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Shock Waves

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Outline

- What is a shock wave?
- How does a shock wave form?
- Wave types
- Shock Waves – Compression & Release
- Shock Wave Reflections

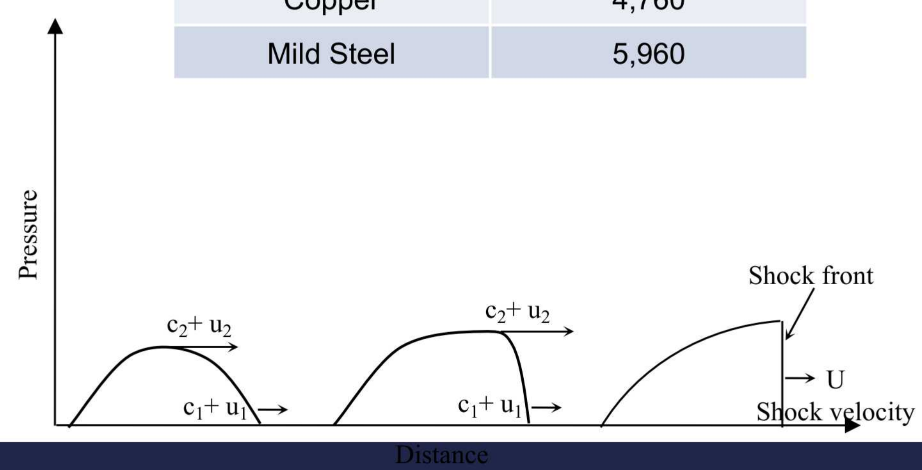
The course will mainly focus on solids

What is a Shock Wave?

- Most materials will transmit sound at a speed that increases with increasing pressure and/or density above a minimum pressure amplitude
- Above the minimum pressure amplitude, the disturbance or compression wave will steepen until it propagates as a jump or discontinuous disturbance which is considered a shock wave

$$c = \sqrt{\frac{dP}{d\rho}}$$

Material	Speed (m/s)
Air (0 ℃) Air (20 ℃)	331 343
Water, sea	1,531
Aluminum	6,420
Copper	4,760
Mild Steel	5,960



What is a Shock Wave?

- The speed of this compression wave is $c + u$ (c is the sound speed and u is the velocity of the material at a point of interest)
- The speed of the shock wave after formation is U

$$c = \sqrt{\frac{dP}{d\rho}}$$

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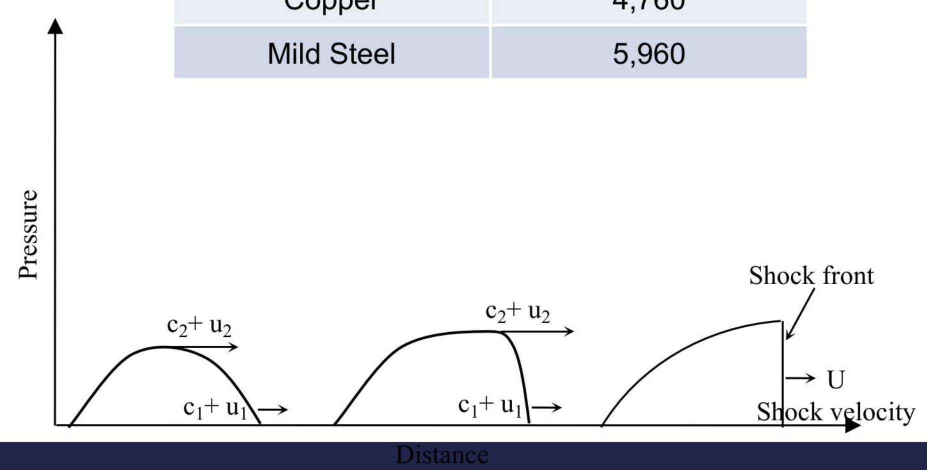
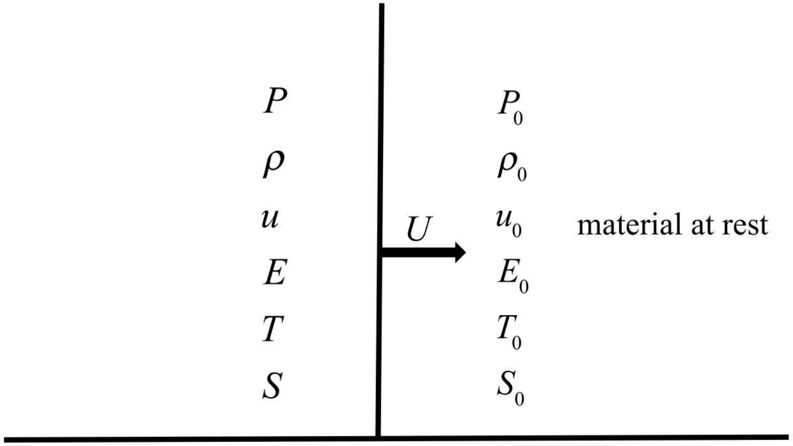


What is a Shock wave?

- The shock wave produces a jump in pressure (P), density (ρ), particle velocity (u), energy (E), temperature (T), and entropy (S)



Examples of How a Shock Wave can Form

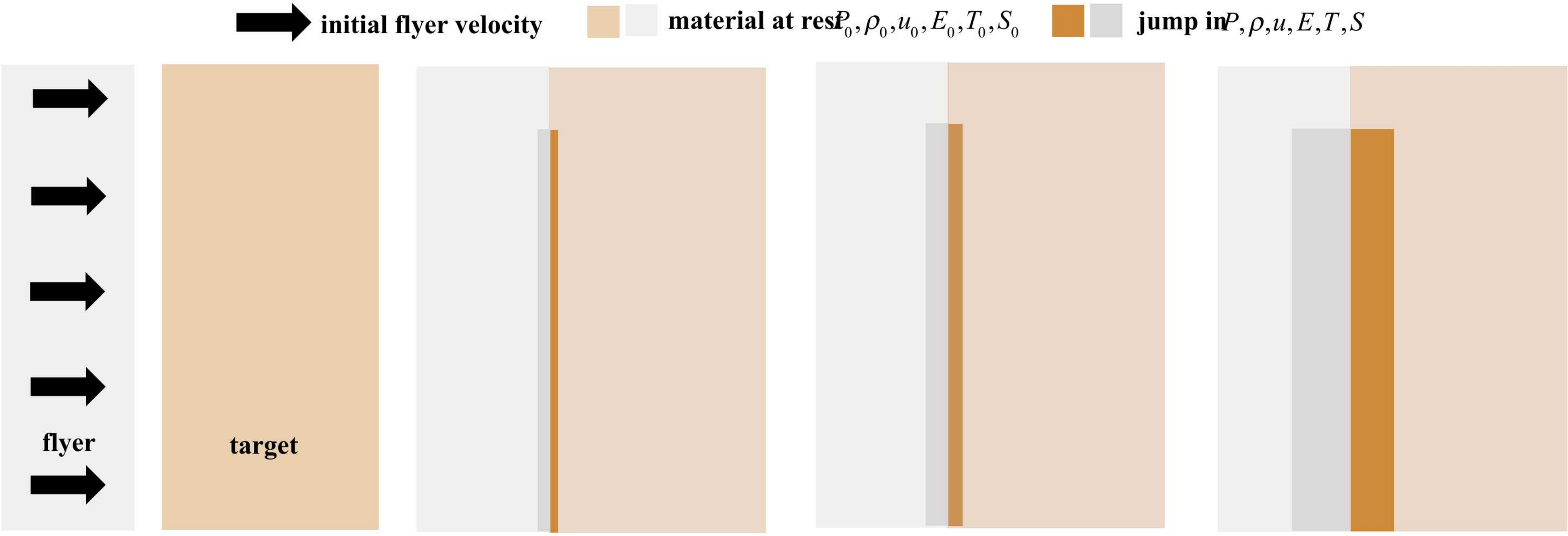
- Lighting bolt
- Meteor impact
- Pulsed power
- Accidental or deliberate impacts
- Accidental or deliberate explosions
- Supersonic flow (air flow around jet airplanes)
- Etc.

Types of Shock Waves

- Compressive
  - Steady
  - Attenuating
- Release
  - Edge
  - Rarefaction
- Collision
  - Compressive
  - Rarefaction
  - Spall

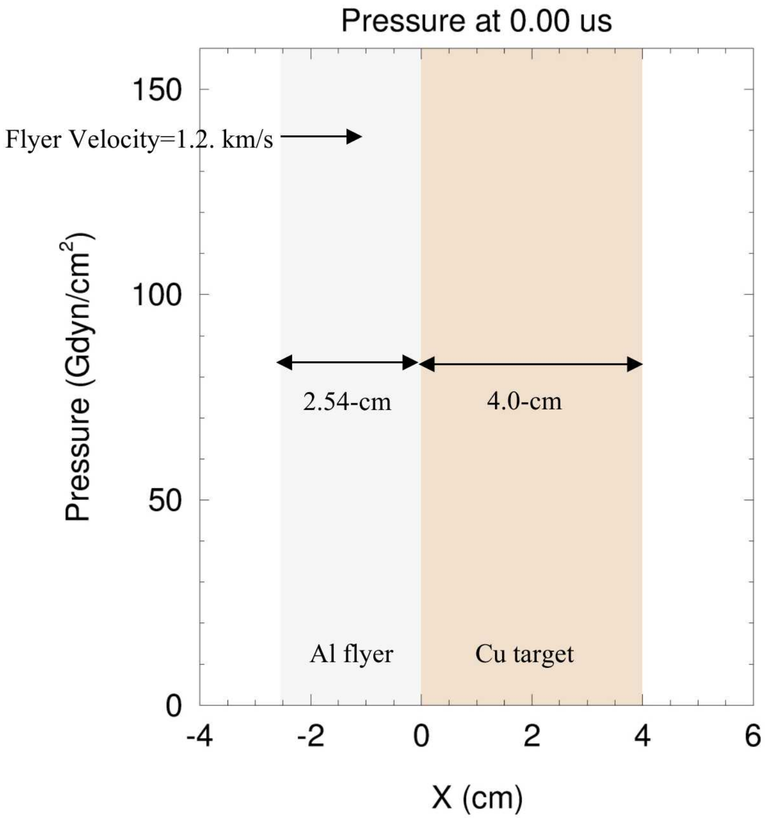
Compressive Waves

- Occur when pressure is suddenly applied to a material boundary (surface)



Compressive Wave

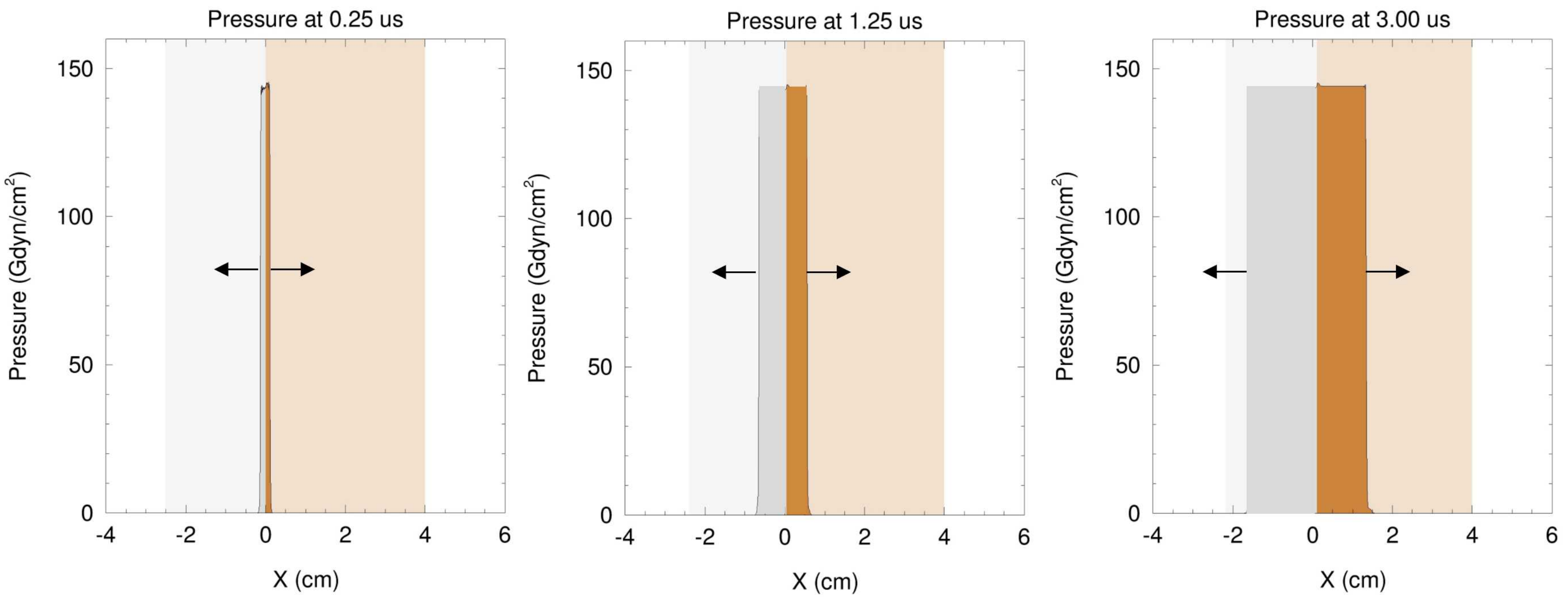
- Aluminum flyer impacting a Copper target
  - 2.54-cm (1-in) Al flyer (1.2 km/s)
  - 4.0-cm (1.575-in) Cu target
  - Upon impact, shock wave propagates into Al flyer and Cu target at the same P and u_p



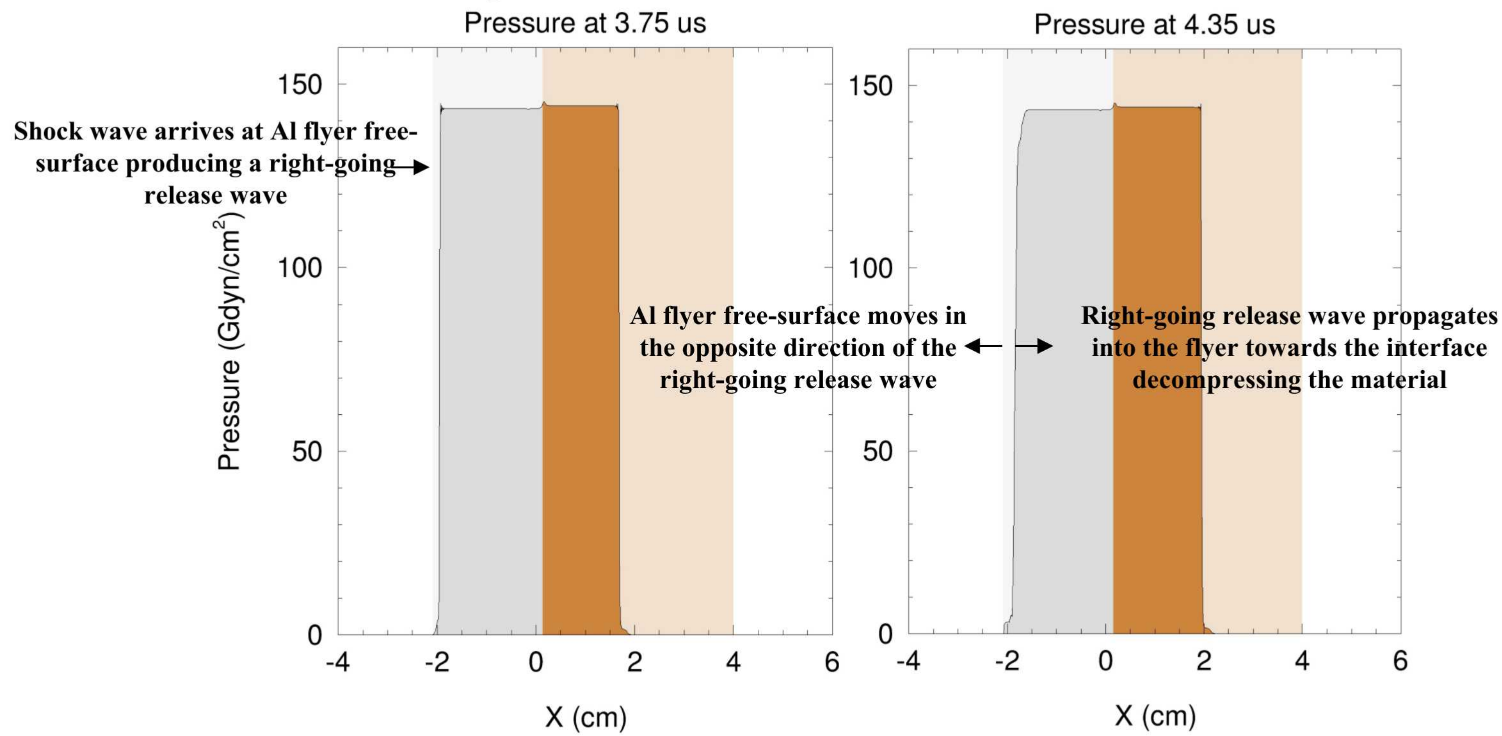
Impact Compresses The Material

- Aluminum flyer impacting a Copper target

Shock (compression) Wave Propagation

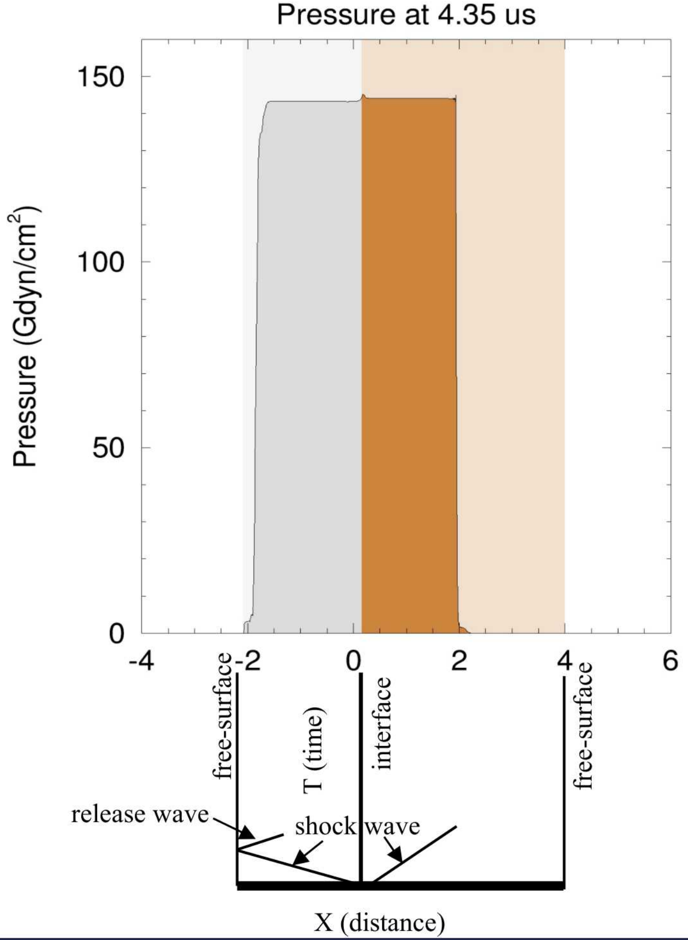


Decompression of The Material



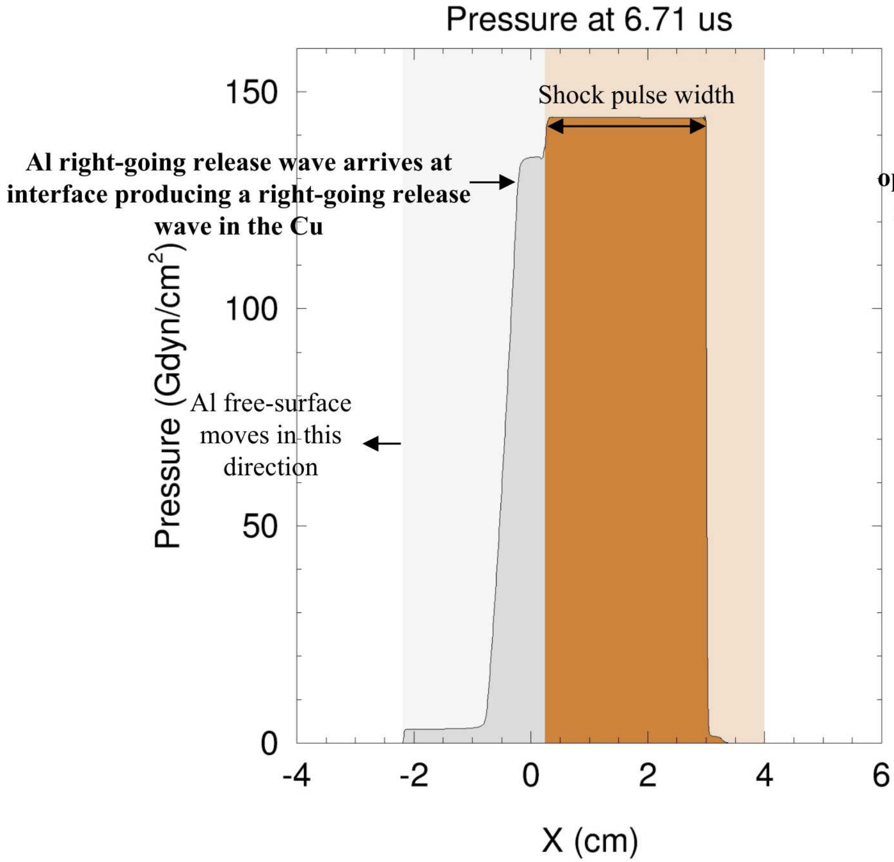
- When the shock wave reaches a free-surface, the free-surface starts to move in a direction away from the interface
- This creates a release, relief, or rarefaction (to rarify) wave that starts to a decompress the material

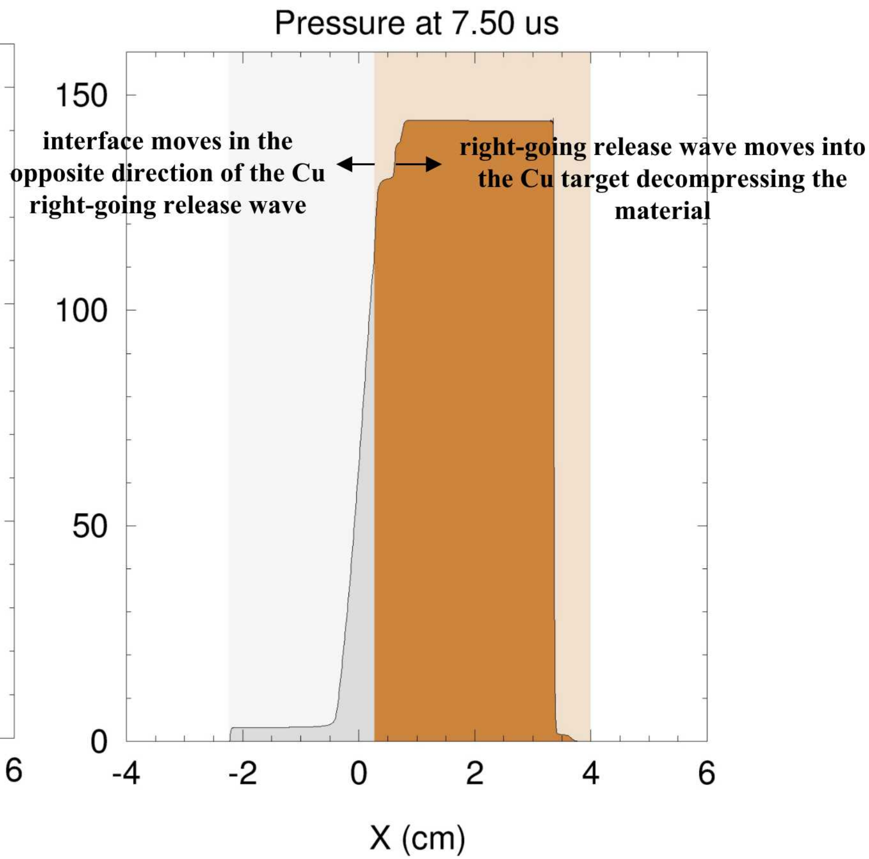
X – T diagram



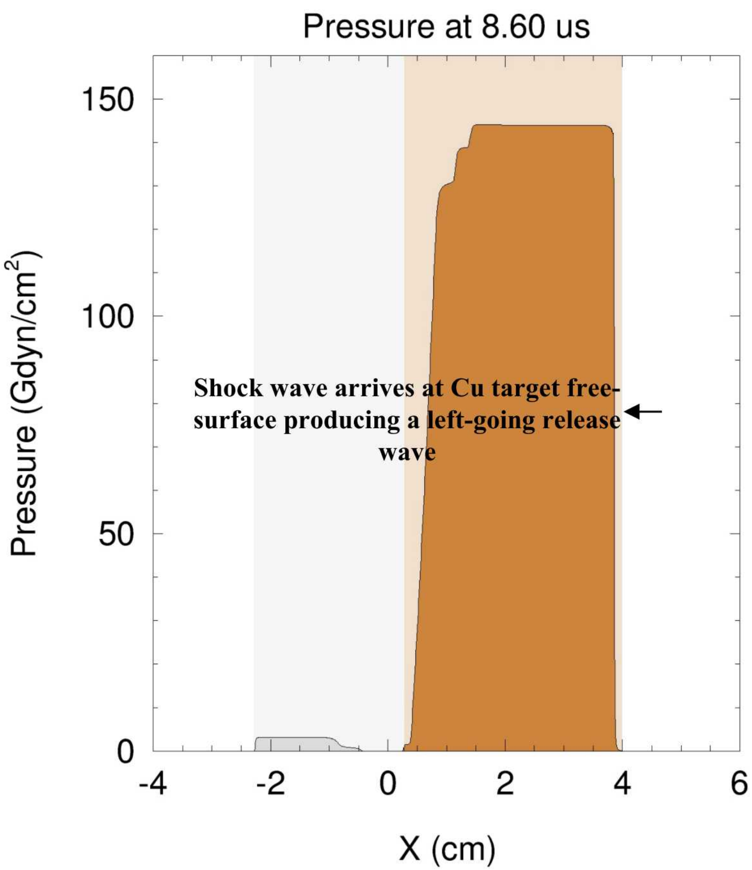
Pressure at 4.35 us
Pressure (Gdyn/cm^2)
150
100
50
0
-4
-2
0
2
4
6
free-surface
T (time)
interface
free-surface
release wave
shock wave
X (distance)

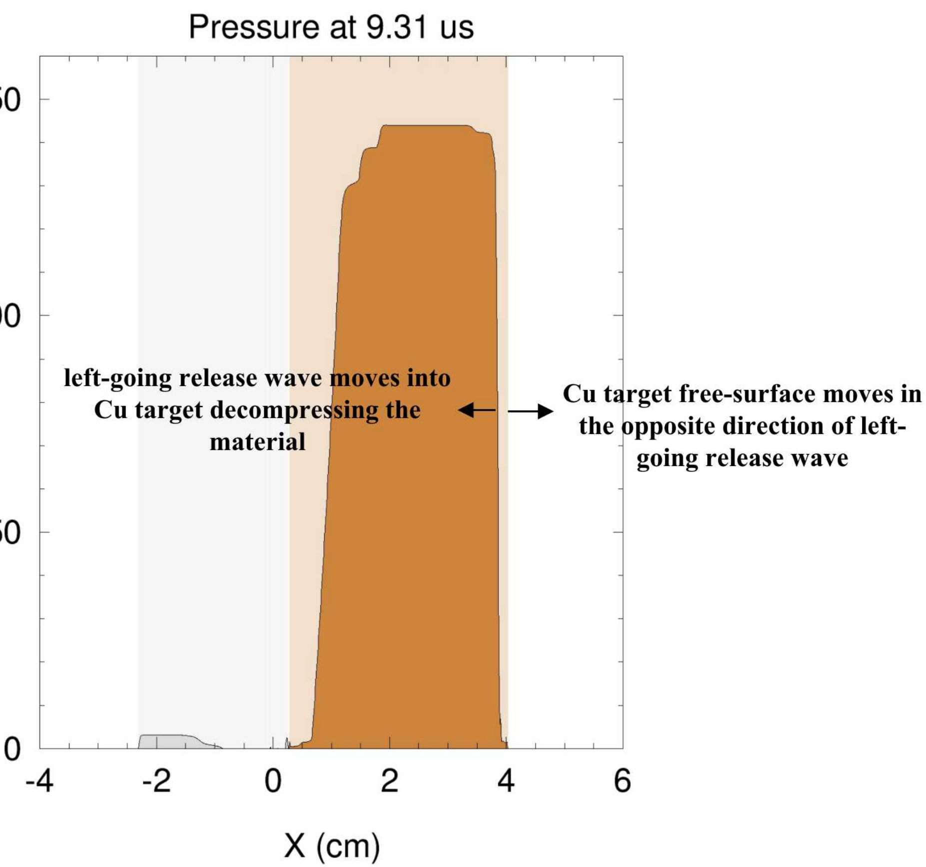
Decompression of the Material



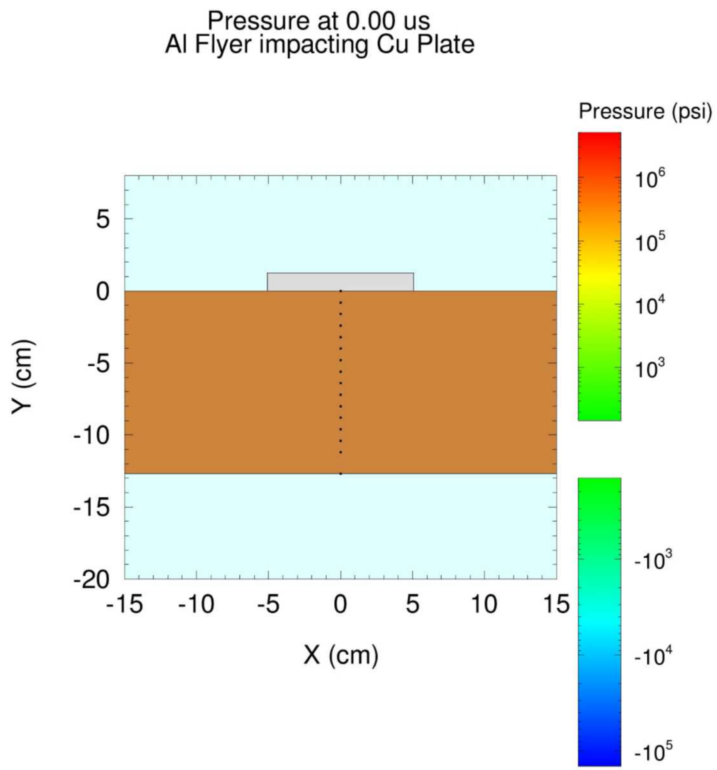


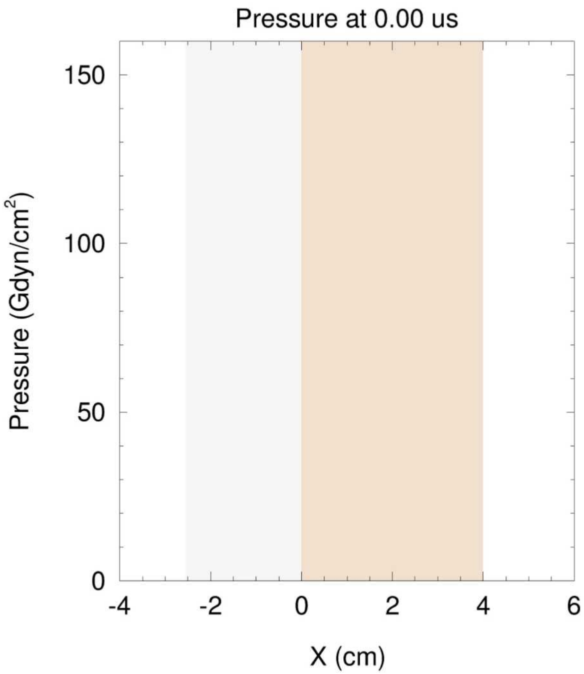
Decompression of the Material





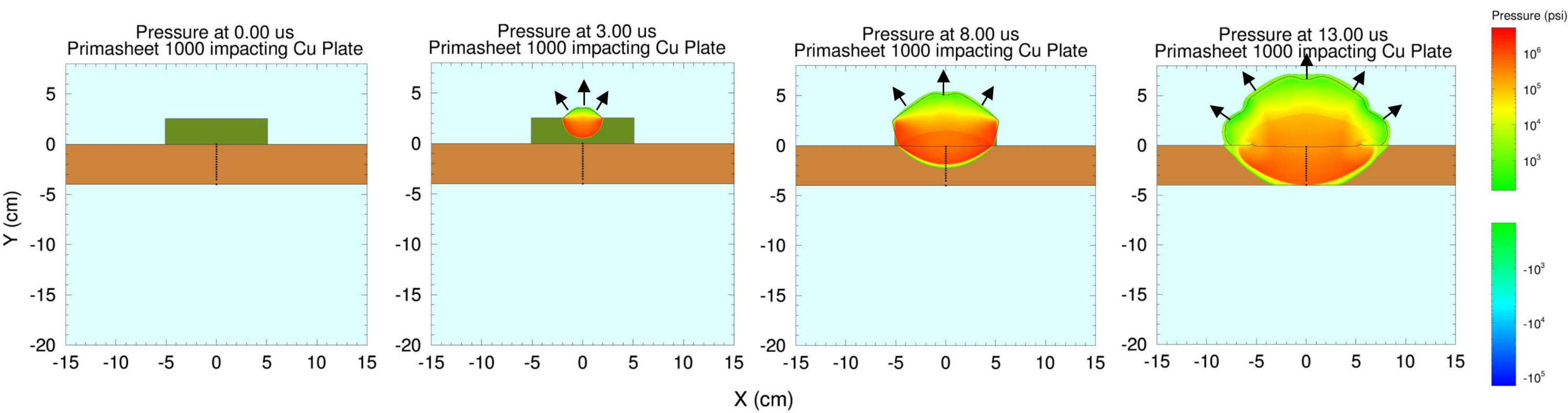
Al Flyer Impacting Cu Target



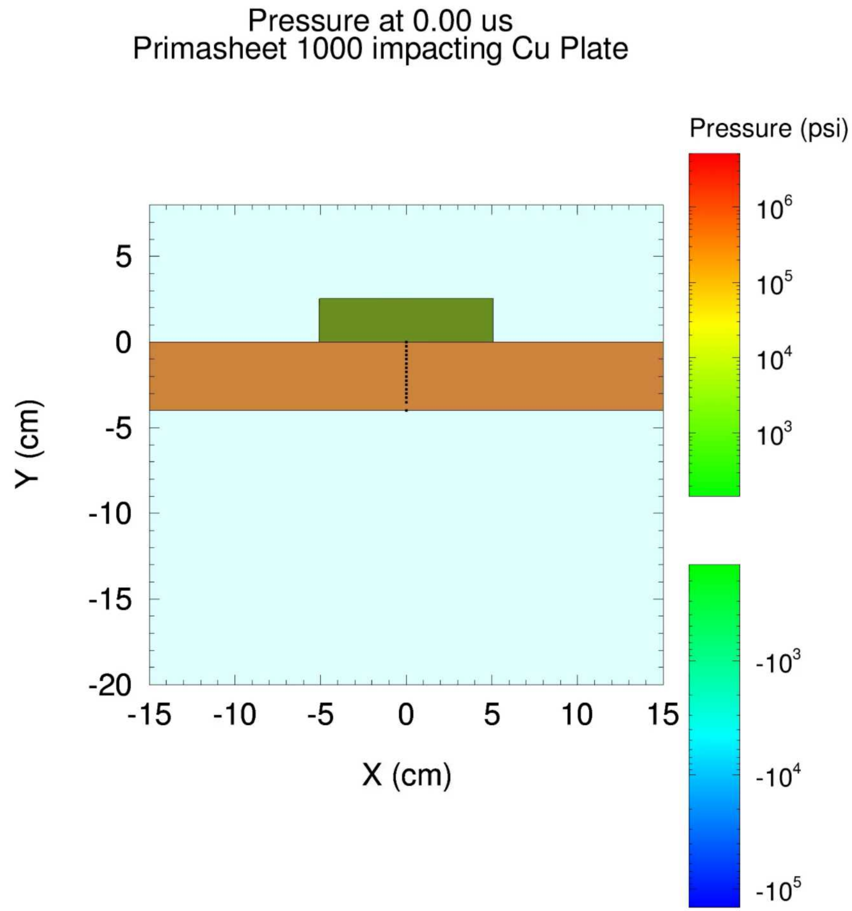


Creating Shock Waves With Explosives

- Pressure in material is generated from high pressure detonation products
- Pressure decreases as detonation products expands
- The Release/relief/rarefaction wave is dependent on how rapidly the detonation products expands

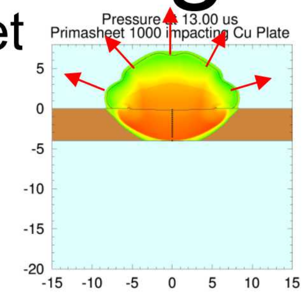


Creating Shock Waves With Explosives

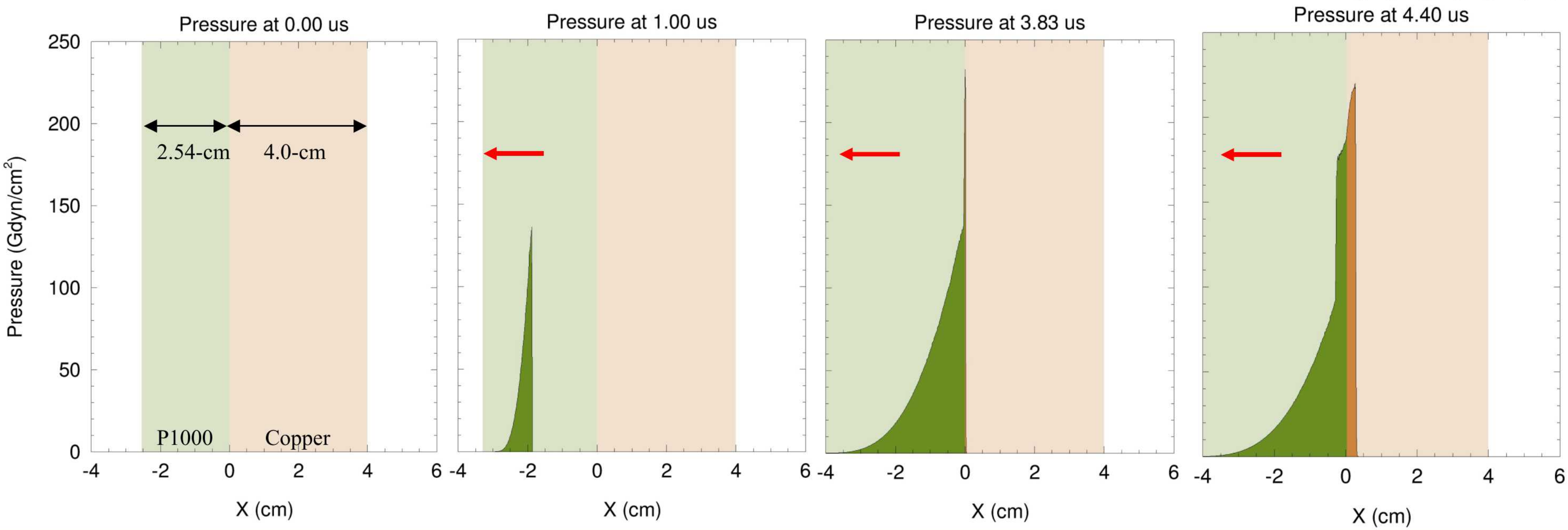


Characteristics of Explosive Loading

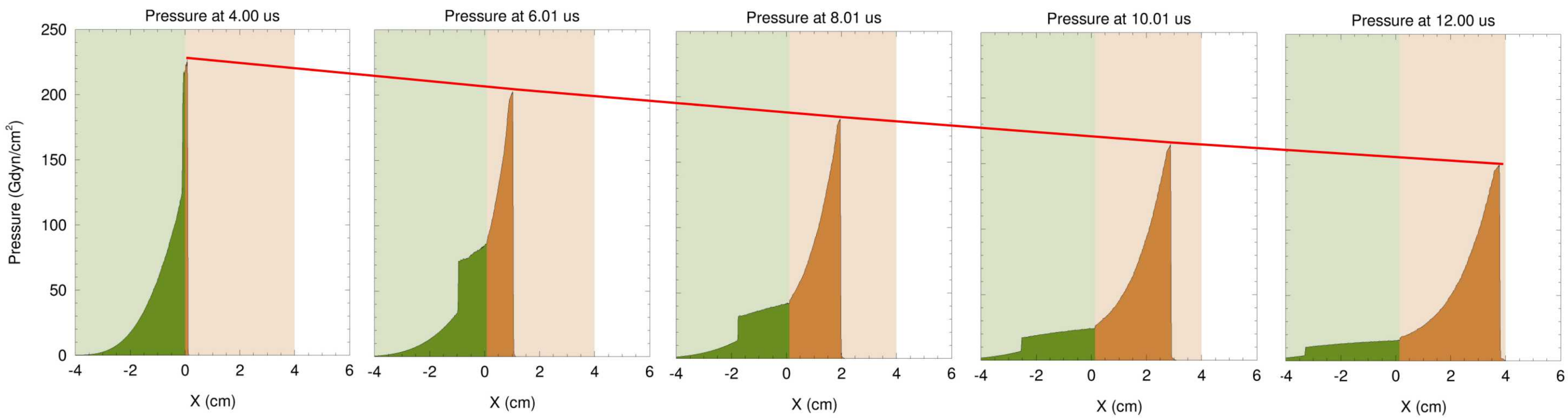
- Primasheet 1000 (P1000) explosively loading Copper target
  - 2.54-cm (1-in) thick P1000
  - 4.0-cm (1.575-in) Cu target



Detonation products are rapidly expanding radially outward



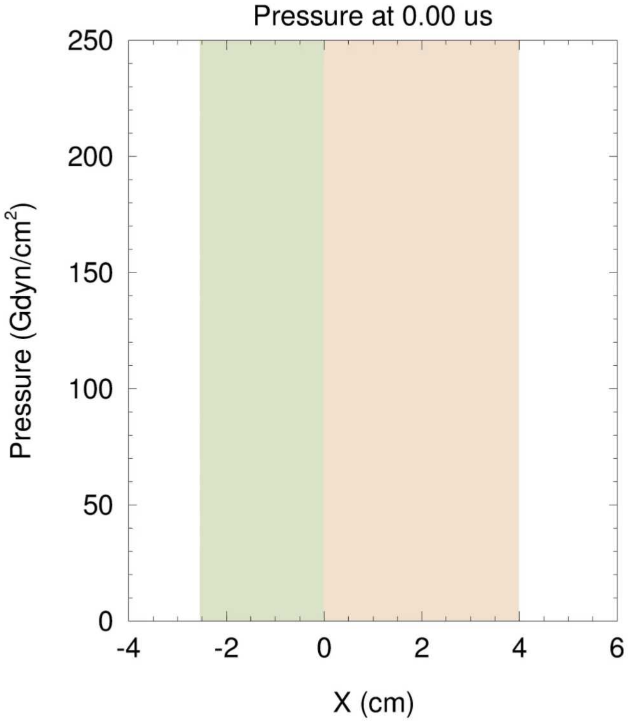
Shock Wave Attenuation



Detonation products are
expanding rapidly

The relief (rarefaction) wave from the explosive/steel interface collides with the relief (rarefaction) wave from the free surface generating a tensile loading that's amplitude produces a spall plane

Characteristics of Explosive Loading



Shock Wave Impedance Matching

- Benefits of understanding shock wave impedance matching
  - Determining the peak stress of a material subjected to an impact or explosive load
  - Determine the influence of the peak stress of a shock wave as it propagates through multiple layers (composite systems) of materials in contact with each other
  - Aid in developing tools, applications, and/or techniques that enhance or mitigate a shock wave

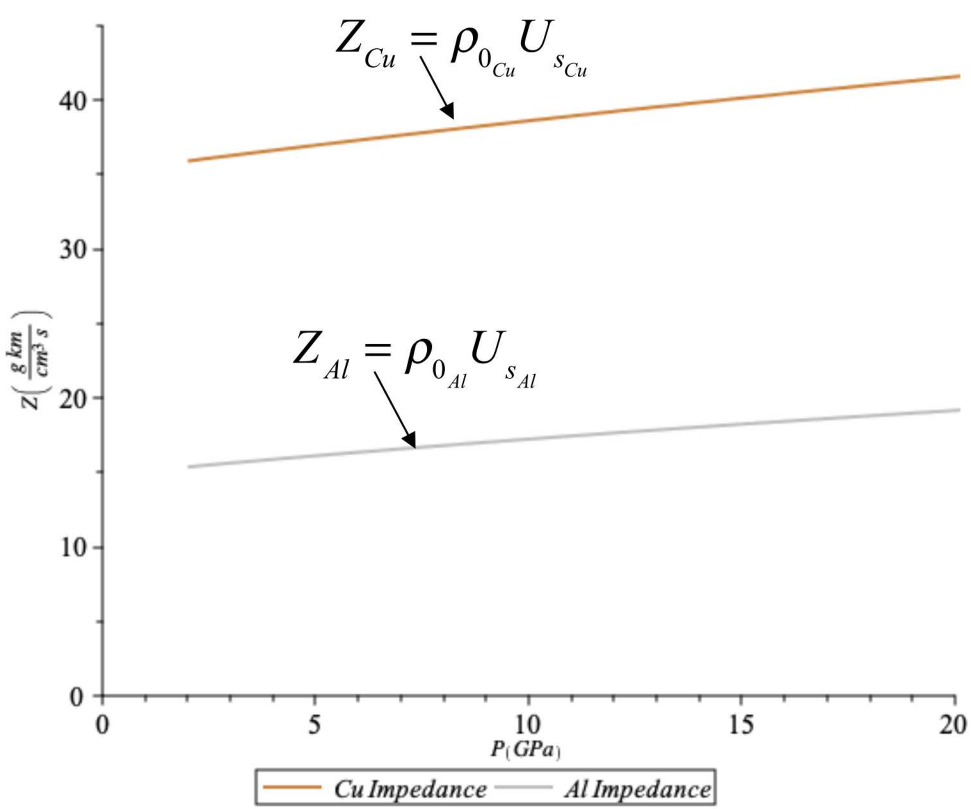
Shock Wave Impedance Matching

- Impedance matching of interest
  - Impact of two materials
  - Interaction of a shock wave at a boundary
  - Interaction of two shock waves
  - Interaction of two release waves

Shock Wave Impedance Matching

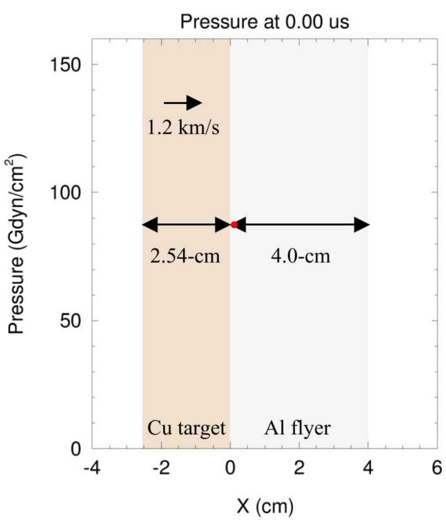
- What is shock wave impedance?
  - A measure of a material to resist compression
  - A measure of a material's ability to generate pressure under a given loading conditions

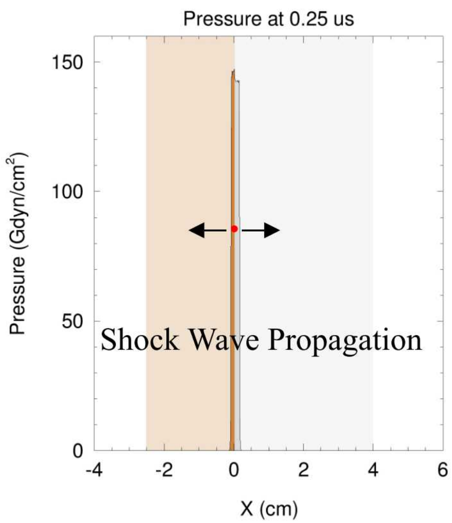
$$P = \rho_0 U_s u_p = Z u_p,\ Z = \rho_0 U_s$$

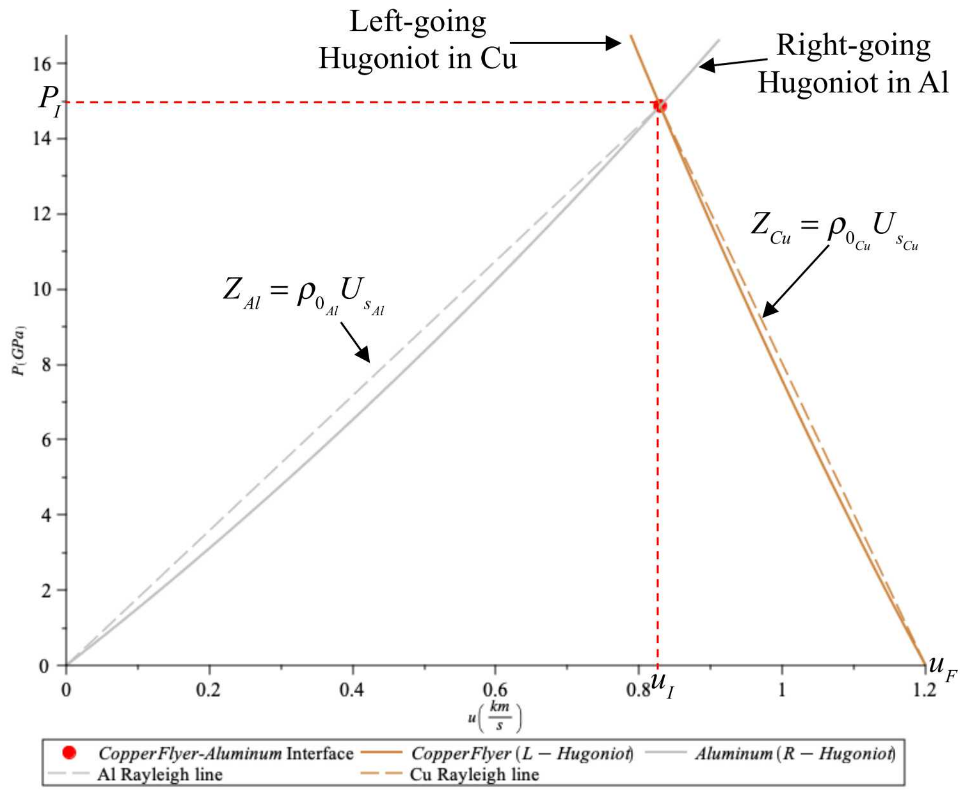


Shock Impedance Matching: Impact

The shock impedance Z_{Al} and Z_{Cu} represent the slope of the Rayleigh line for the $P - u_p$

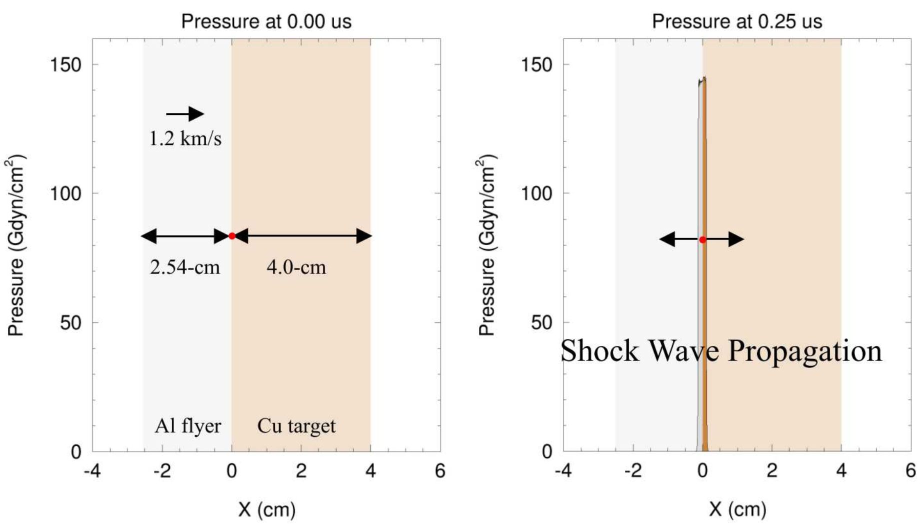


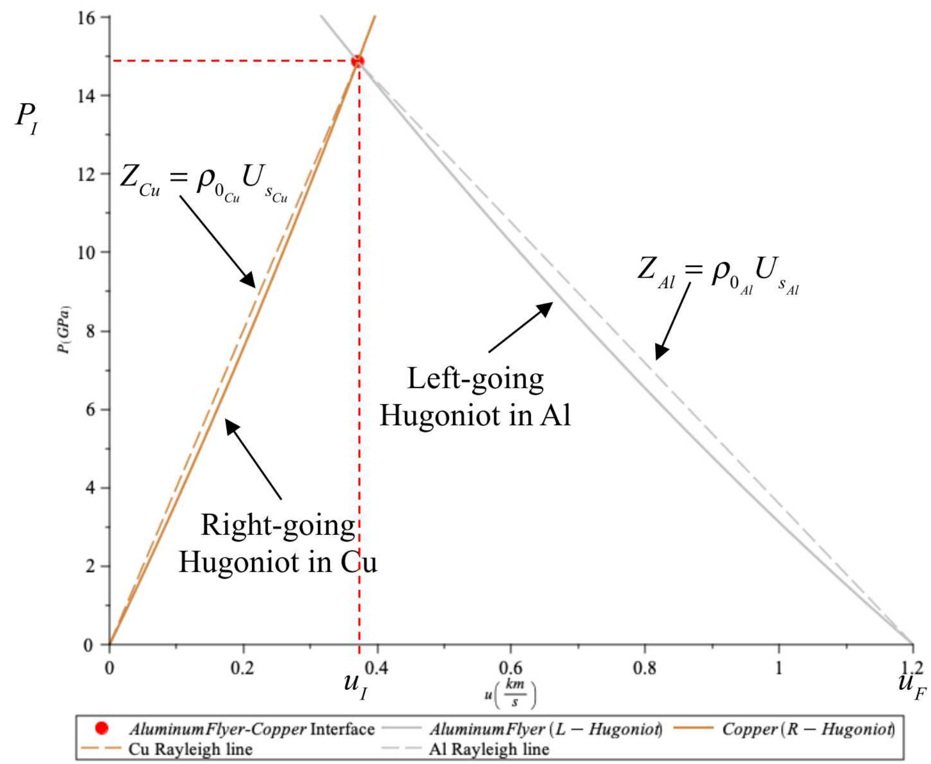




$$Z_{Cu} > Z_{Al}$$

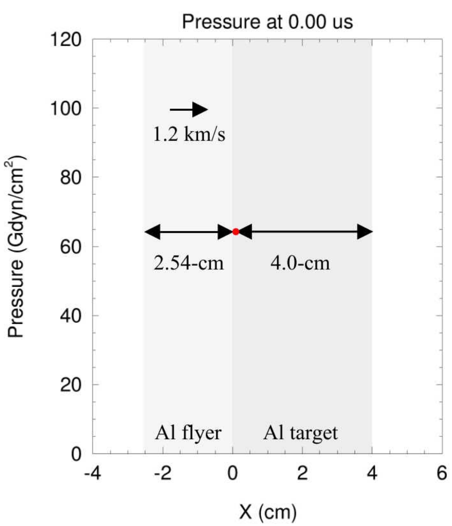
Shock Impedance Matching: Impact

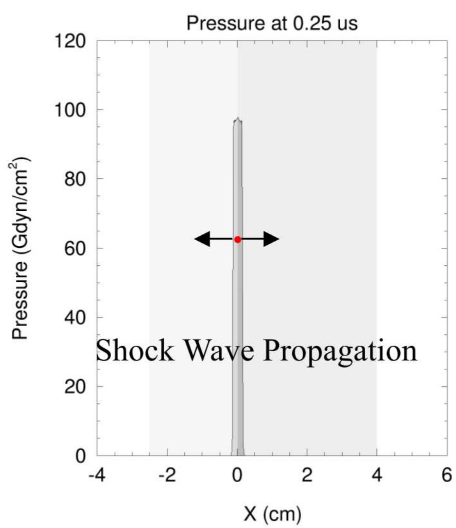




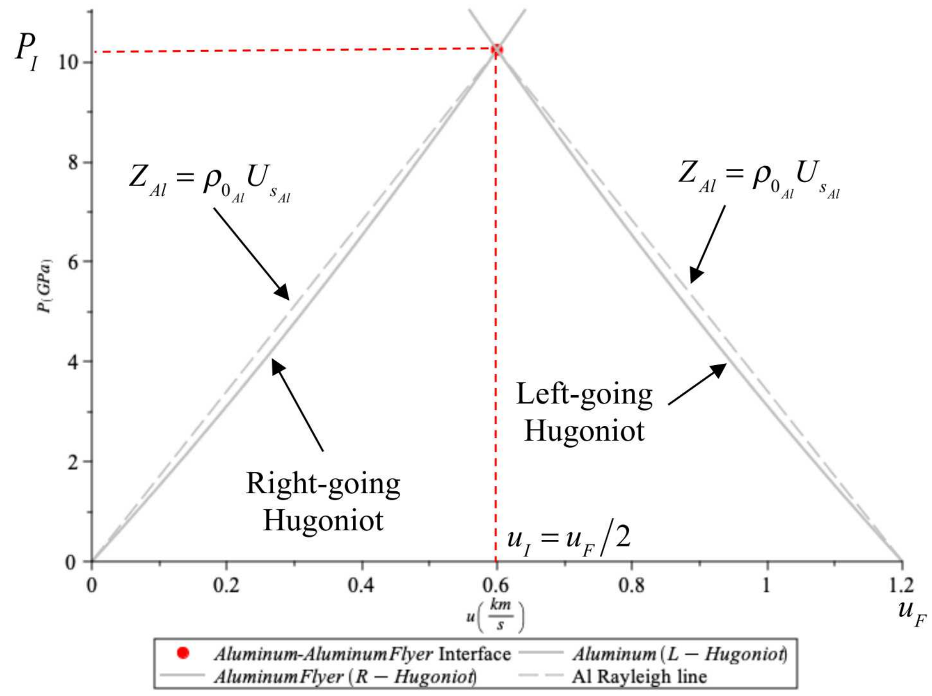
$$Z_{Al} < Z_{Cu}$$

Shock Impedance Matching: Impact



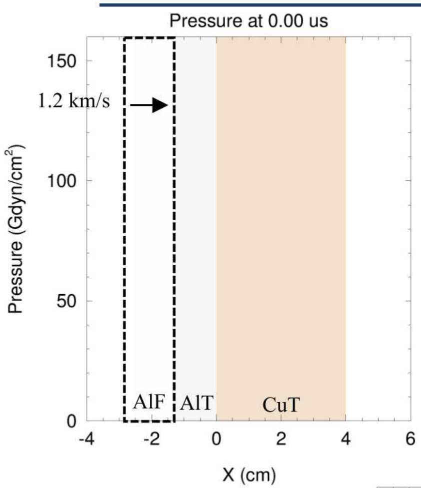


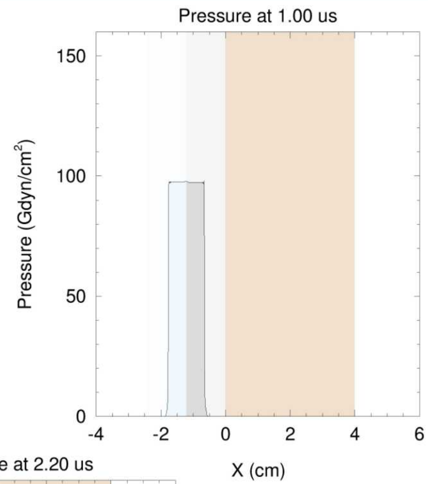
Symmetric impact

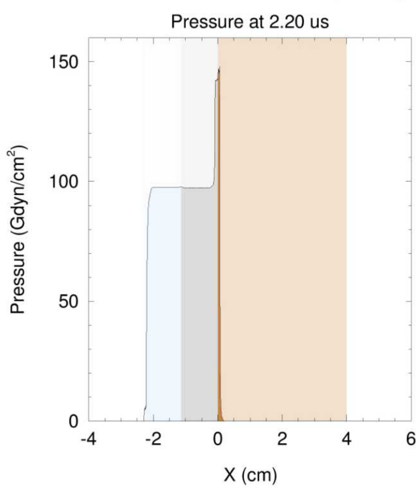


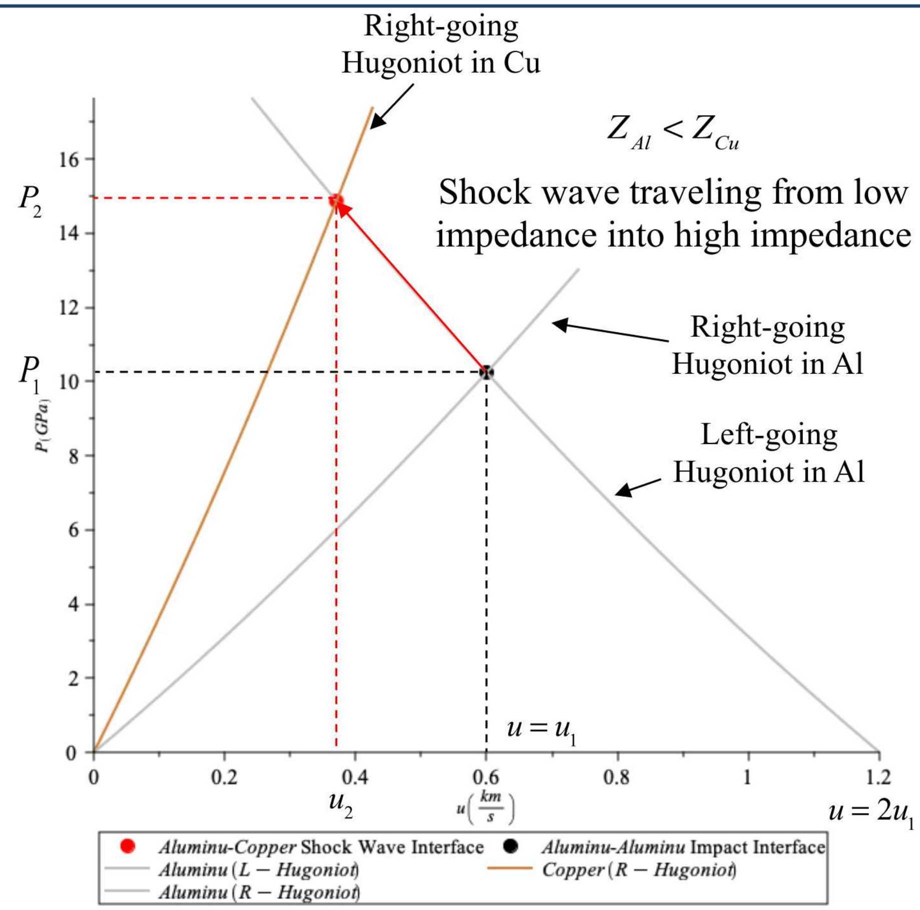
$$Z_{Al} = Z_{Al}$$

Shock Waves at an Interface

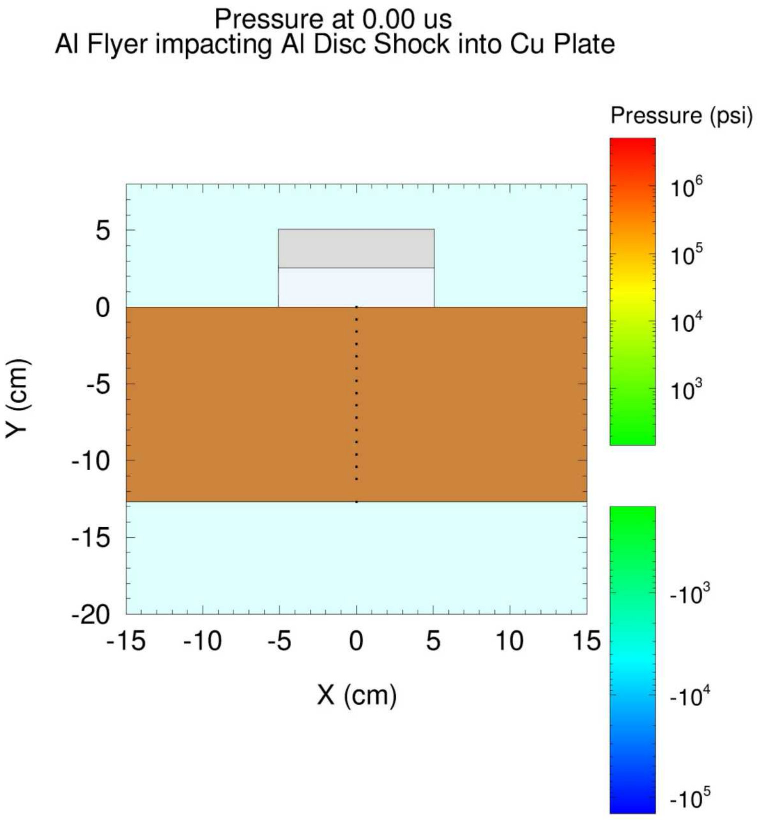


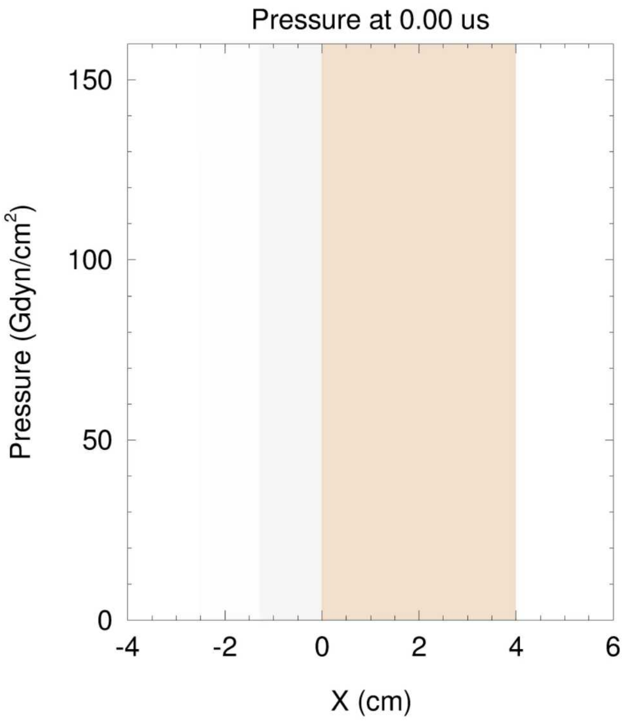




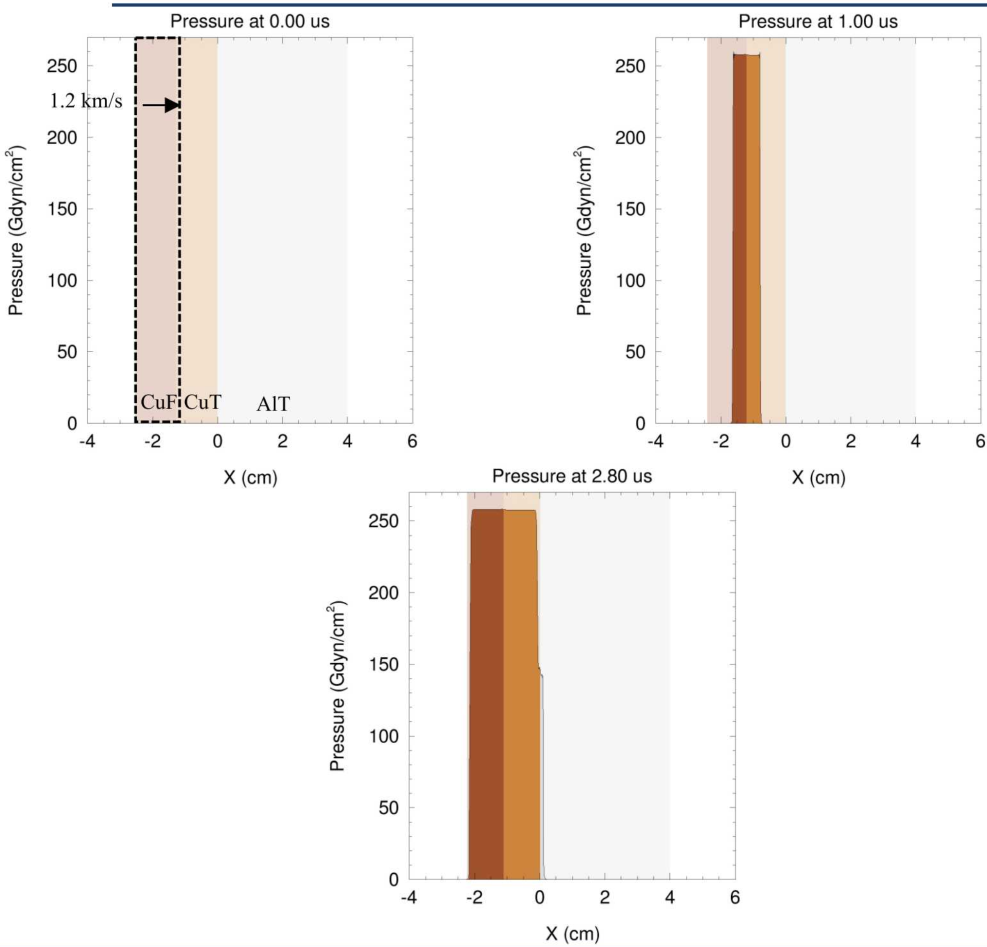


Shock Waves at an Interface

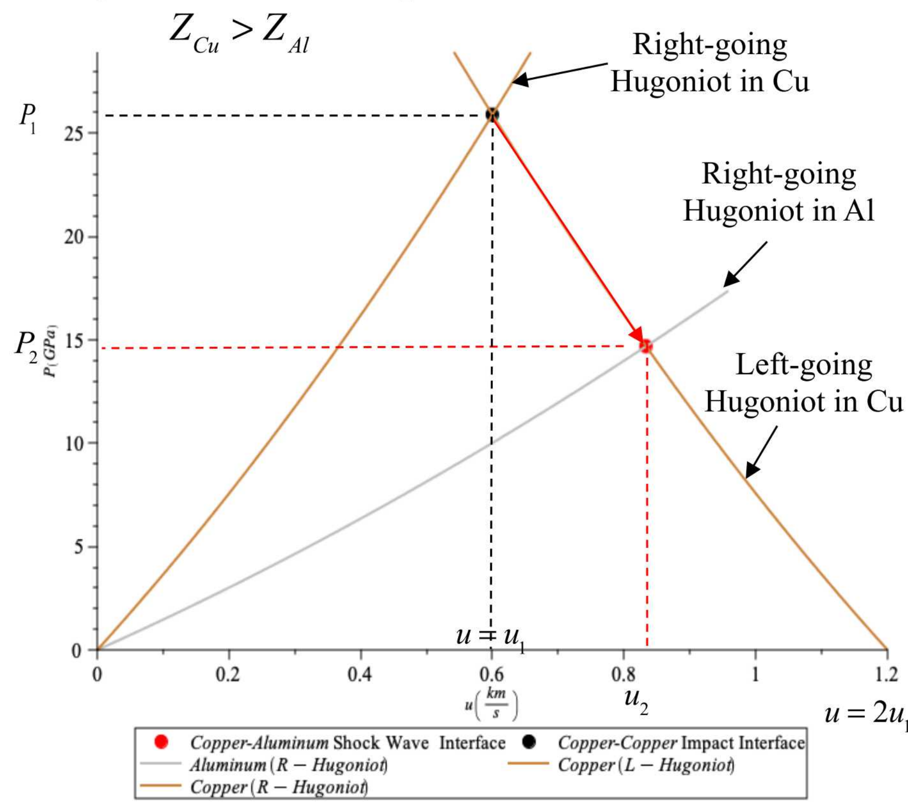




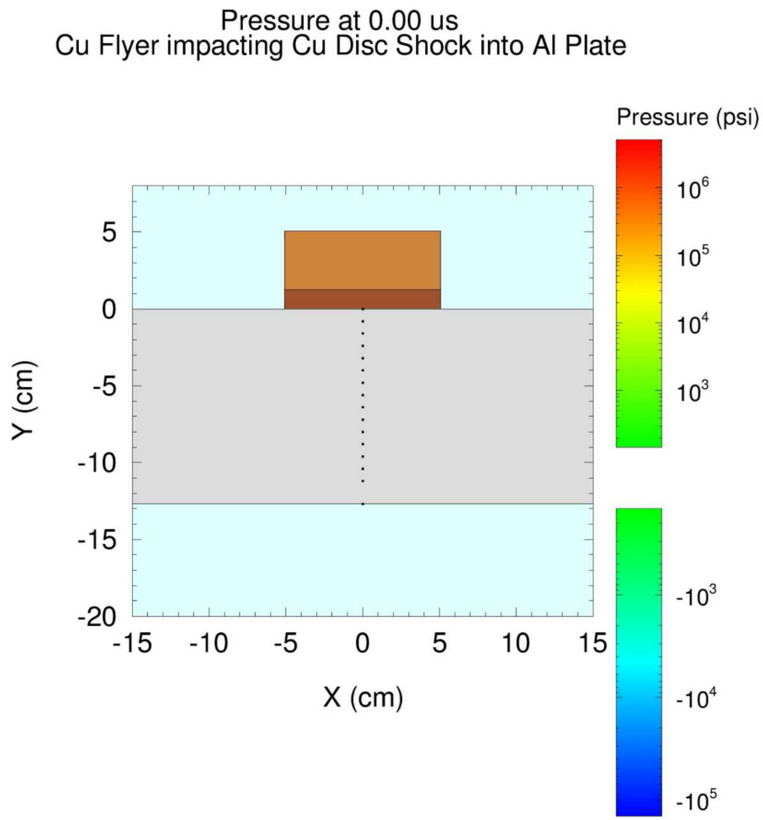
Shock Waves at an Interface

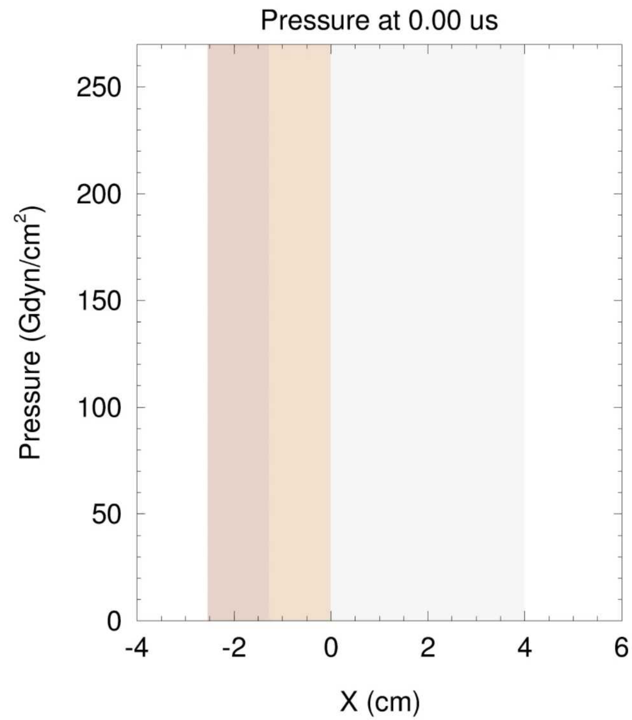


Shock wave traveling from high impedance into low impedance

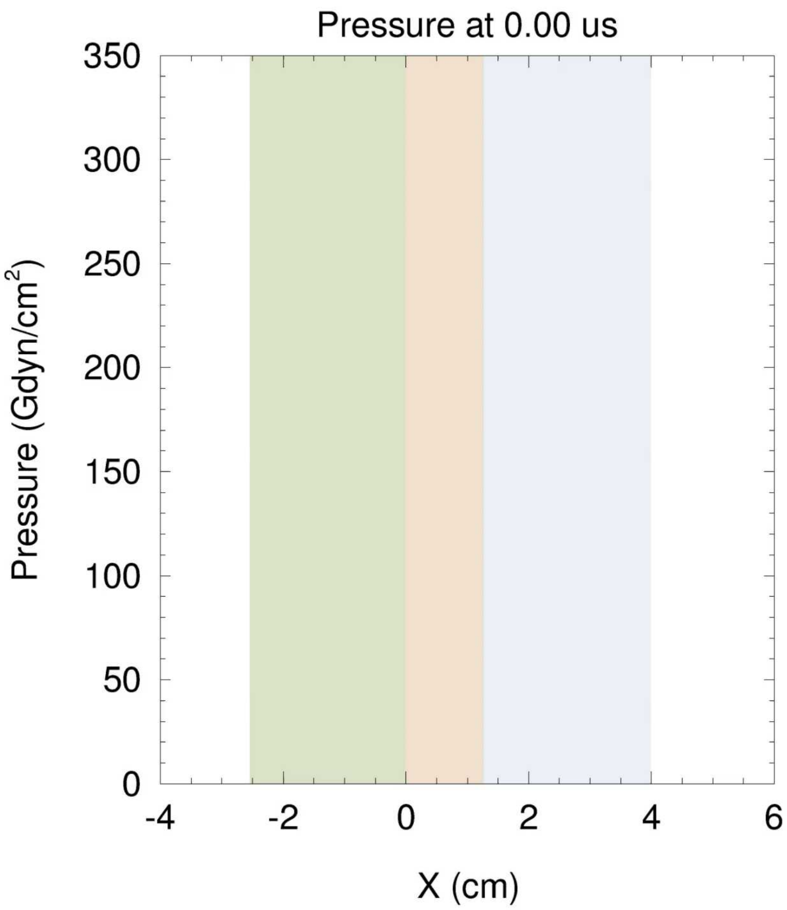


Shock Waves at an Interface

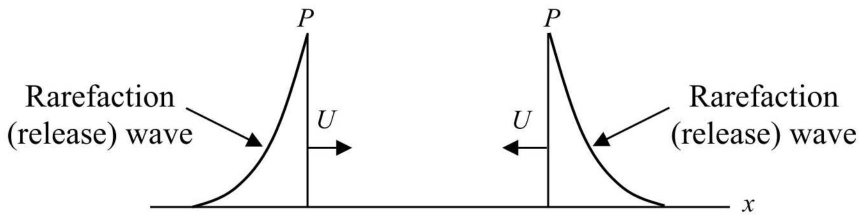




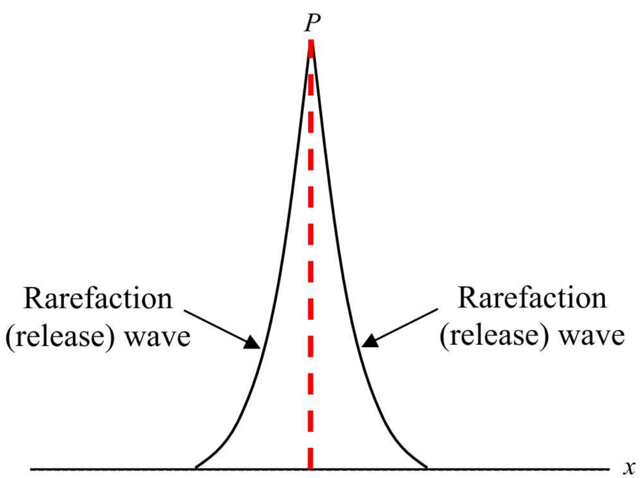
Shock Waves at an Interface



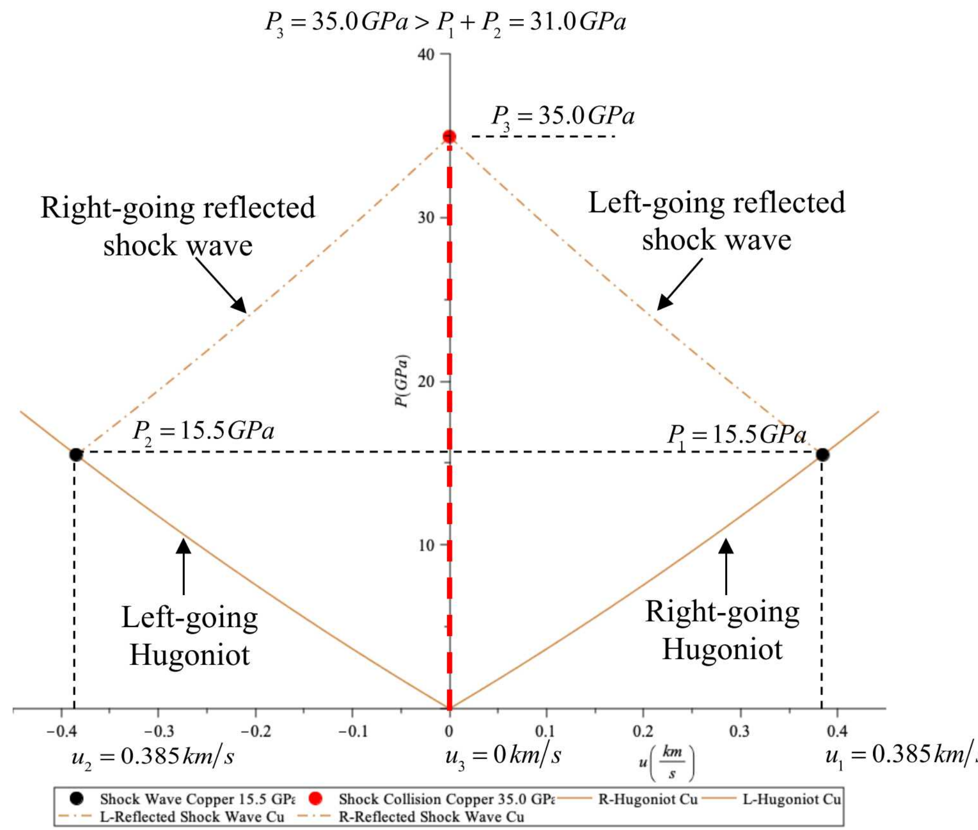
Collision of Shock Waves



two shock waves (same pressure amplitude)
propagating toward each other in mild steel



two shock waves (same pressure amplitude)
collide in mild steel



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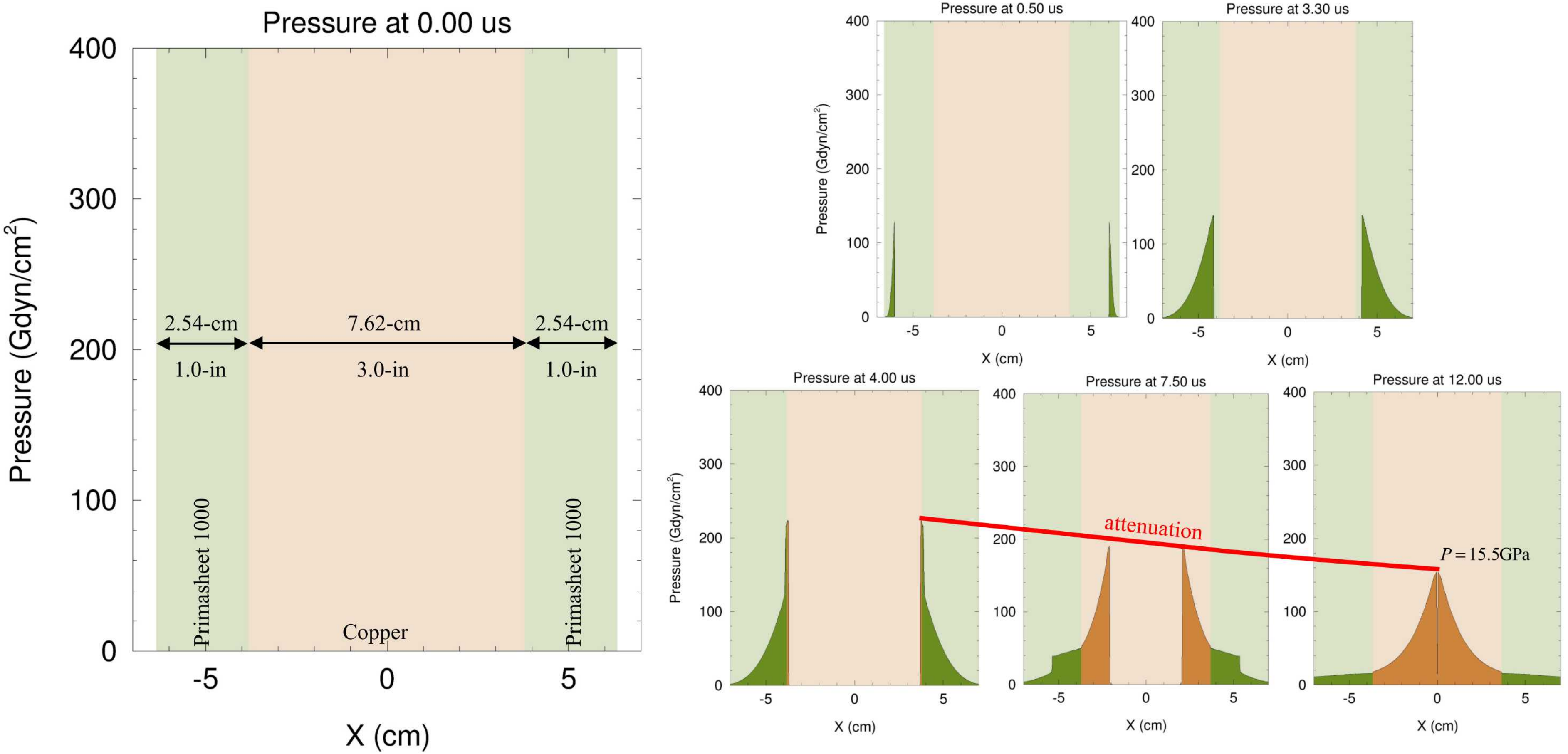
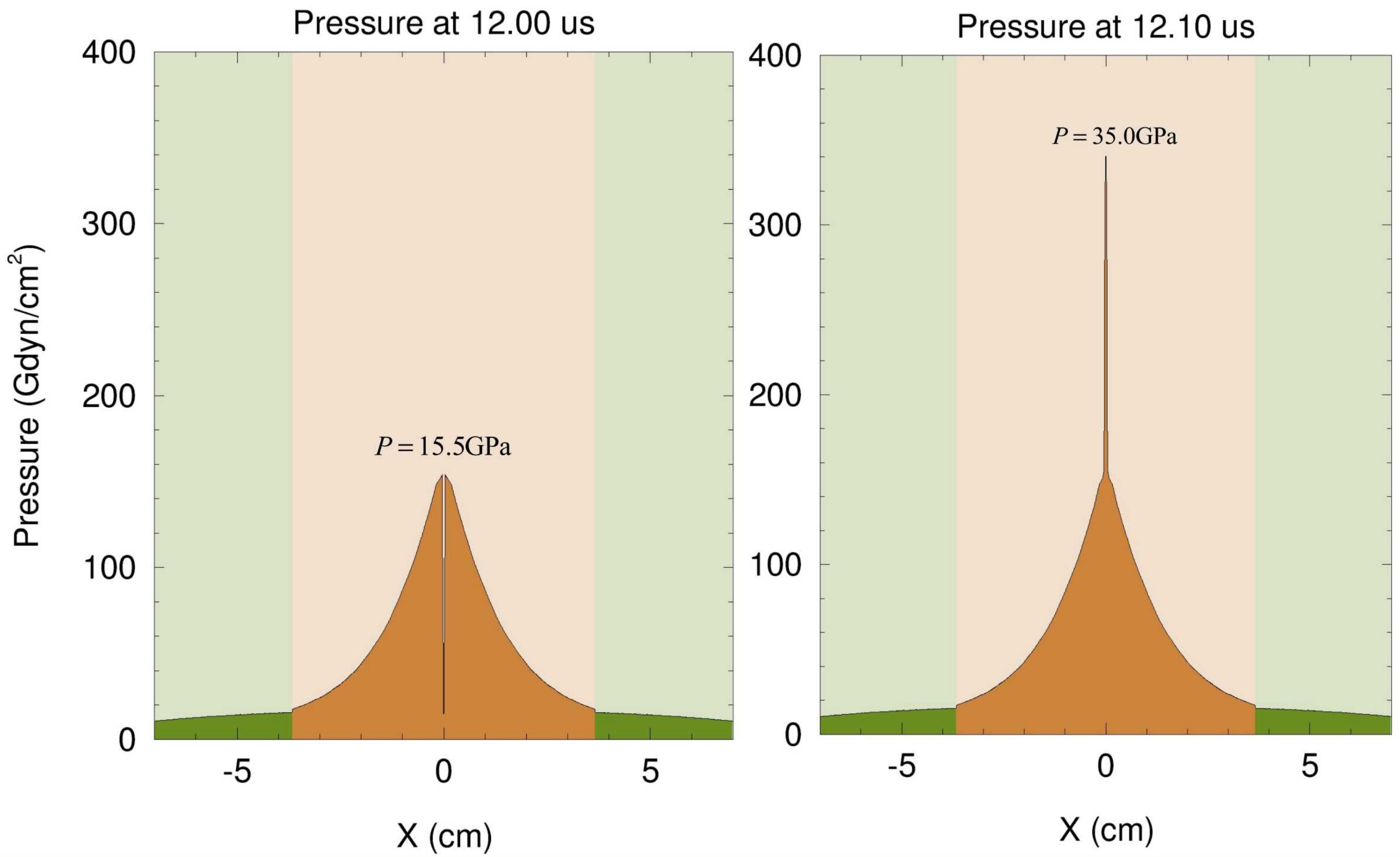
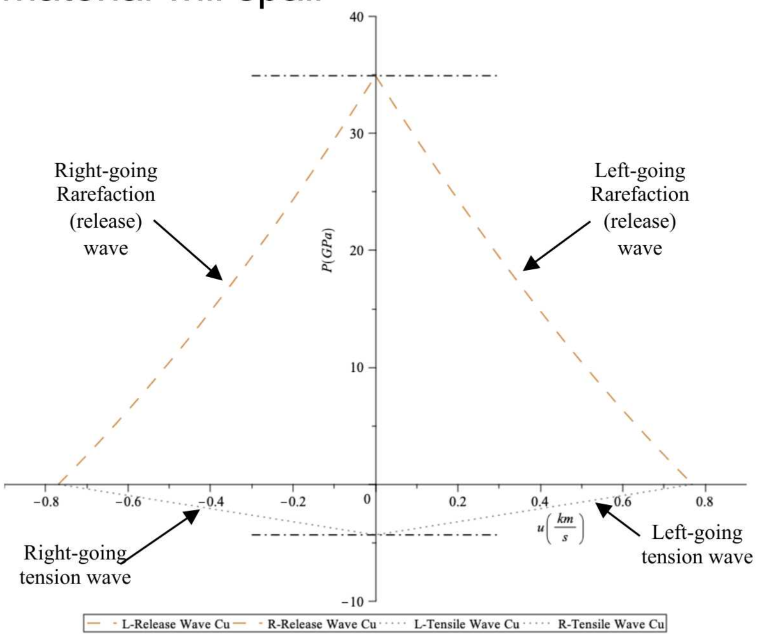


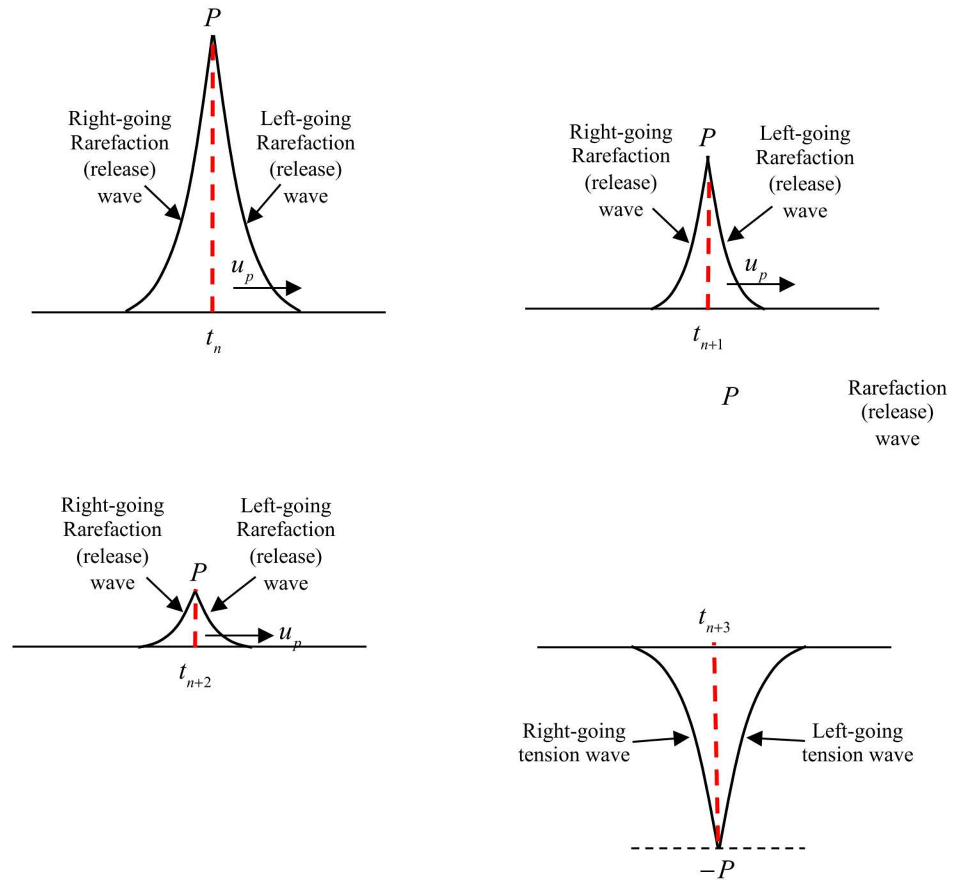
Collision of Shock Waves



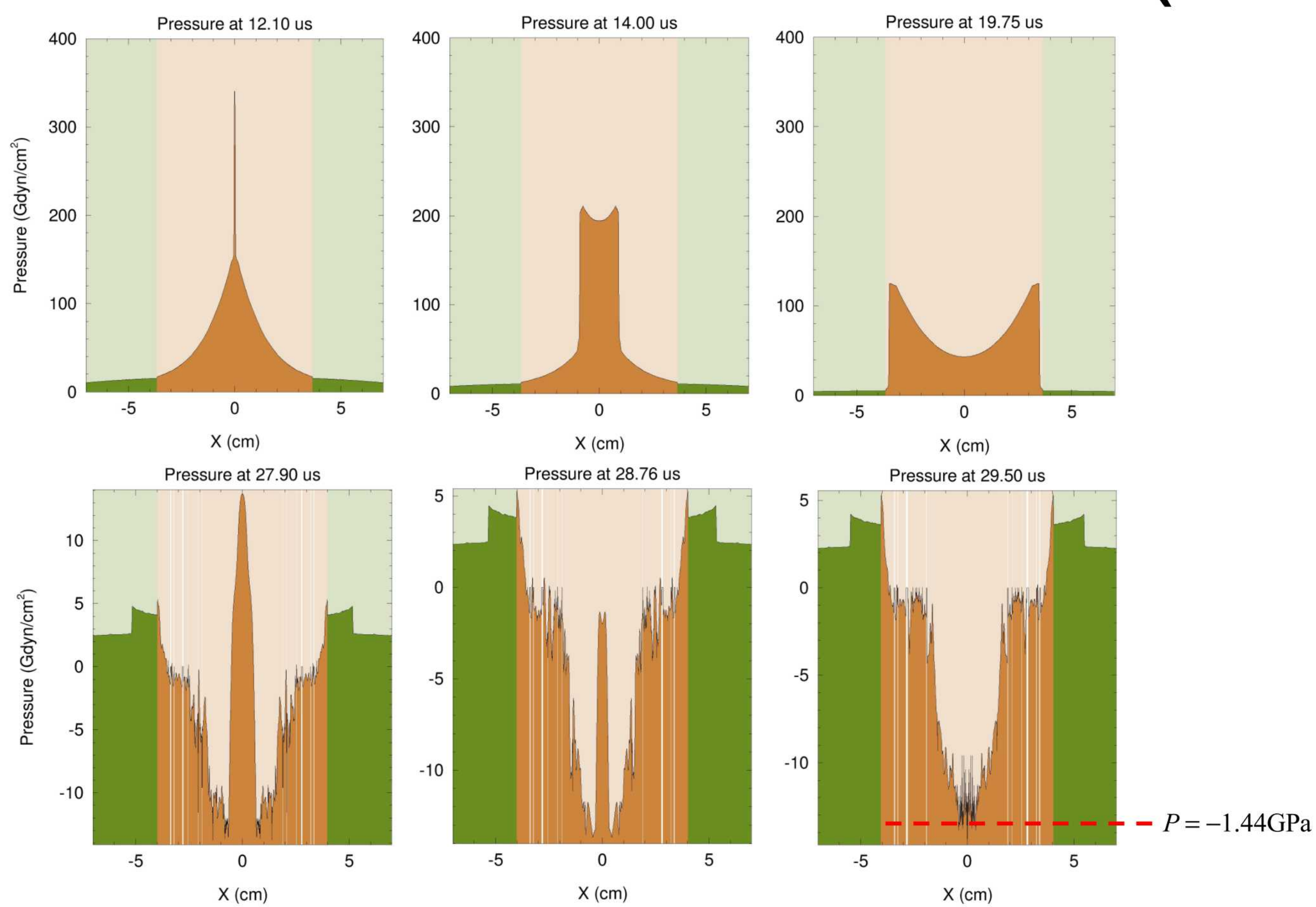
Collision of Rarefaction Waves

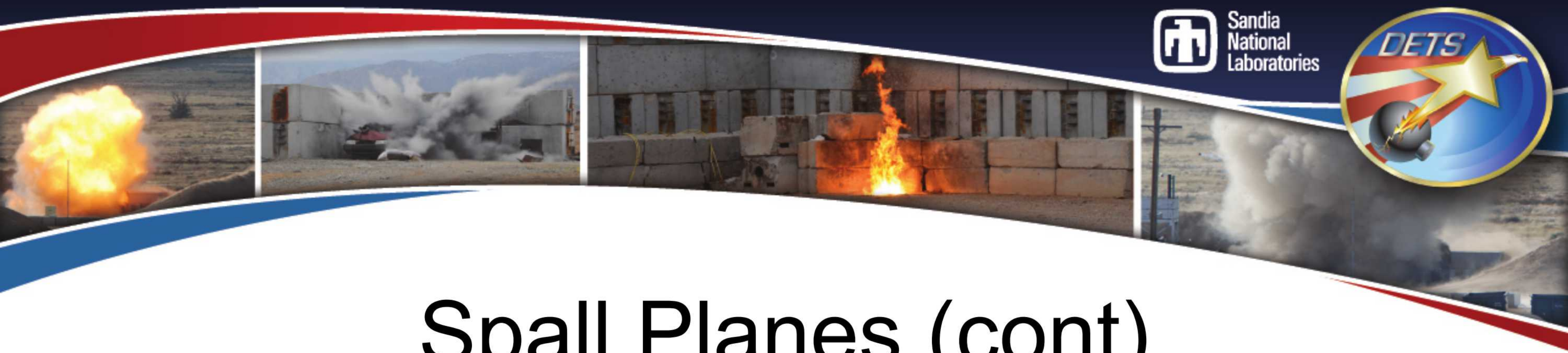
- Material mass velocity, u_p, is decelerating and starting to have velocity in the opposite direction. It is decompressing
- If the tensile pressure is large enough the material will spall



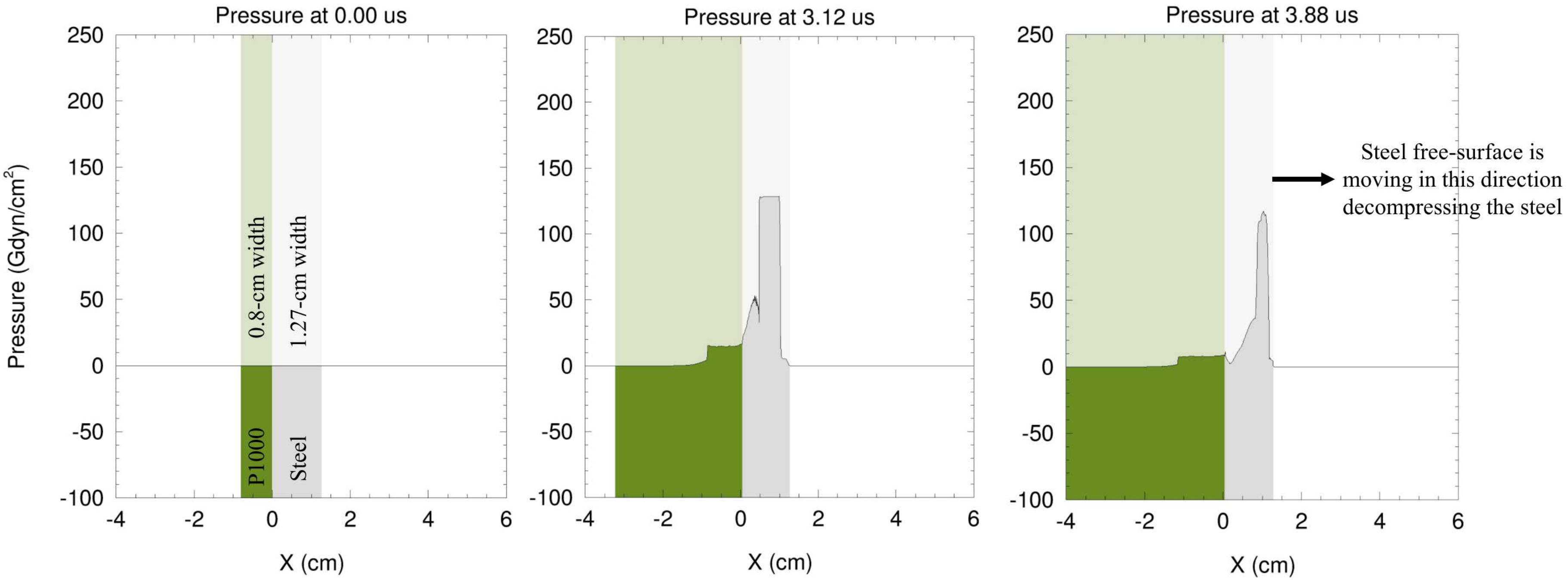


Collision of Rarefaction Wave (cont)

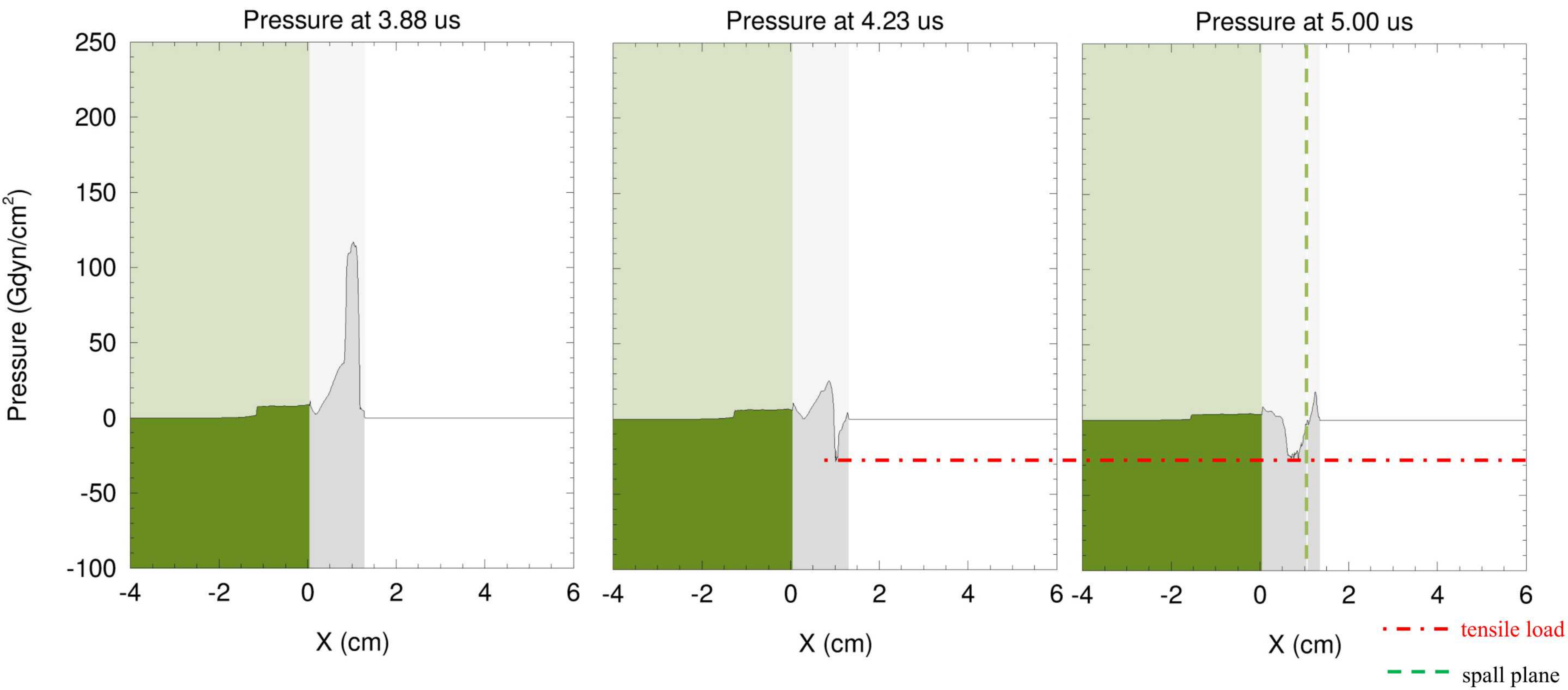




Spall Planes (cont)

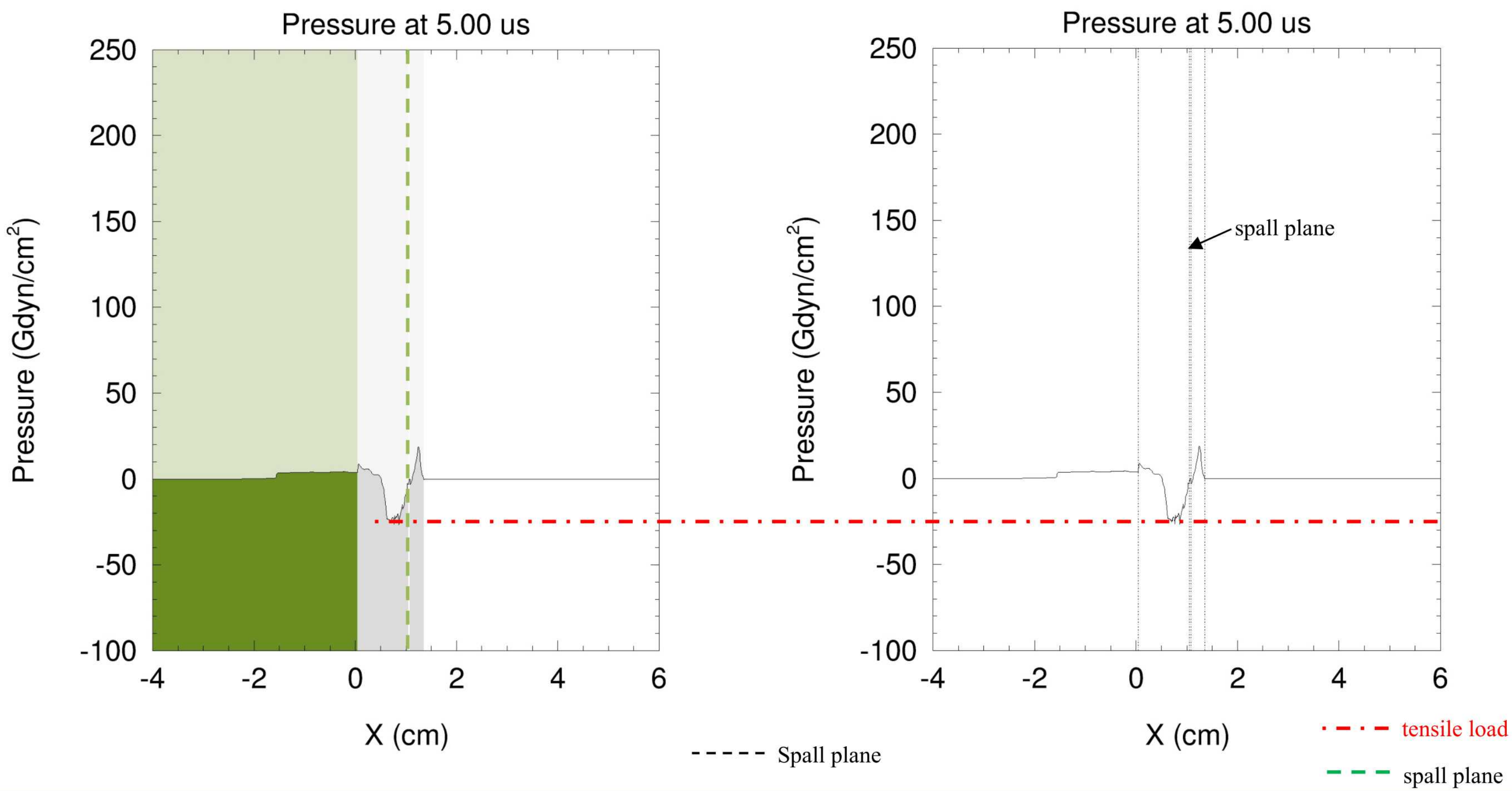


Spall Planes (cont)



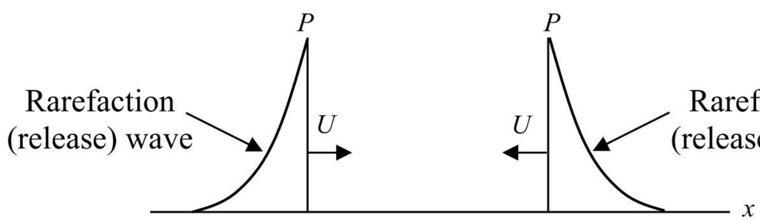
The relief (rarefaction) wave from the explosive/steel interface collides with the relief (rarefaction) wave from the free surface generating a tensile loading that's amplitude is large enough to produce a spall plane

Spall Planes (cont)

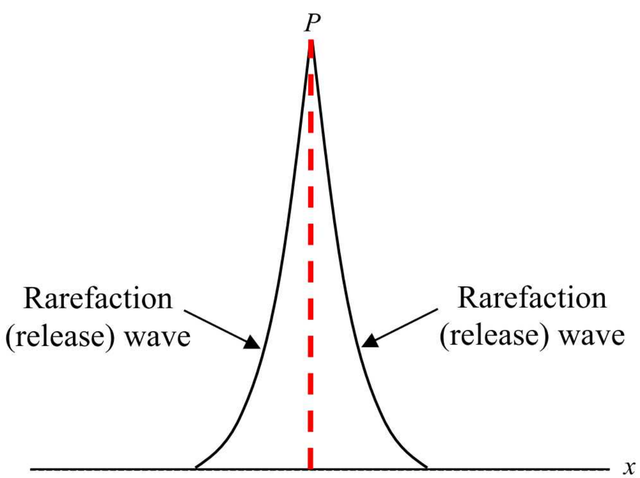


Questions?

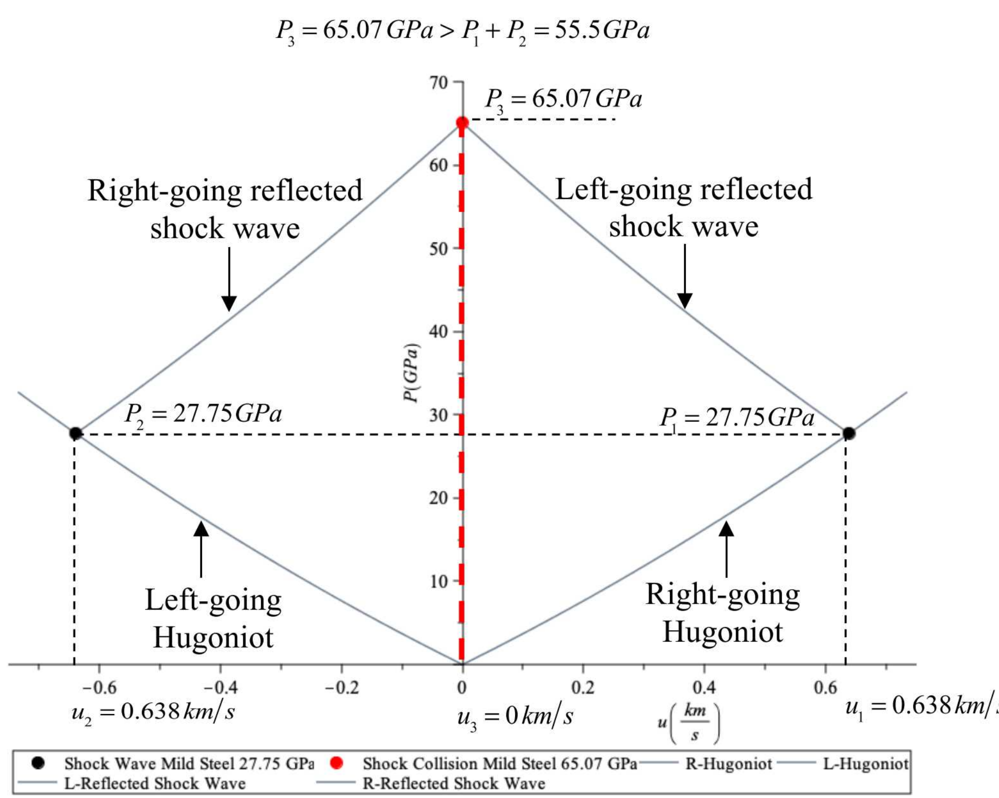
Collision of Shock Waves



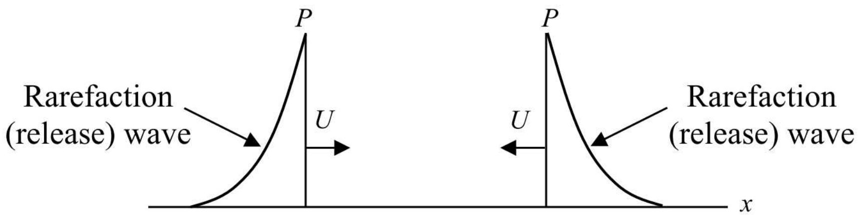
two shock waves (same pressure amplitude) propagating toward each other in mild steel



two shock waves (same pressure amplitude) collide in mild steel



Collision of Shock Waves



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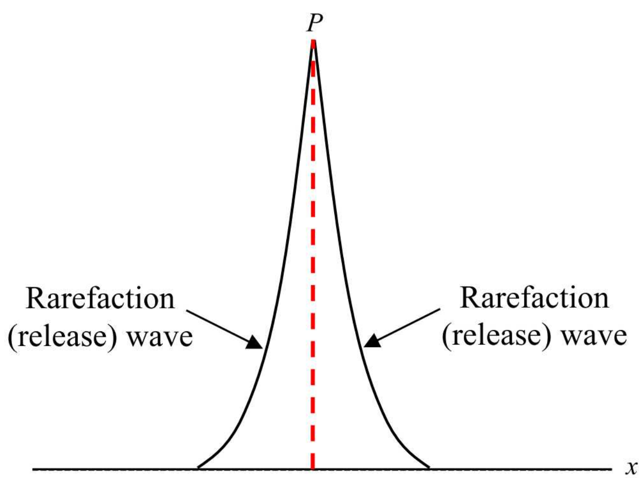

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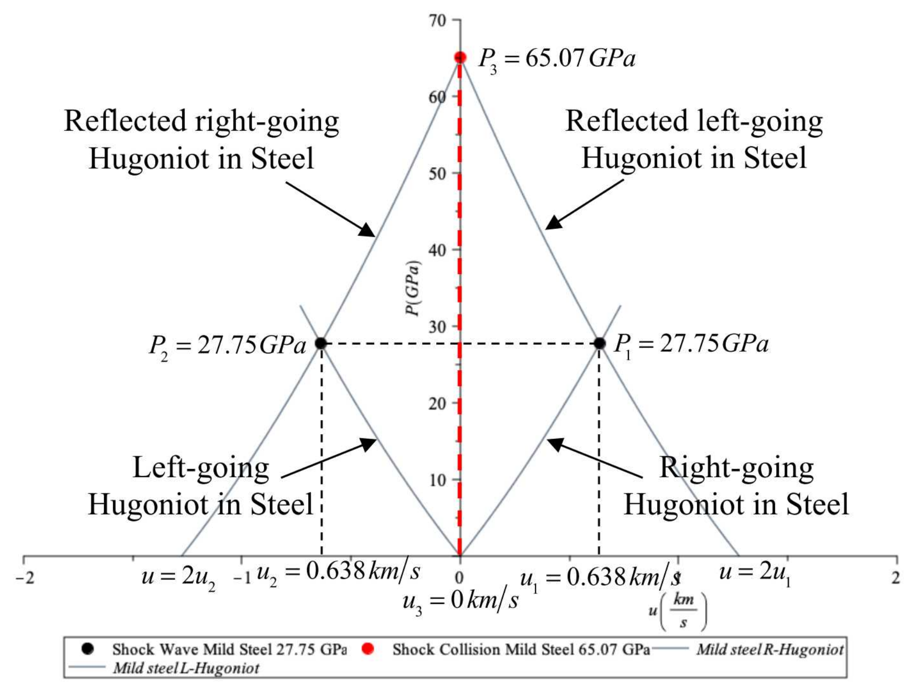

$$P_3 = 65.07\,GPa > P_1 + P_2 = 55.5\,GPa$$