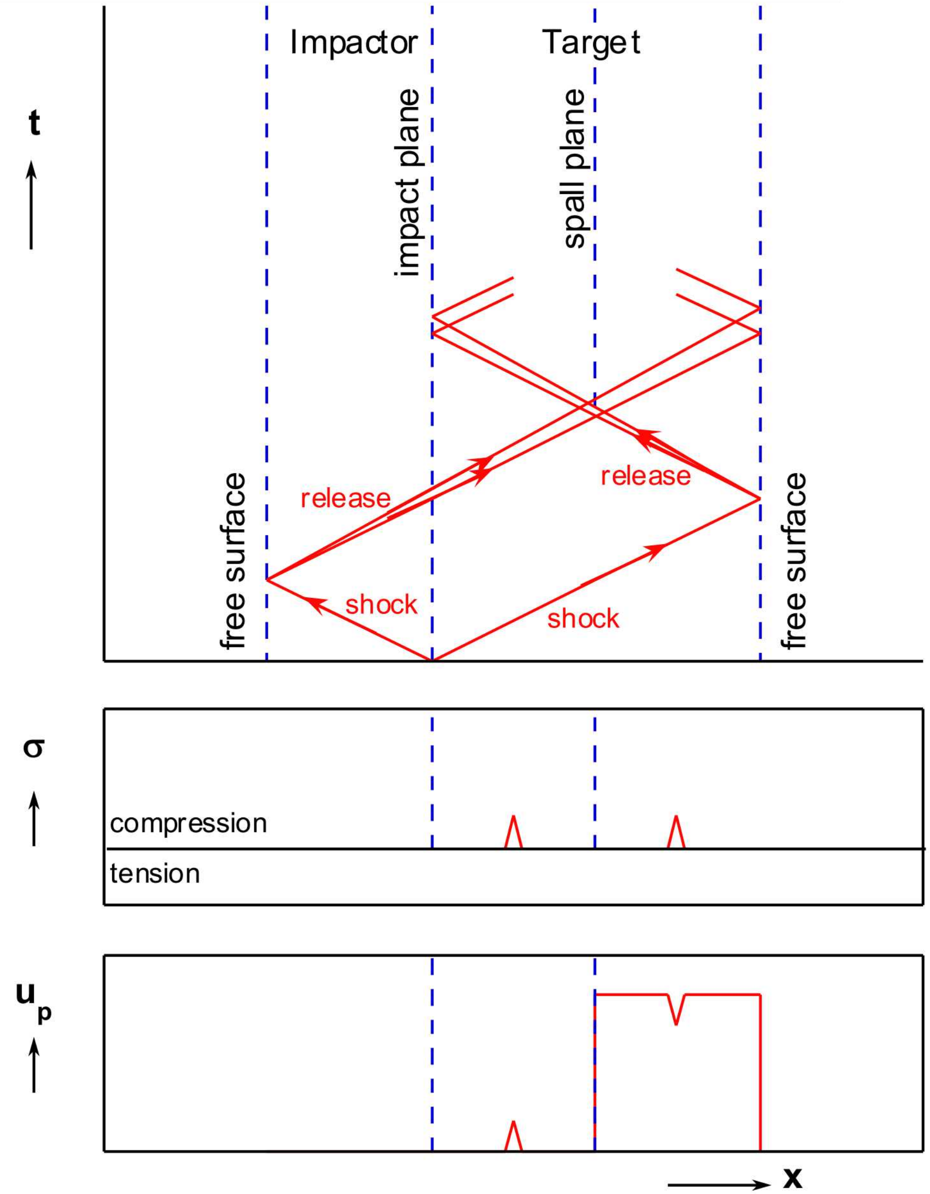
The Canonical Spall Experiment

- impactor hits stationary target at t = 0
- shocks travel into impactor and target
- shock in impactor reflects from free surface as release (unloading) wave (rarefaction fan)
- same thing happens in target
- release waves intersect at mid-plane and cause tensile stresses to build
- if stresses are large enough, sample fails in tension and spall plane forms



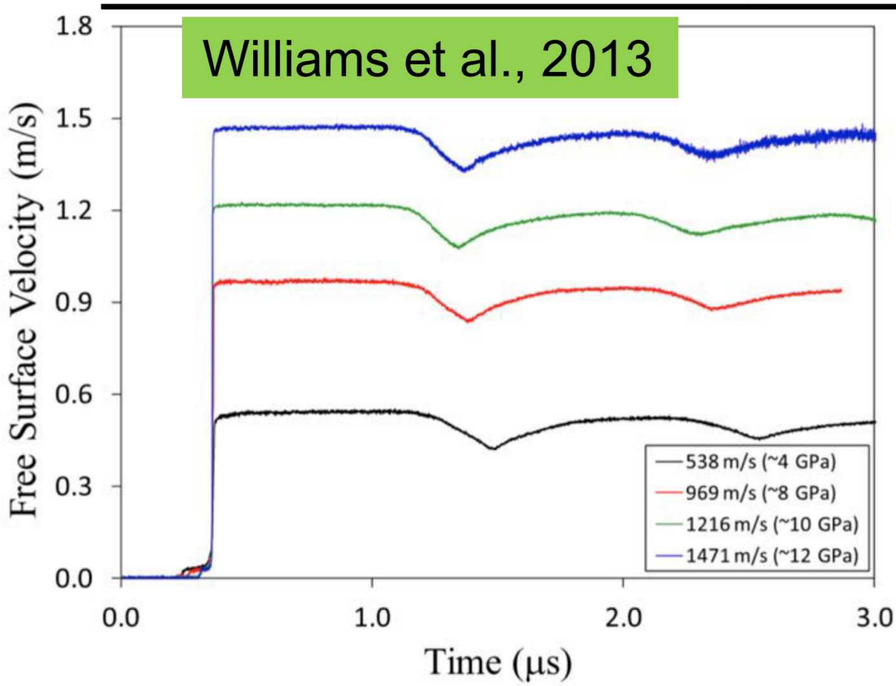
The Canonical Spall Experiment

- impactor hits stationary target at t = 0
- shocks travel into impactor and target
- shock in impactor reflects from free surface as release (unloading) wave (rarefaction fan)
- same thing happens in target
- release waves intersect at mid-plane and cause tensile stresses to build
- if stresses are large enough, sample fails in tension and spall plane forms
- sample separates at spall plane; waves continue to "ring" in spalled sample

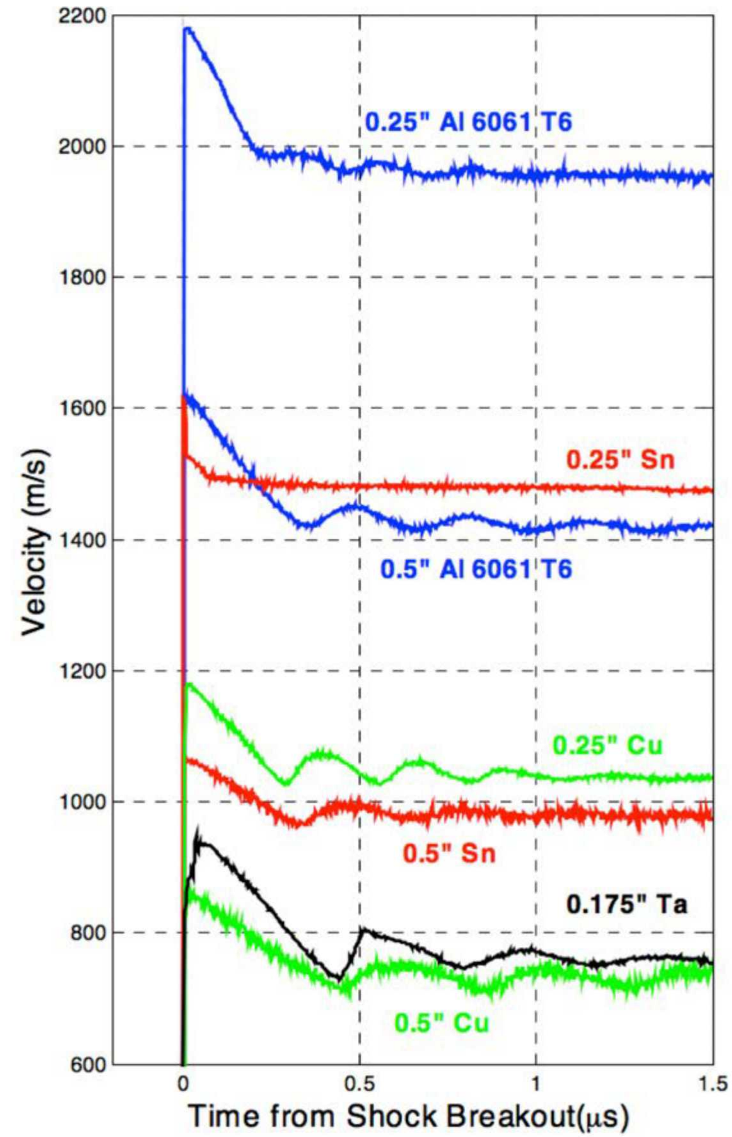


Typical Velocity Records: Plate Impact and HE Drive

Williams et al., 2013



Holtcamp et al., SCCM 2004

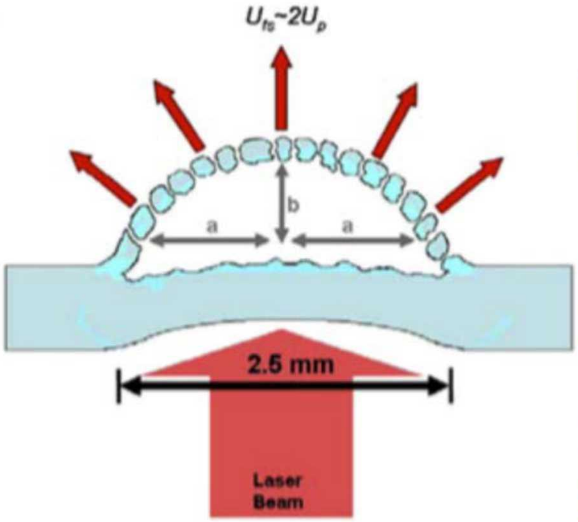


- velocity measured at free surface of target using VISAR or PDV
- acoustic approximation for spall strength:

$$\sigma_{sp} = \frac{1}{2}\rho_o c_o \Delta u_{fs}$$

- complications include elastic-plastic behavior and wave interactions

Other Configurations: HE Drive, Laser Spall, Projectile Impact



Burtsev et al., CESW 2011

Holtcamp et al., SCCM 2004

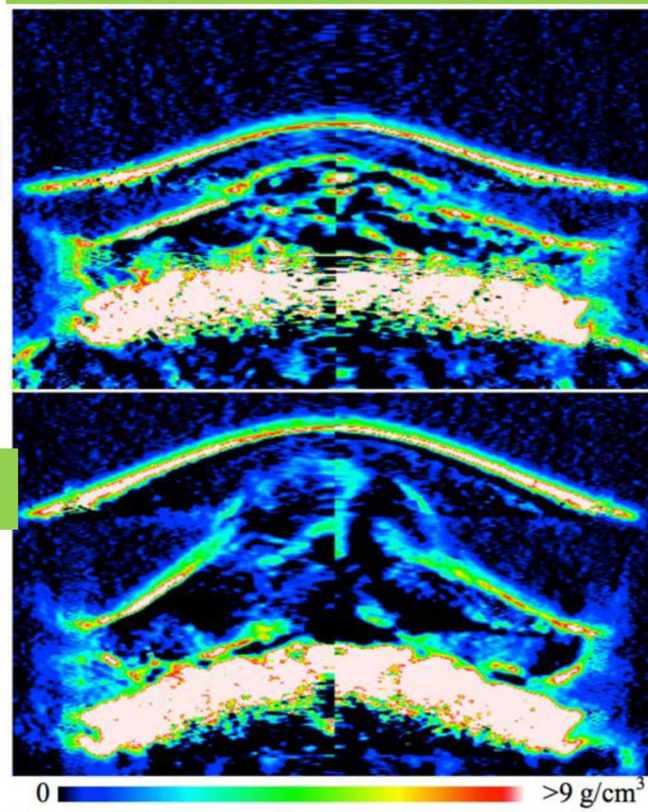
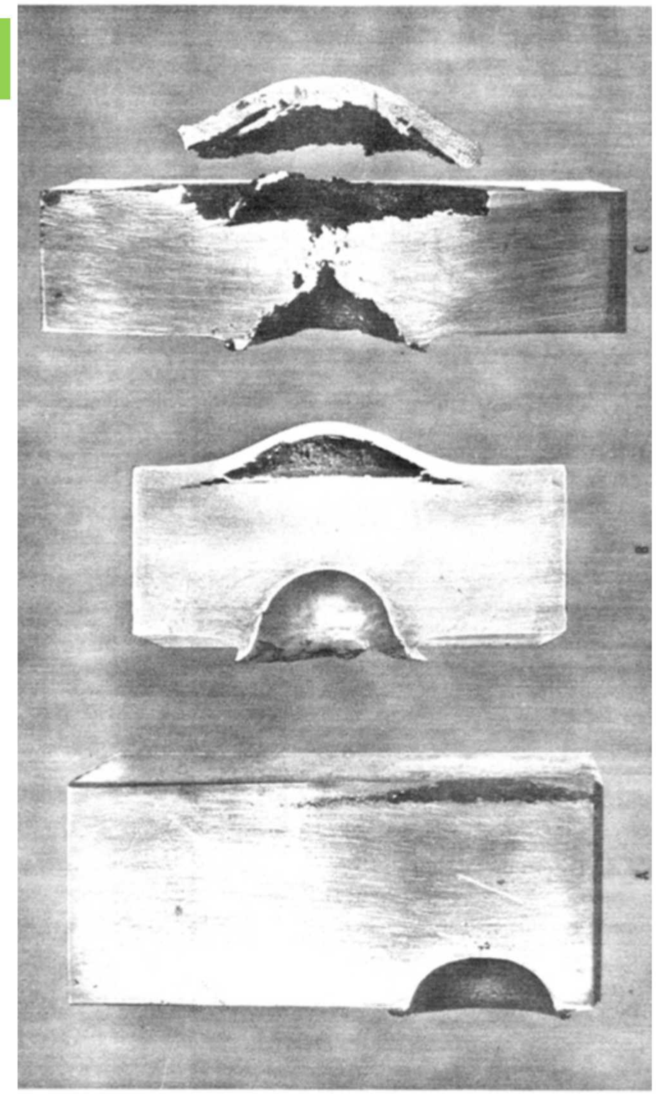


FIGURE 4. Abel inverted volume densities of ¼" Copper at 32.3 μs (top) and 60.9 μs (bottom) after detonator initiation. Each image is 50 mm (Horiz) by 30 mm (Vert).

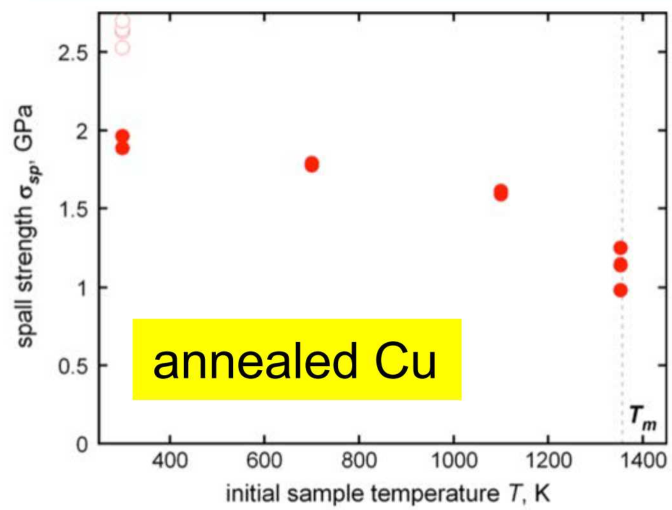


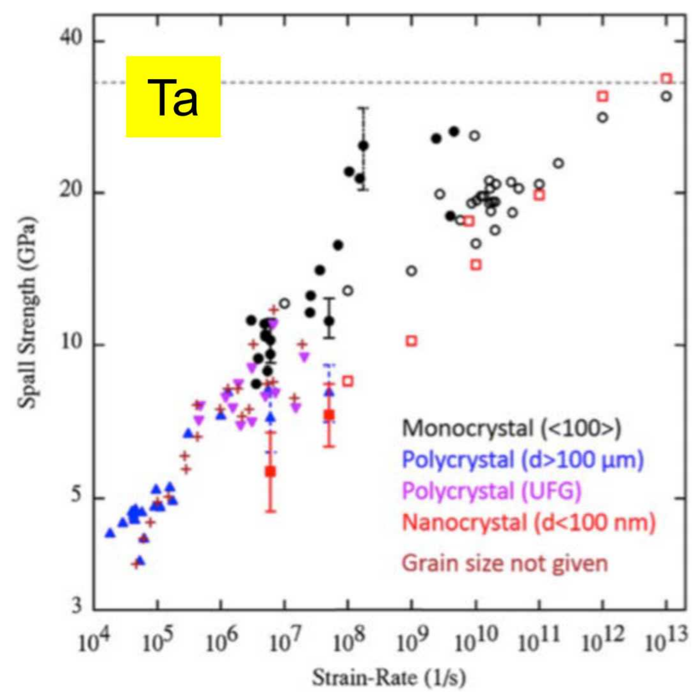
Trends (1)

- spall strength increases with strain rate ($\sigma_{sp} \propto \dot{\varepsilon}^m$)
- initial shock amplitude affects spall strength due to defects/damage and increased temperature; "failure front" in brittle materials
- spall strength falls off near melt

Hahn et al., Acta Mat. 2017

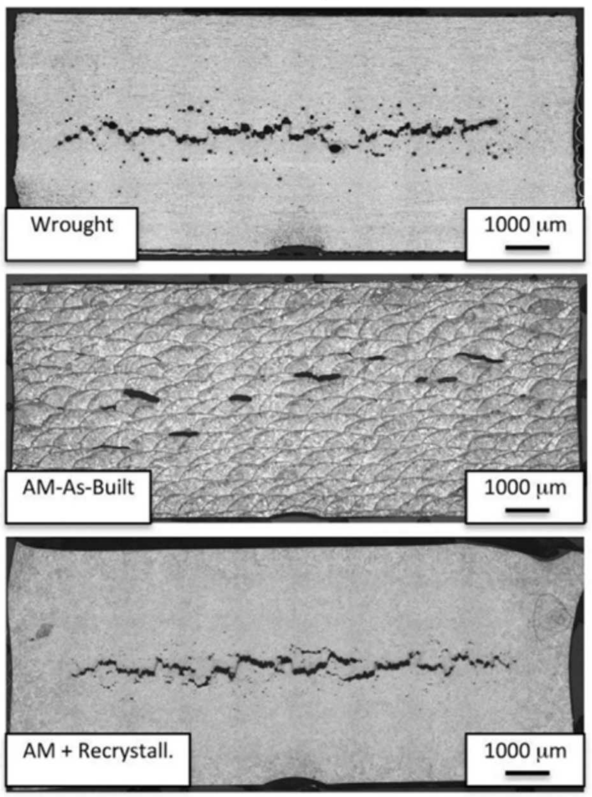
Zaretsky & Kanel, JAP 2013



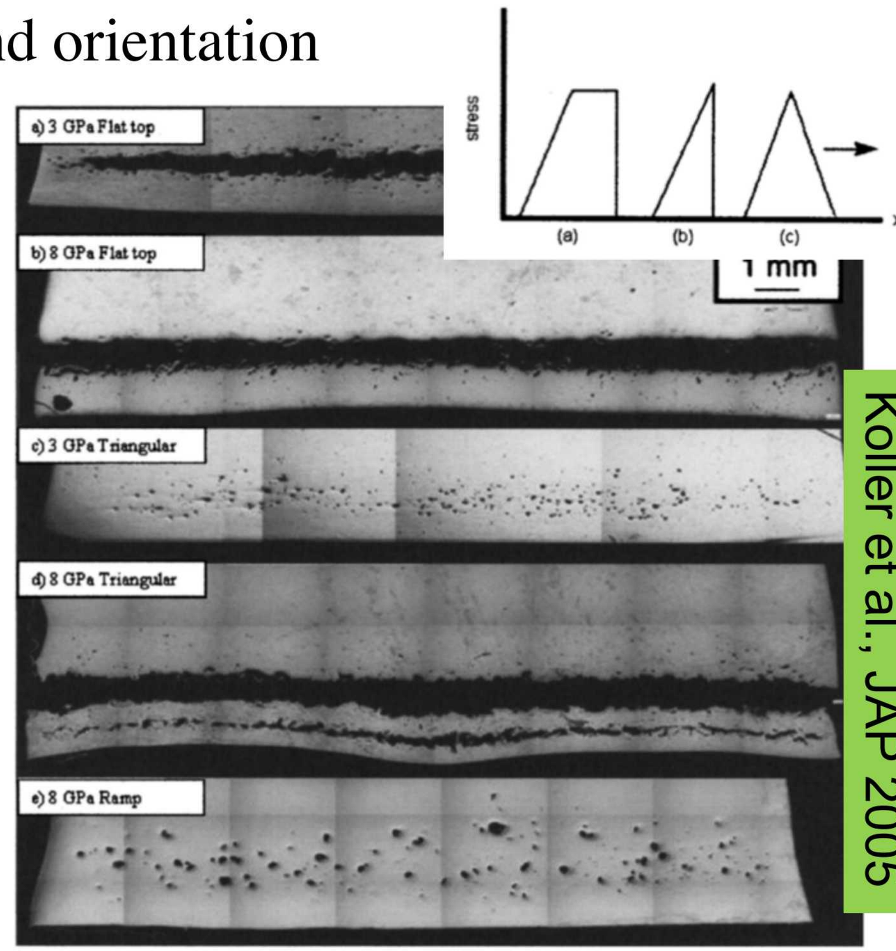


Trends (2)

- ”clean” materials have higher spall strengths; single crystals have highest
- microstructure and flaw distribution can influence spall
- wave shape (i.e. loading history) and orientation (normal vs. sweeping) affect spall



Gray et al., Acta Mat. 2017



Koller et al., JAP 2005

Typical Spall Strengths

metals

	σ_{sp} (GPa)
Al alloy	0.8-1.6
Cu	0.8-1.6
Mg	0.8
Ti-6-4	4.1
U	2.4
Ta	4.6
W	0.4-0.66
Iron	1.4-1.6
304 SS	2.1
4330V steel	4.8

Tarabay et al., page 142

brittle materials

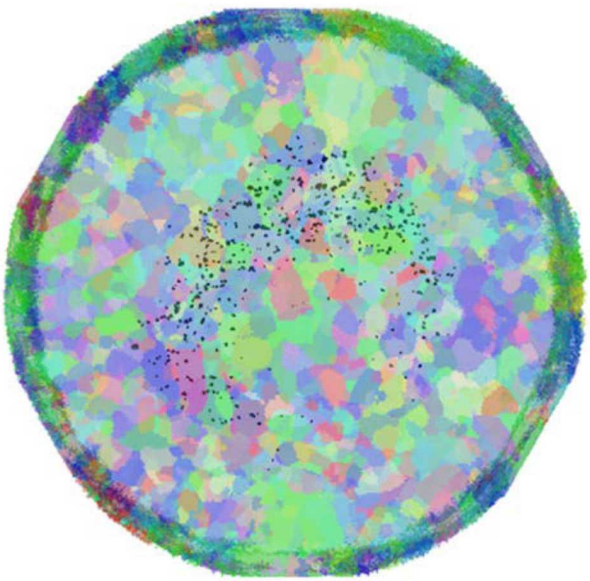
	σ_{sp} (GPa)	
BeO	0.08	Yaziv et al. 1986
B4C	0.6-0.8	Winkler & Stilp, 1992
SiC	0.5-1.1	
TiB2	0-0.5	
WC	1.0-2.0	Dandekar 2004
sapphire (elast)	2-2.5	Kanel et al. 2009
diamond	3-16	Abrosimov et al. 2015

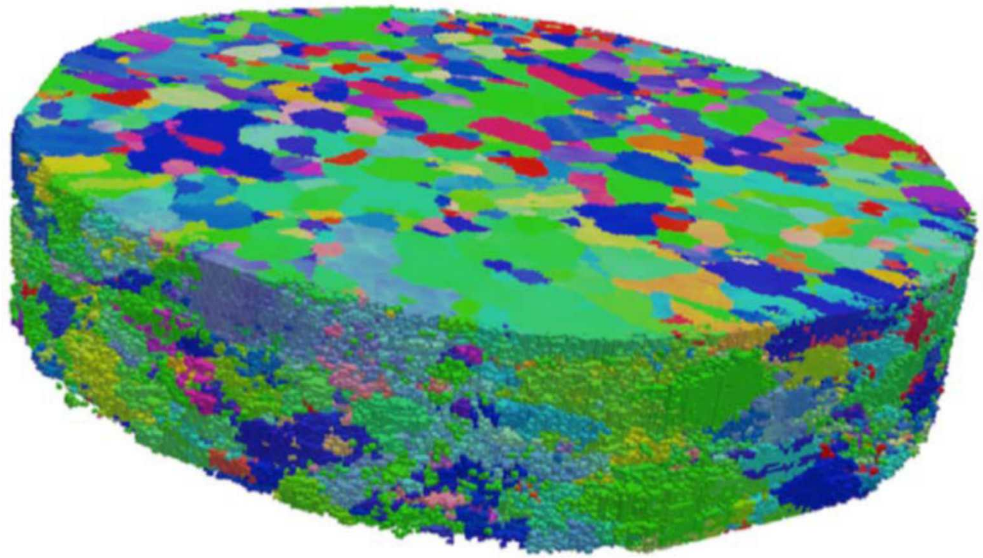
liquids

	s_{sp} (MPa)	
H2O	5-40	Boetler & Suth. 2004
H2O	140-150	Stan et al., 2016
Sn (540 K)	120	Kanel et al. 2015
Pb	<30	Kanel et al. 2015
Zn (693 K)	40-50	Zaretsky 2016

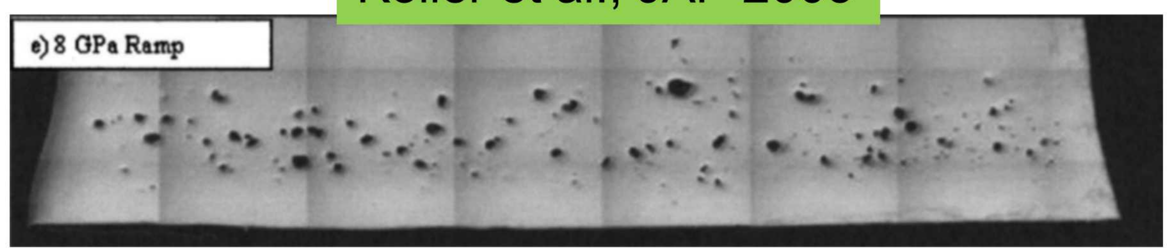
Recovery Studies

Lieberman et al., AM 2016





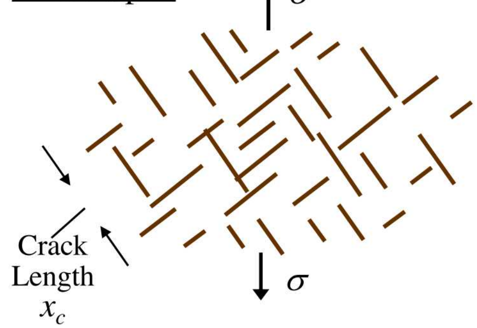
Koller et al., JAP 2005



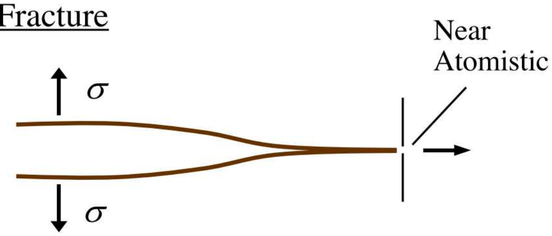
recovery is almost never as soft as you would like!

Micromechanisms of Spall

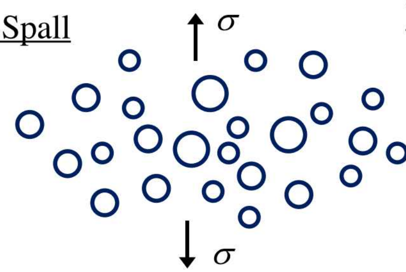
Brittle Spall



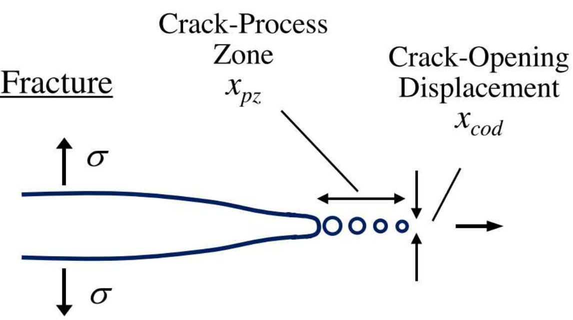
Brittle Fracture



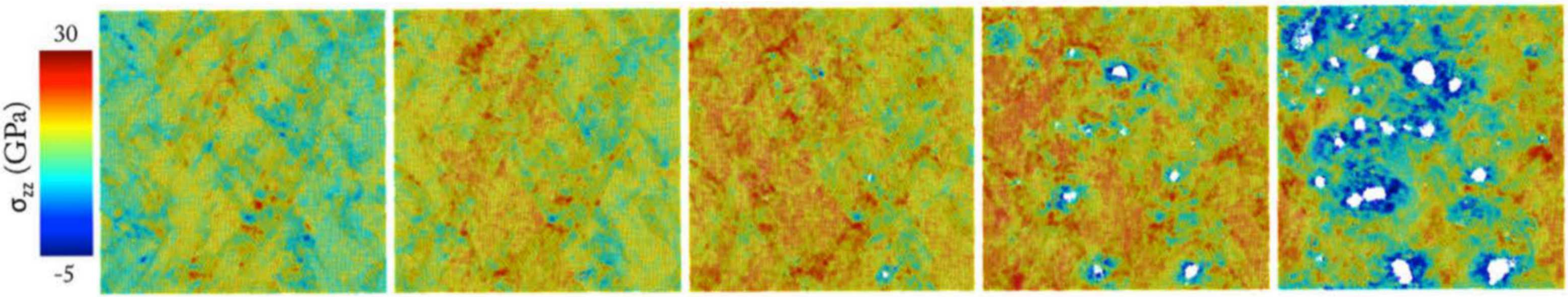
Ductile Spall



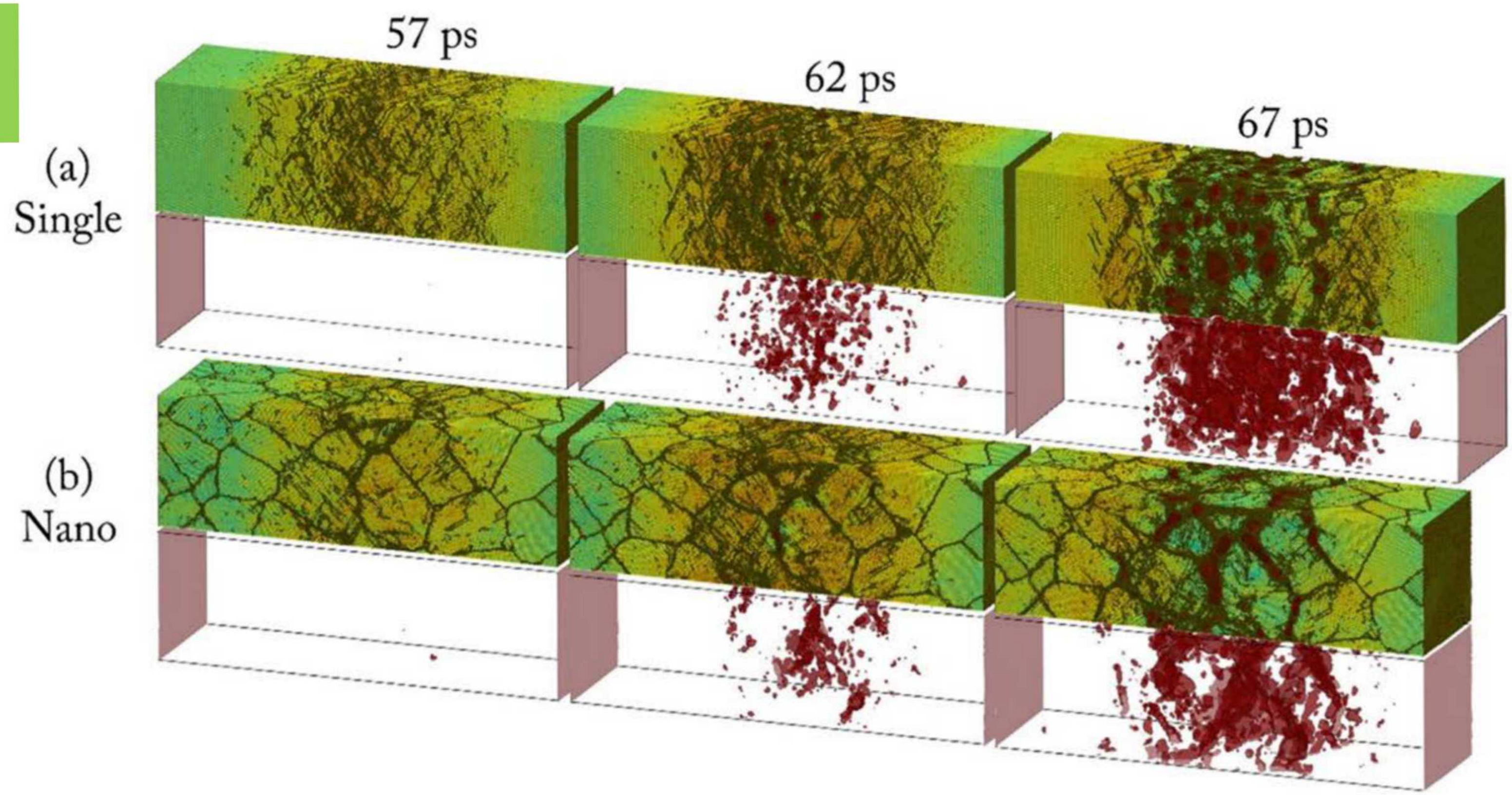
Ductile Fracture



Spall at the Atomic Level

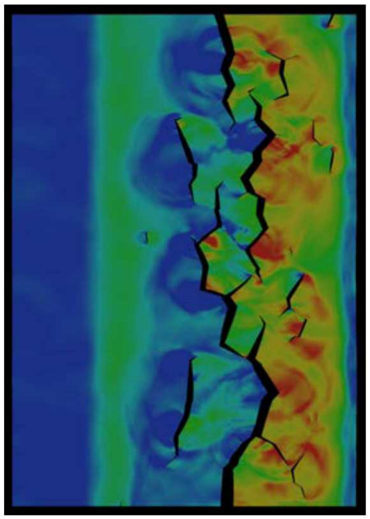


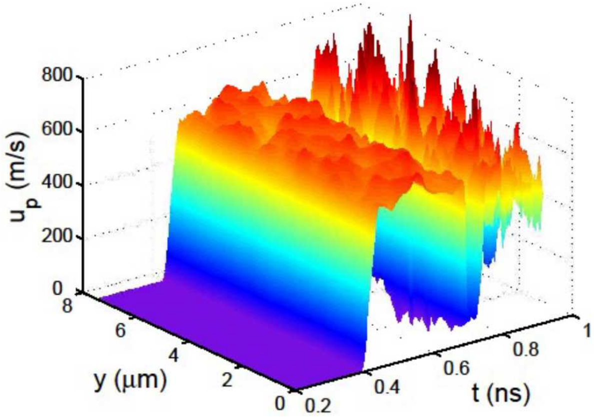
Hahn et al., Acta Mat. 2017

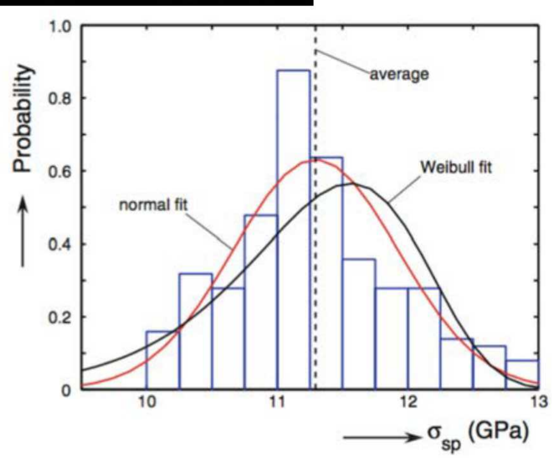


Modeling Spall at the Grain Scale

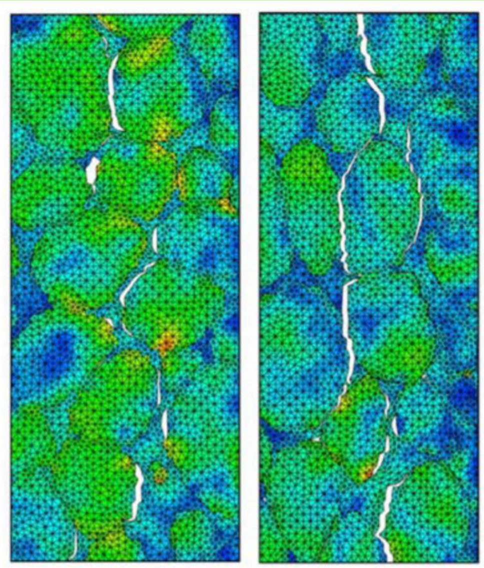
Foulk & Vogler, IJF 2010



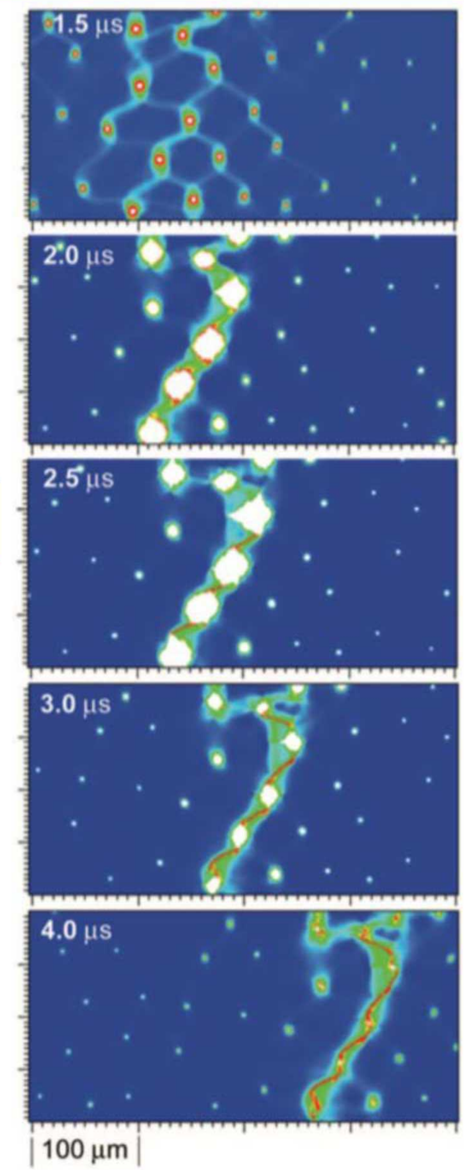




Vogler & Clayton, JMPS 2008



Becker et al., JAP 2007



Modeling Spall at the Continuum Level

Tuler & Butcher, IJFM 1968

$$\mathrm{D(x,t)} = \frac{D_o}{t_o}\int_{-\infty}^{t}\left(\frac{\sigma(x,\tau)-\sigma_o}{\sigma_o}\right)^{\lambda} d\tau$$

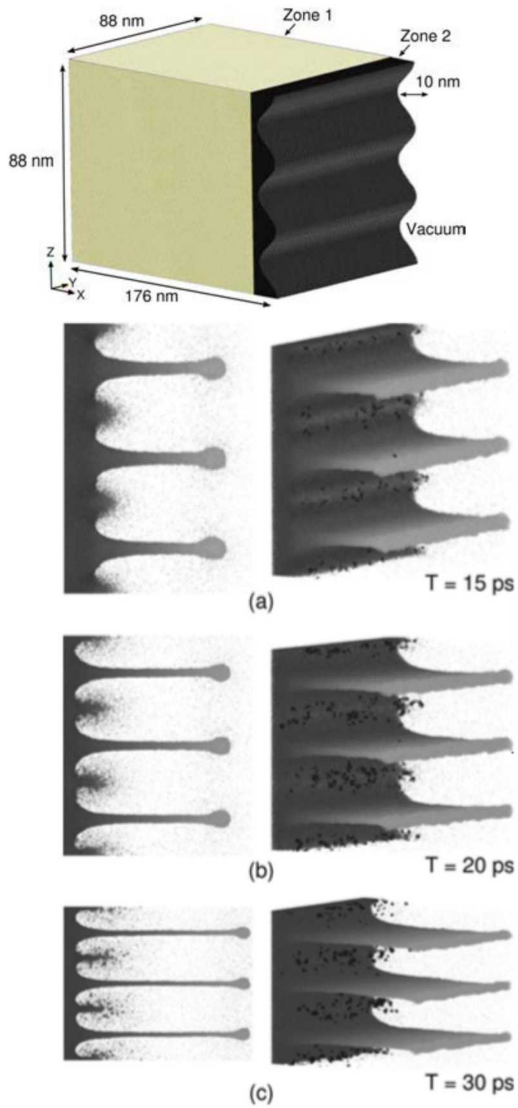
SRI

$$\dot{N} = \dot{N}_0 \exp\left[(\sigma - \sigma_{no})/\sigma_1\right]$$

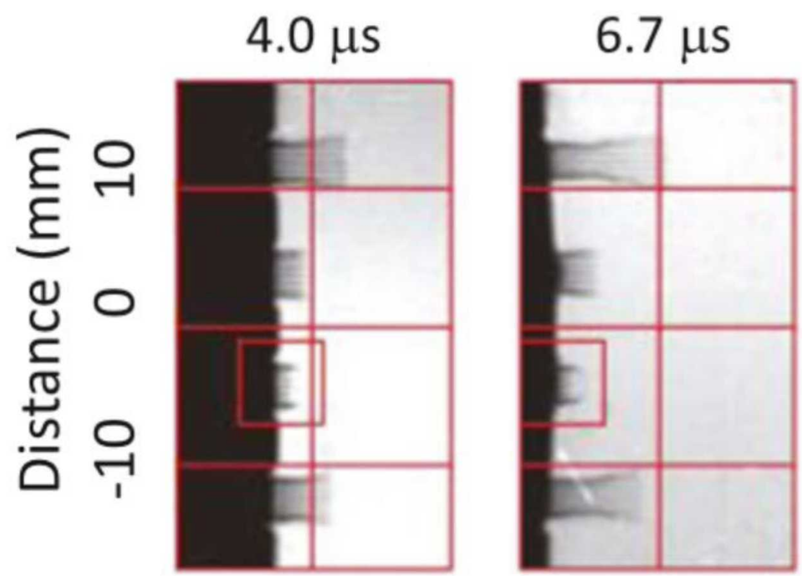
$$\dot{R} = \left(\frac{\sigma - \sigma_{go}}{4\eta}\right) R$$

Eecta at Surfaces

Durand & Soulard, JAP 2012



Morris et al., EM 2016

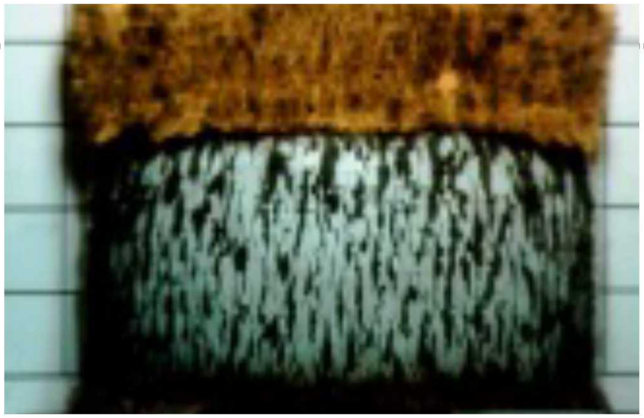


- Brief Introduction to Shock Physics
- Spall
- Fragmentation
- Closure and Acknowledgements

Fragmentation

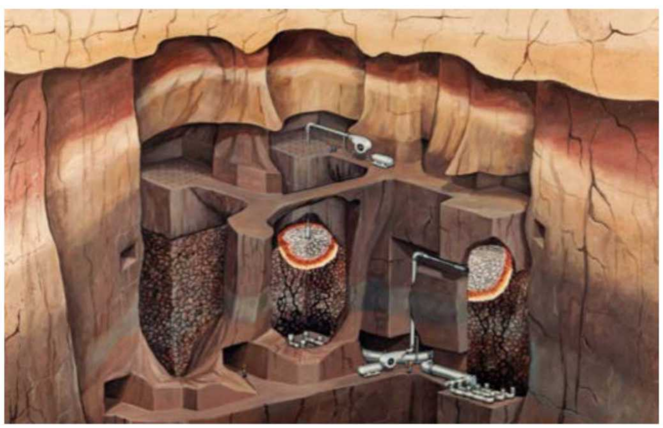
- breakage of a body into many pieces (J. Bishop - ”pervasive fracture”) under dynamic loading
- quantities of interest are typically:
  - fragment size/mass distribution
  - velocity
- relevant from very small (atomic nuclei) to very large (the universe) length scales
- often, modeling of fragmentation involves the search for scaling laws to capture sub-grid physics
- different physics (e.g. brittle fracture, surface-tension dominated breakup) leads to different scaling laws

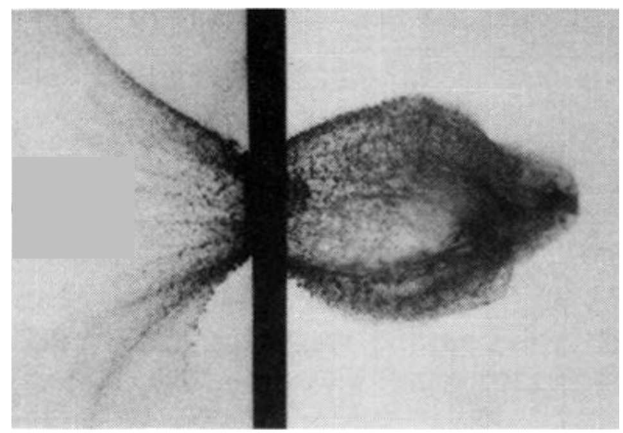
Fragmention - Motivation



WEAPONS
- Conventional munitions
- Range safety

SAFEGUARDS
- Accidents
- Reactor Safety

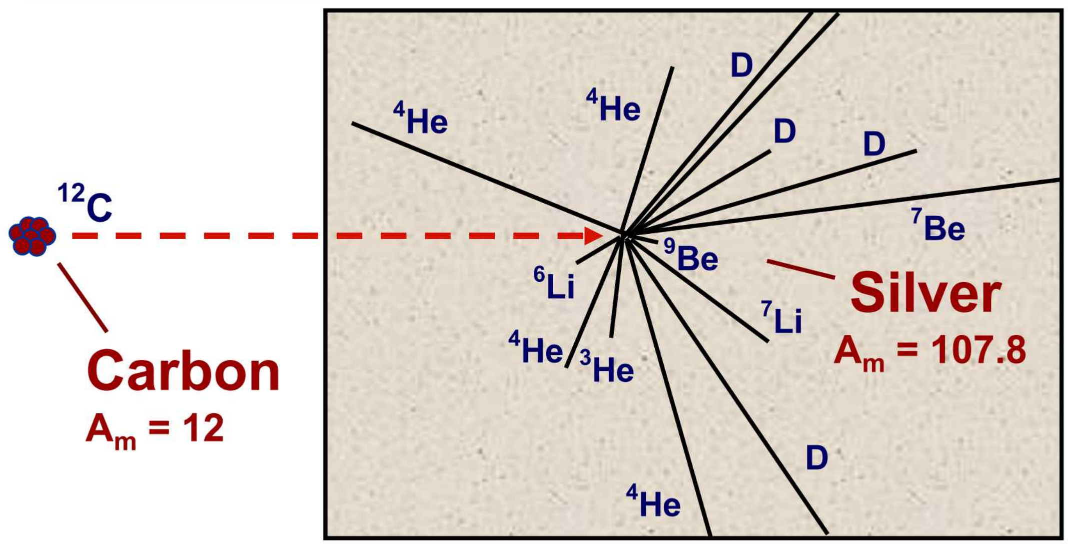


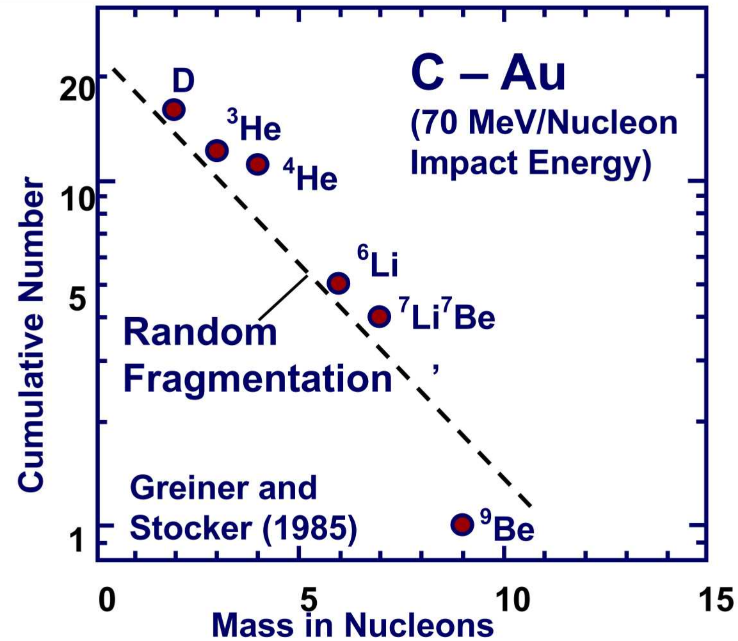


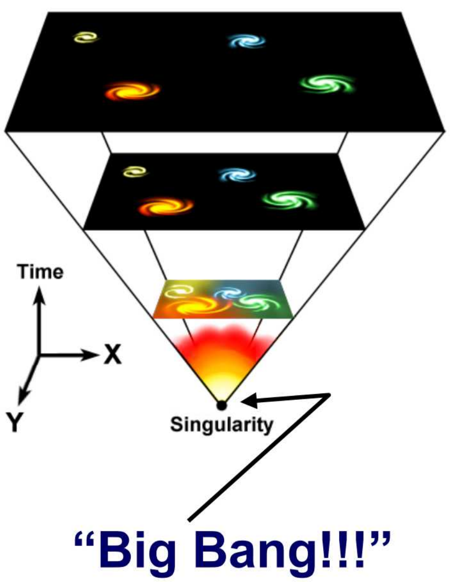
ENERGY
- In Situ Oil Shale Recovery
- Enhance Oil and Gas Extraction

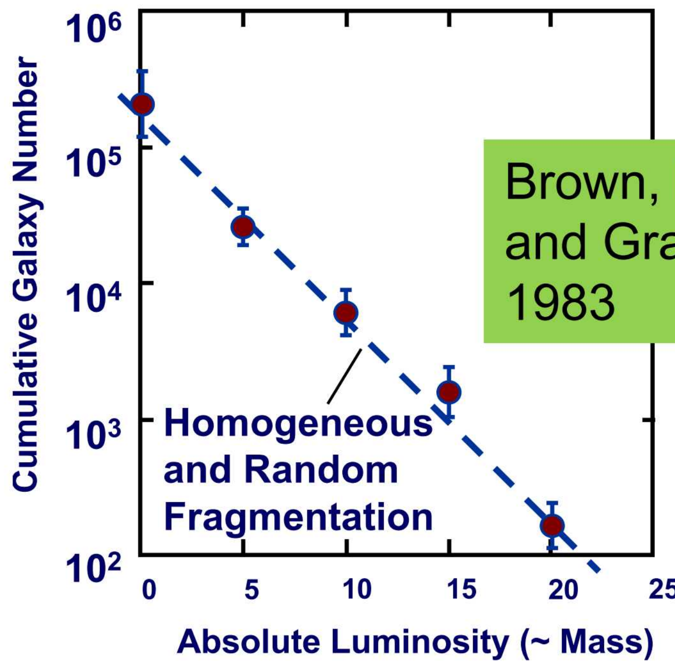
SHIELDING
- Orbital debris
- Behind armor debris

Fragmentation: Examples





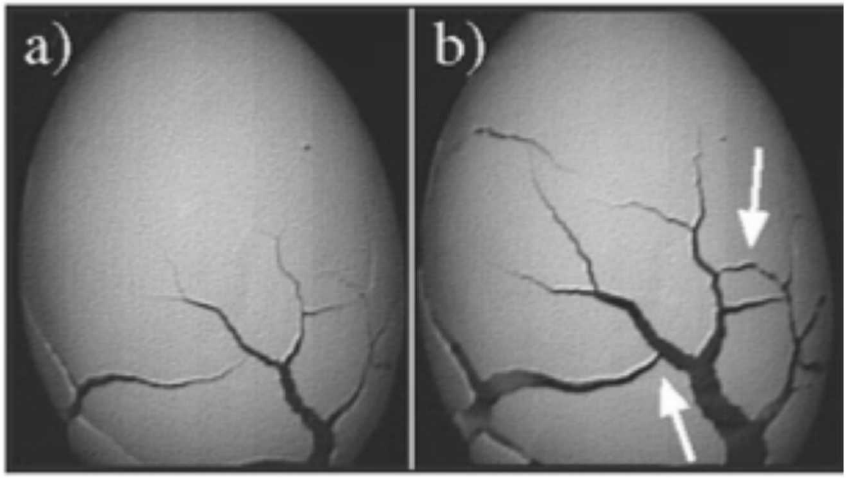




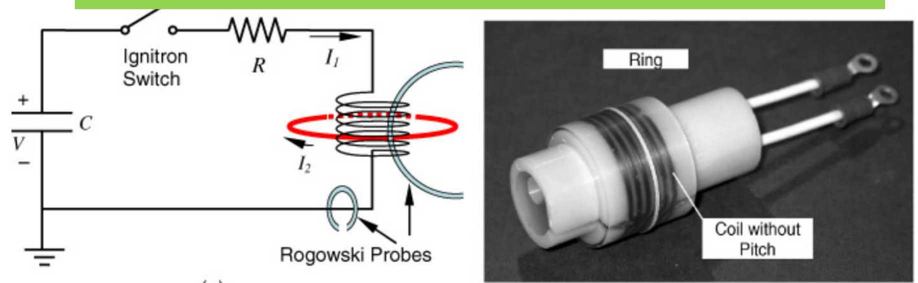
Brown, Karpp, and Grady, 1983

Fragmentation Experiments

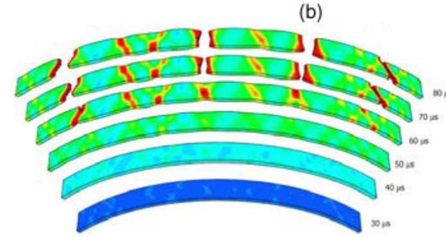
Kun et al., PRL 2004



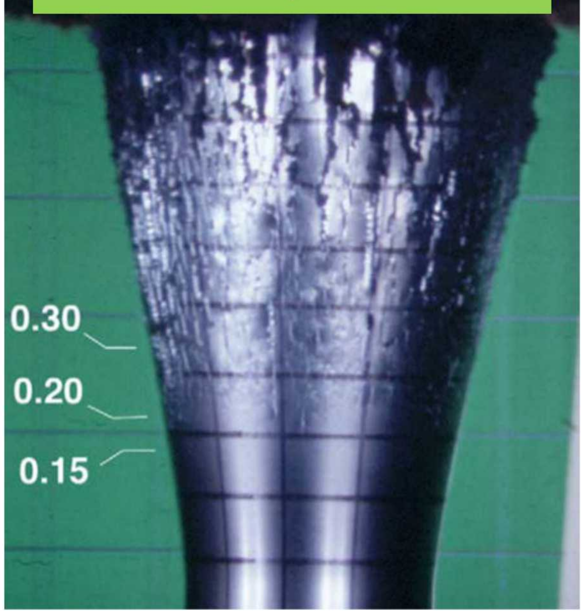
Zhang & Ravi-Chandar, JPD 2009



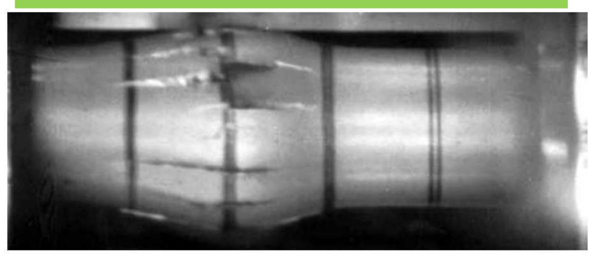
(a) (b)

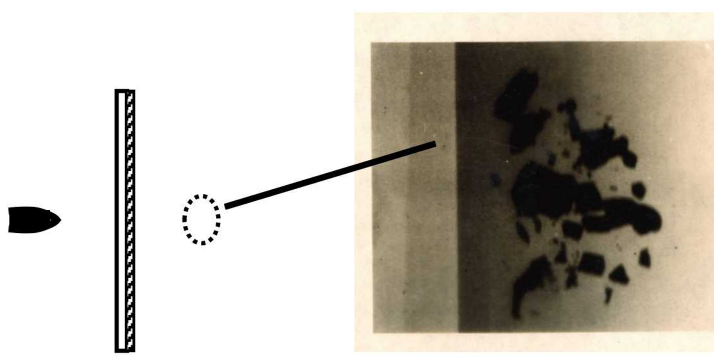


Goto et al., IJIE 2008

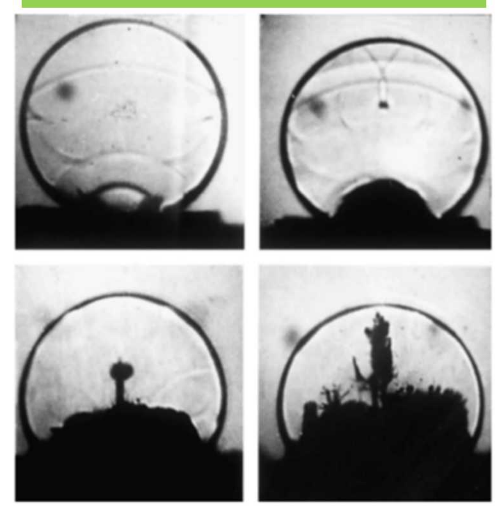


Vogler et al., IJIE 2003



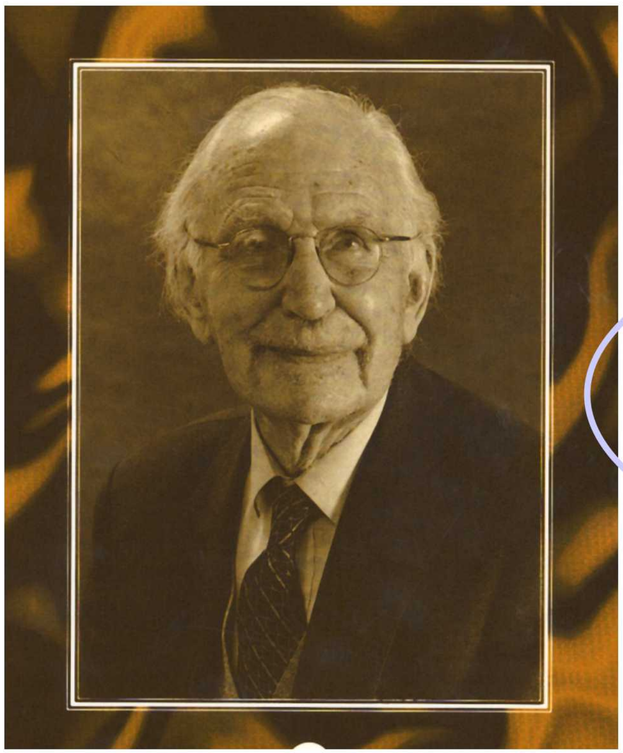


Schonert, PT 2004



Sir Nevill Mott

Professor of Theoretical Physics at Bristol College(1939)



Scientific Advisor to Commanding General of Anti-Aircraft Command (40-42)

Head of Mathematical Research on Armament at Woolwich Arsenal, Fort Halstead (42-45) w/ G. I. Taylor. R. Hill, E. H. Lee, H. Bishop, and others …

Nobel Laureate in Physics

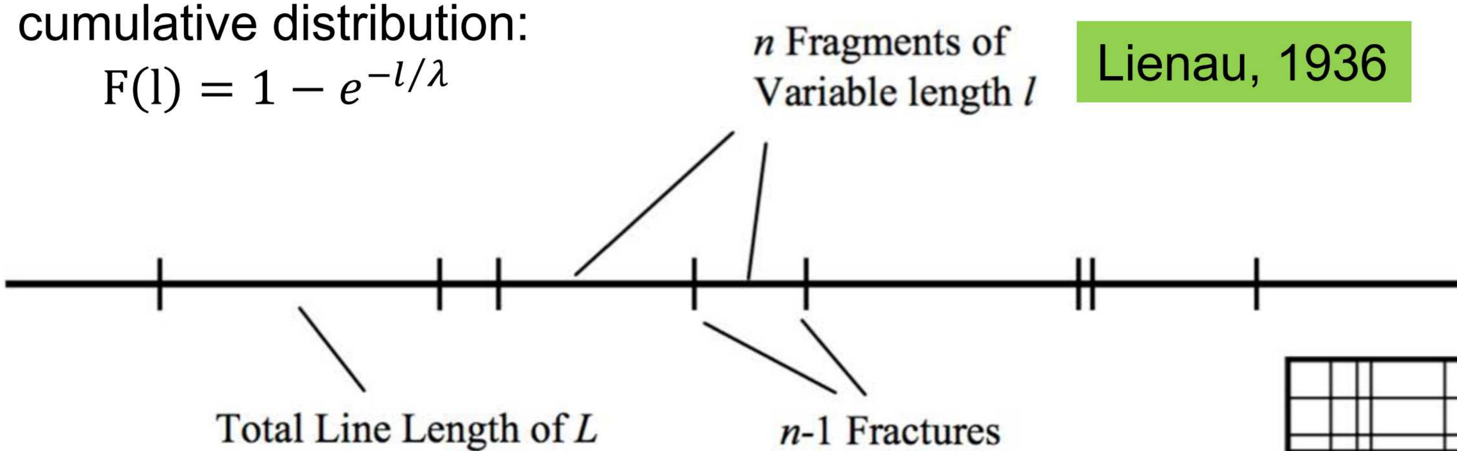
Knight of the British Realm

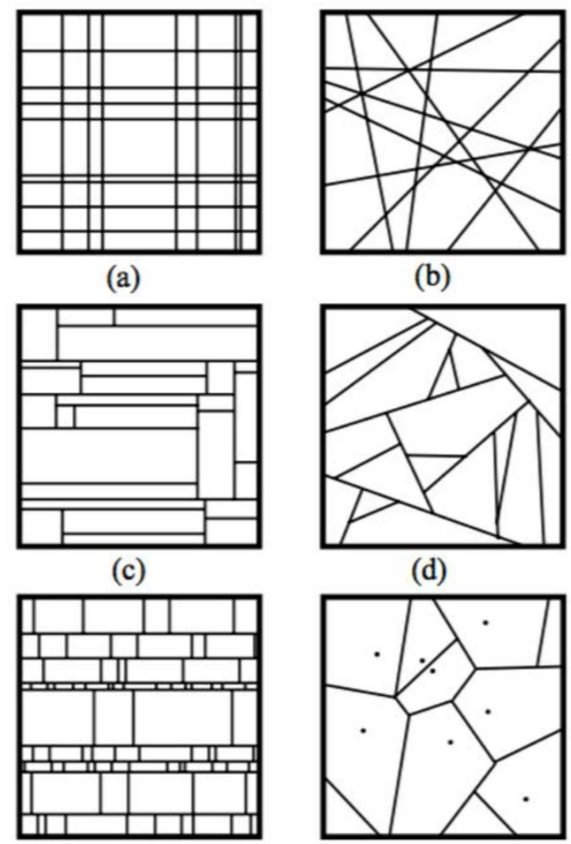
Geometric Arguments

cumulative distribution:

$$F(l) = 1 - e^{-l/\lambda}$$

Lienau, 1936





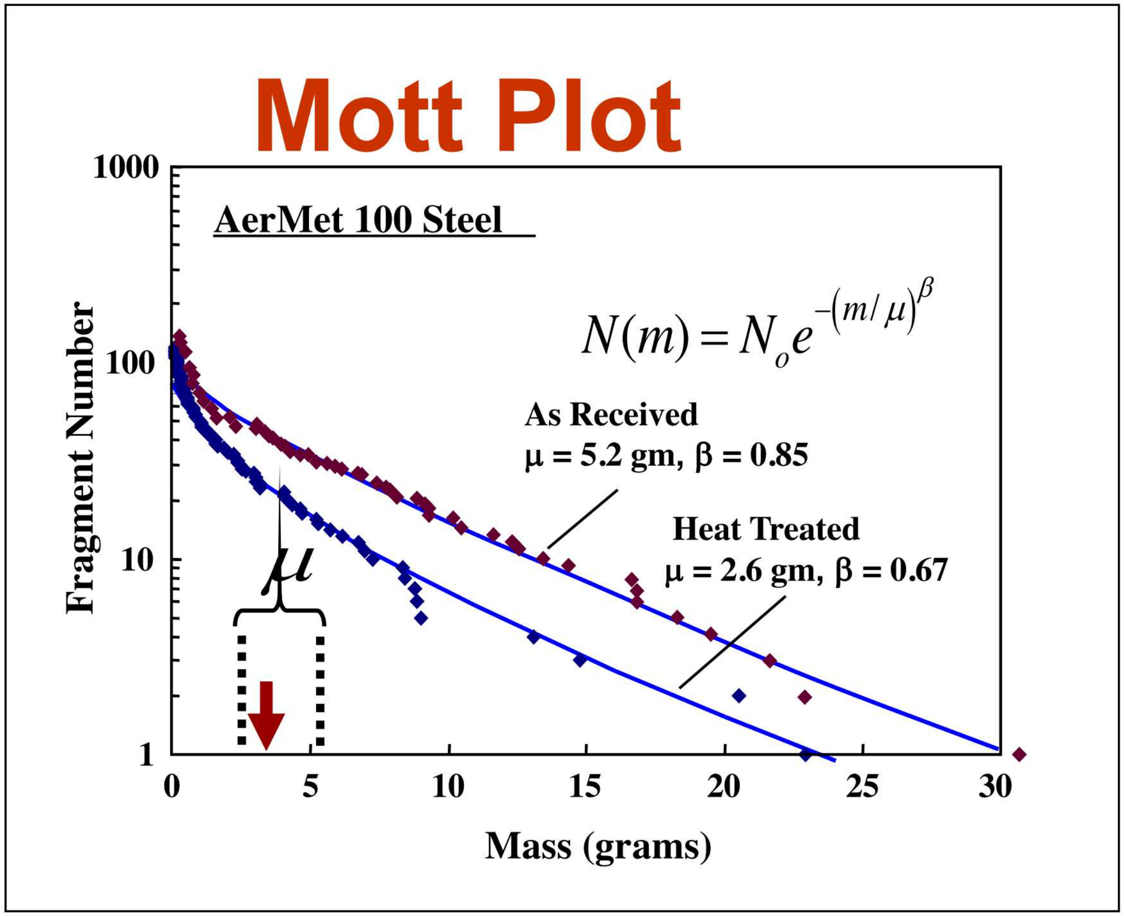
Mott & Linfoot, 1943

cumulative distribution:

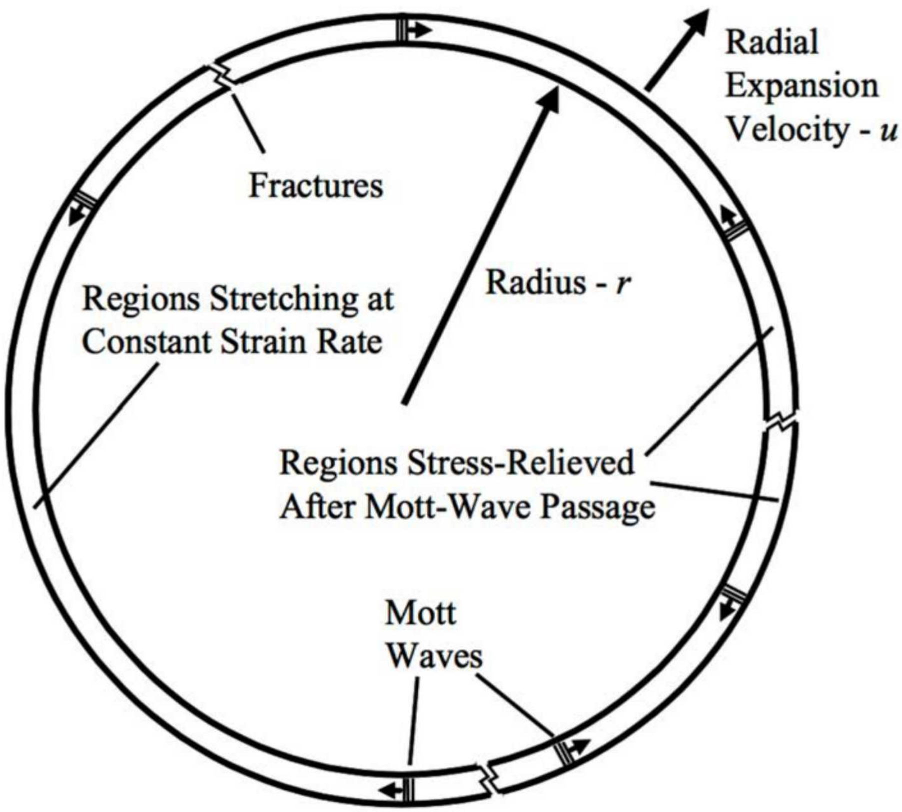
$$F(m) = 1 - e^{-(m/\mu)^{1/2}}$$

generalized results of Lineau motivated by observed mass distributions from fragmenting munitions

The Mott-Linfoot Distribution



Fragmentation of Rings (1)



- consider uniformly expanding ring (or long rod)
- failure initiates at certain locations and occurs instantaneously
- Mott considered rigid-plastic material, but elastic-plastic response is similar
- unloading waves propagate as

$$x = \sqrt{\frac{2Yt}{\rho \dot{\varepsilon}}}t$$

- unloading waves unload material so it can no longer fail

Fragmentation of Rings (2)

- Mott considered the probability of fracture $\lambda(\varepsilon)$ to be:

$$\lambda(\varepsilon) = \lambda_o$$
$$\lambda(\varepsilon) = \frac{n}{\sigma}\left(\frac{\varepsilon}{\sigma}\right)^{n-1}$$
$$\lambda(\varepsilon) = \mathrm{A}e^{\gamma\varepsilon}$$

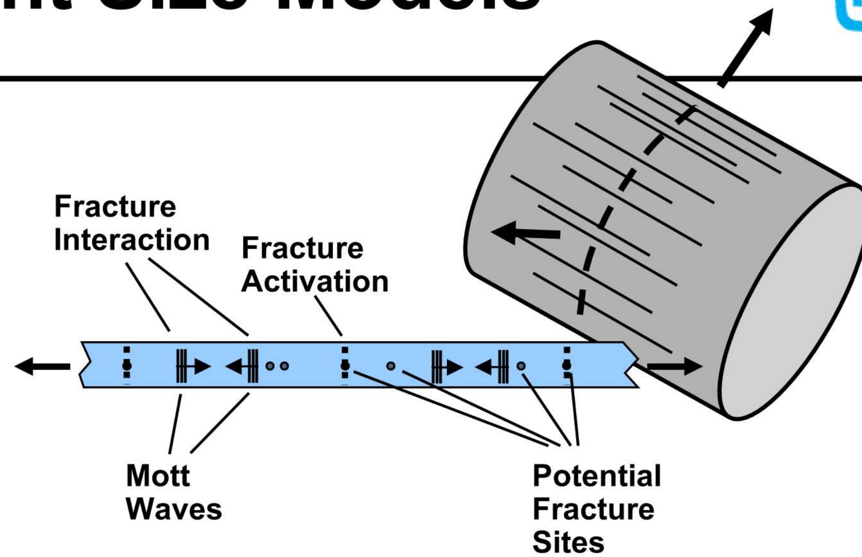
unloading waves unload material so it can no longer fail

Fragment Size Models

Mott Fragment Size (1943)

- Cylinder Fragmentation
- Fracture Statistics Based

$$\lambda \approx \sqrt{\frac{2Y\sigma}{\rho\dot{\varepsilon}}}$$



Grady Fragment Size (1982)

- More General Fragmentation
- Energy Based

$$\lambda \approx \left(\frac{48\Gamma}{\rho\dot{\varepsilon}}\right)^{1/3}$$

Brittle Fragmentation Distribution

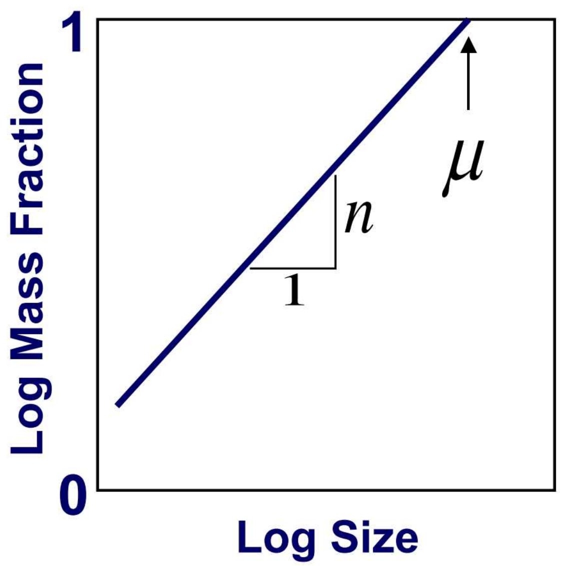
Schuhmann (1940) Mass-Size Distribution

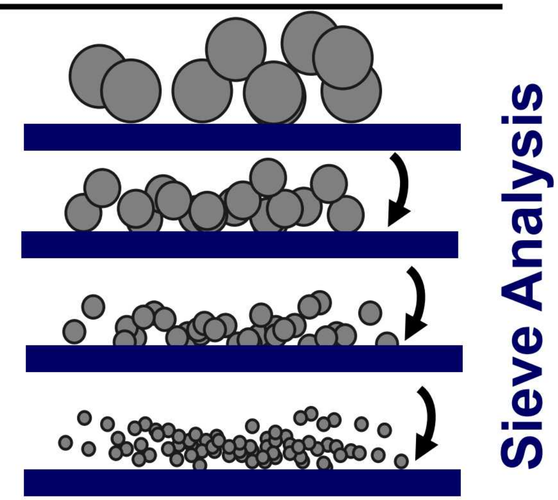
Cumulative Mass Fraction Finer

$$\frac{M(x)}{M_o} = \left(\frac{x}{\mu}\right)^n$$

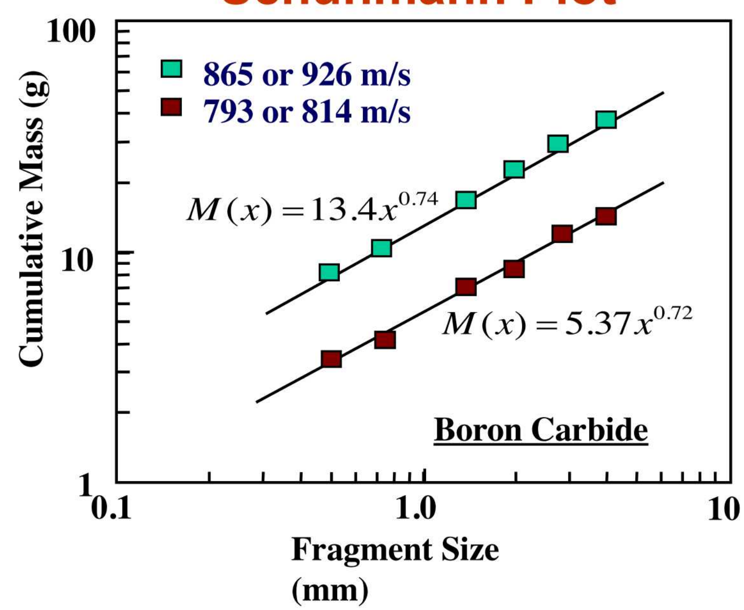
Schuhmann Size Scale

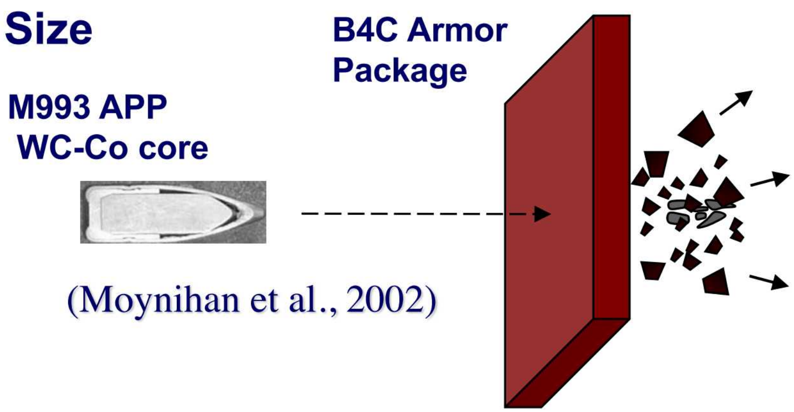
Schuhmann Index





Schuhmann Plot





(Moynihan et al., 2002)

Span of Length Scales

- **Horizon Criterion**

$$\lambda \le 2ct$$

- **Energy Criterion (SE + KE ≥ FE)**

$$\frac{1}{2}\frac{P^2}{\rho c^2} + \frac{1}{120}\rho\varepsilon^2\lambda^2 \ge \frac{3\Gamma}{ct}$$

- **Dynamic Loading**

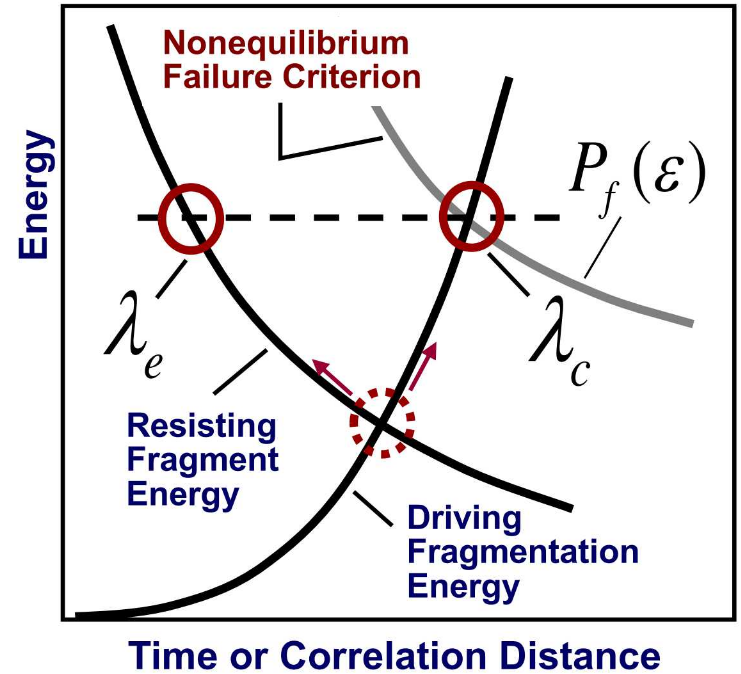
$$P = \rho c^2 \varepsilon t$$

- **Fragmentation Resistance**

$$\Gamma(\varepsilon, T, \lambda)$$

- **Failure Stress (Energy)**

$$P_f(\varepsilon)$$



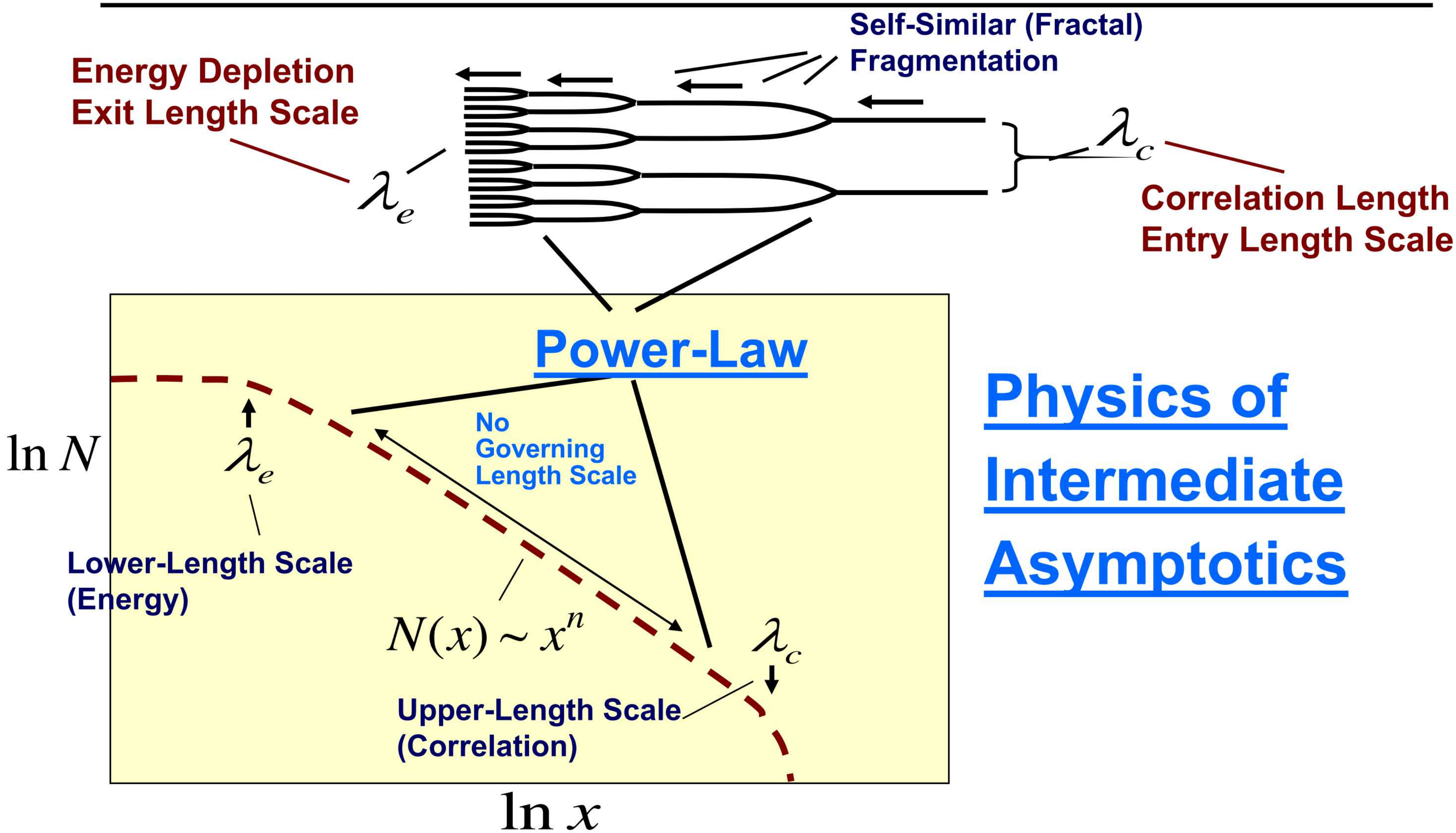
Entry Fragment Size

$$\lambda_c = 2P_f / \rho c\varepsilon$$

Exit Fragment Size

$$\lambda_e = 12\rho c^2 \Gamma / P_f^2$$

Power-Law Physics



Physics of Intermediate Asymptotics

- Brief Introduction to Shock Physics
- Spall Phenomenology and Applications
- Fragmentation
- Closure and Acknowledgements

Conclusions

- **spall is internal fracture caused by the interactions of waves**
  - material (type, flaws/impurities, microstructure, etc.)
  - loading (amplitude, strain rate, shape, direction, etc.)
- **fragmentation is dynamic breakup into many pieces**
  - rings, cylinders, sphere impact, etc.
  - often approached through scaling laws
  - scaling different for flaw-driven, energy driven, and brittle cases

Acknowledgements

John Clayton (ARL) - WHA modeling

Jay Foulk (SNL-CA) – SiC spall modeling

Staff of 1646 – Dan Dolan, Seth Root, Jean-Paul Davis, Mike Furnish, Jack Wise, Marcus Knudson, Justin Brown

W.D. Reinhart, C.S. Alexander, T.F. Thornhill, J. Martinez, R. Palomino, H. Anderson - STAR facility gas gun experiments

J.R. Asay, L.C. Chhabildas, D.E. Grady - decades of shock physics experience

thanks to Dennis Grady for slides on fragmentation