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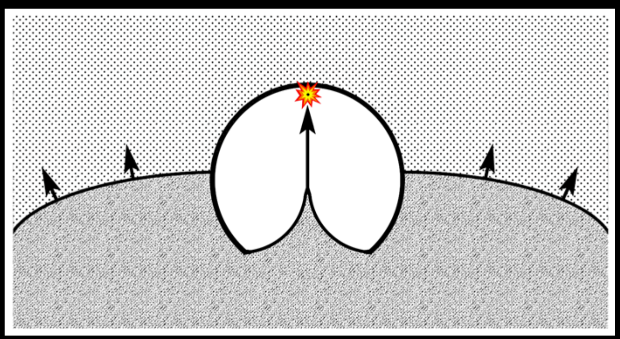

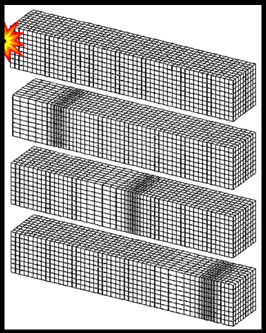

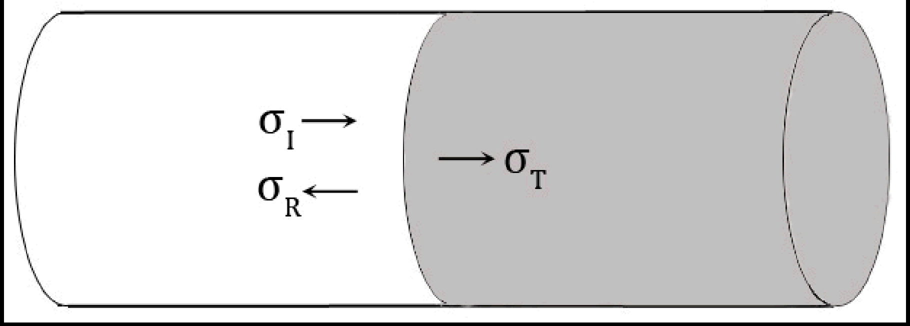

Physics of Explosives Initiation

Jason J . Phillips

Energetics Characterization, Org. 2555

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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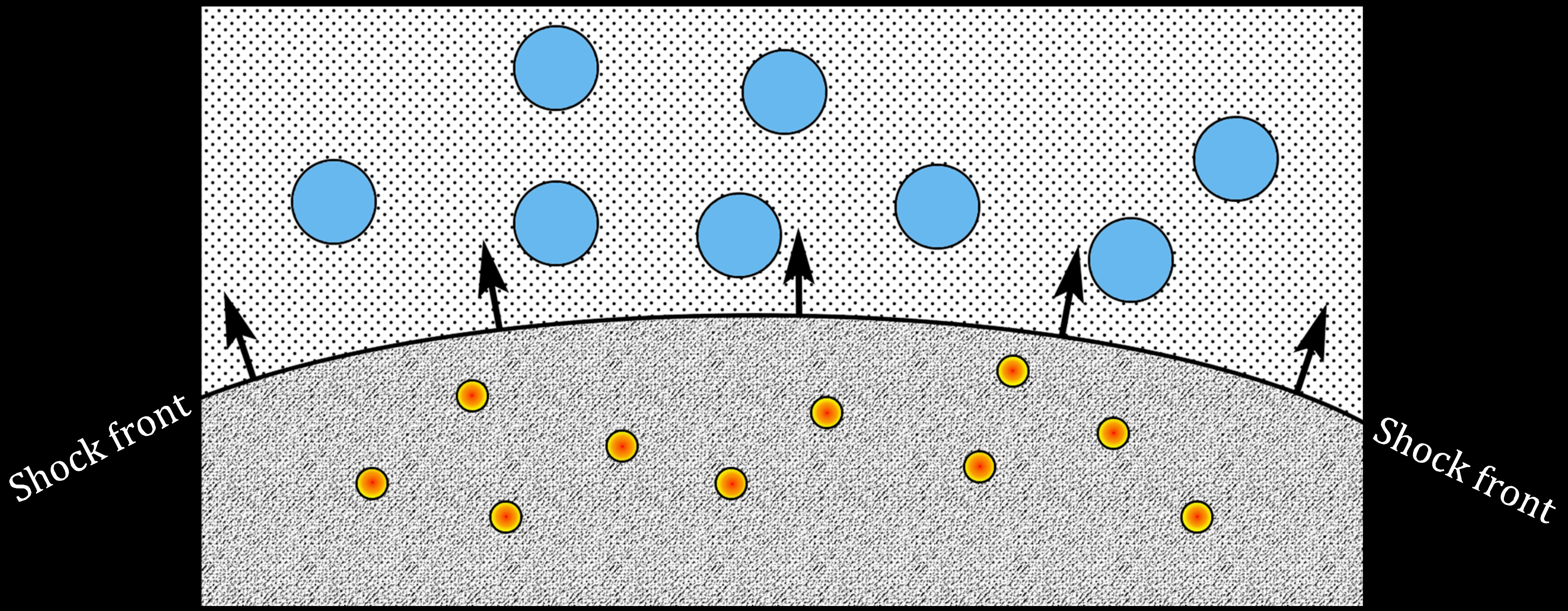
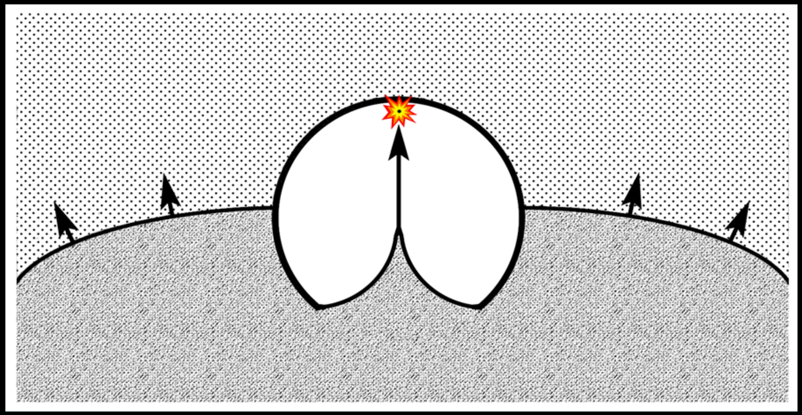
Basic Hot Spot Theory

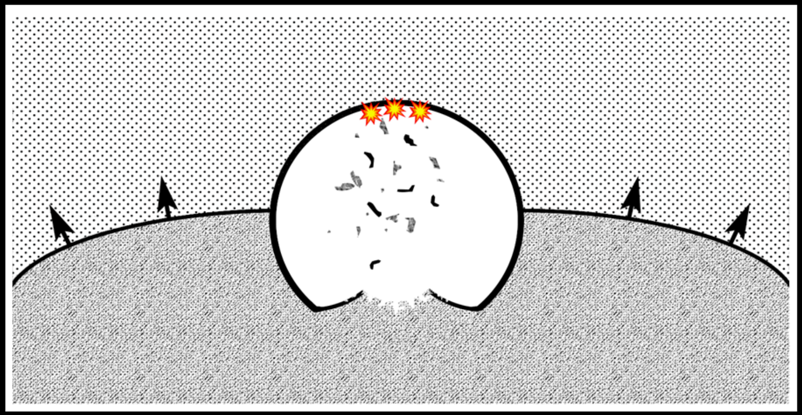


Rapid, adiabatic shock compression of gas filled pores/voids causes localized temperature spikes and decomposition of energetic material.

Hot Spot Theory – Additional Mechanisms

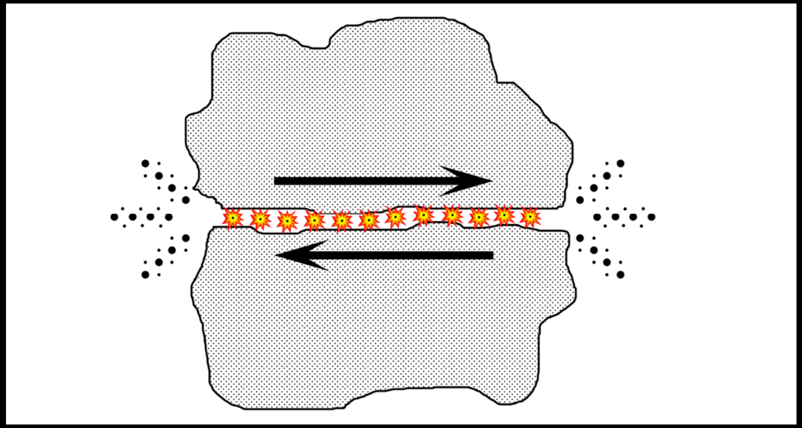


Viscous Flow/Jetting

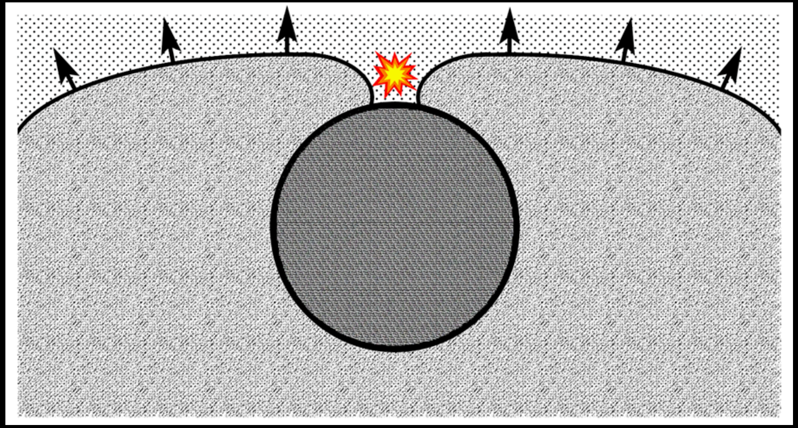


Jetting/Spallation

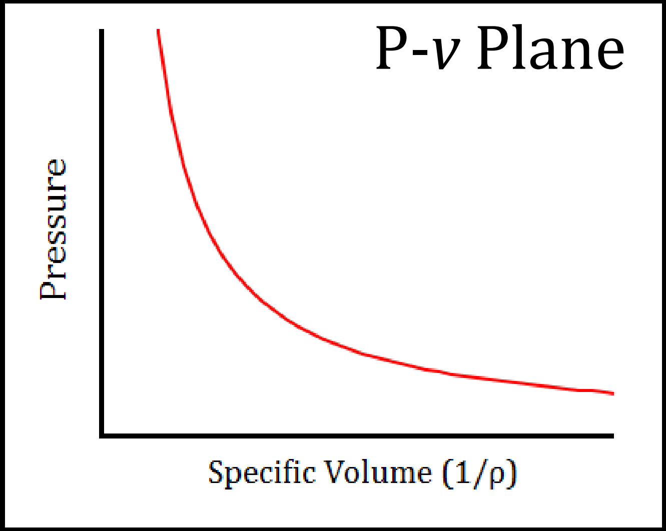
Friction

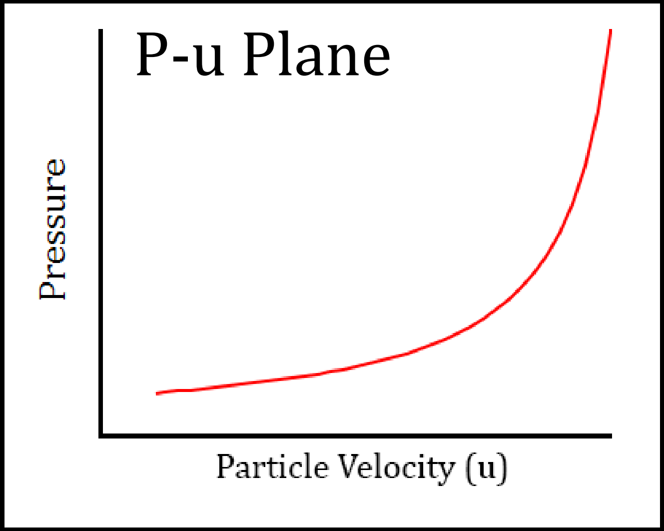


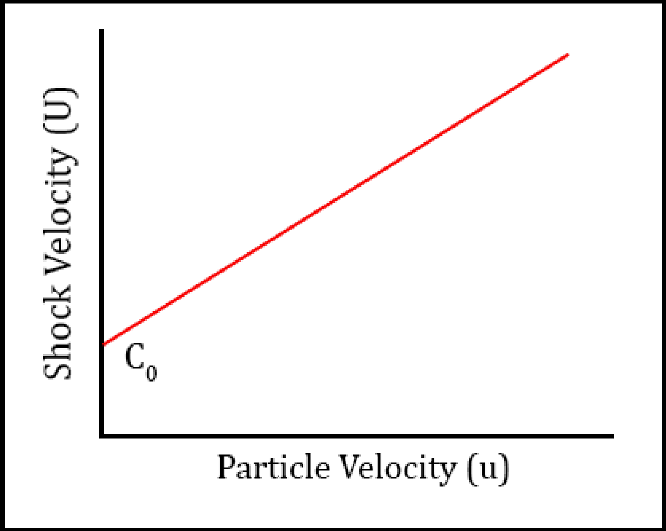
Shock Interaction



Hugoniot Overview







- 3 useful Hugoniot planes
- Y-intercept in the U-u Hugoniot plane represents the bulk sound speed (C_0).

Shock vs Particle Velocity (U vs u)

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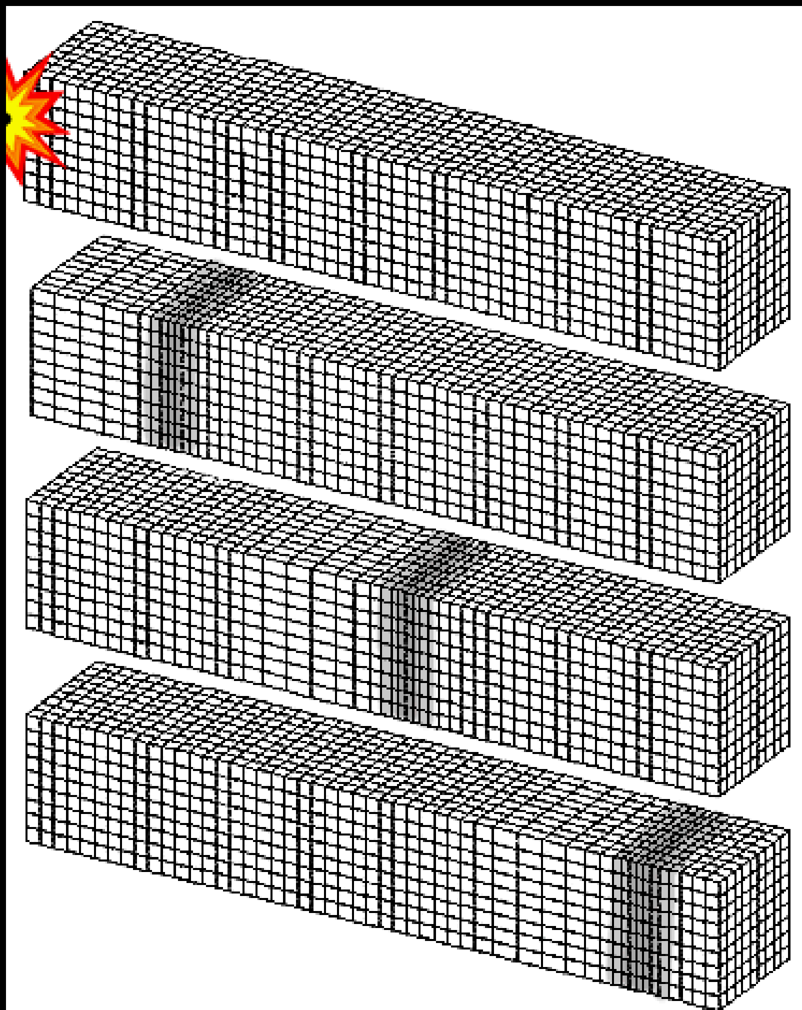
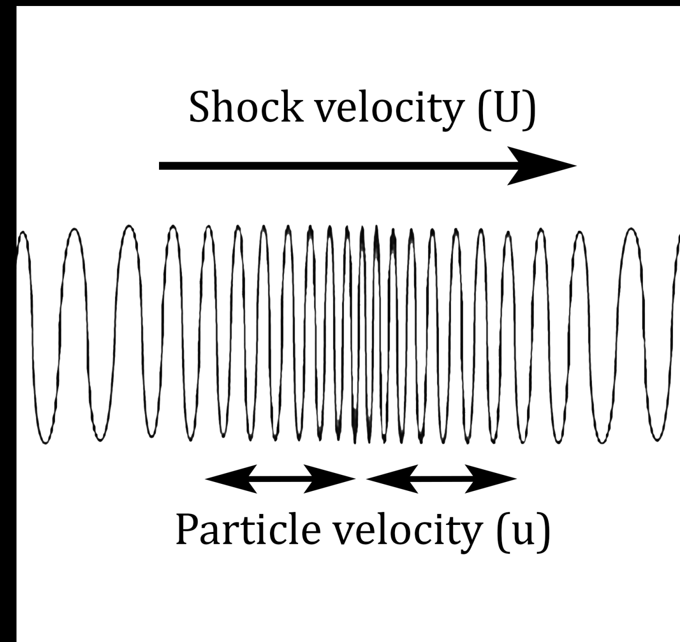
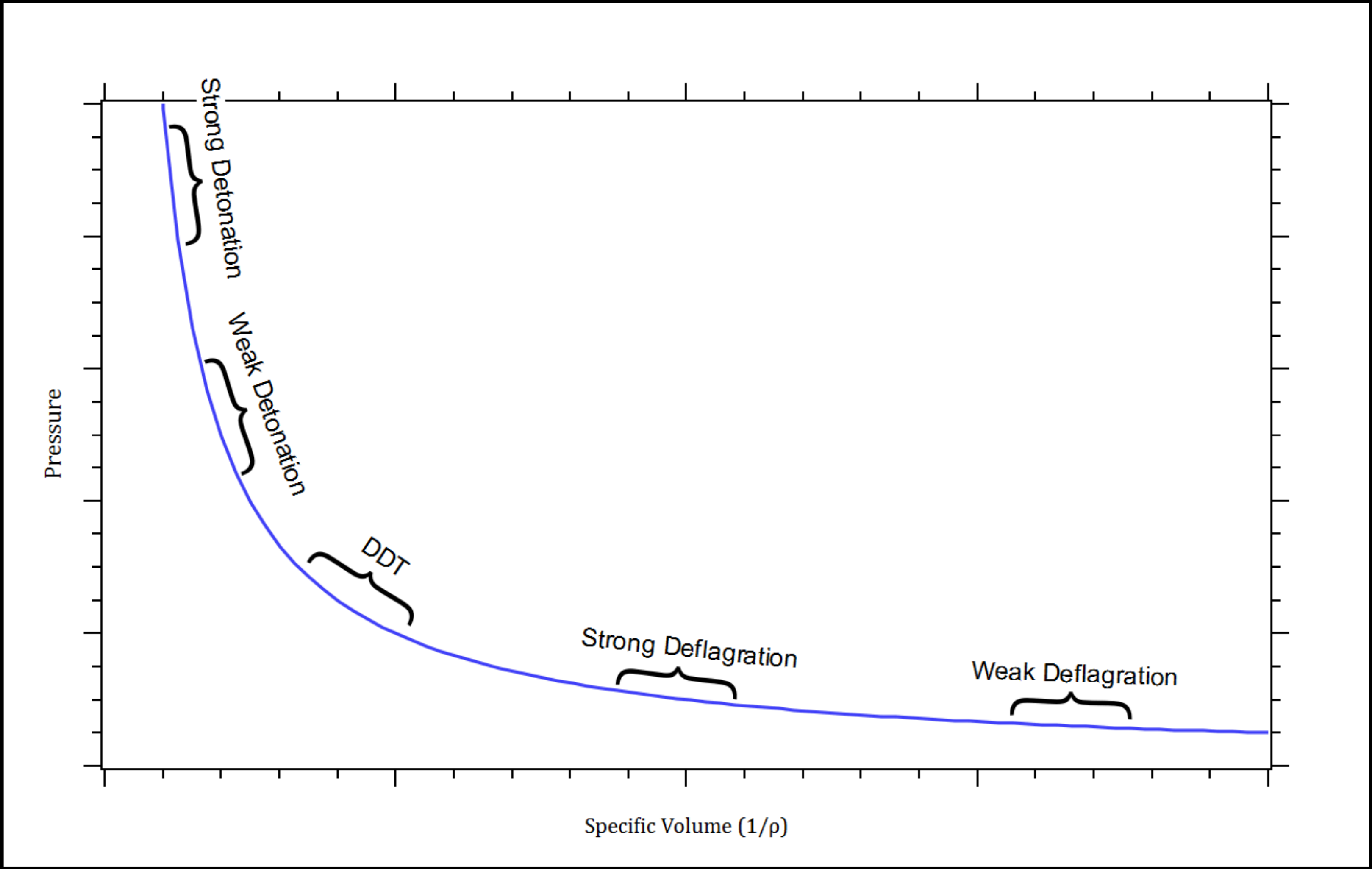




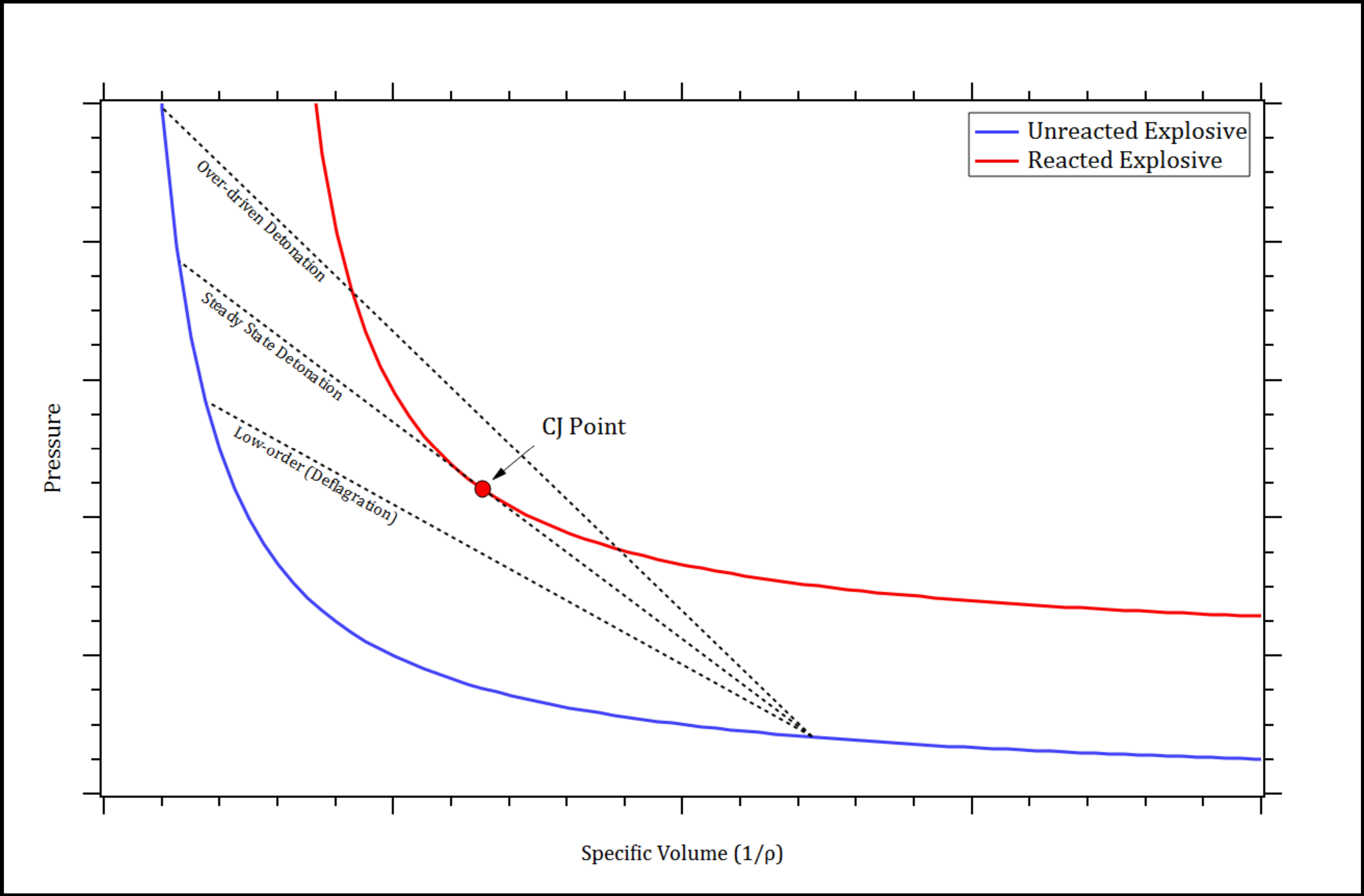
u – Refers to relative motion within the shock disturbance

U – Refers to the propagation of the disturbance through the material

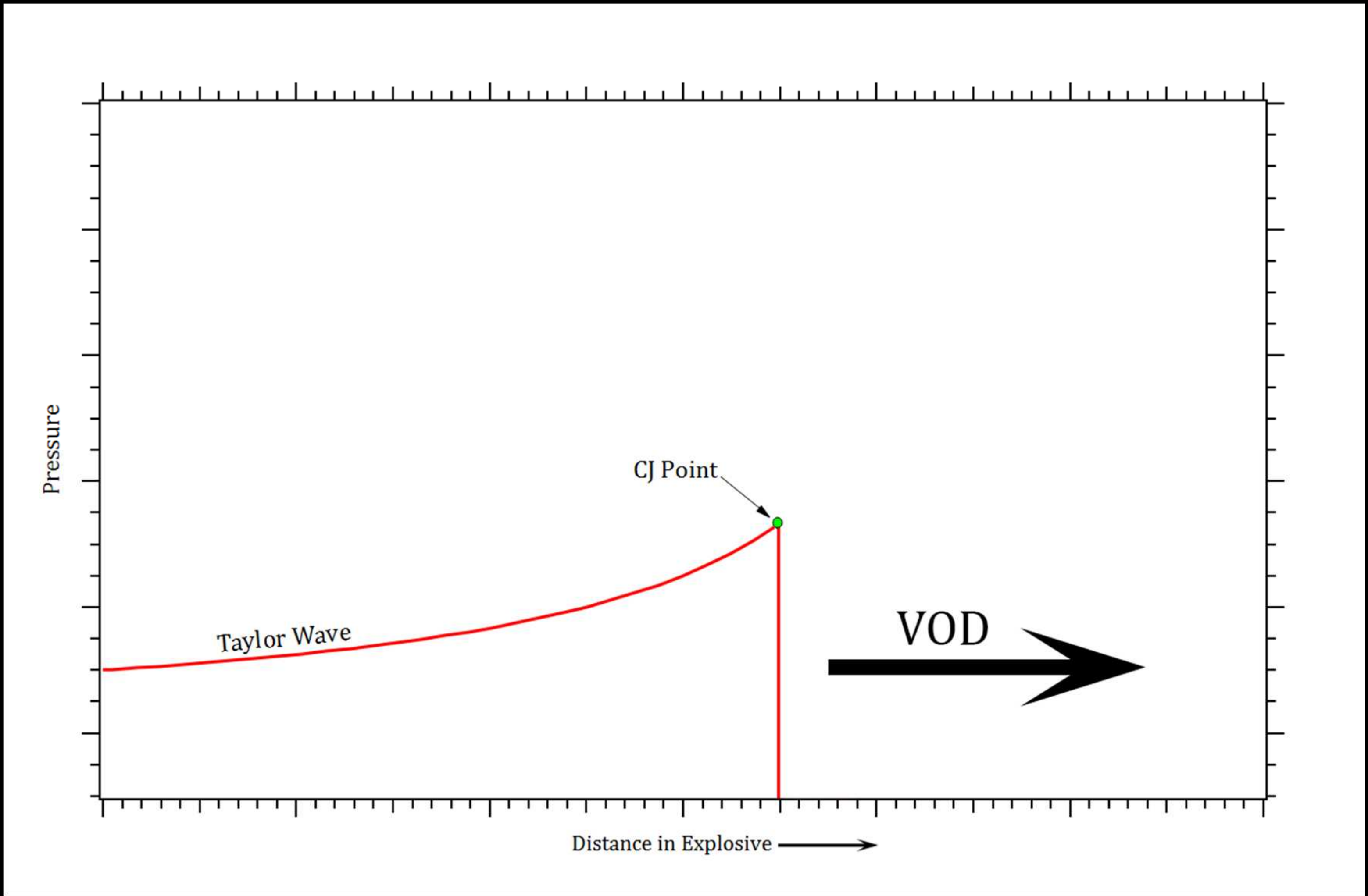
Hugoniot Overview



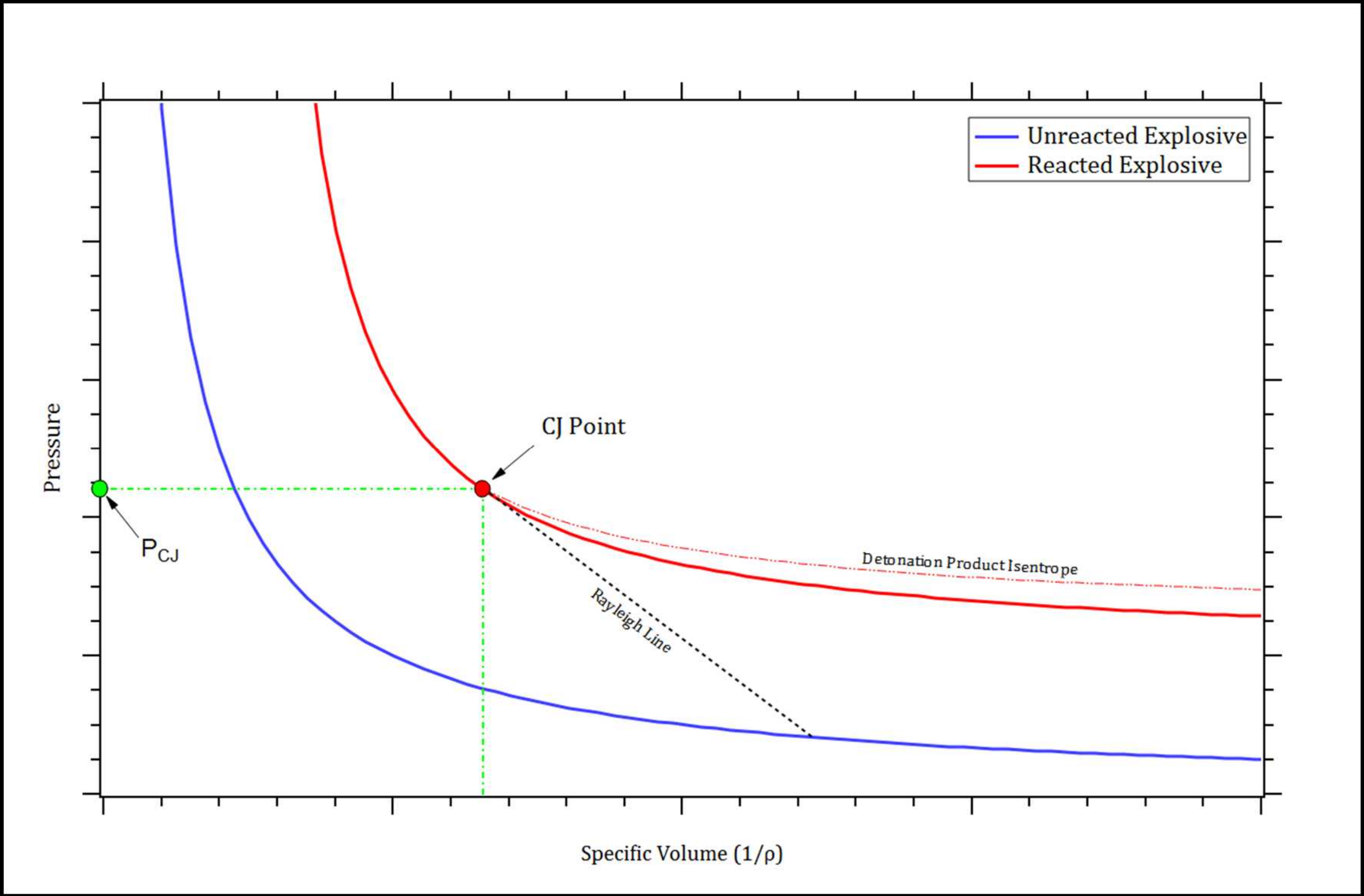
Rayleigh Line Overview



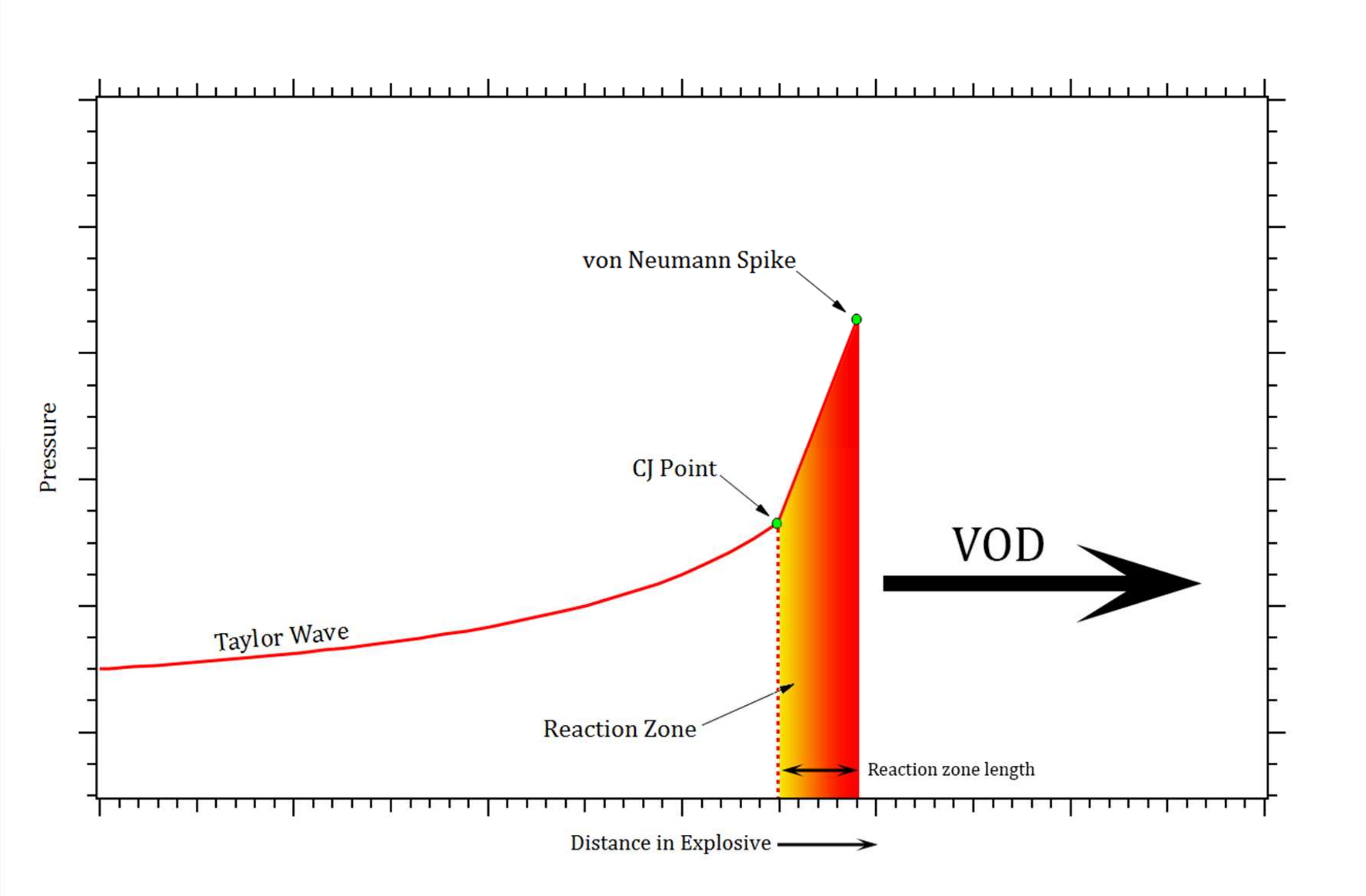
CJ Detonation Model



CJ Detonation Model

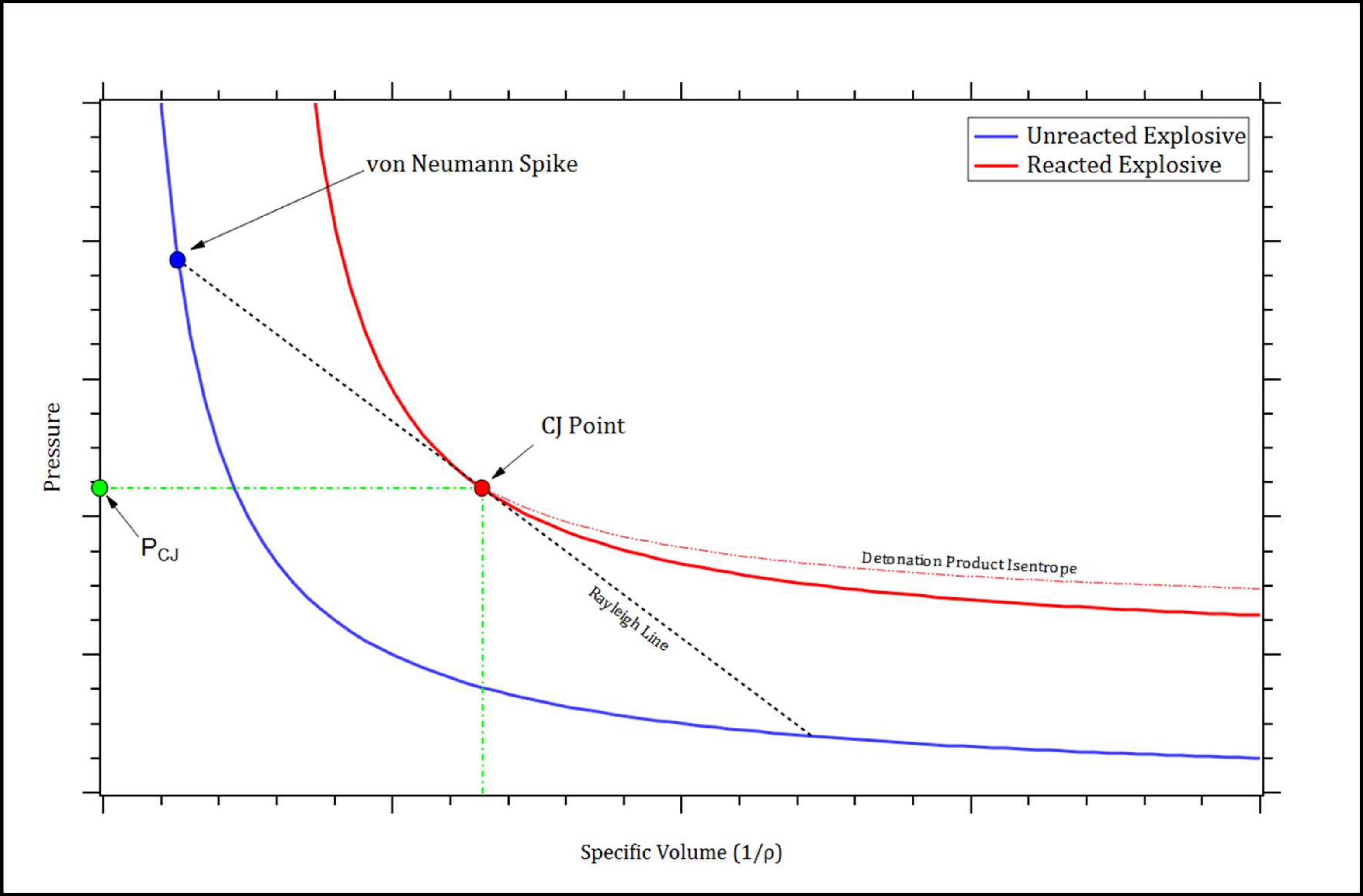


ZND* Detonation Model

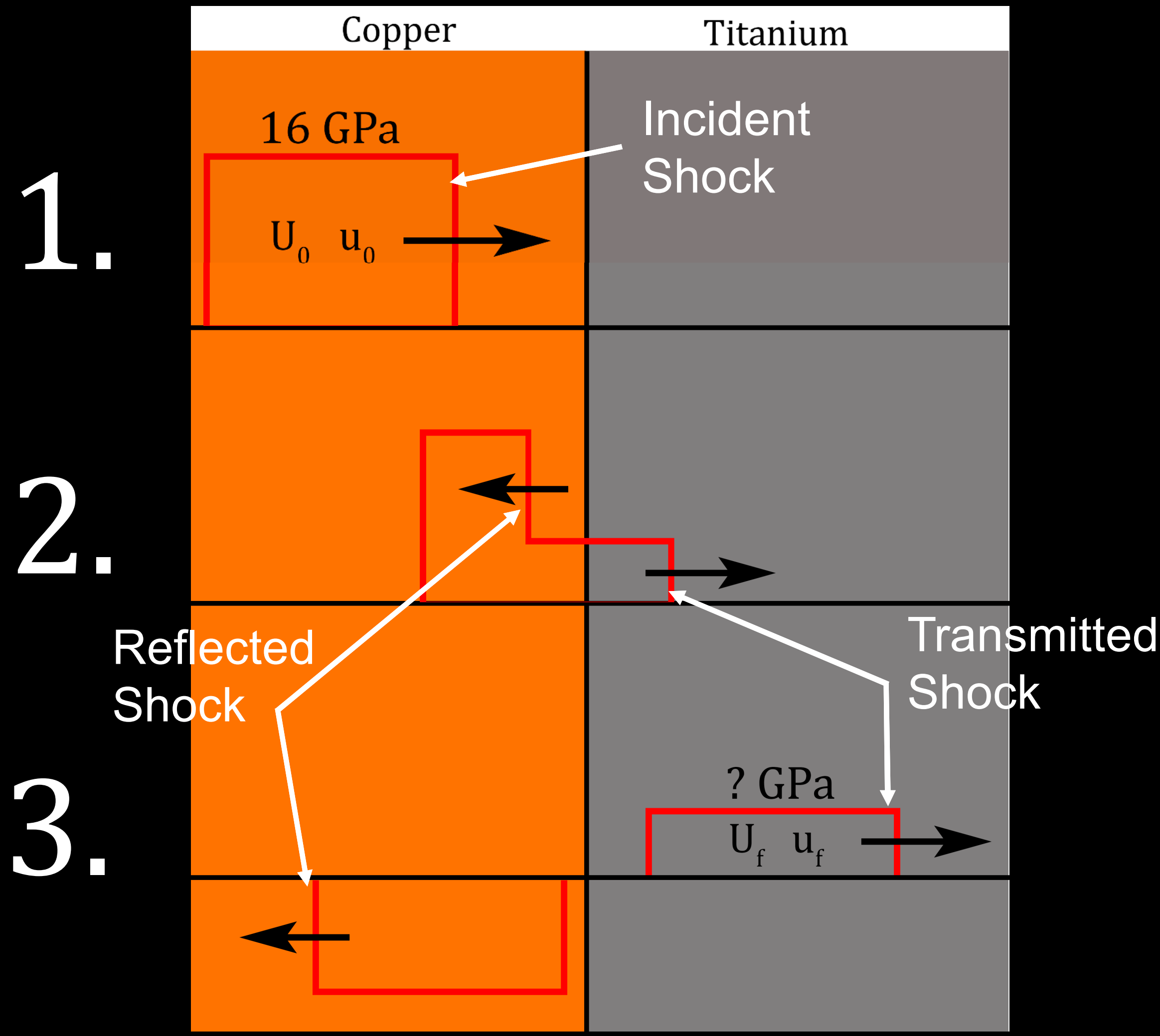


*Zel'dovich, von Neumann, Döring

ZND Detonation Model



Shock Propagation Example



Impedance (Z):

Effectively, a material's resistance to shock propagation

$$Z_{Cu} > Z_{Ti}$$

Calculated Solution

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$U = C_0 + su$ ← U-u relationship (derived via empirical testing)

$P = \rho_0 C_0 u_1 + \rho_0 s u_1^2$ ← P-u relationship in a neat material

$P = \rho_0 C_0 (u_0 - u_1) + \rho_0 s (u_0 - u_1)^2$ ← P-u relationship at an interface/discontinuity

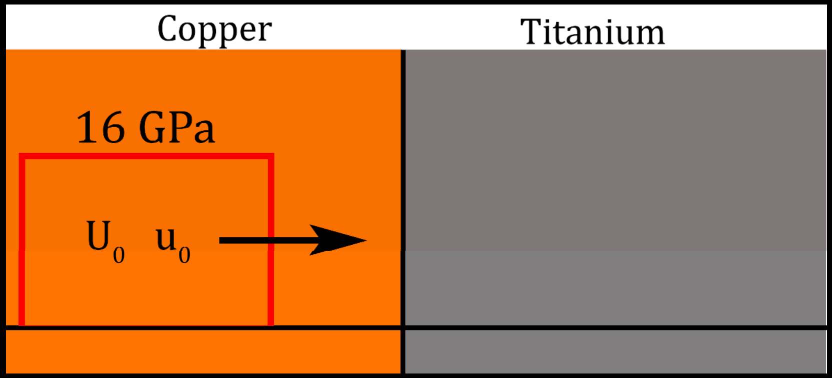
P: pressure (GPa)
ρ_0: density (g/cm^3)
C_0: bulk sound velocity (km/s)

U: shock velocity (km/s)
s: constant (slope value)
u: particle velocity (km/s)

ρ_{Cu} = 8.924 g/cm^3	C_{Cu} = 4.76 km/s	s_{Cu} = 1.439
ρ_{Ti} = 4.527 g/cm^3	C_{Ti} = 6.16 km/s	s_{Ti} = 0.976

Calculated Solution - 1

Step 1: Calculate initial particle/shock velocity in the copper: P_1 = 16 GPa



$$P_1 = \rho_{Cu} C_{Cu} u_0 + \rho_{Cu} s_{Cu} u_0^2$$
$$16 = (8.924)(4.76)u_0 + (8.924)(1.439)u_0^2$$

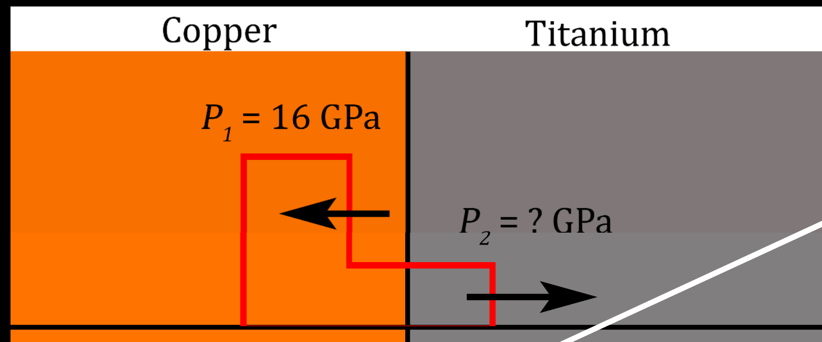
$$u_0 = 0.34 \text{ km/s}$$

$$U_0 = C_{Cu} + s_{Cu} u_0$$
$$U_0 = 4.76 + (1.439)(0.34)$$

$$U_0 = 5.25\ km/s$$

Calculated Solution - 2

Step 2: Set up the calculations for the interface



Due to reflection!

<u>Reflected shock in Cu</u>:

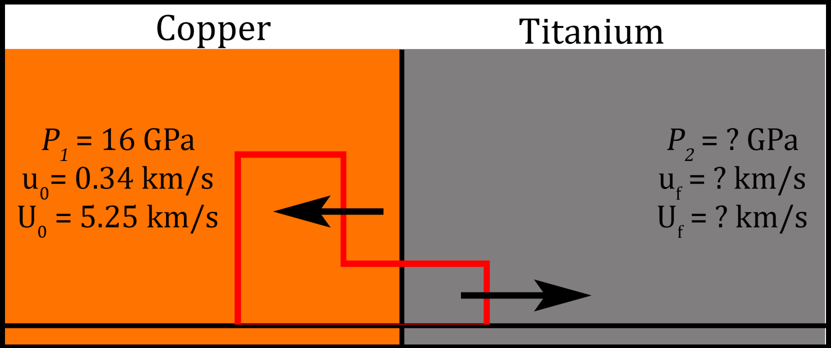
$$P_2 = (8.924)(4.76)\left(2 \times 0.34 - u_f\right) + (8.924)(1.439)(2 \times 0.34 - u_\mathrm{f})^2$$
$$P_2 = 32.45 - 58.91u_\mathrm{f} + 12.84u_\mathrm{f}^2$$

<u>Transmitted shock in Ti</u>:

$$P_2 = (4.527)(6.16)u_\mathrm{f} + (4.527)(0.976)u_\mathrm{f}^2$$
$$P_2 = 27.89u_\mathrm{f} + 4.418u_\mathrm{f}^2$$

Calculated Solution - 3

Step 3: Set equations equal to each other and solve



$$32.45 - 58.91u_f + 12.84u_f^2 = 27.89u_f + 4.418u_f^2$$
$$0 = 32.45 - 86.80u_f + 8.42u_f^2$$

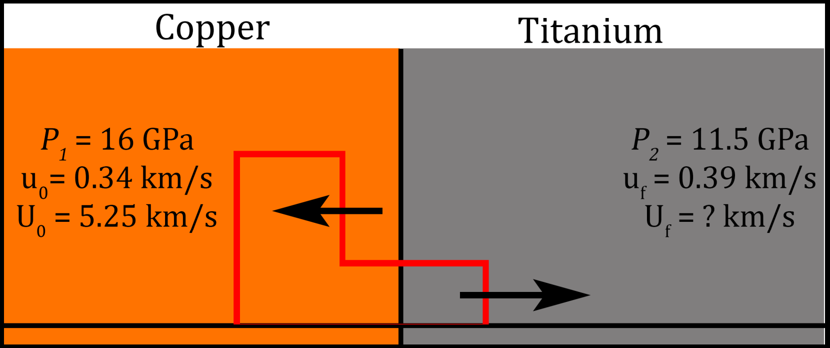
$$u_f = 0.39 \text{ km/s}$$

$$P_2 = 27.89(0.39) + 4.418(0.39)^2$$

$$P_2 = 11.5 \text{ GPa}$$

Calculated Solution - 4

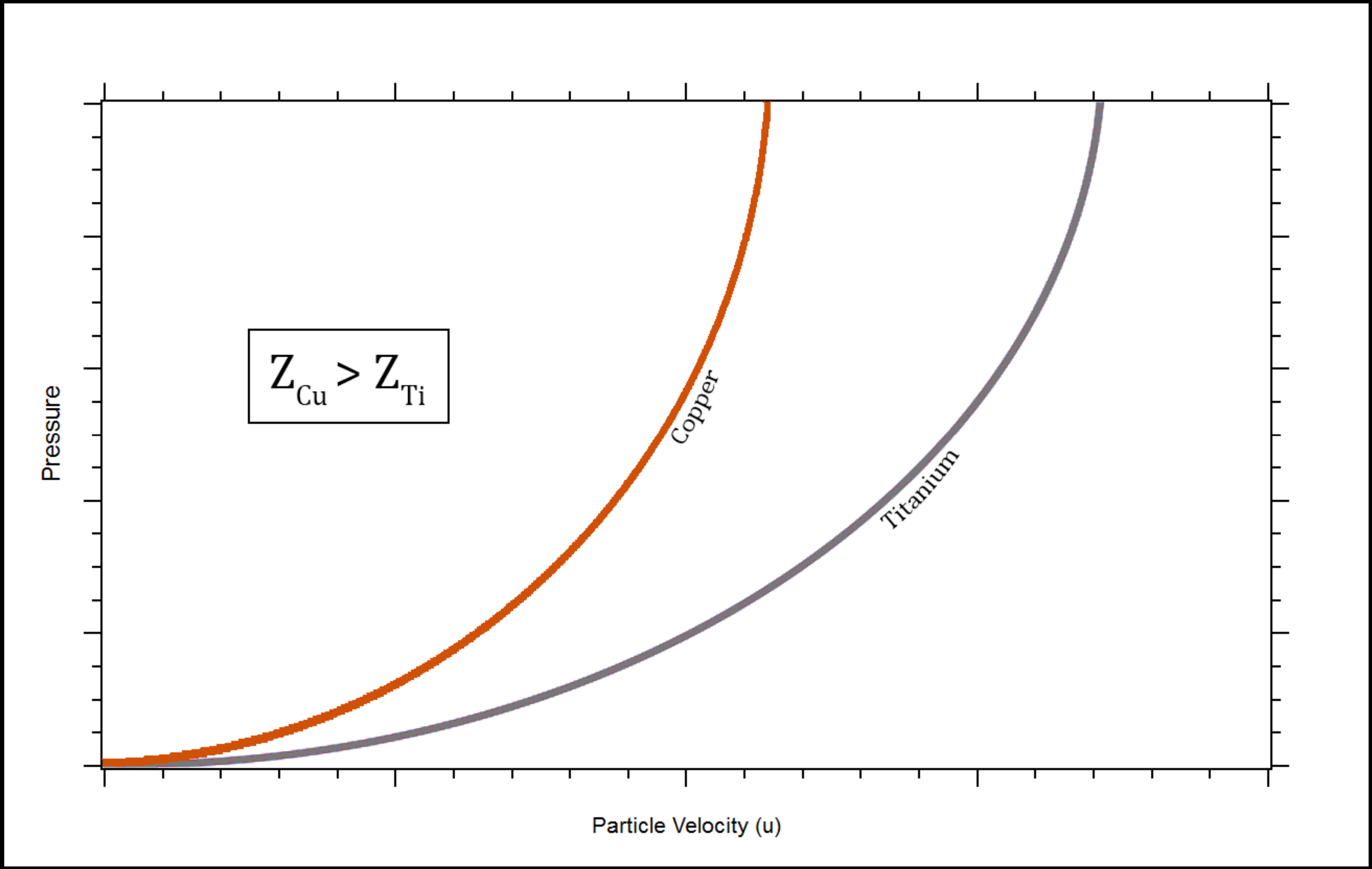
Step 4: Solve for final shock velocity



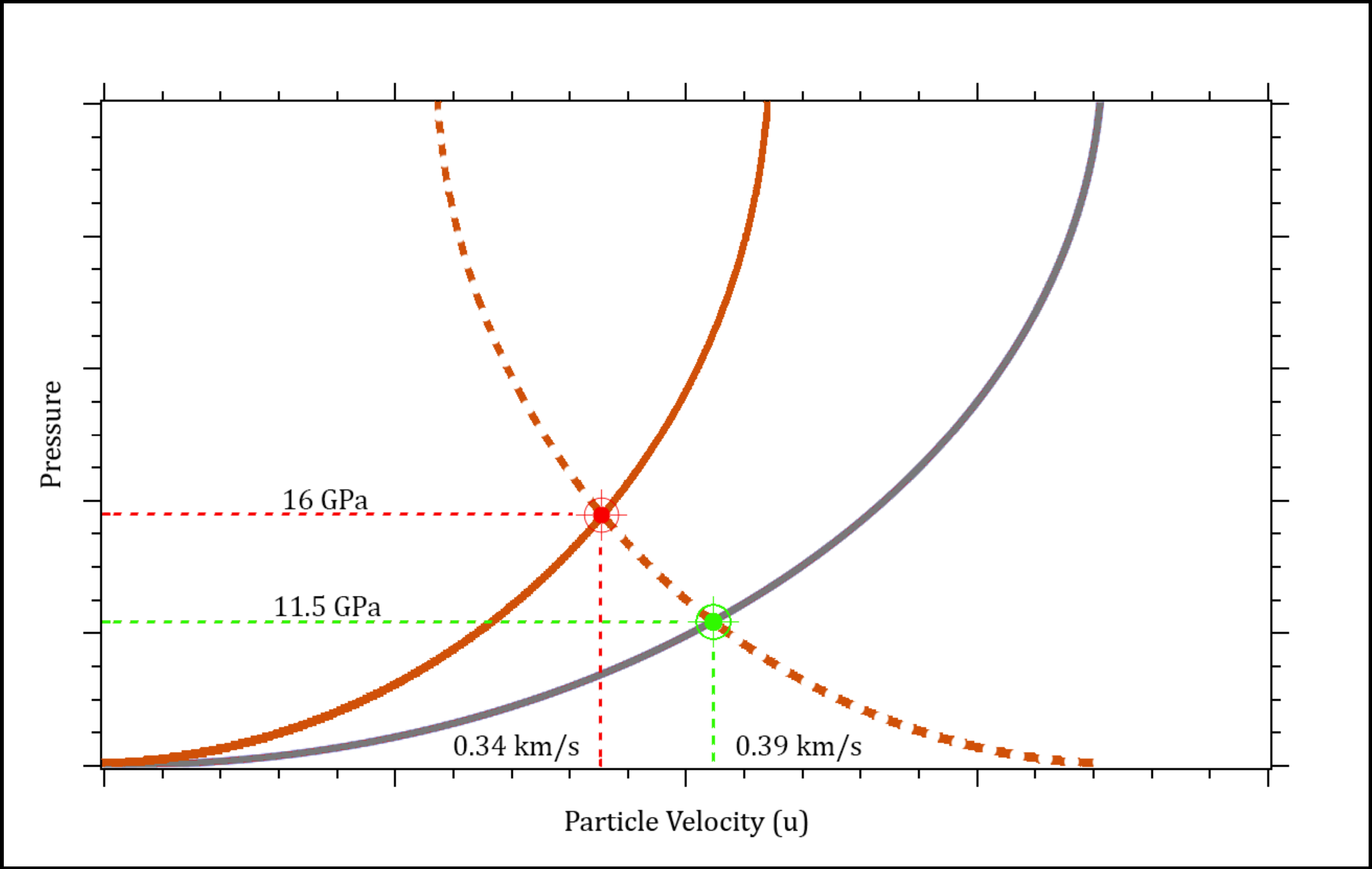
$$U_f = C_{Ti} + s_{Ti}u_f$$
$$U_f = 6.16 + (0.976)(0.39)$$

$$U_f = 6.54 \text{ km/s}$$

Graphical Solution - 1



Graphical Solution - 2



References – Initiation/Hot Spot Theory

Bowden, F. P., and Yoffe, A. D., 1952, *Initiation and Growth of Explosion in Liquids and Solids*, Cambridge University Press, Cambridge, U.K.

Yoffe, A. D., 1949, "Influence of Entrapped Gas on Initiation of Explosion in Liquids and Solids," Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, 198 (1054), pp. 373-388.

Chaudhri, M. M., and Field, J. E., 1974, "The Role of Rapidly Compressed Gas Pockets in the Initiation of Condensed Explosives," Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, 340 (1620), pp. 113-128.

Taylor, W., and Weale, A., 1932, "The Mechanism of the Initiation and Propagation of Detonation in Solid Explosives," Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, 138 (834), pp. 92-116.

Bourne, N. K., and Field, J. E., 1999, "Explosive Ignition by the Collapse of Cavities," Proceedings of the Royal Society of London: Series A, Mathematical, Physical, and Engineering Sciences, 455 (1987), pp. 2411-2426.

Blackburn, J. H., and Seely, L. B., 1965, "Detonation Light in Granular Explosives," Transactions of the Faraday Society, 61, pp. 537-545.

Eirich, F. R., and Tabor, D., 1948, "Collisions through Liquid Films," Mathematical Proceedings of the Cambridge Philosophical Society, 44, pp. 566-580.

Bowden, F. P., 1950, "On Detonation," Proceedings of the Royal Society of London. Series A, Mathematical Physical and Engineering Sciences, 204 (1076), pp. 20-25.

References - Hugoniots

Marsh, S. P., Ed. *LASL Shock Hugoniot Data. Los Alamos Series on Dynamic Material Properties*. Los Angeles, University of California Press, 1980.

Cooper, P. W., 1996, *Explosives Engineering*, Wiley-VCH, New York.