Explosion Effects

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Topics

Introduction

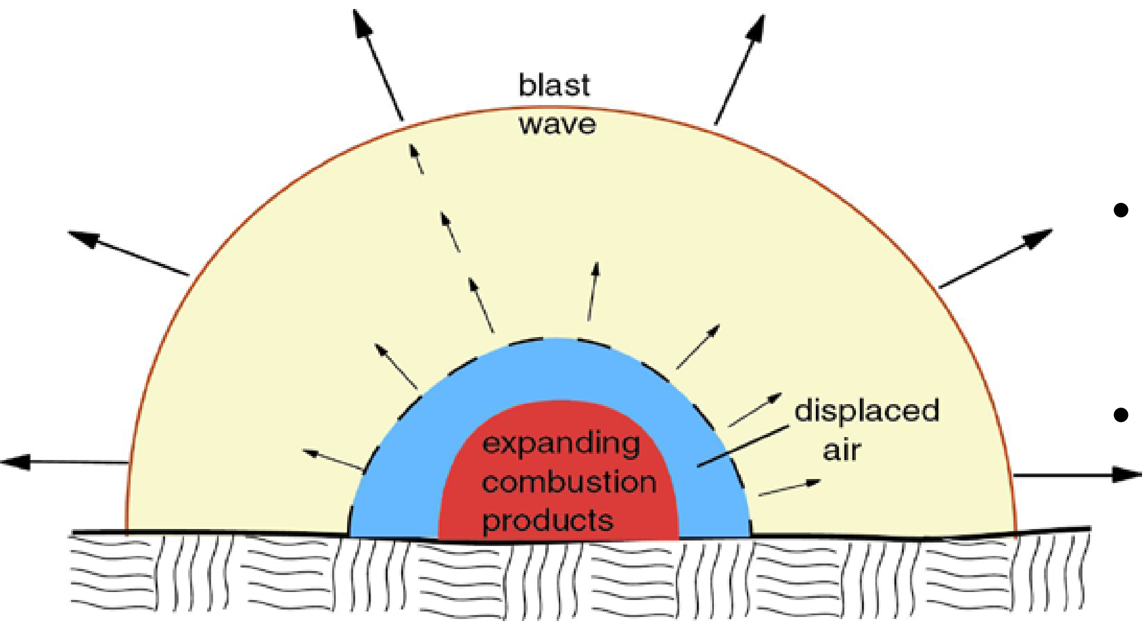
Explosions create high-pressure, high-temperature gases that can cause:

1. Mechanical failure due to pressure or blast waves or internal pressure build-up.
    1. Permanent deformation or equipment or structures
    2. Rupture or tearing of metal or building components
    3. Creating flying fragments or missiles
    4. Blast, fragment or impact injury

2. Thermal failure due to heat transfer from fireball or hot combustion products.
    1. Softening of metal structures
    2. Ignition of building materials, electrical insulation, plastic or paper products
    3. Burn injuries to skin and eyes

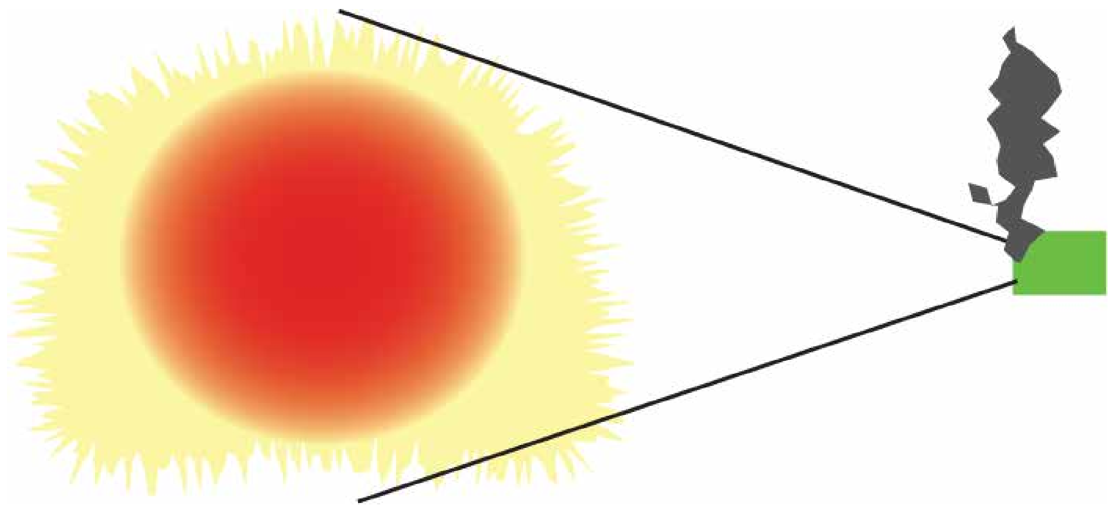
3. Combination of fire and explosion, thermal and mechanical effects often occur.

Mechanical effects from high pressure



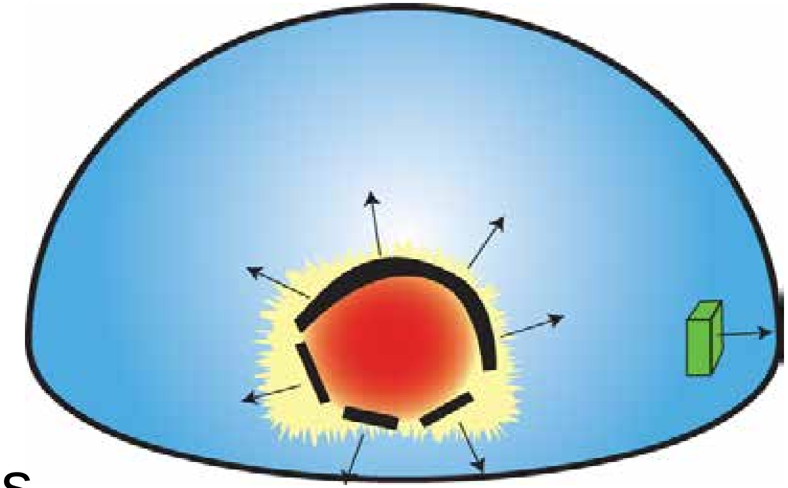
- Expansion of combustion products due to conversion of chemical to thermal energy in combustion and creation of gaseous products in high explosives
- Expansion ratio for gaseous explosions depends on thermodynamics
- Expansion rate depends on chemical kinetics and fluid mechanics
  - Flame speeds
  - Detonation velocity

Thermal effects from high temperature



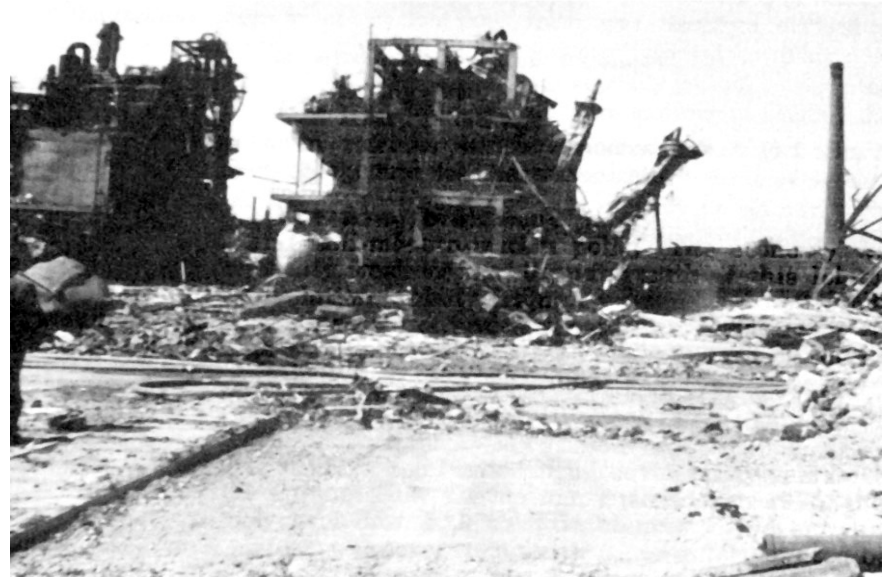
- Hot gases radiate strongly in IR, particularly for sooting explosion like BLEVE.
  - Fireballs cause injury (skin burns) and secondary ignition of structures
- Internal explosions create high-speed gas and convective heat transfer in addition to IR radiation
  - Heat up equipment, ignite flammable materials

Fragment effects from structural failure



- Primary fragments
  - Created by rupture of vessel or structure
  - Some fraction of explosion energy transferred to fragment
  - Follows a ballistic trajectory
- Secondary fragments
  - Created by blast wave and following flow
  - Accelerated by flow, eventually follows a ballistic trajectory
- Both lift and drag important in determining trajectories

Pasadena TX 1989 – C_2H_4

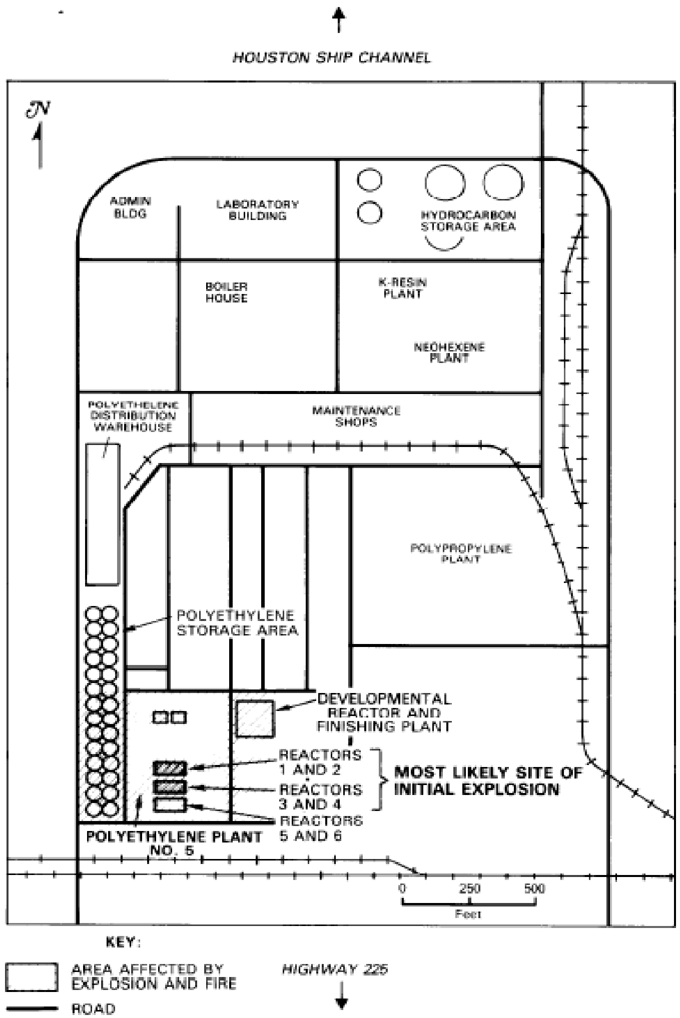


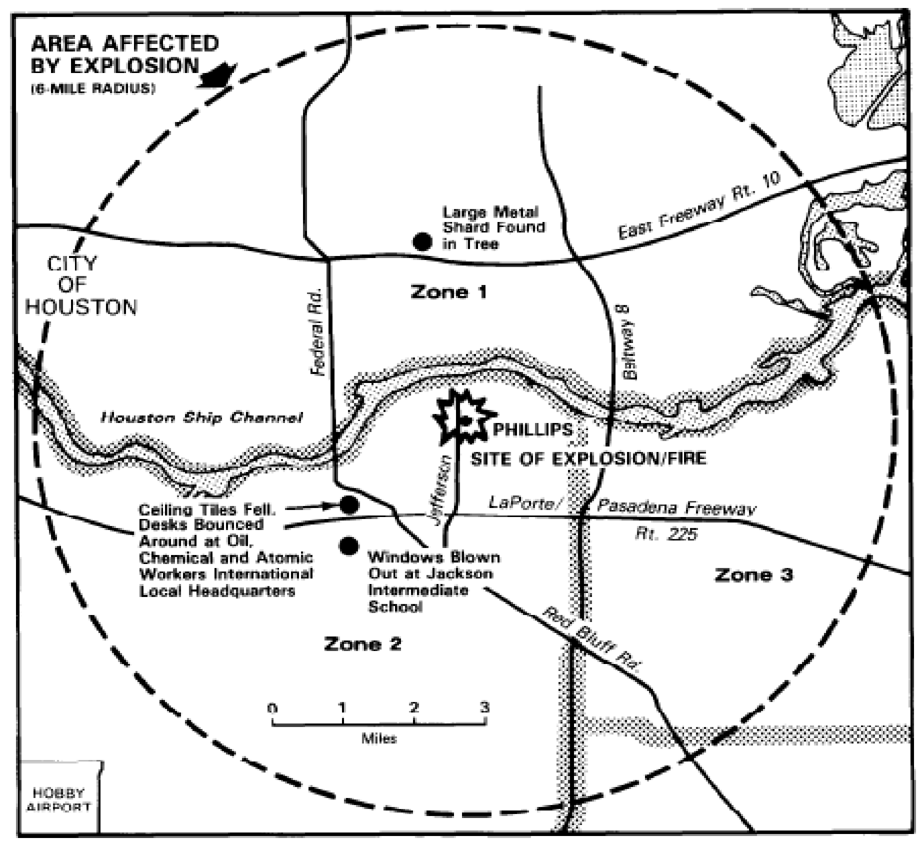
Flixborough 1974 - cyclohexane

(20 Kg H_2)

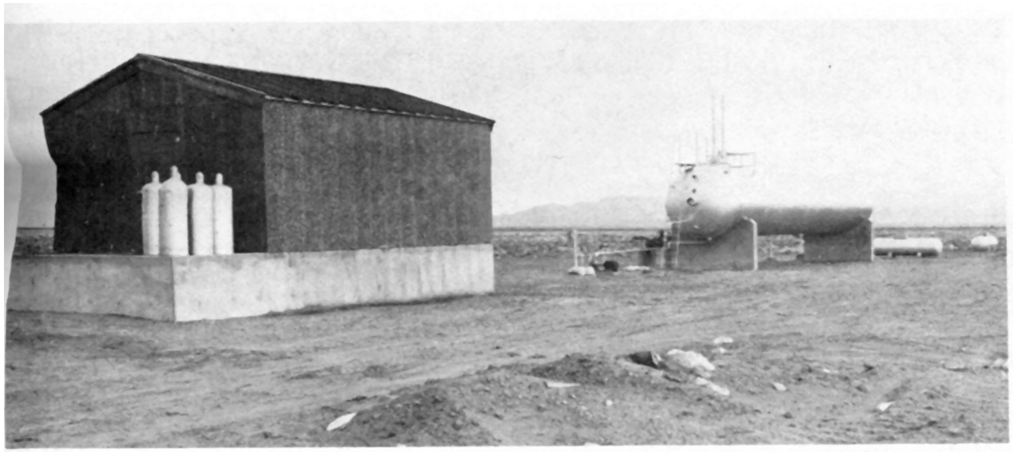
Port Hudson 1974 – C_3H_8

Pasadena TX 1989





Nuclear Blast Wave Damage – 5 psi (34 kPa)



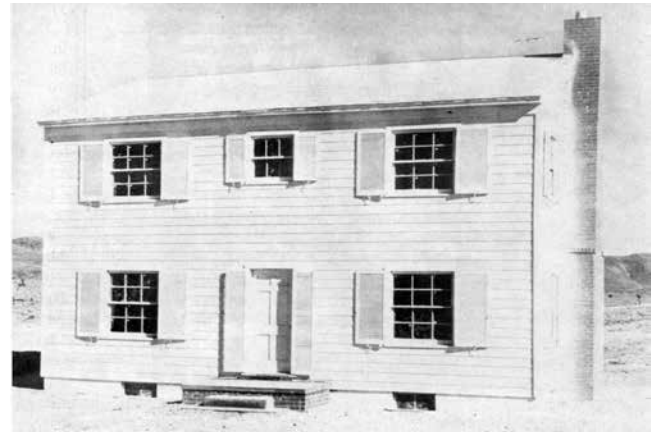
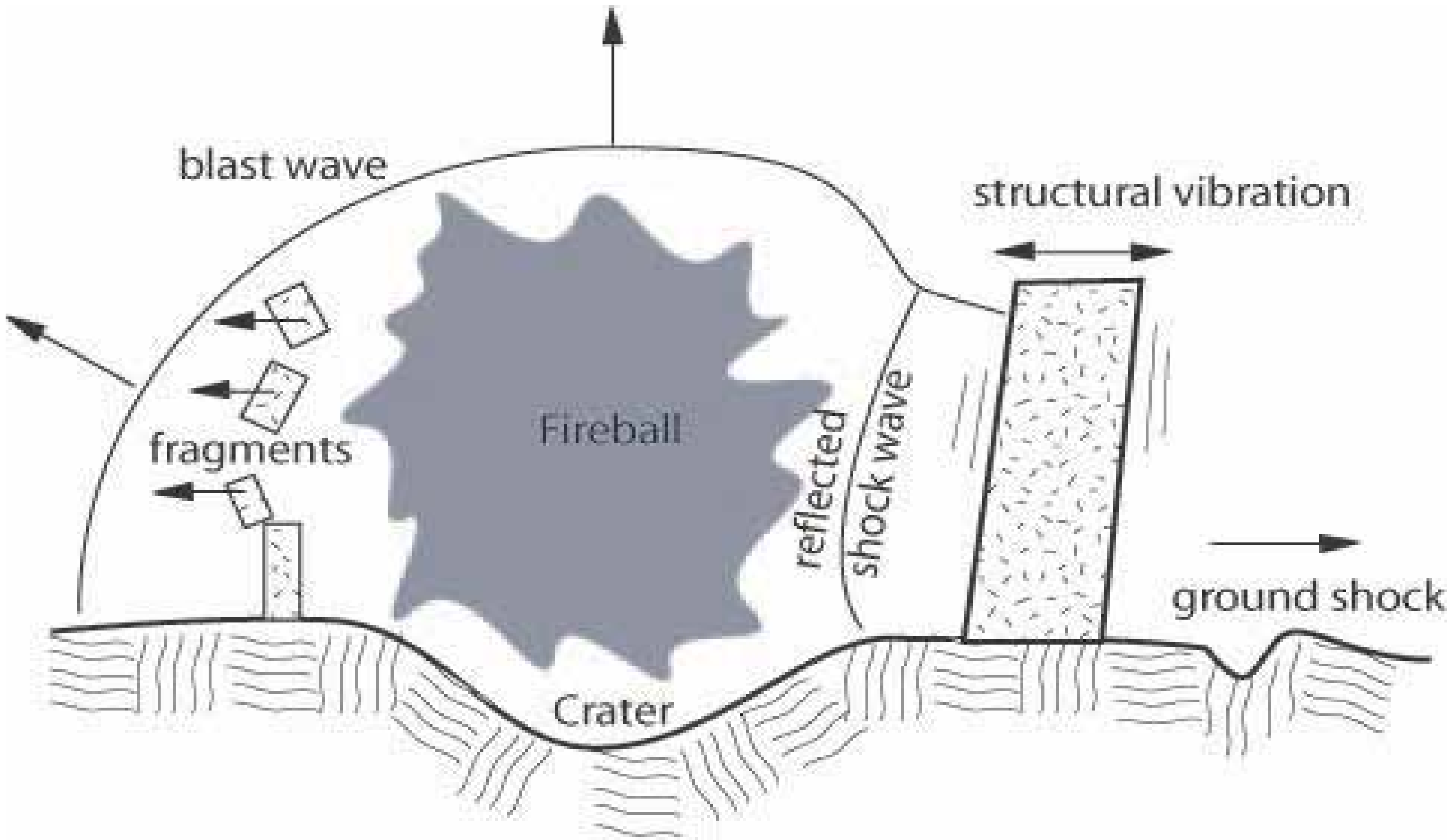


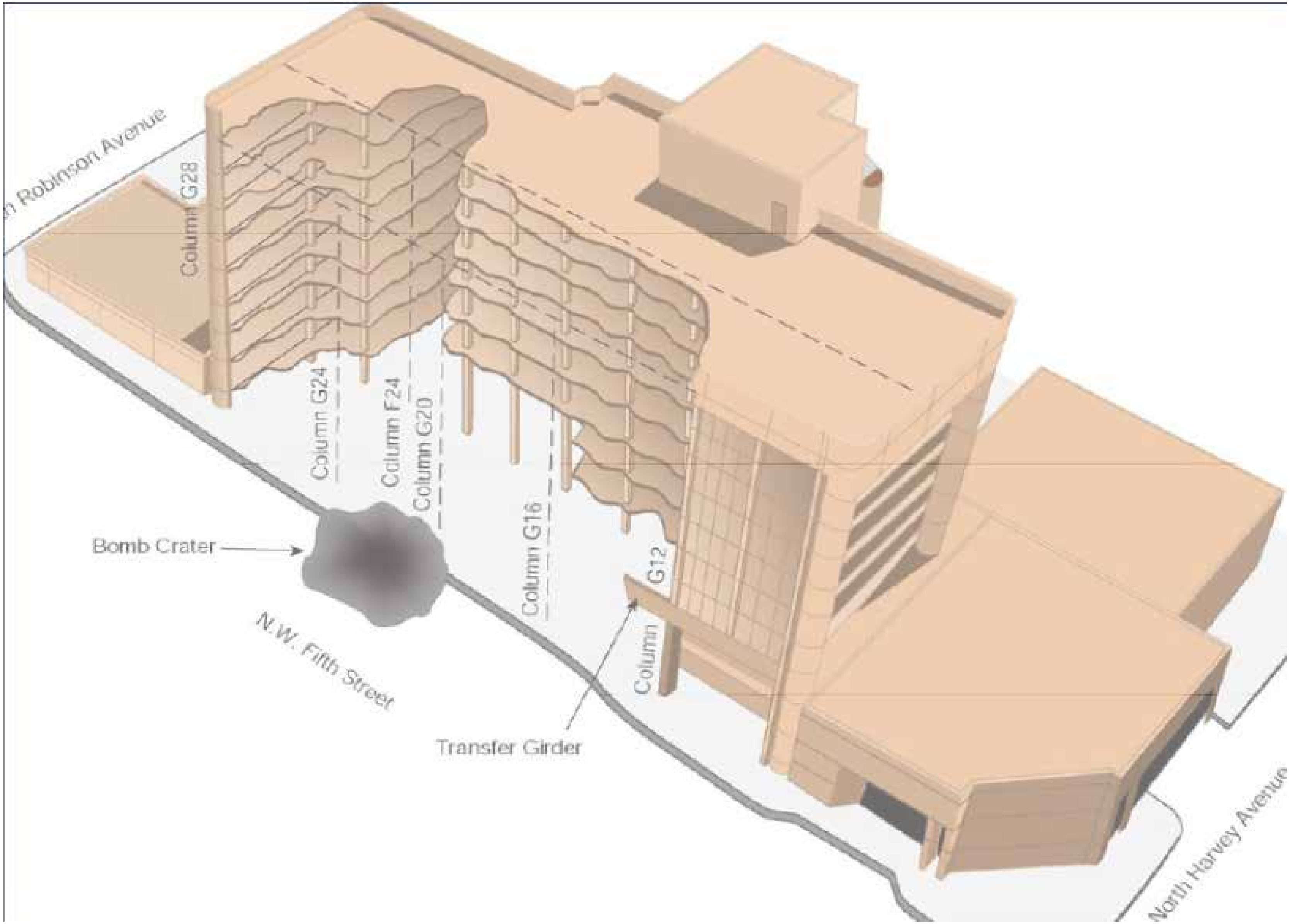
Figure 5.55. Wood-frame house before a nuclear explosion, Nevada Test Site.

Figure 5.57. Wood-frame house after a nuclear explosion (5 psi peak overpressure).

Effects of High Explosive Detonation



Truck Bomb – 4000 lb TNT_e



Response of a Large Structure is Complex!

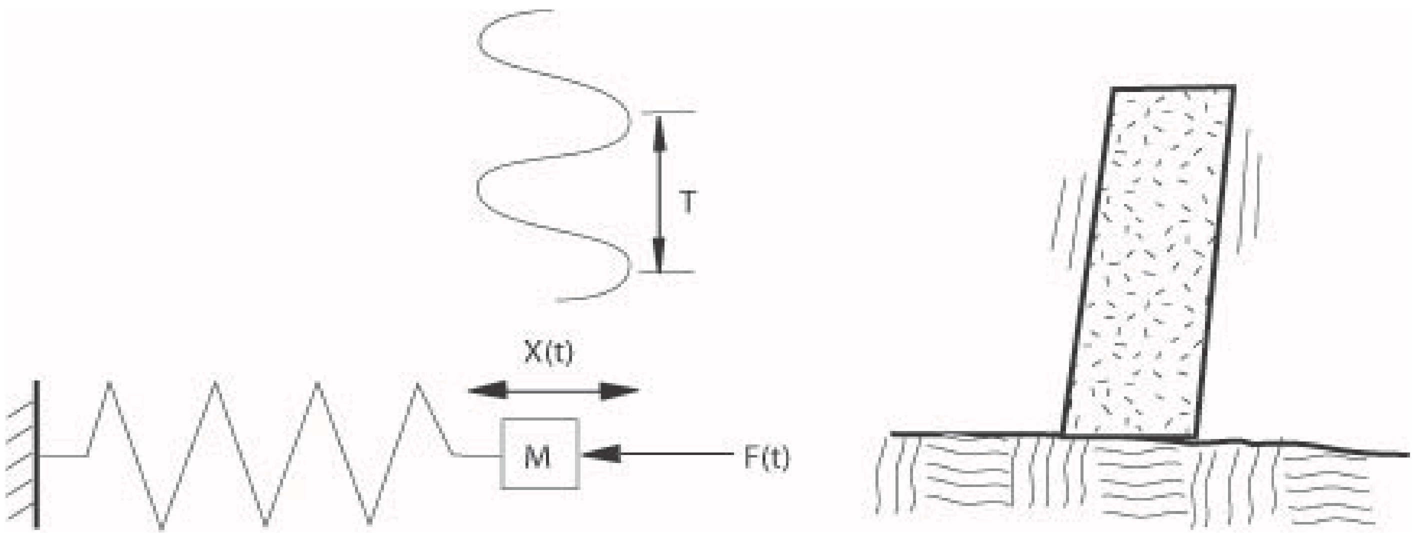
- Blast effects cause a small number of columns and slabs to directly fail
- Increased load on other structural elements leads to *progressive collapse*
- In Murrah Building, 40% of floor area destroyed due to progressive collapse, only 4% due to direct blast.
- Factors in progressive collapse
  - Building design (seismic resistance can help)
  - Fires can weaken structural elements (WTC)
- Detailed analysis and testing is needed to understand or predict response

Preview – Structural Response Analysis

- First, estimate static capacity of structure. Failure can occur to do either
  - Excessive stress – plastic deformation or fracture makes structure too weak for service
  - Excessive deformation – structure not useable due to leaks in fittings or misfit of components (rotating shafts, etc).
- Second, what are structural response times?
    - Large spectrum for a complex structure
    - Single value for simple structure
  - How do these compare to loading and unloading times of pressure wave?
    - Loading time
    - Unloading time
- Third, estimate dynamic peak deflection and stresses based on response times and loading history
  - High peak load is acceptable if duration is short (impulsive case)
  - Lower peak load limit if duration is long and rapidly applied (sudden case)

Structural Response

- Structures move in response to forces (Newton's Law)
  - Structure has mass and stiffness
  - Structure "pushes back"

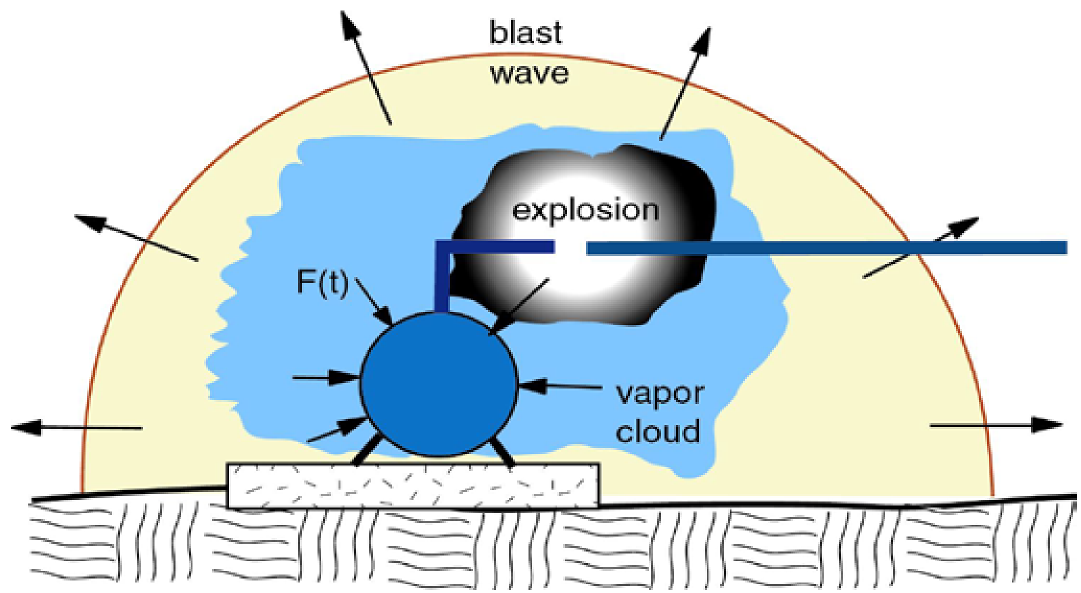


Determining structural loads

- Load generally means "applied force" in this context. The primary load is usually thought of as due to pressure differences created by the explosion process. Pressure differences across components of a structure create forces on the structure and internal stresses.
- Three simple cases
  - External explosion
  - Blast wave interaction
  - Internal explosion

External Explosion

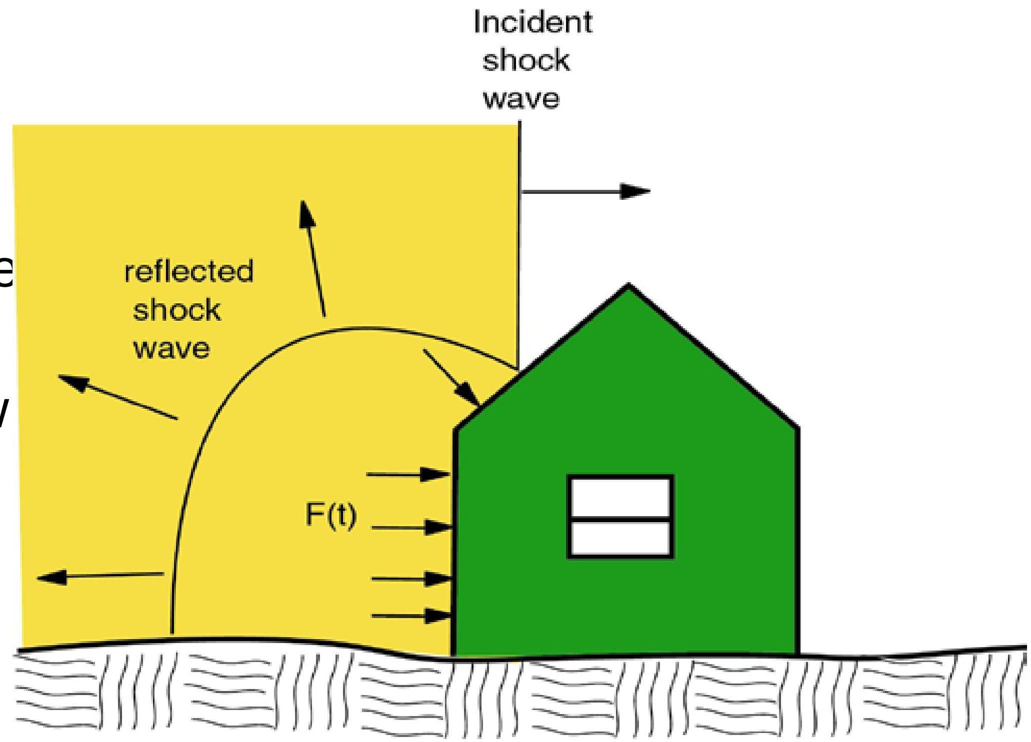
- Explosion due to accidental vapor cloud release and ignition source starting a combustion wave
- Flame accelerates due to instabilities and turbulence due to flow over facility structures
- Volume displacement of combustion (“source of volume”) compresses gas and creates motion locally and at a distance
  – Blast wave propagates away from source



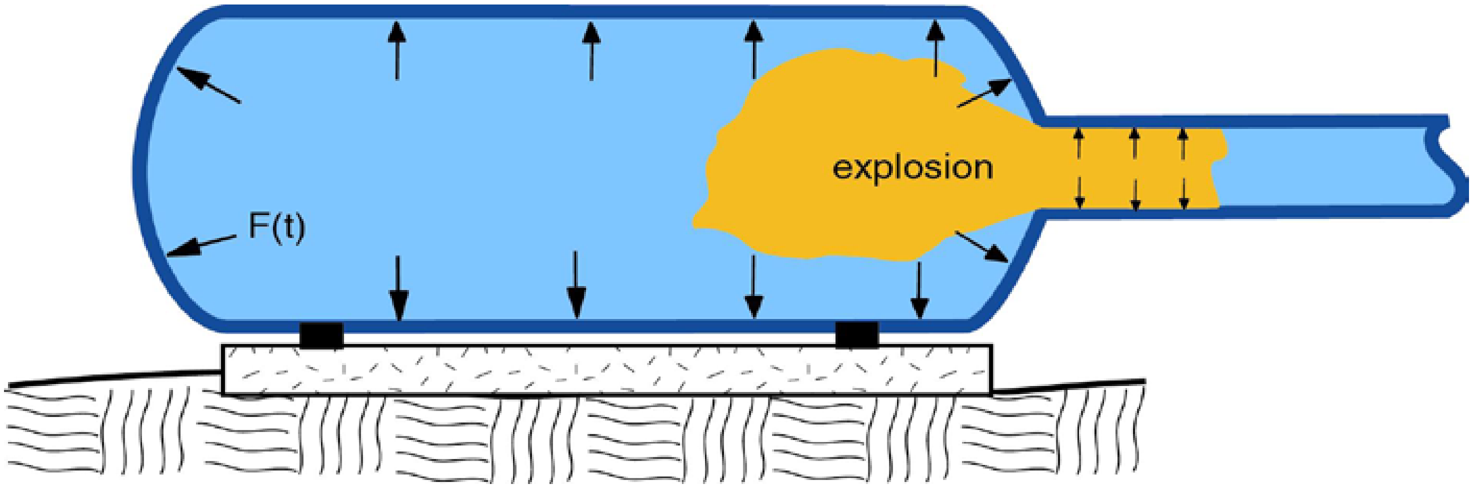
Unconfined **V**apor **C**loud **E**xplosion (UVCE)

Blast Wave Interaction

- Blast wave consists of
  - Leading shock front
  - Flow behind front
- Pressure loading
  - Incident and reflected pressure behind shock
  - Stagnation pressure from flow
- Factors in loading
  - Blast decay time
  - Diffraction time
  - Distance from blast origin



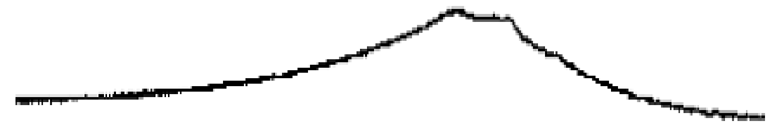
Internal Explosion



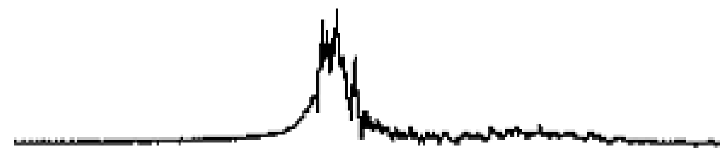
- Can be deflagration or detonation
- Deflagration
  - Pressure independent of position, slow
- Detonation
  - Spatial dependence of pressure
  - Local peak associated with detonation wave formation and propagation

Loading Histories

- Pressure-time histories can be derived from several sources
  - Experimental measurements
  - Analytical models with thermodynamic computation of parameters
  - Detailed numerical simulations using computation fluid dynamics
  - Empirical correlations of data
  - Approximate numerical models of blast wave propagation (Blast-X)
- Characterizing pressure-time histories
  - Single peak or multiple peaks
  - Rise time
  - Peak pressure
  - Duration

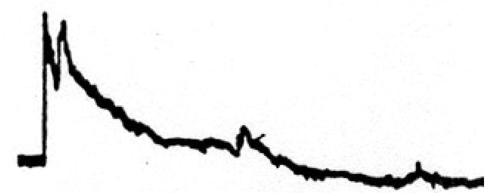


Slow flame in vessel



High speed flame in vessel

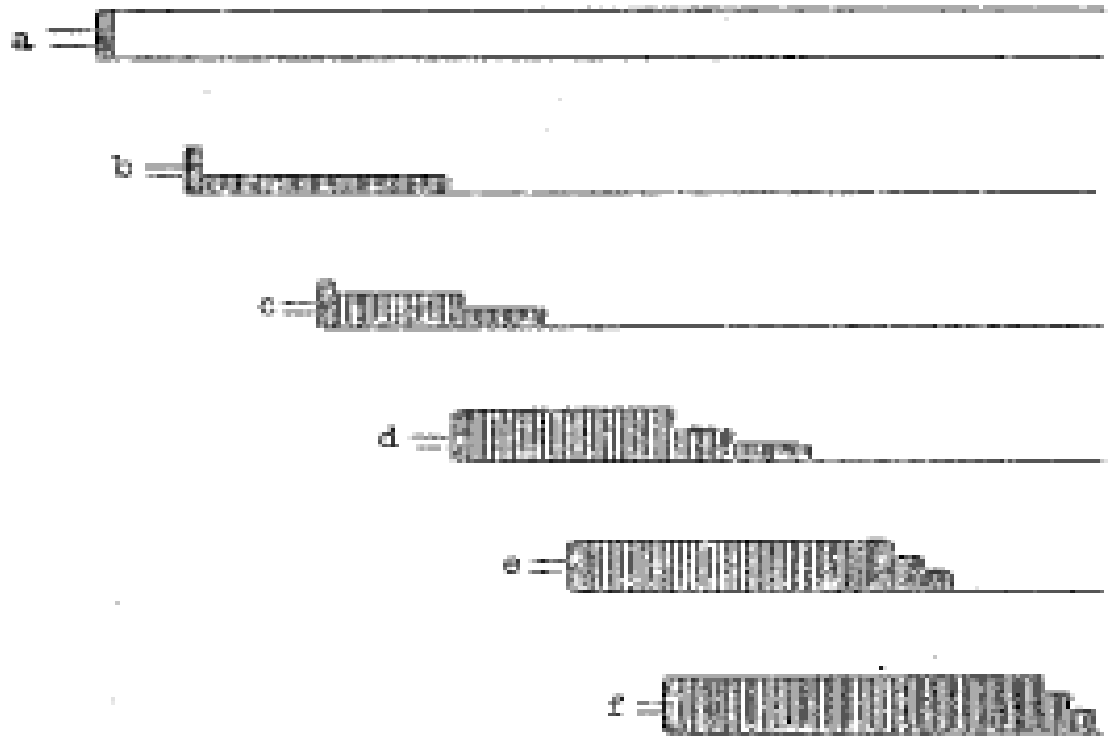
Nonideal explosion



Ideal blast wave

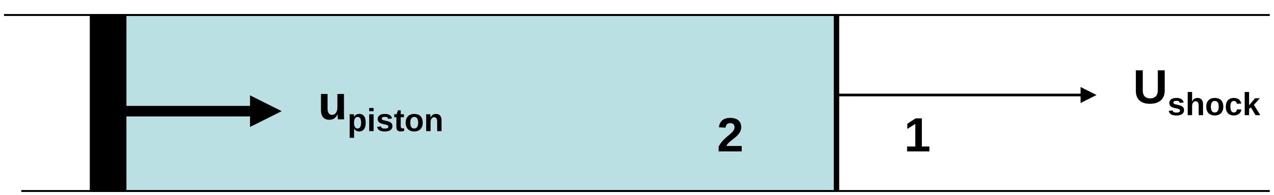
Ideal Blast Waves

Formation of a Shock Wave



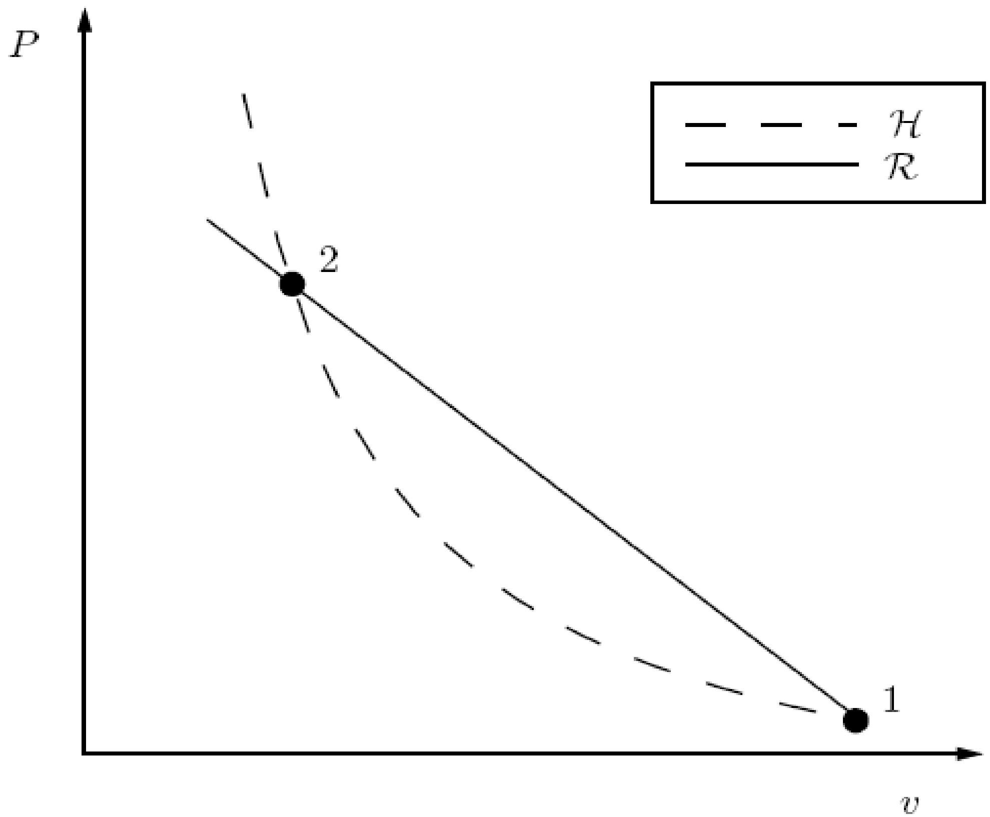
Characteristics of Shock Waves

- **Supersonic compression wave**
- **Very thin (0.1 um for NTP)**
- **Common examples:**
  - **Sonic booms**
  - **Blast waves from explosions**
  - **Leading shock in detonation**
- **Described by Rankine-Hugoniot relations**
- **Piston model**



Rankine-Hugoniot Relations

Combine conservation of mass, momentum, and energy across the wave front



Rankine-Hugoniot Eqn H

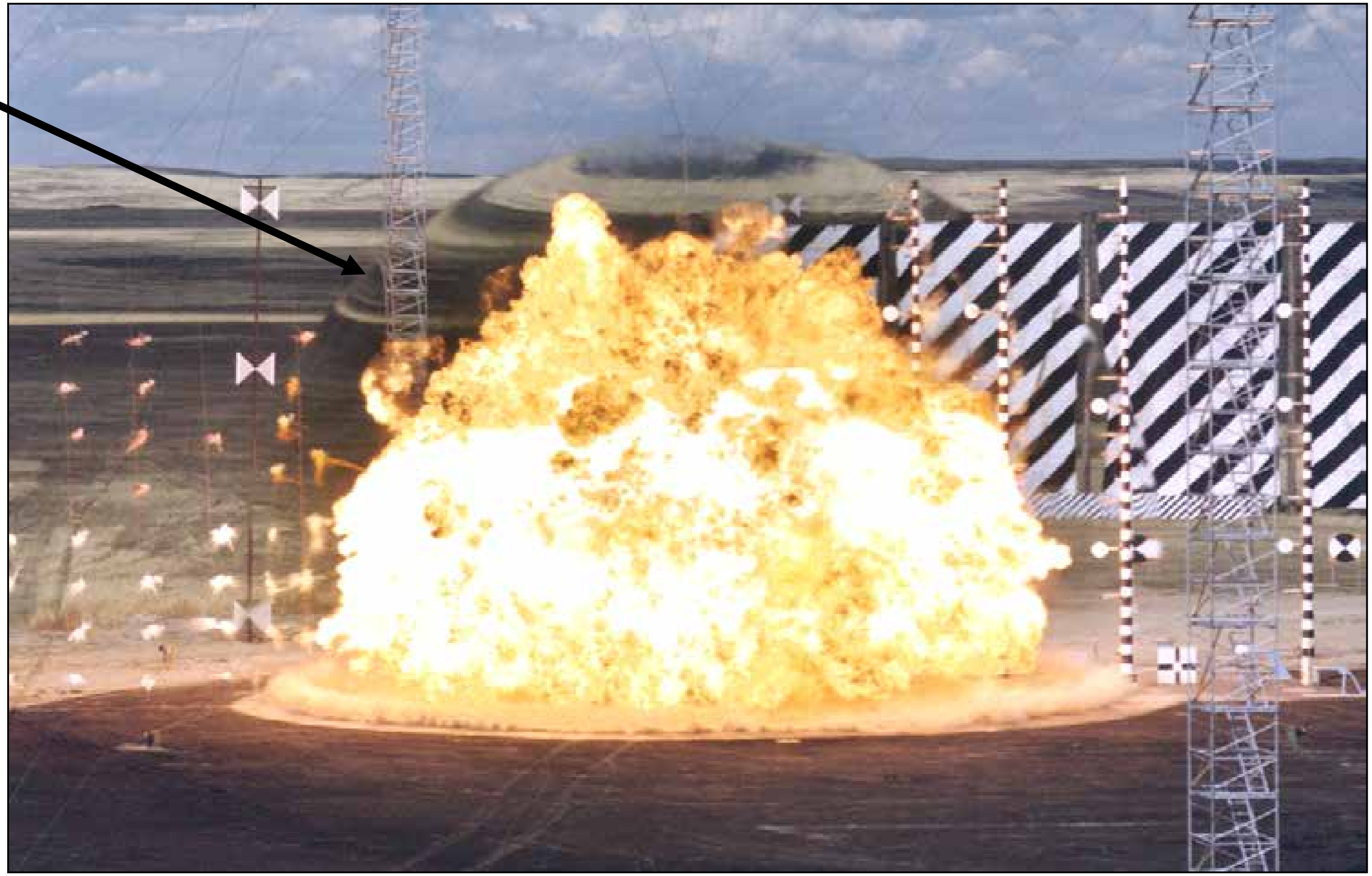
$$h_2 - h_1 = \frac{1}{2}(P_2 - P_1)(v_1 + v_2)$$

Rayleigh Eqn R

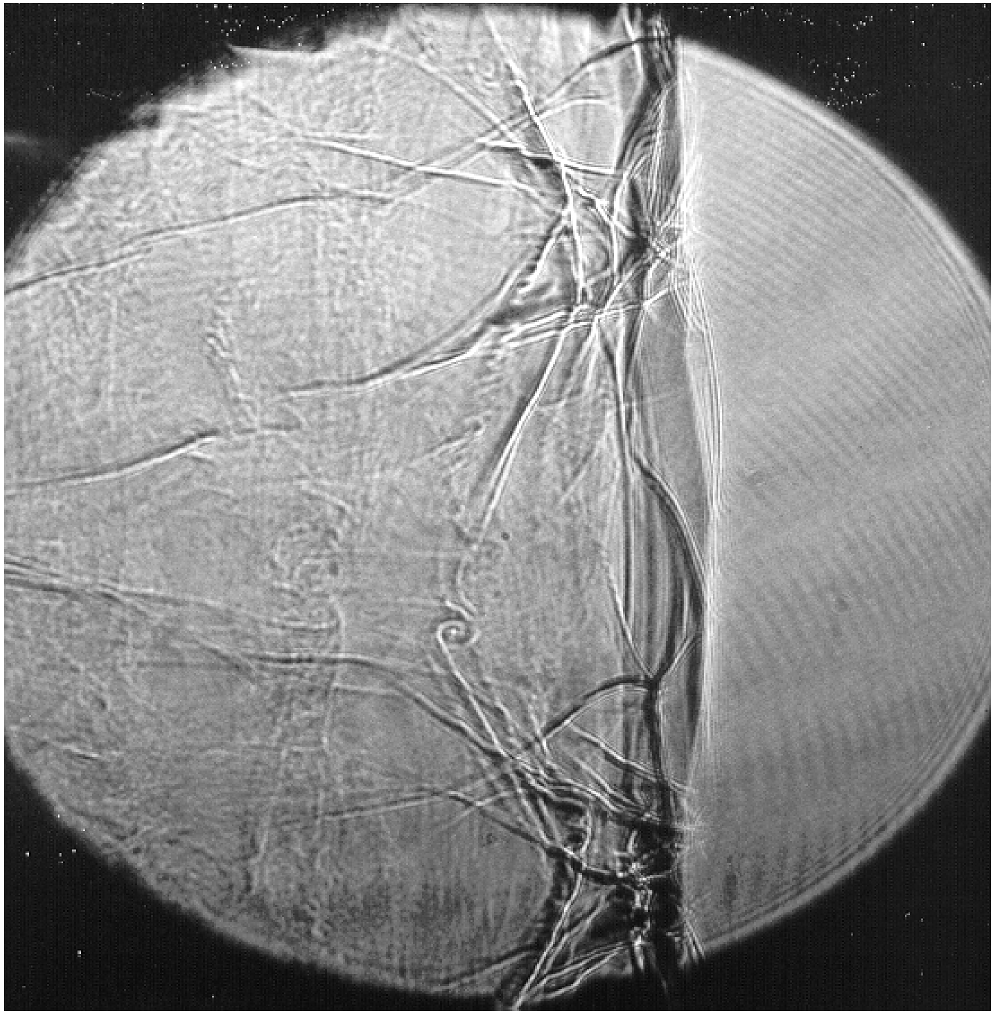
$$\frac{P_2 - P_1}{v_2 - v_1} = -\left(\frac{\mathrm{U}_s}{v_1}\right)^2$$

Blast Wave

shock

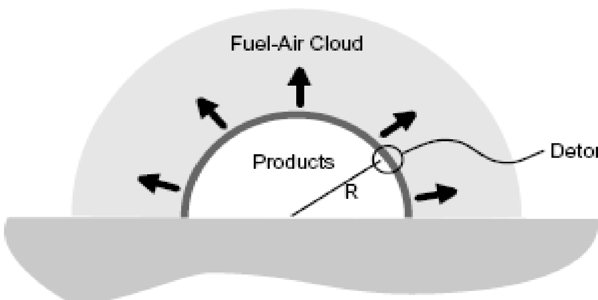


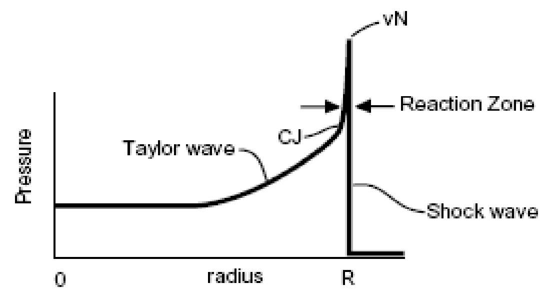
Detonation



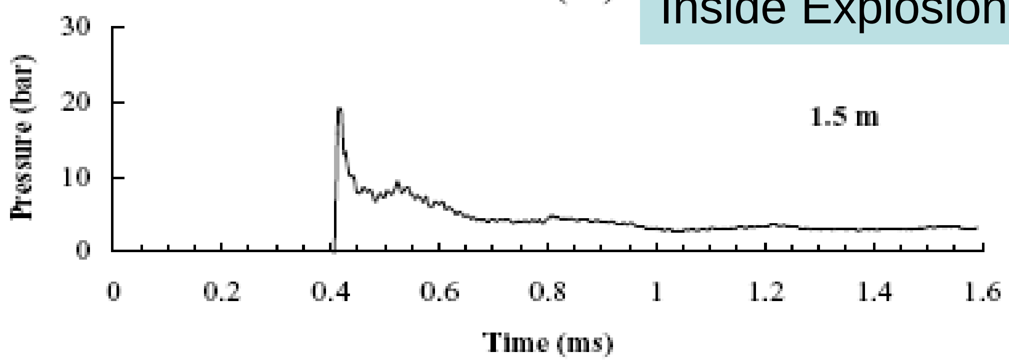
Ideal Blast Wave Sources

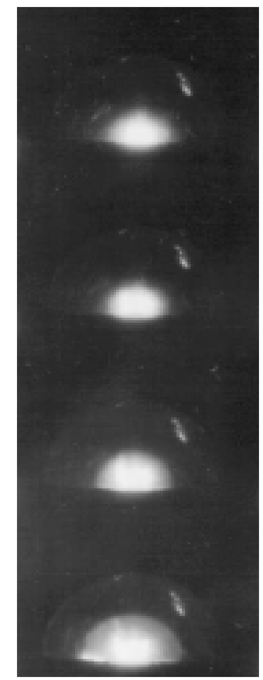
Simplest form of pressure loading – due concentrated, rapid release of energy
High explosive or “prompt” gaseous detonation. Main shock wave followed by pressure wave and gas motion, possibly secondary waves.





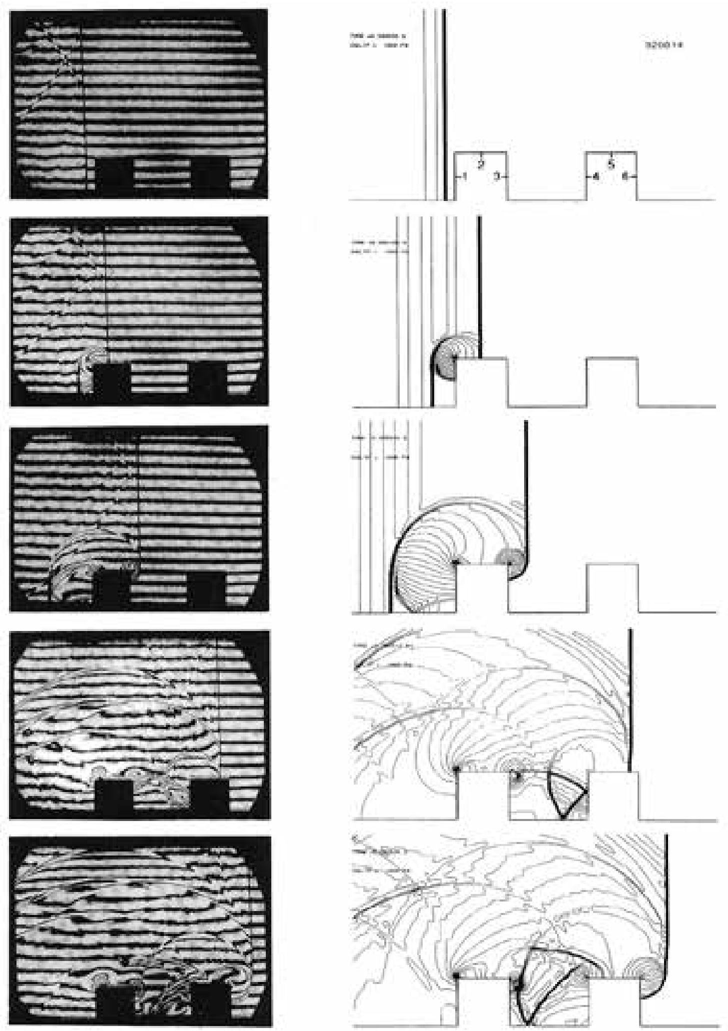
Inside Explosion

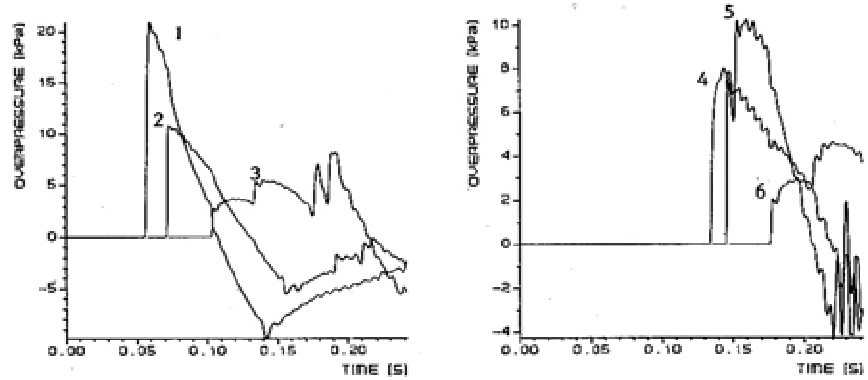




Pfortner

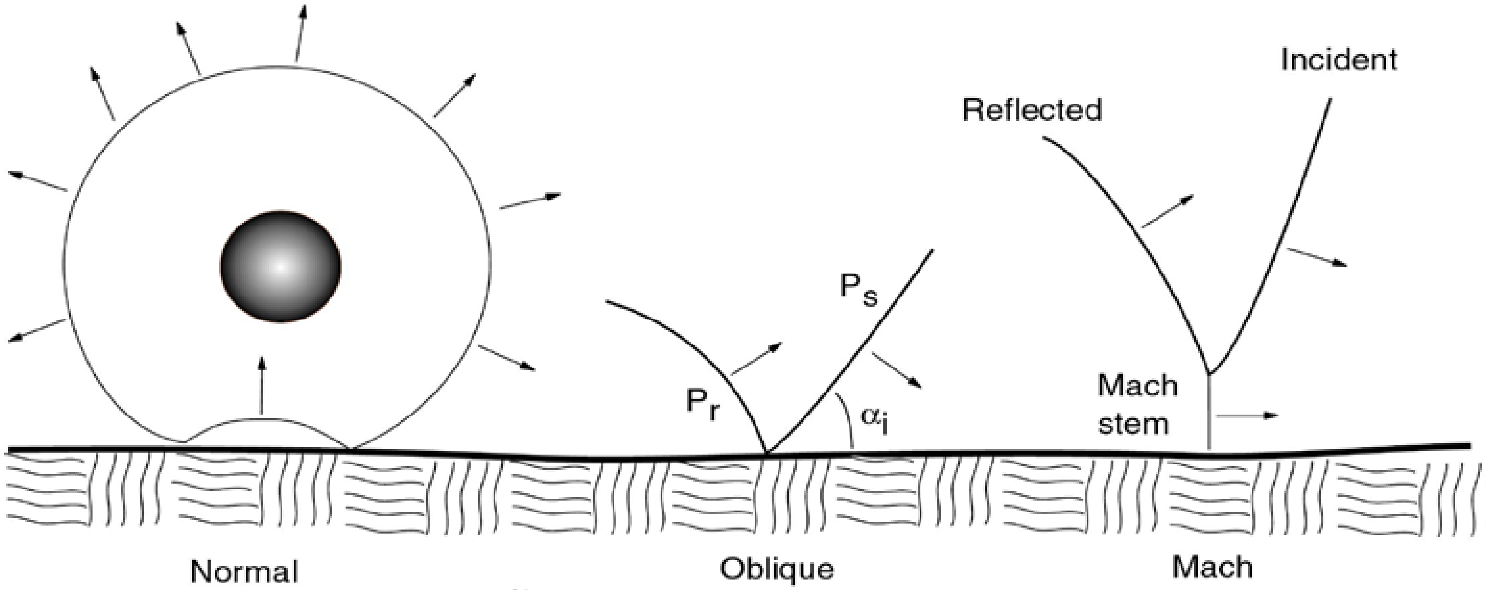
Interaction of Blast Waves with Structures





Blast-wave interactions with multiple structures LHJ Absil, AC van den Berg, J. Weerheijm p. 685 - 290,
Shock Waves, Vol. 1, Ed. Sturtevant, Hornung, Shepherd, World Scientific, 1996.

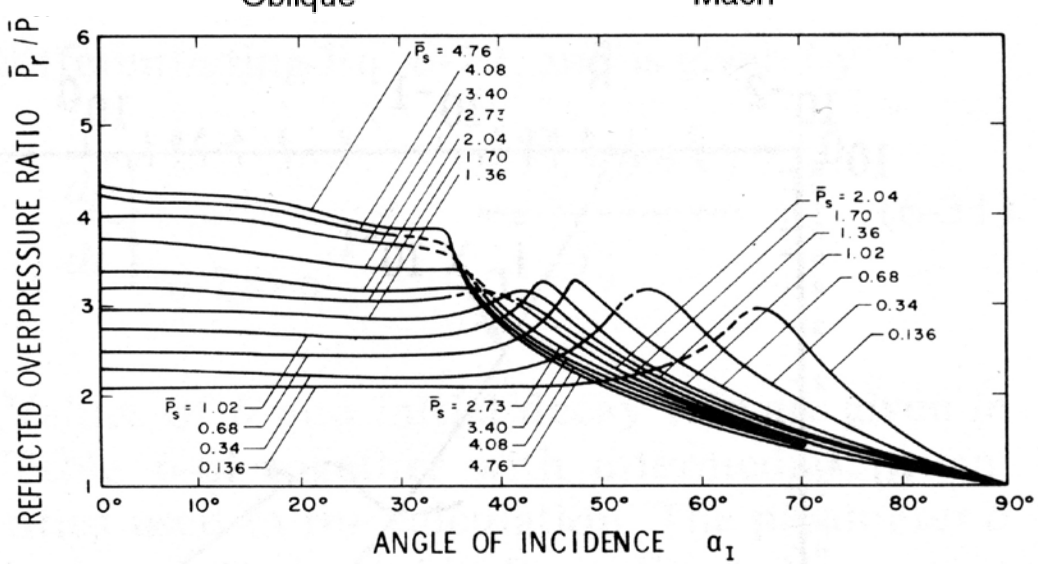
Idealized Interactions



Enhancement depends:

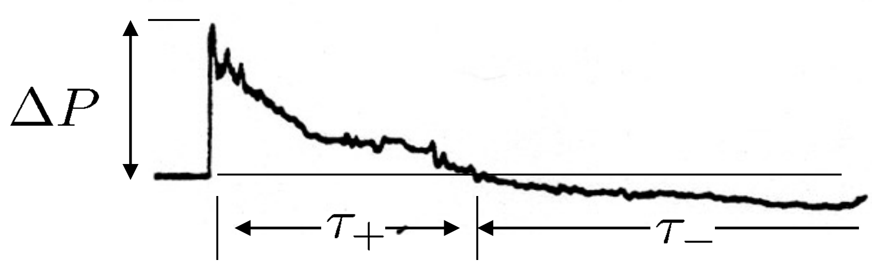
Incident wave strength

Angle of incidence



"Explosions in Air" Baker

Blast and Shock Waves



$$\Delta P = \frac{2\gamma}{\gamma + 1}(M_s^2 - 1)$$

$$u_s = \frac{2c_1}{\gamma + 1}(M_s - \frac{1}{M_s})$$

$$M_s = U_s/c_1 \qquad c_1 = \sqrt{\gamma R T_1}$$

$$\mathcal{I} = \int_o^{\tau_+} \Delta P \, dt$$

Specific impulse!

- Leading shock front pressure jump determined by wave speed – shock Mach number.
- Gas is set into motion by shock then returns to rest
- Wave decays with distance
- Loading determined by
  - Peak pressure rise
  - Impulse
  - Positive and negative phase durations

Scaling Ideal Blast Waves I.

- Dimensional analysis (Hopkinson 1915, Sachs 1944, Taylor-Sedov)
  - Total energy release E = Mq
    - M = mass of explosive atmosphere (kg)
    - q = specific heat of combustion (J/kg)
  - Initial state of atmosphere P_o or r_o and c_o
- Limiting cases
  - Strength of shock wave
    - Strong $D P >> P_o$
    - Weak $D P << P_o$
  - Distance from source
    - Near $R \sim R_{source}$
    - Far $R >> R_{source}$

Scaling Ideal Blast Waves II.

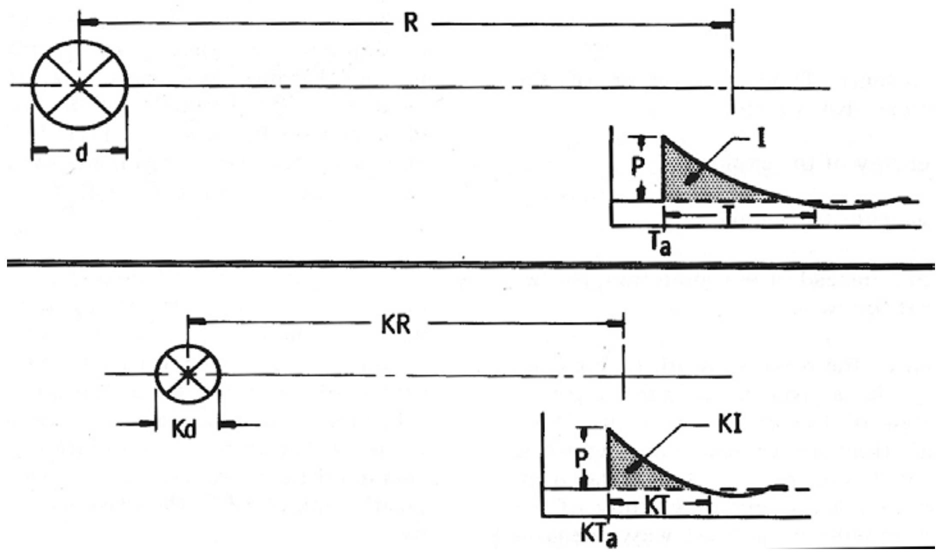
- Scale parameters
  - Blast length scale $R_s = (E/P_o)^{1/3}$
  - Time scale $T_s = R_s/c_o$
  - Pressure scale
    - Close to explosion P_{exp} (usually bounded by P_{CJ})
    - Far from explosion P_o
- Nondimensional variables
  - pressure $\Delta P/P_o$
  - distance R/R_s
  - time t/T_s
  - Impulse (specific) $I/(P_o T_s)$

Relationships:

$\Delta P = P_o F(R/R_s)$

$I = P_o T_s G(R/R_s)$

Cube Root Scaling in Standard atmosphere



- Simplest expression of scaling (Hopkinson)
  - At a given scaled range $R/M^{1/3}$, you will have the same scaled impulse $I/M^{1/3}$ and overpressure D P
  - When you increase the charge size by K, overpressure will remain constant at a distance KR, and the duration and arrival time will increase by K.

TNT Equivalent

- Ideal blast wave from gaseous explosion equivalent to that from High Explosive (TNT) when energy of gaseous explosive is correctly chosen
- Universal blast wave curves in *far field* when expressed in Sachs' scaled variables

$$R^* = \frac{R p_0^{1/3}}{E^{1/3}}, \quad P^* = P / p_0, \quad I^* = \frac{I a_0}{E^{1/3} p_0^{2/3}}$$

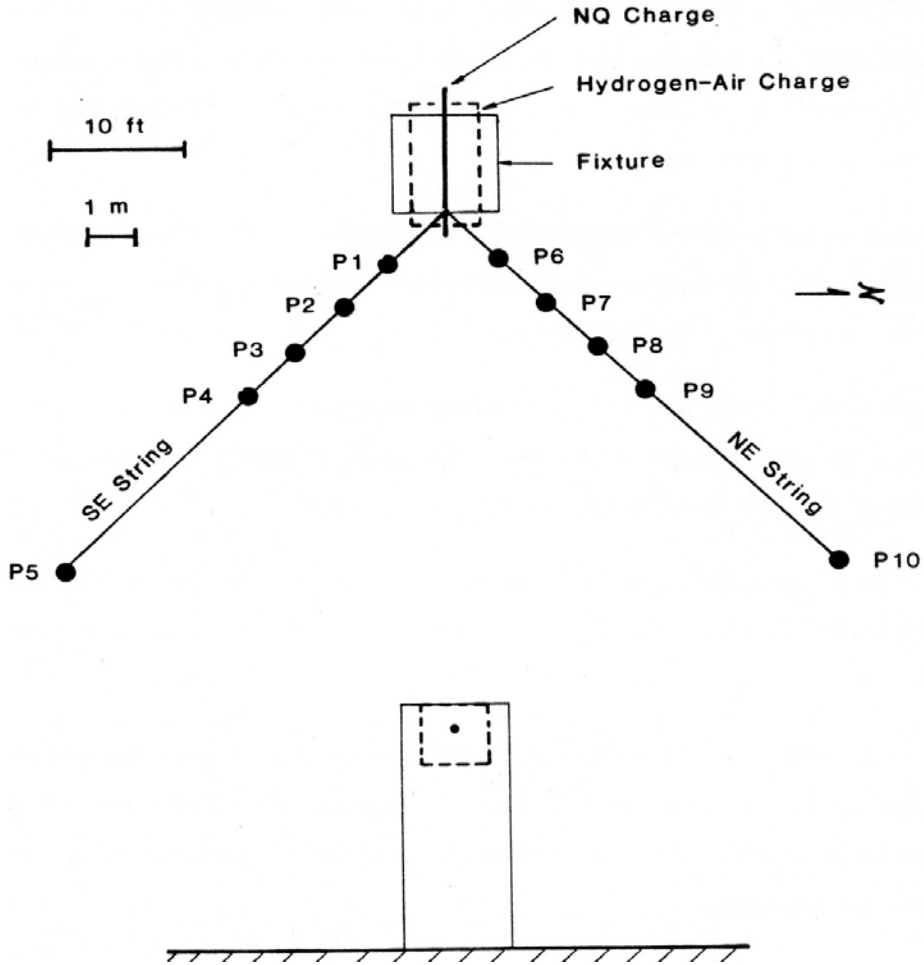
- For ideal gas explosions (detonations) E is some fixed fraction of the heat of combustion (Q = qM)
- For nonideal gas explosions (unconfined vapor clouds), E is quite a bit smaller. Key issues:
  - How to correctly select energy equivalence?
  - How to correctly treat near field?

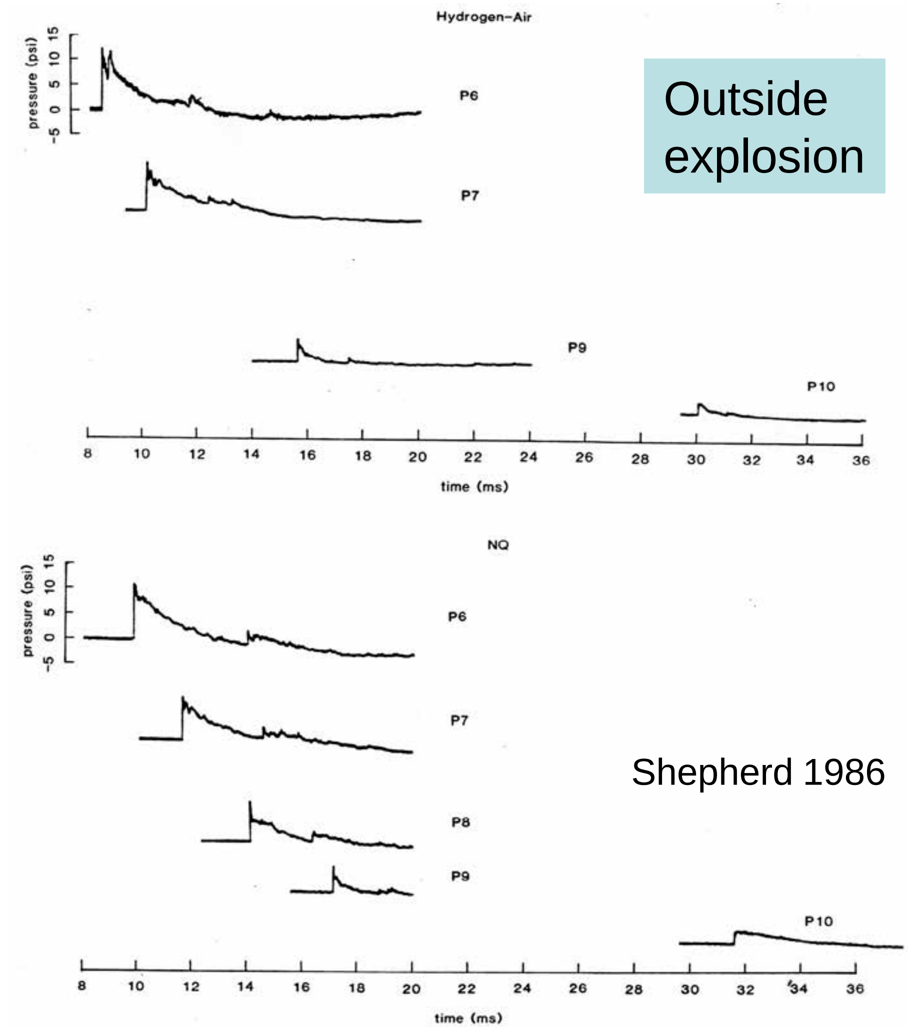
Energy Equivalent for Common Explosives

Explosive	Q (MJ/kg)	Density (g/cc)	CJ velocity (km/s)	CJ Pressure (kbar)
TNT	4.52	1.6	6.7	210
RDX	5.36	1.65	8.7	340
HMX	5.68	1.9	9.1	390
Tetryl	4.52	1.73	7.85	260
C6H14	45 (1.62)	0.66	1.8	0.018
H2	100 (2.7*)	8.2E-5	1.97	0.015

Values from Baker et al.
* For fuel-air mixture

Blast Wave from Hydrogen-Air Detonation

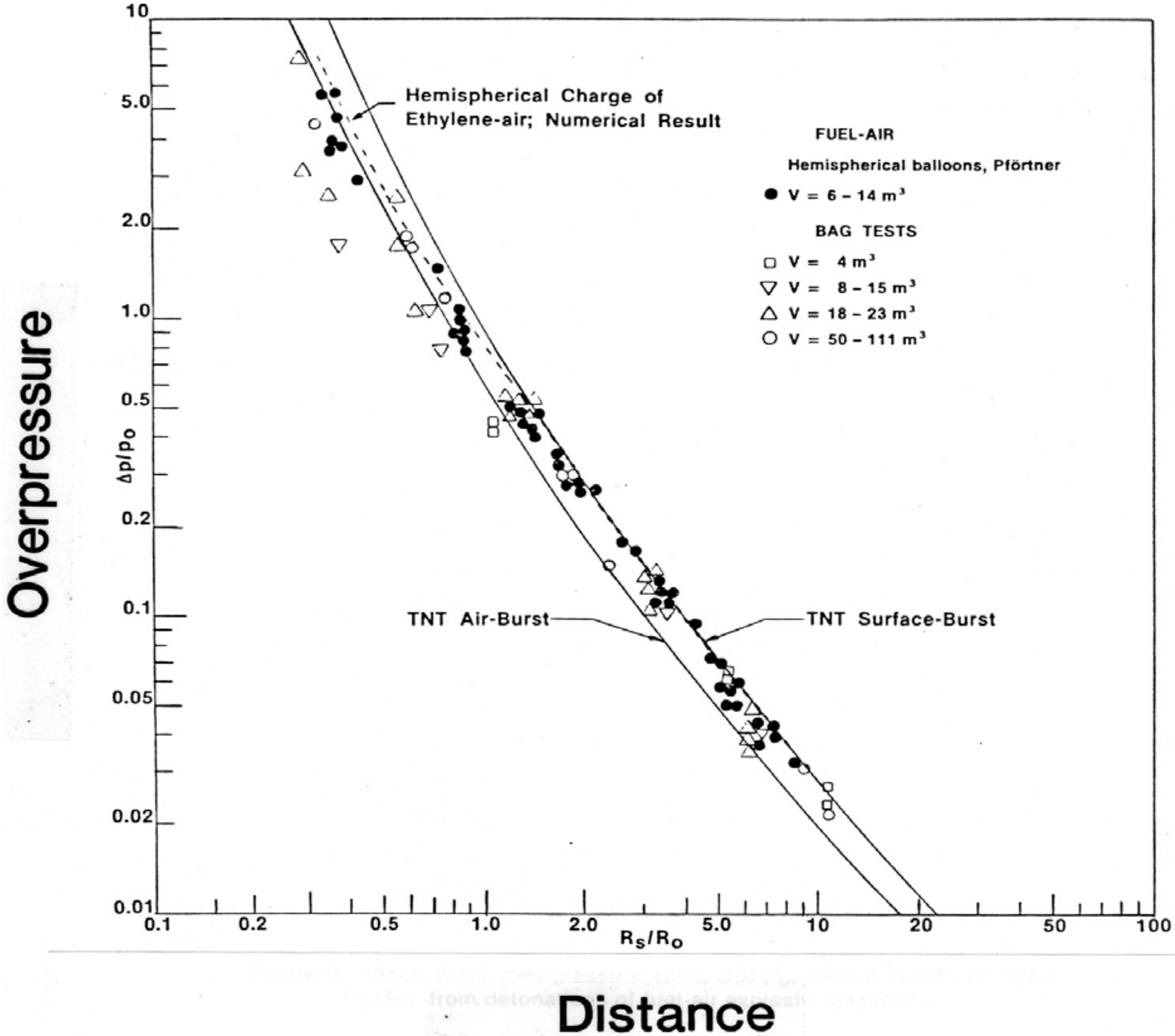




Outside explosion

Shepherd 1986

Scaling of Blast Pressure – Ideal Detonation

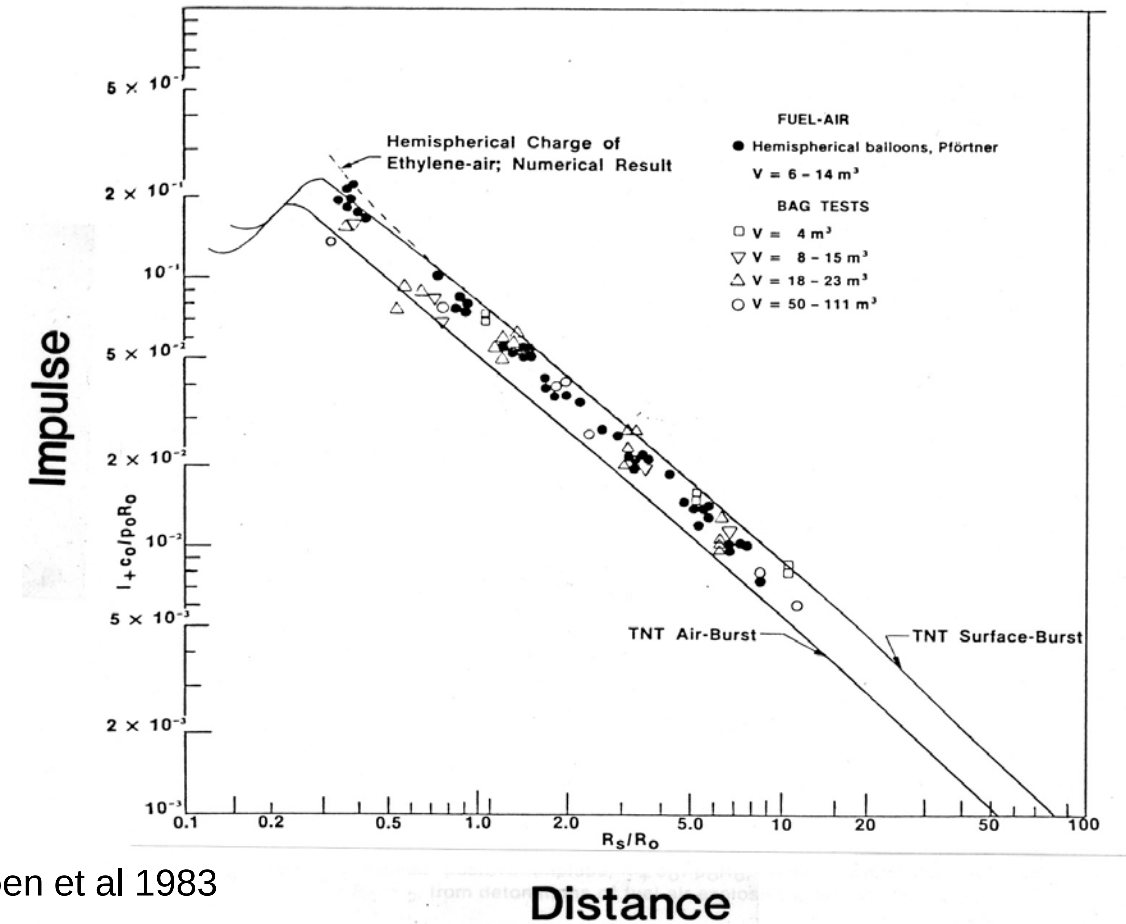


Comparison of fuel-air bag tests to high explosives

Work done at DRES (Suffield, CANADA) in 1980s

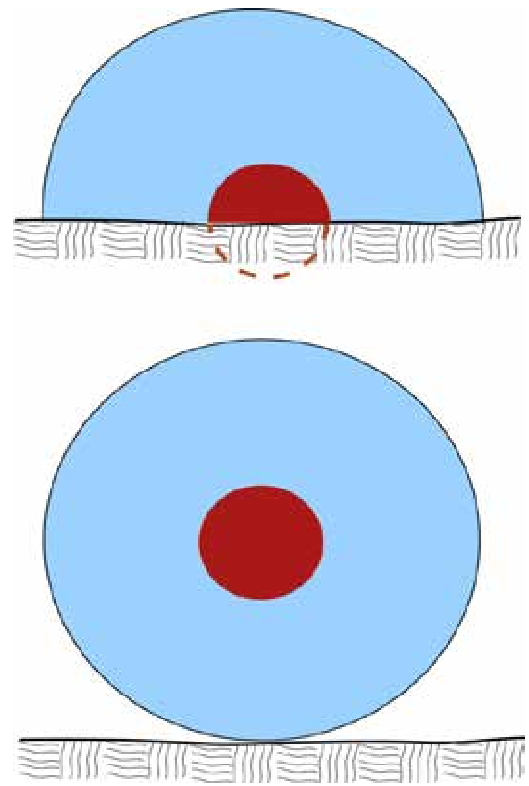
Moen et al 1983

Scaling of Impulse – Ideal Detonation



Moen et al 1983

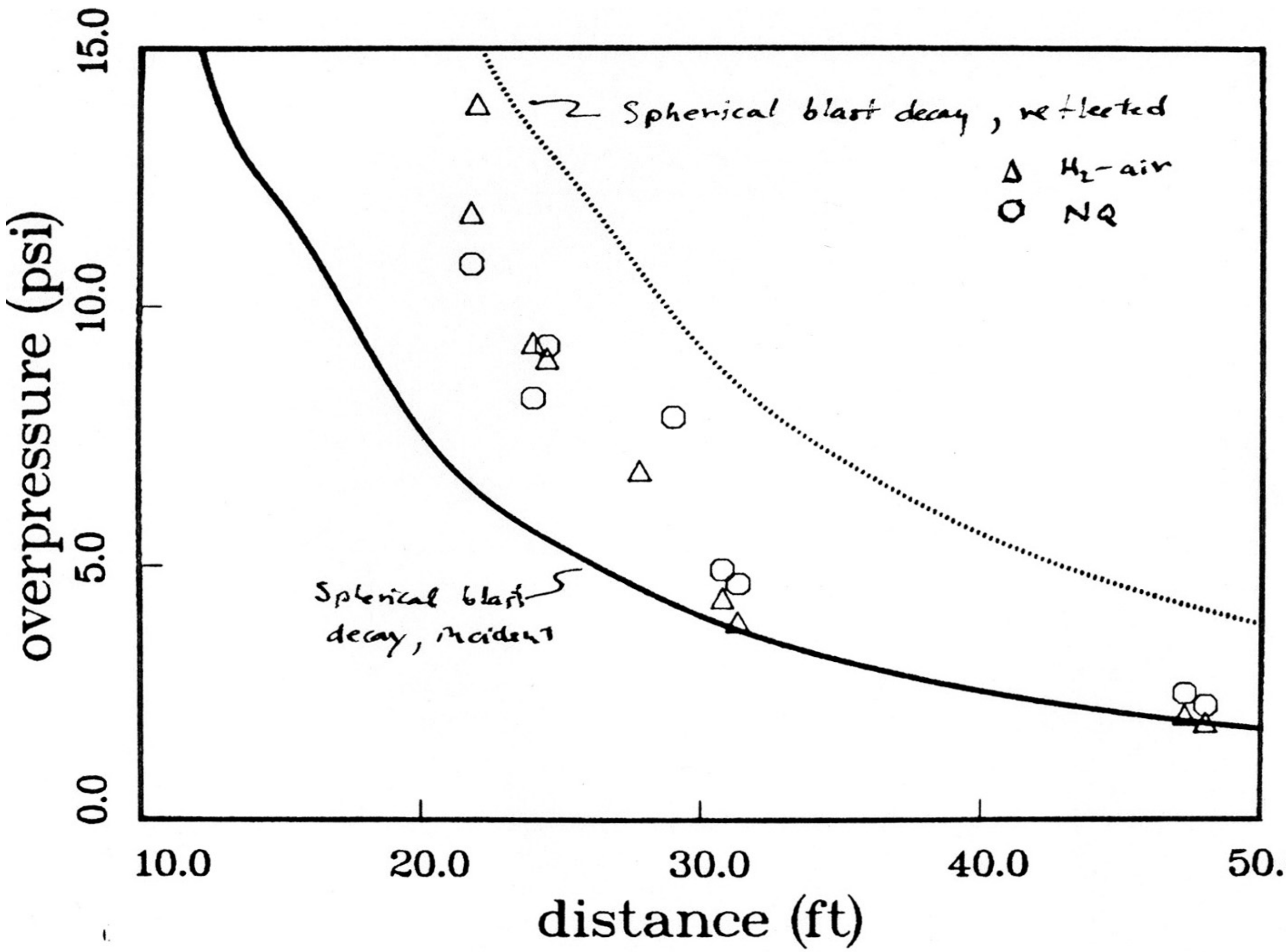
Surface burst



Air burst

For the same overpressure or scaled impulse at a given distance, M(surface) = 1/2 M(air)

Energy scaling of H2-air blast



Energy Equivalence

100 MJ/kg of H2

or

2.71 MJ/kg of fuel-air mix for stoichiometric.

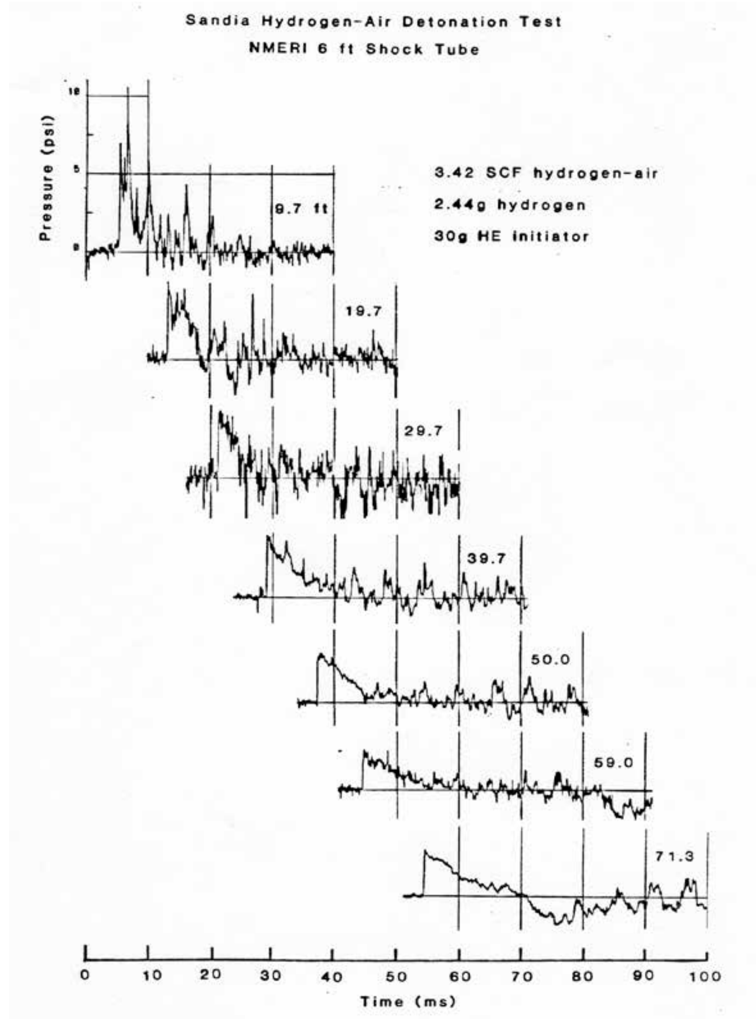
Shepherd 1986

Hydrogen-air Detonation in a Duct

- Blast waves in ducts decay much more slowly than unconfined blasts

  $$D P \sim x^{-1/2}$$

- Multiple shock waves created by reverberation of transverse waves within duct
- Pressure profile approaches triangular waveshape at large distances.



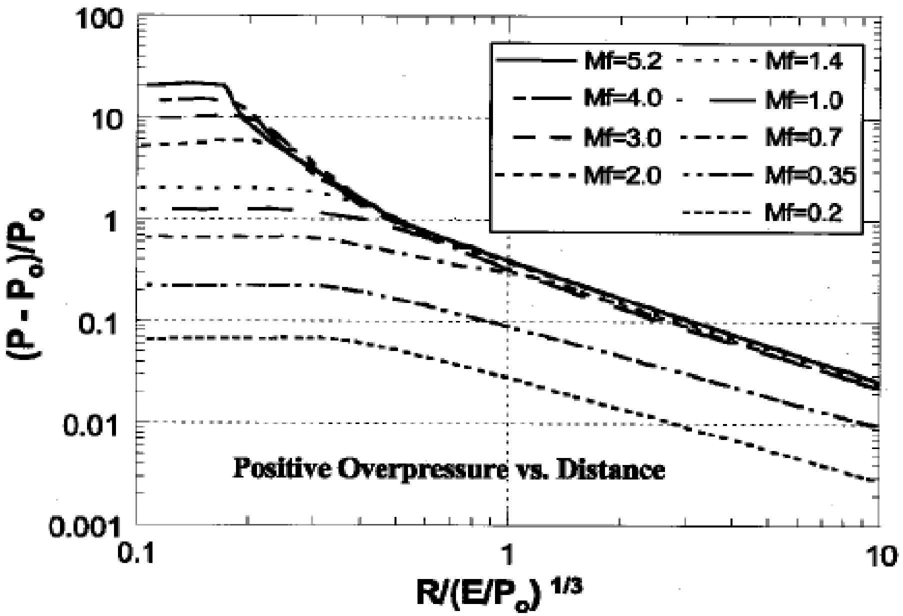
Thibault et al 1986

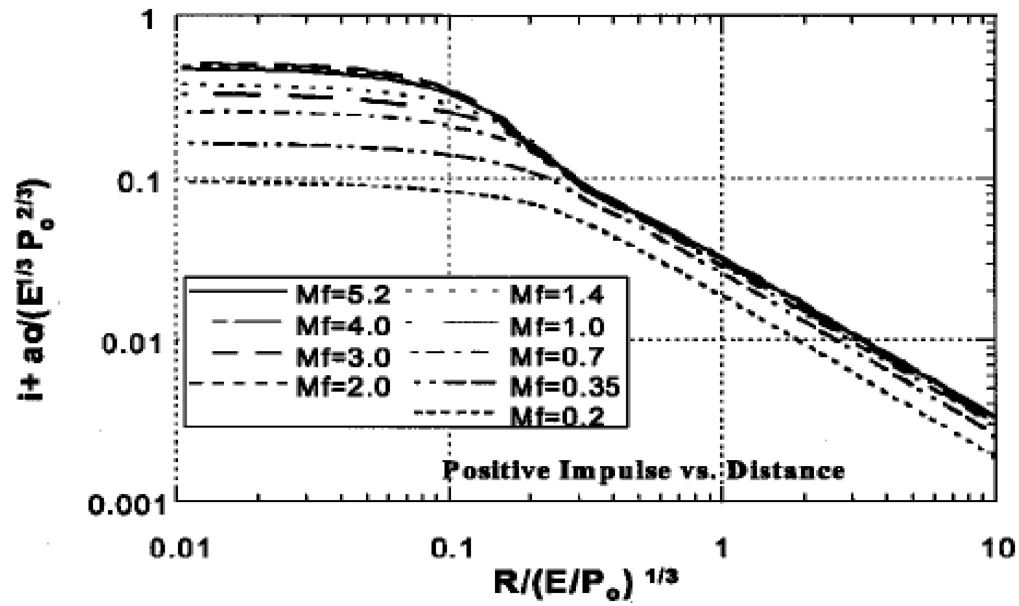
Nonideal Explosions

- Blast pressure depends on magnitude of maximum flame speed
- Flame speed is a function of
  - Mixture composition
  - Turbulence level
  - Extent of confinement
- There is no fixed energy equivalent
  - E varies from 0.1 to 10% of Q
- Impulse and peak pressure depend on flame speed and size of cloud – Sachs' scaling has to be expanded to include these

Pressure Waves from Fast Flames

Sachs' scaling with addition parameter – effective flame Mach number M_f. Numerical simulations based on 'porous piston' model and 1-D gas dynamics.





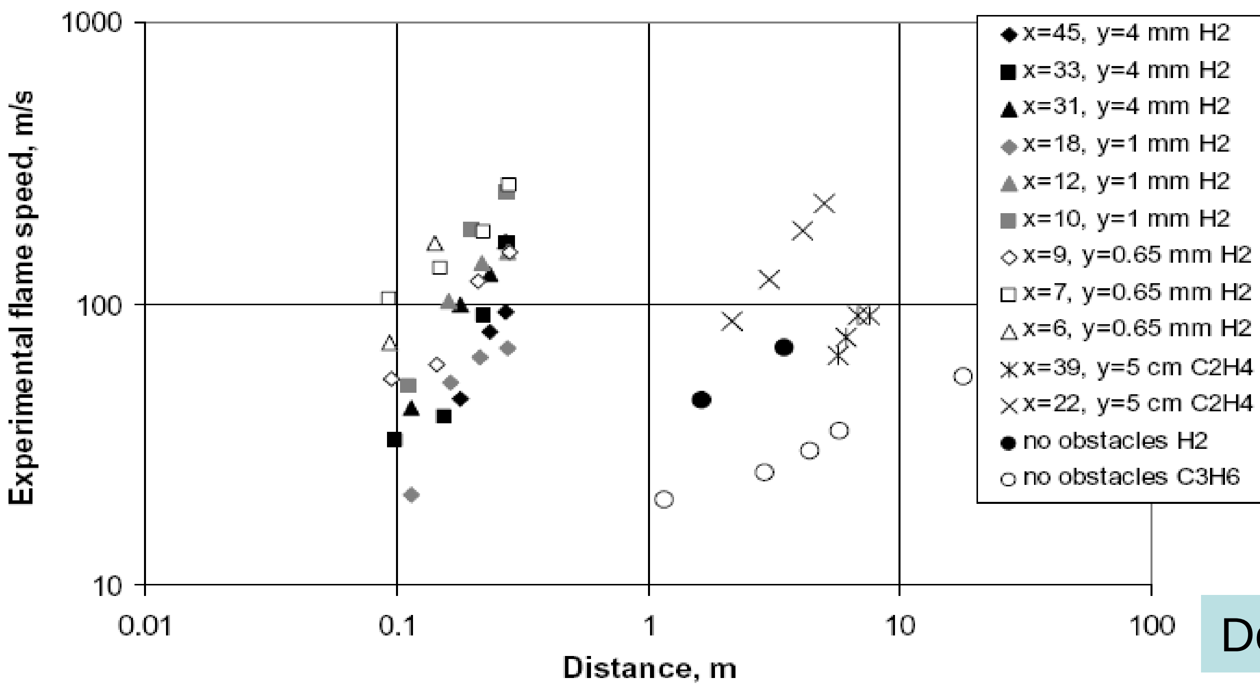
Tang and Baker 1999

What is Effective Flame Speed?

Consider volume displacement
of a wrinkled (turbulent) flame growing in
a mean spherical fashion.

$$V_f = \sigma S_T \frac{A_f}{A_R}$$

Expansion ratio



Dorofeev 2006

Mechanics and Strength of Materials

Forces, Stresses and Strains

- Loading becomes destructive when forces are sufficient to displace structures that are not anchored or else the forces (or thermal expansion) create stresses that exceed yield strength of the material.
- Important cases
  - Rigid body motion – fragments and overturning
  - Deformation due to internal stresses
    - Bending, beams and plates
    - Membrane stresses, pressure vessels

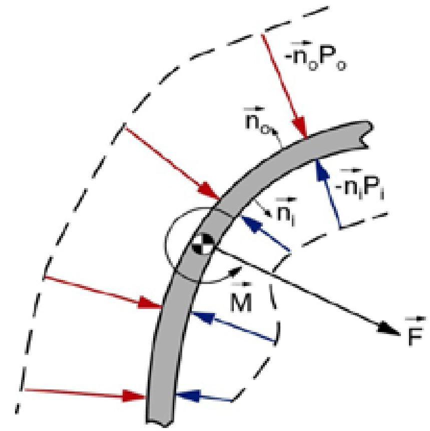
Rigid Body Forces due to Explosion

- Pressure varies with position and time over surface – has to be measured or computed

$$P(\mathbf{x}, t)$$

- Local increment of force on surface due to pressure only in high Reynolds' number flow

$$d\vec{F} = -P(\mathbf{x}, t)\vec{n}dS$$



$$\vec{F} = \int (-\vec{n}P)dS$$

$$\vec{M} = \int \vec{x}' \otimes (-\vec{n}P)dS$$

Geometry and distribution of pressure will result in moments as well as forces!
Be sure to add in contributions from body forces (gravity) to get total force.

Consequence of Forces I.

- Rigid body motions
  - Translation
  - Rotation

$$m \frac{d\vec{V}_{cm}}{dt} = \sum \vec{F} \qquad m = \int \rho \, dx dy dz$$

$$I \frac{d\vec{\omega}_{cm}}{dt} = \sum \vec{M} \qquad I_{jk} = \int \rho \, x'_j x'_k dx dy dz$$

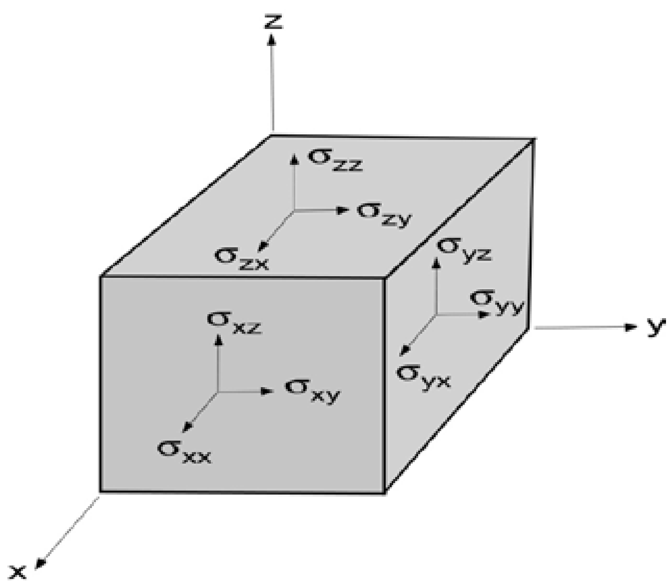
$X' = X - X_{cm}$ distance from center of mass

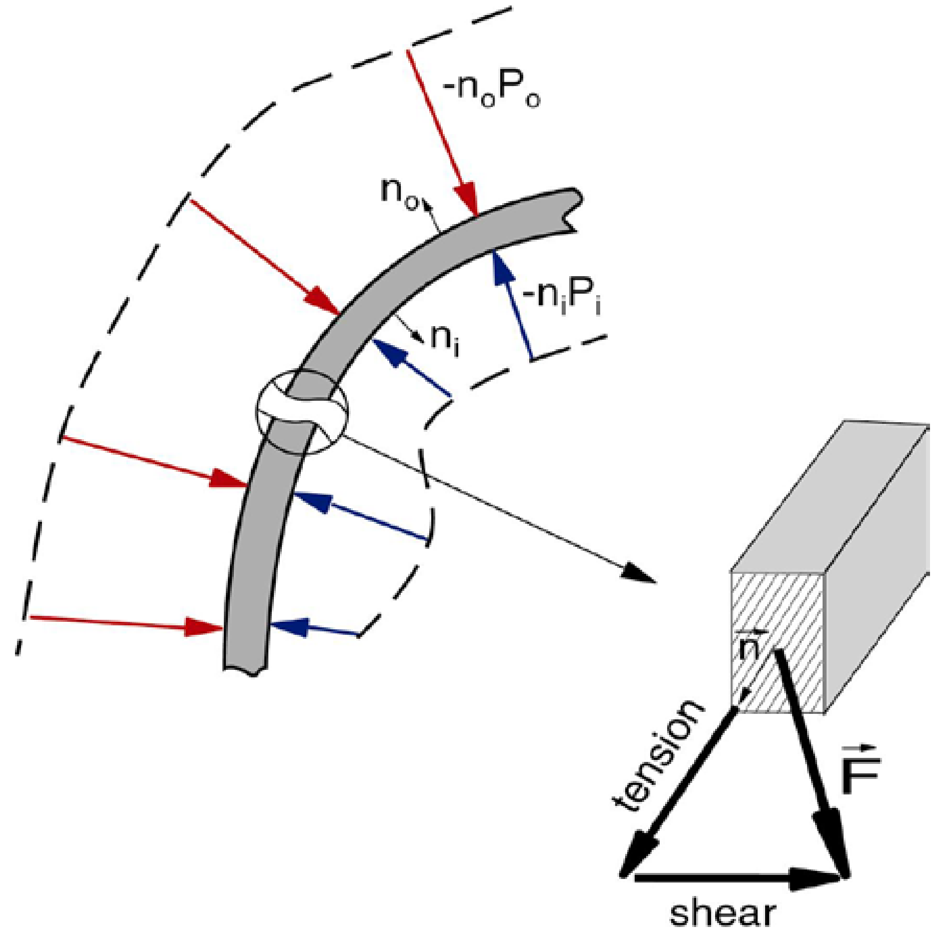
Internal Forces Due to an Explosion

- Force on a surface element dS

$$d\vec{F} = \sigma \cdot \vec{n} dS$$

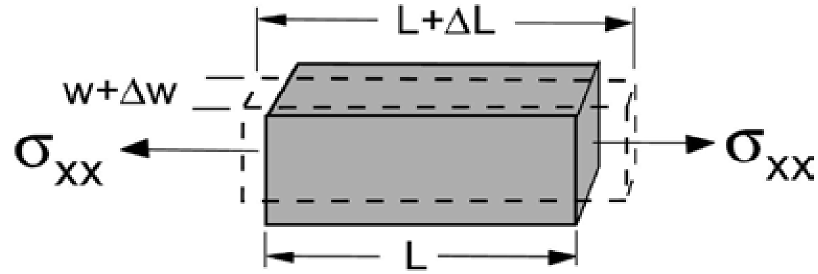
- Stress tensor s





Consequence of forces – small strains (<0.2 %)

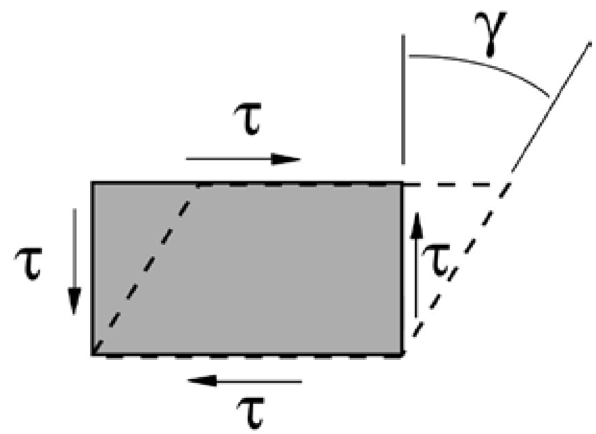
- Elastic deformation
- Elastic strain



$$\epsilon_{xx} = \frac{\Delta L}{L} = \frac{1}{E}\sigma_{xx}$$

$$\epsilon_{yy} = \epsilon_{zz} = \frac{\Delta w}{w} = -\nu\epsilon_{xx}$$

- Elastic shear

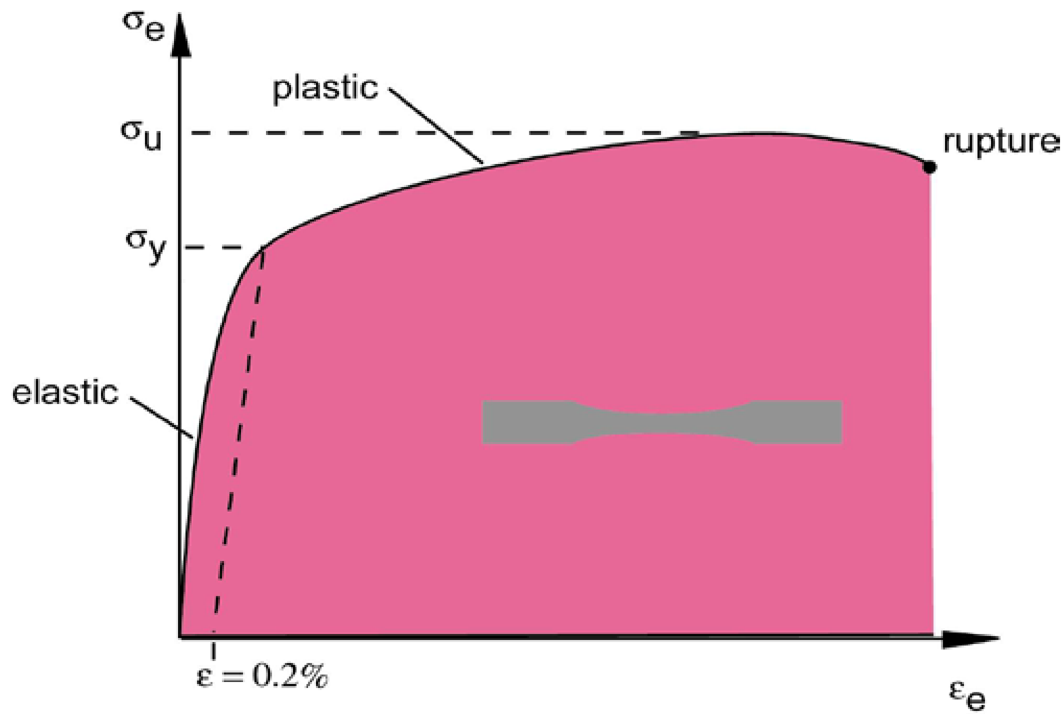


$$\gamma = 2\epsilon_{xy} = \frac{\tau}{G} \quad G = \frac{E}{2(1+\nu)}$$

Youngs' modulus E, shear modulus E, and Poisson ratio n are material properties

Consequences of forces – large strains

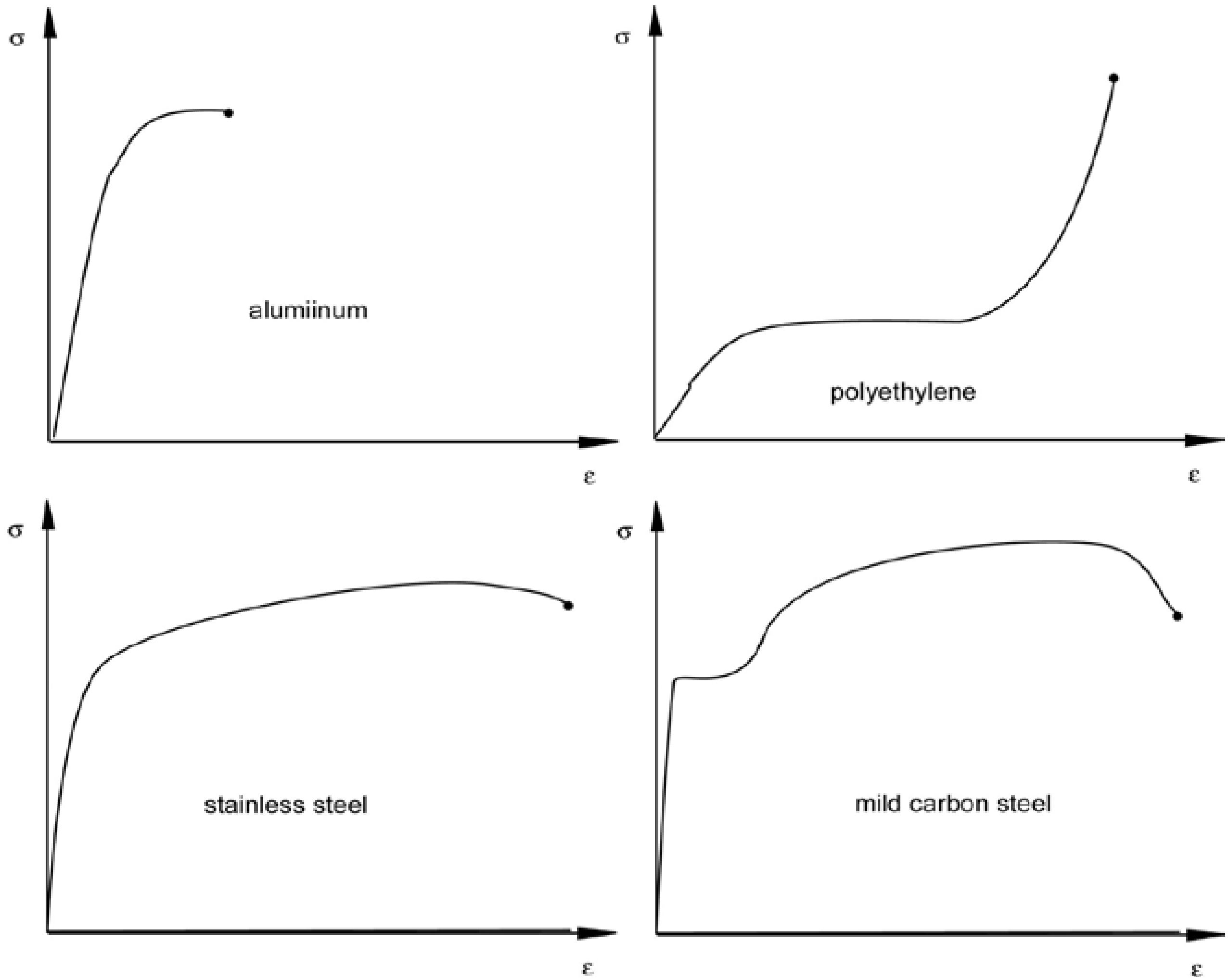
- Onset of yielding for s ~ s_Y
- Necking occurs in plastic regime s > s_Y
- Plastic instability and rupture for s > s_u
- Energy absorption by plastic deformation



Plot is in terms of engineering stress and strain, apparent maximum in stress is due to area reduction caused by necking

$$\epsilon = \int dL/L = \ln(1 + \epsilon_e) \qquad \sigma = \sigma_e(1 + \epsilon_e)$$

Stress-Strain Relationships



Yield and Ultimate Strength

- Yield point s_{YP} determined by uniaxial tension test
- Yielding is actually due to *stress differences* or *shear*. Extension of tension test to multi-axial loading:
  - Maximum shear stress model $t_{max} < s_{YP}/2$
  - Von Mises or octahedral shear stress criterion

$$\tau_{oct} = \frac{1}{3}[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2)]^{1/2}$$

$$\tau_{oct} < 0.47\sigma_{YP}$$

- Onset of localized permanent deformation occurs well before complete *plastic collapse* of structure occurs.

Some Typical Material Properties

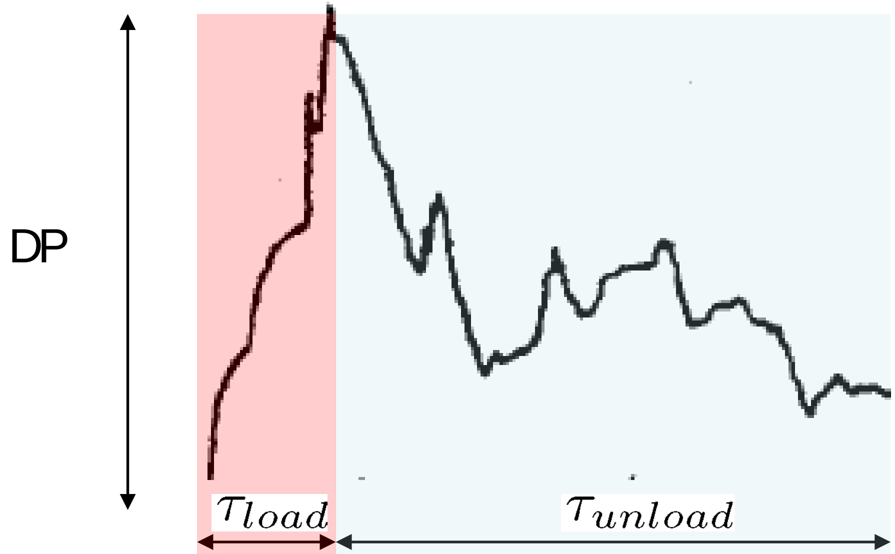
Material	r (kg/m3)	E (GPa)	G (GPa)	n	s_y (MPa)	s_u (MPa)	$e_{rupture}$
Aluminum 6061-T6	2.71×10^3	70	25.9	0.351	241	290	0.05
Aluminum 2024-T4	2.77×10^3	73	27.6	0.342	290	441	0.3
Steel (mild)	7.85×10^3	200	79	0.266	248	410-550	0.18-0.25
Steel stainless	7.6×10^3	190	73	0.31	286-500	760-1280	0.45-0.65
Steel (HSLA)	7.6×10^3	200		0.29	1500-1900	1500-2000	0.3-0.6
Concrete	7.6×10^3	30-50			20-30	-	0
Fiberglass	$1.5\text{-}1.9 \times 10^3$	35-45			-	100-300	-
Polycarbonate	$1.2\text{-}1.3 \times 10^3$	2.6			55	60	-
PVC	$1.3\text{-}1.6 \times 10^3$	0.2-0.6			45-48	-	-
Wood	$0.4\text{-}0.8 \times 10^3$	1-10			-	33-55	-
Polyethylene (HD)	$0.94\text{-}0.97 \times 10^3$	0.7			20-30	37	-

Modes of Structural Response

Mechanism of Structural Deformation

- Stress waves
  - Longitudinal or transverse
  - Short time scale
- Flexural waves
  - Shock or detonation propagation inside tubes
  - Vibrations in shells
- tension or compression
  - Deforms shells
- shearing loads
  - Bends beams and plates

Pressure Loading Characterization



- Structural response time T vs. loading τ_l and unloading τ_u time scales
- Peak pressure D P vs. Capacity of structure
- Loading regimes
  - Slow (quasi-static), typical of flame inside vessels T << t_L or t_u
  - Sudden, shock or detonation waves t_L << T
    - Short duration – Impulsive t_U << T
    - Long duration - Step load T << t_U

Statics vs. Dynamics

- Static loading $T \ll t_l, t_u$
  - Loading and unloading times long compared to characteristic structural response time
  - Inertia unimportant
  - Response determined completely by stiffness, magnitude of load.
- Dynamic loading $T \geq t_l, t_u$
  - Loading or unloading time short compared to characteristic structural response time
  - Inertia important
  - Response depends on time history of loading

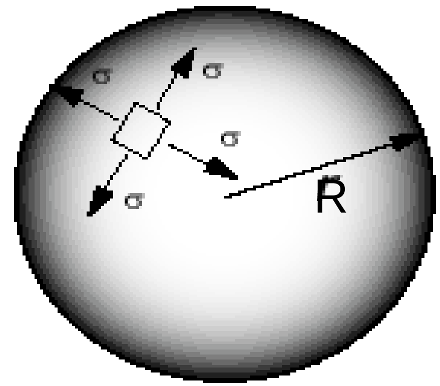
Static Stresses in Spherical Shell

- Balance membrane stresses with internal pressure loading
- Force balance on equator

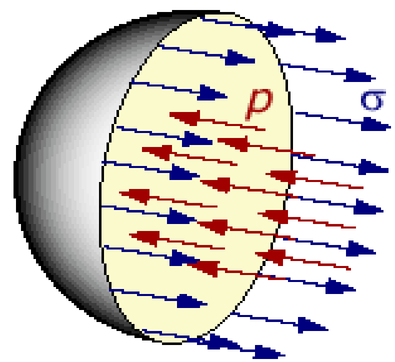
$$4\pi R h \sigma = \pi R^2 \Delta P$$

- Membrane stress

$$\sigma = \frac{R}{2h}\Delta P$$

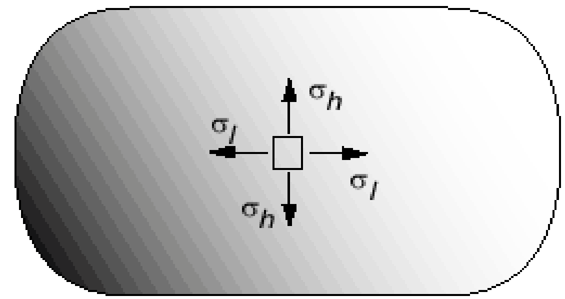


R

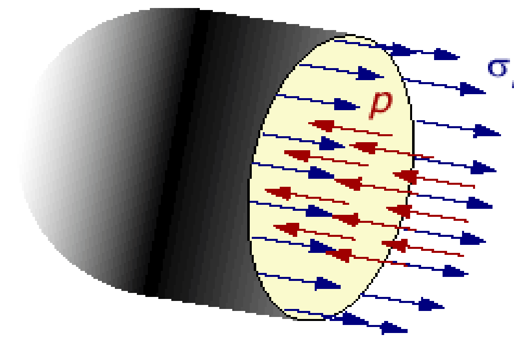


Validate only for thin-wall vessels h < 0.2 R

Static Stresses in Cylindrical Shells

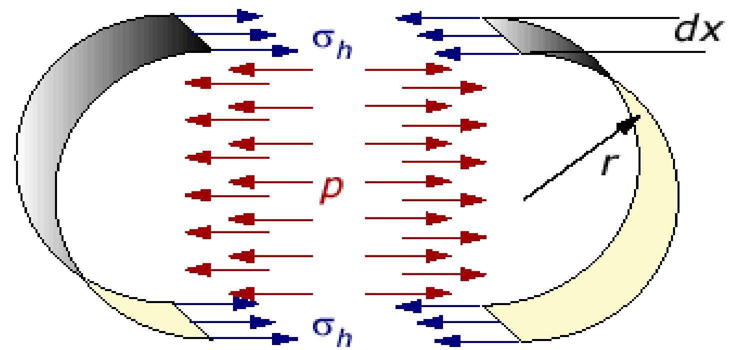


- Biaxial state of stress
- Longitudinal stress due to projected force on end caps.



$$\pi R^2 \Delta P = 2\pi R h \sigma_l \quad \sigma_l = \frac{R}{2h}\Delta P$$

- Radial (hoop) stress due to projected force on equator



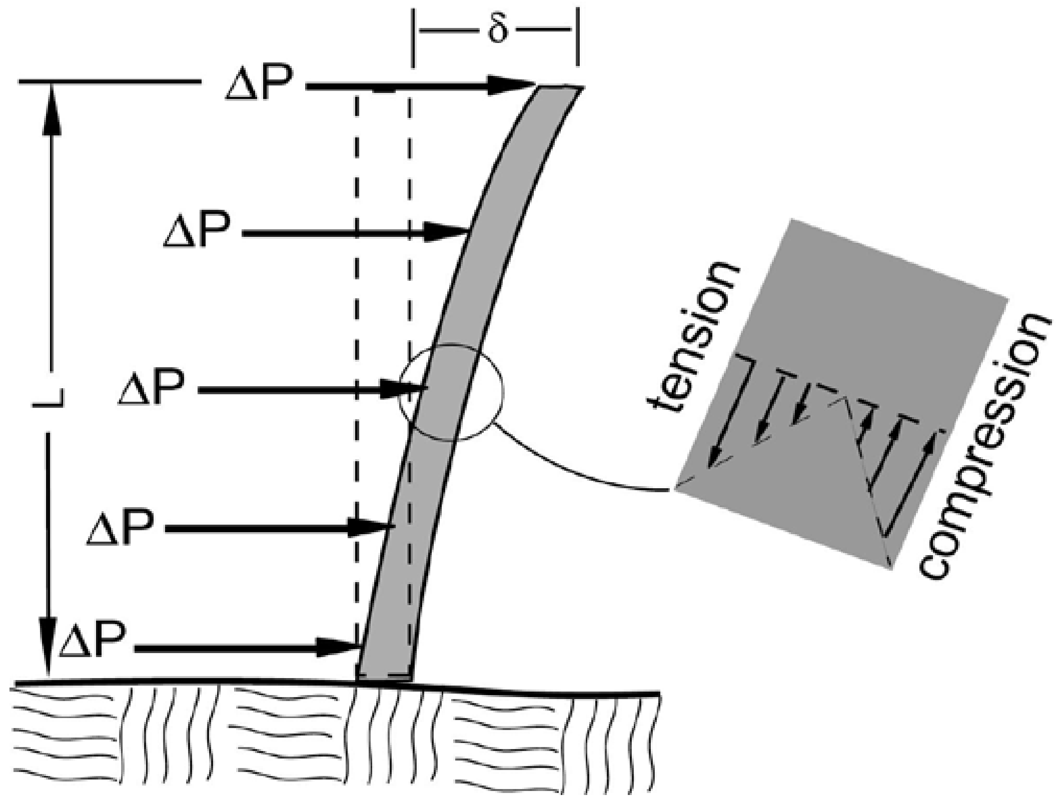
$$2hL\sigma_h = L2R\Delta P \quad \sigma_h = \frac{R}{h}\Delta P$$

Bending of Beams

- Force on beam due to integrated effects of pressure loading

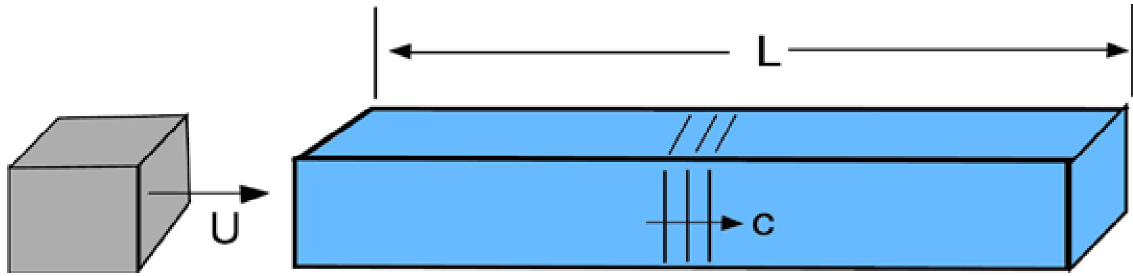
$$F = \int \Delta P dx dy$$

- Pure bending has no net longitudinal stress
- Deflection for uniform loading



$$F = K\delta \qquad K = \frac{8EI}{L^3} \qquad I = \frac{1}{12}bh^3$$

Stress Wave propagation in Solids



- Dynamic loading by impact or high explosive detonation in contact with structure
- Two main types
  - Longitudinal (compression, P-waves)
  - Transverse (shear, S-waves
- Stress-velocity relationship (for bar P-waves)

$$c_l \approx \sqrt{\frac{E}{\rho}} \qquad c_s = \sqrt{\frac{G}{\rho}}$$

C_l exact for bar

$$\sigma = \rho c u$$

Is direct stress wave propagation important?

- Time scale very fast compared to main structural response $T \sim L/C$

	C_l (m/s)	C_s(m/s)
Steel	6100	3205
Aluminum	3205	3155

  - Average out in microseconds (10^{-6} s)

- Stress level low compared to yield stress

  $s \sim D\,P \sim 10$ MPa $\ll s_Y = 200$- 500 MPa

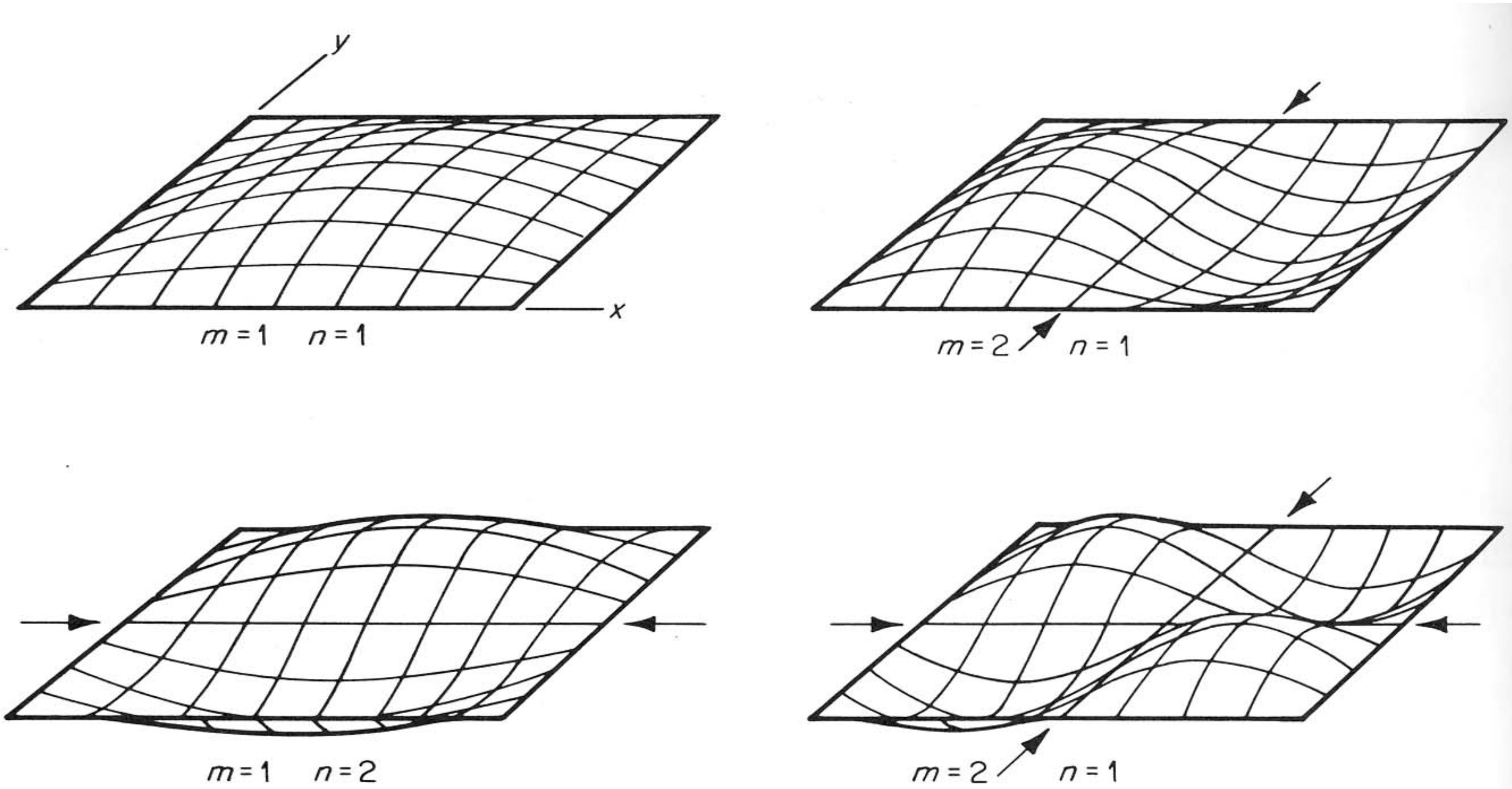
Direct stress propagation within the structural elements is usually not relevant for structural response to gaseous explosions. Important for high explosive when structure is very close or in direct contact with explosive

Vibration of Plates, Beams, & Structures

- Element vibrations
  - Membranes or shells $$\rho h \frac{\partial^2 w}{\partial^2 t} - \Sigma \nabla_\perp^2 w = \Delta P \quad \Sigma = \text{tension}$$
  - Plates or beams $$\rho h \frac{\partial^2 w}{\partial^2 t} - D \nabla_\perp^4 w = \Delta P \quad D = \frac{Eh^3}{12(1-\nu^2)}$$
  - Modes of flexural motion
    - Standing waves, frequencies w_i
    - Propagating dispersive waves w(k)
- Coupled motions of entire structure

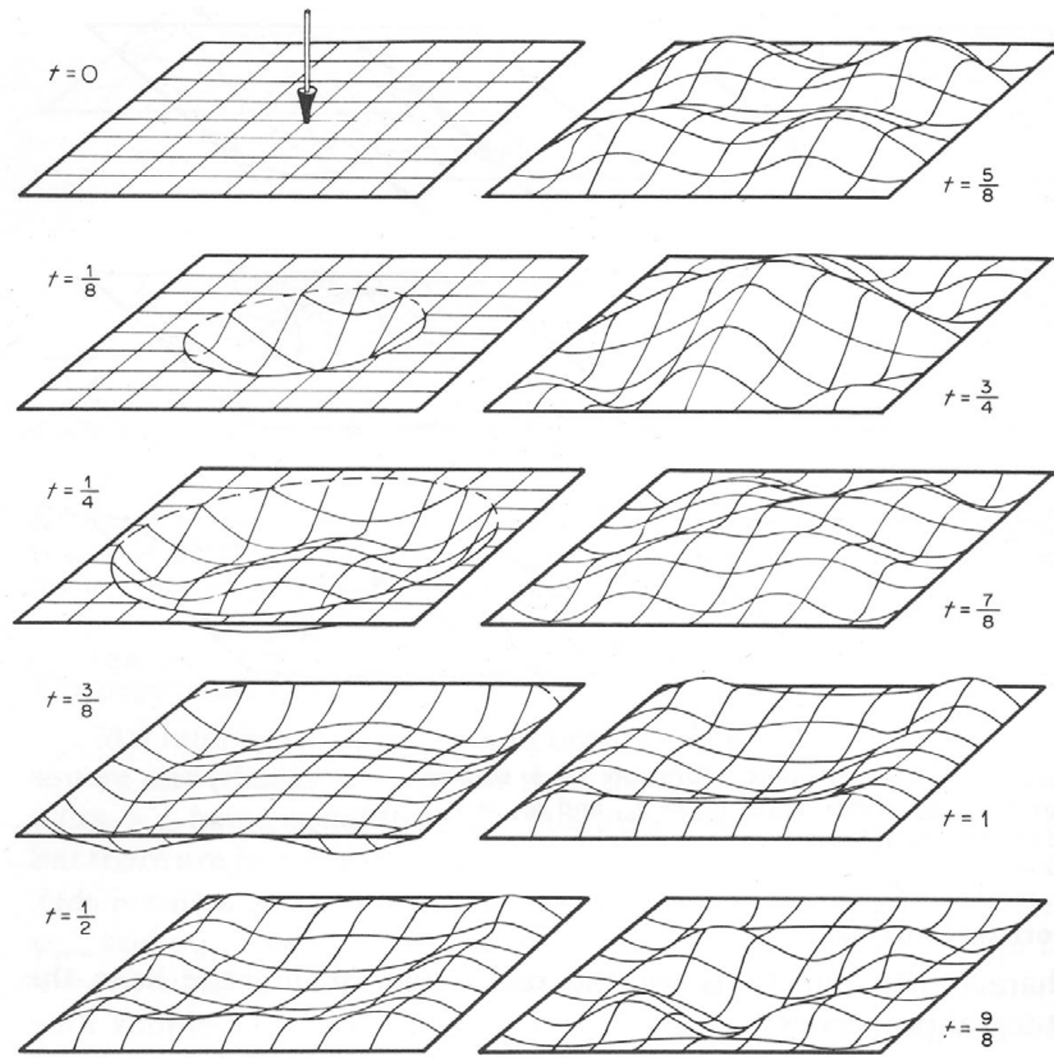
$$M \frac{d^2 \vec{X}}{dt^2} + K\vec{X} = \vec{F}$$

Free Vibration of Clamped Plate



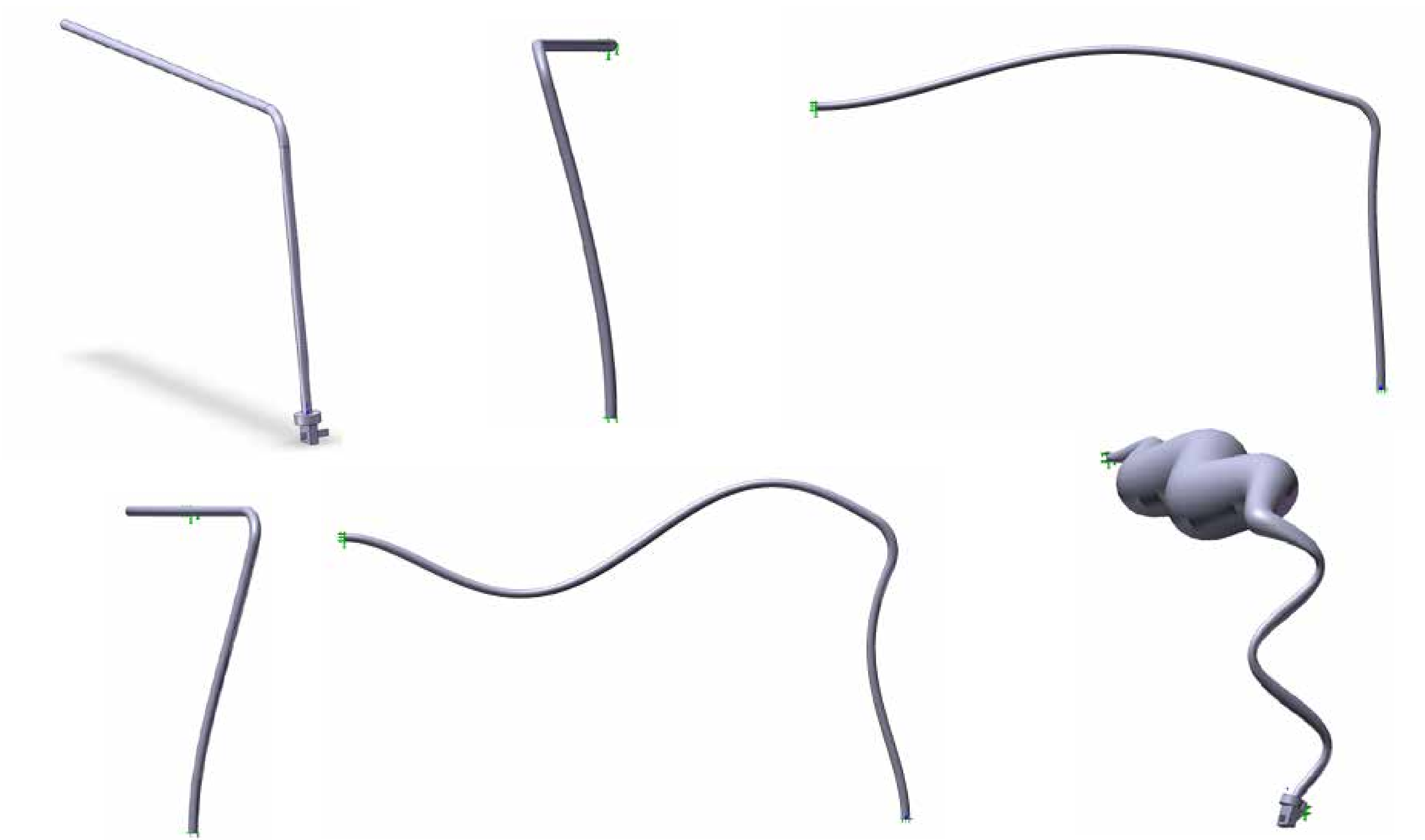
Morse and Ingard Theoretical Acoustics

Transient Response of Clamped Plate

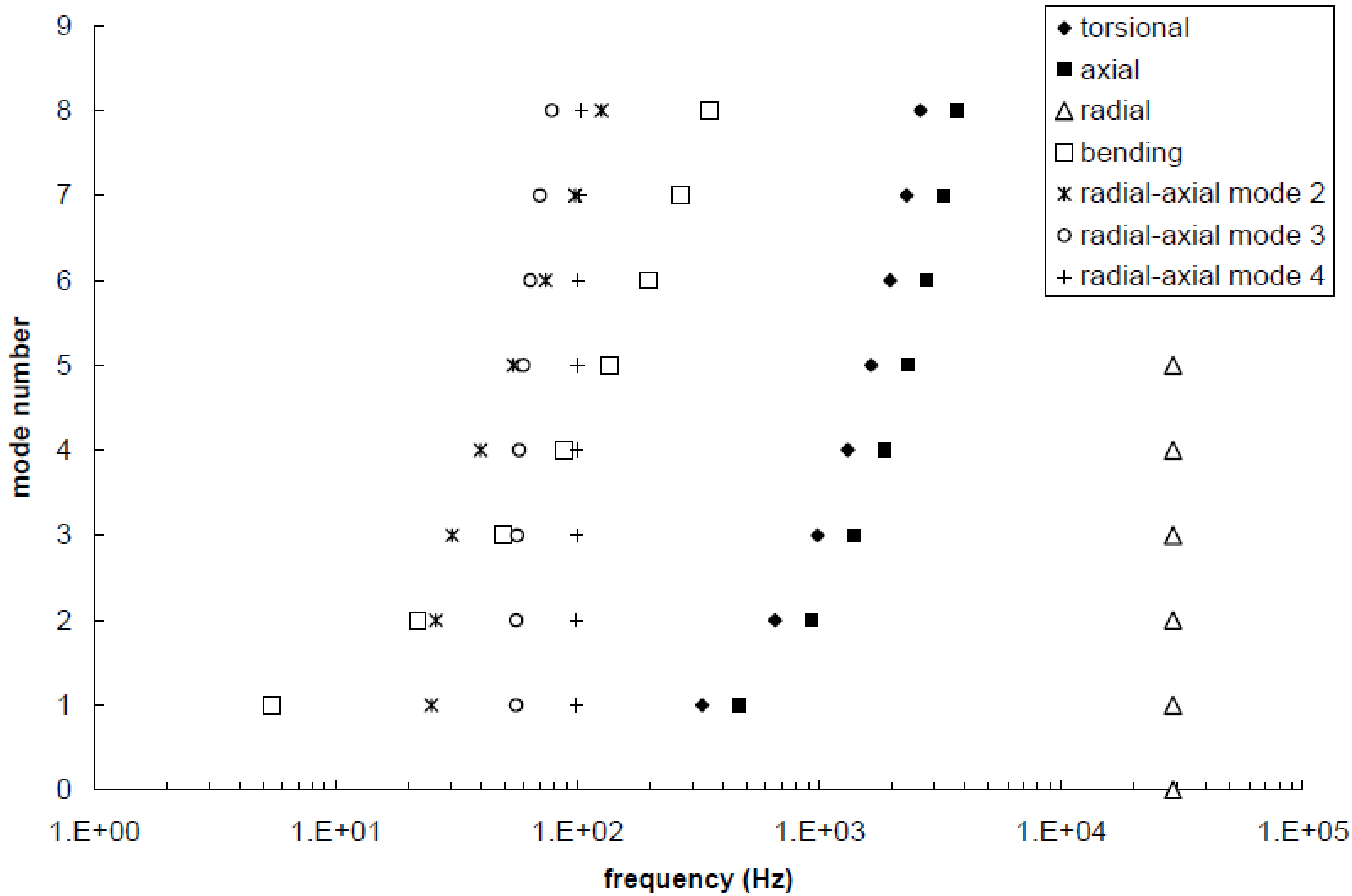


Morse and Ingard
Theoretical Acoustics

Modes of a Piping System



Piping System Oscillation Frequencies



Two Special Situations

- Loading on small objects
  - Represent forces as drag coefficients dependent on shape and orientation and function of flow speed.

$$F = ½\ r\ \ V^2\ C_D(\text{Mach No, Reynolds No})\ \text{x Frontal Area}$$

- Thermal stresses.
  - Thermal stresses are stresses that are created by differential thermal expansion caused by time-dependent heat transfer from hot explosion gases. This is distinct from the loss of strength of materials due to bulk heating, which is a very important factor in fires which occur over very much longer durations than explosions.

$$e = s/E\ + a\ D\,T$$

Modeling Structural Response

Determining structural response

- Issues
  - Static or dynamic
    - depends on time scale of response compared to that of load
      - impulsive (short loading duration)
      - sudden (short rise time)
      - quasi-static (long rise time)
  - Elastic or elastic-plastic
    - depends on magnitude of stresses and deformation
      - yield stress limit appropriate for vessels designed to contain explosions
      - maximum displacement or deformation limit appropriate for determining or preventing leaks or rupture under accident conditions

Simple estimates

- Strength of materials approach assuming equivalent static load
  - Useful only for very slow combustion (static loads) and negligible thermal load
- Theory of elasticity and analytical solutions
  - static solutions for many common vessels and components (Roarke's Handbook)
  - dynamic solutions available for simple shapes – mode shapes and vibrational periods are tabulated.
  - Energy methods with assumed mode shapes (Baker et al method)
  - Analytical models for traveling loads available for shock and detonation waves
  - Transient thermo-elastic solutions available for simple shapes
- Theory of plasticity
  - rigid-plastic solutions available for simple shapes and impulsive loads.
  - Energy methods can provide quick bounds on deformation
- Empirical correlations
  - Test data available for certain shapes (clamped plates) and impulsive loads
  - Pressure-impulse damage criteria have been measured for many items and people subjected to blast loading
- Spring-mass system models
  - single degree of freedom
  - multi-degree of freedom
  - elastic vs plastic spring elements

Simple Structural Models

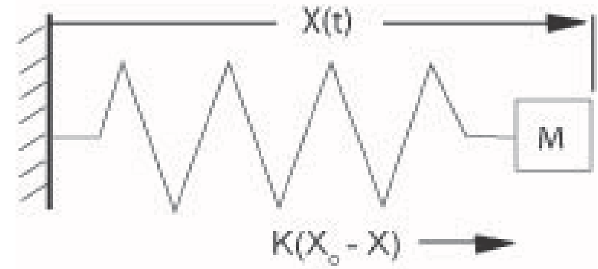
- Ignore elastic wave propagation within structure
- Lump mass and stiffness into discrete elements
  - Mass matrix M
  - Stiffness matrix K
  - Displacements X_i
  - Applied forces F_i
- Equivalent to modeling structure as coupled "spring-mass" system

$$\sum_k M_{ik} \frac{d^2 X_k}{dt^2} + \sum_k K_{ik} X_k = F_i$$

- Results in a spectrum of vibrational frequencies w_l corresponding to different vibrational modes
  - Fundamental (lowest) mode usually most relevant

Single Degree of Freedom Models (SDOF)

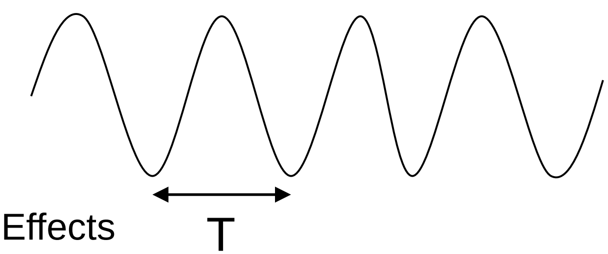
- Effective mass M
- Effective stiffness K
- One displacement motion X
- Force = mass x acceleration
- Equivalent to spring-mass system
- Elastic motion is oscillation of displacement x = X-X_o with period T



$$k(X_o - X) = M\frac{d^2}{dt^2}(X - X_o)$$

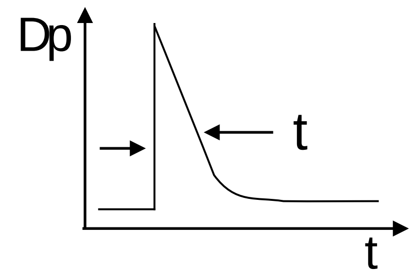
$$\frac{d^2x}{dt^2} + \omega^2 x = 0$$

$$\omega = \sqrt{\frac{K}{M}} = \frac{2\pi}{T}$$



Forced Oscillation of SDOF system

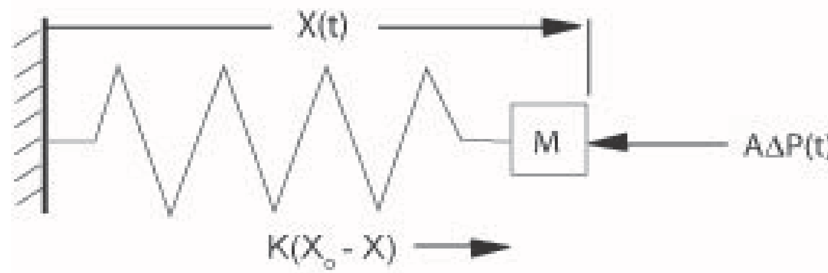
- Blast wave characterized by
  - Peak pressure DP
  - Decay time t



- Forced harmonic oscillator,

F(t) = ADP(t)

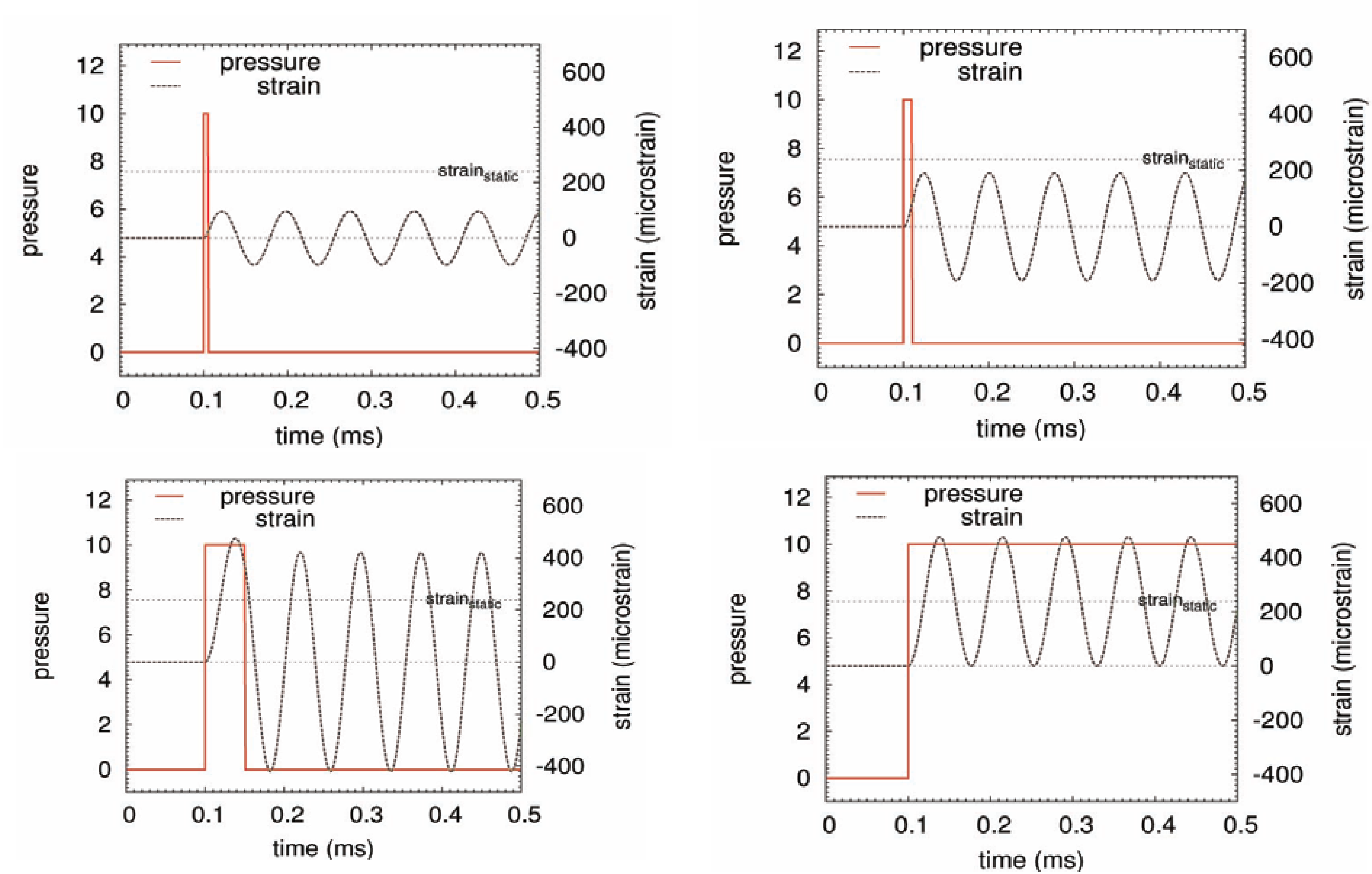
$$\frac{d^2x}{dt^2} + \omega^2 x = \frac{F(t)}{M}$$



- Response is forced oscillation

$$x(t) = \int_0^t \frac{F(t)}{M} \frac{\sin \omega (t - t')}{\omega} \, dt'$$

SODF - Square Pulse



SDOF -Impulsive Regime

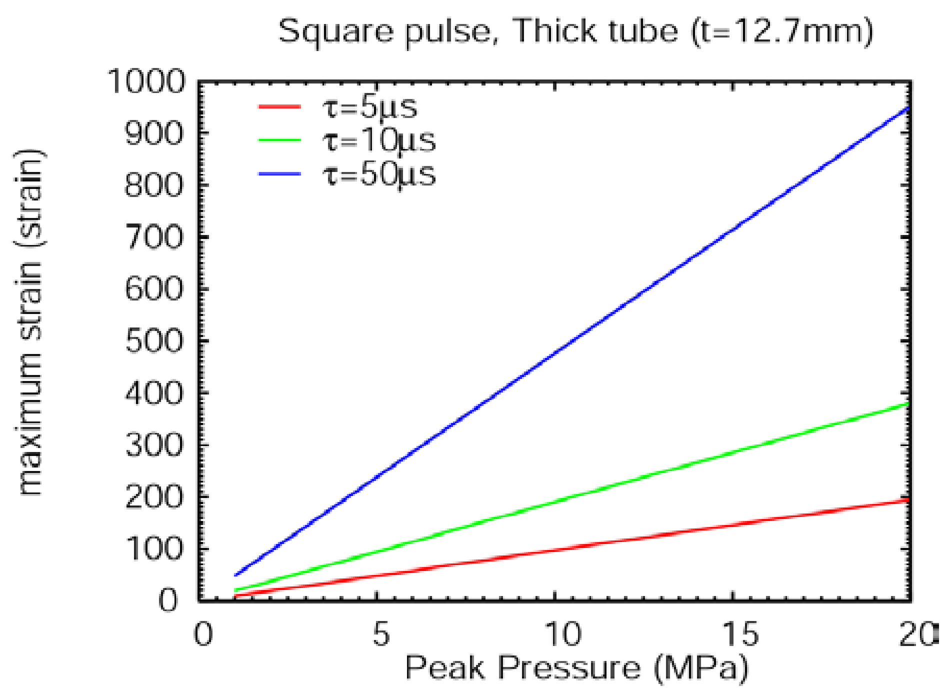
- Sudden load application, short duration of loading t << T
- Linear scaling between maximum strain/ displacement and impulse in elastic regime:
- Impulse generates initial velocity

$$v(0+) = \frac{\mathcal{I}}{m} \qquad \mathcal{I} = \int_o^\tau F(t)\, dt$$

- Energy conservation determines maximum deflection

$$\frac{1}{2} m v(0+)^2 = \frac{1}{2} k X_{max}^2$$

$$X_{max} = \mathcal{I}/\sqrt{km}$$

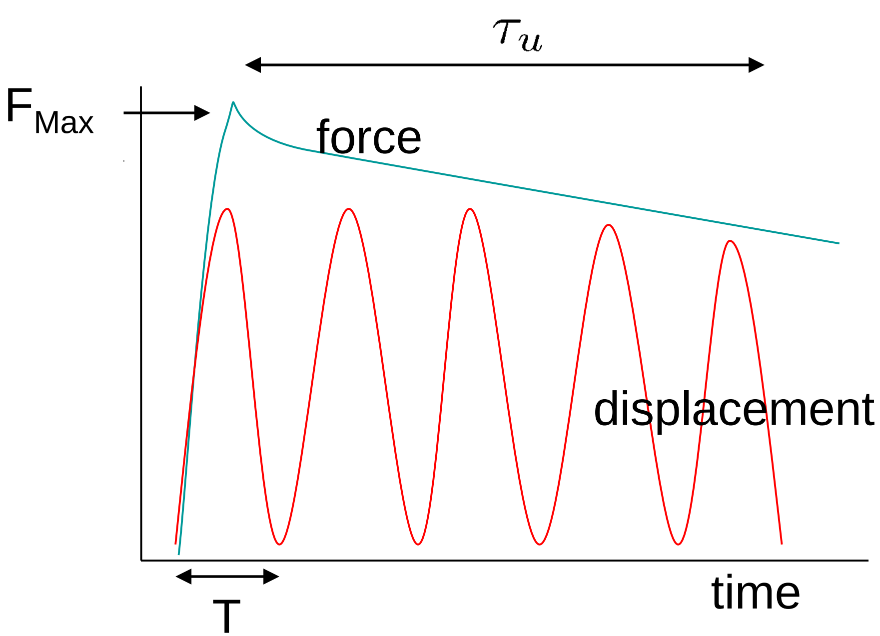


SDOF – Sudden regime

- Quick application of load and long duration

$$t_u >> T$$

- Peak deflection is twice static value for same maximum load



$$\int_o^{t_{max}} \frac{dX}{dt} \times \left(m \frac{d^2X}{dt^2} + kX = F(t) \right) dt$$

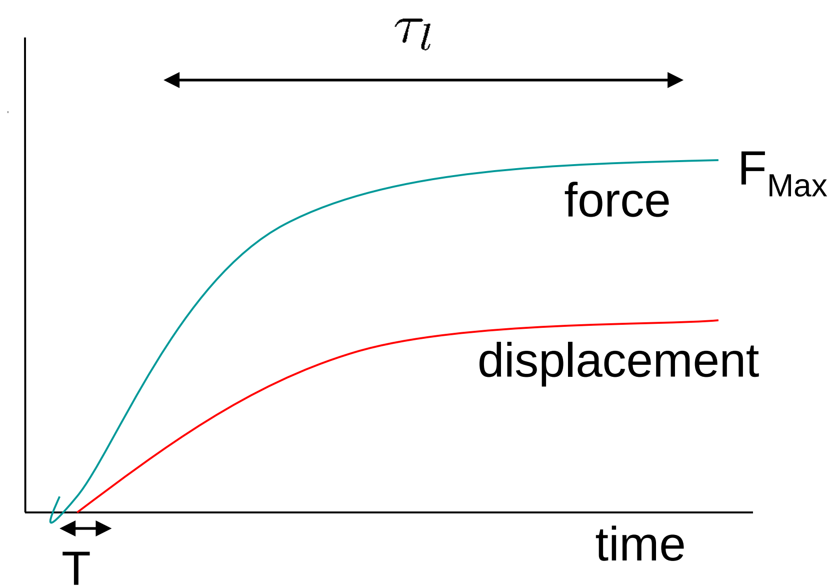
$$X_{max} = 2\frac{F_{max}}{k} = 2X_{static}$$

SDOF – Static Regime

- Very slow application of load – (quasi-static) no oscillations

$$T << t_u \text{ or } t_L$$

- Static deflection



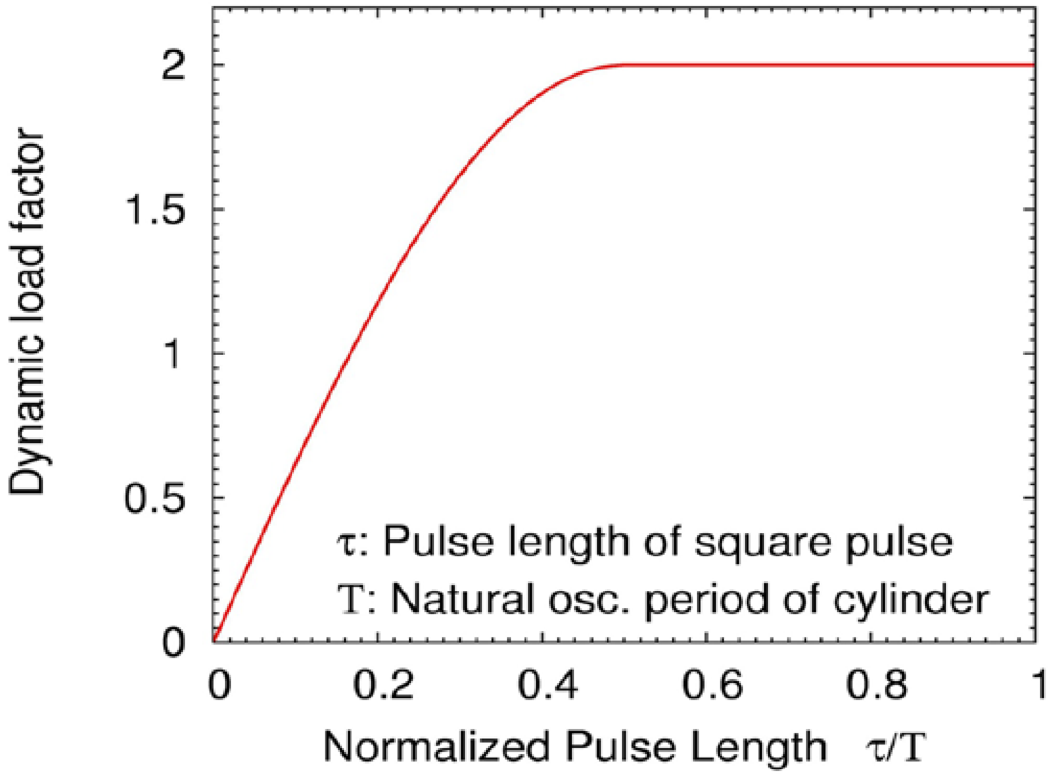
$$m\frac{d^2x}{dt^2} = 0$$

$$kX_{static}(s) = F(t)$$

$$X_{max} = \frac{F_{max}}{k}$$

SDOF - Dynamic load factor (DLF)

$$\text{DLF} = X_{max}/X_{static} = \Phi(\tau/T)$$



SDOF - Plasticity

- Replace kX with nonlinear relationship based on flow stress curve s(e)
- Energy absorbed by plastic work is much higher than elastic work
- Peak deformation for impulsive load scales with impulse squared.

$$\int_0^{\epsilon_y} \sigma \, d\epsilon = \frac{\sigma_y \epsilon_y}{2} \; .$$

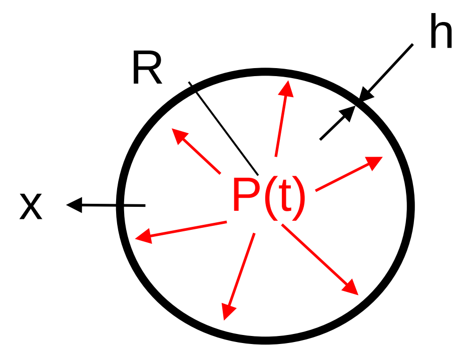
$$\epsilon_{max} = \frac{\rho}{2\sigma_y} \left(\frac{I}{\rho h} \right)^2$$

$$\epsilon_{max} = \frac{P_m^2 \, \tau^2}{2\sigma_y \rho h^2} \; .$$

Example of SDOF Modeling

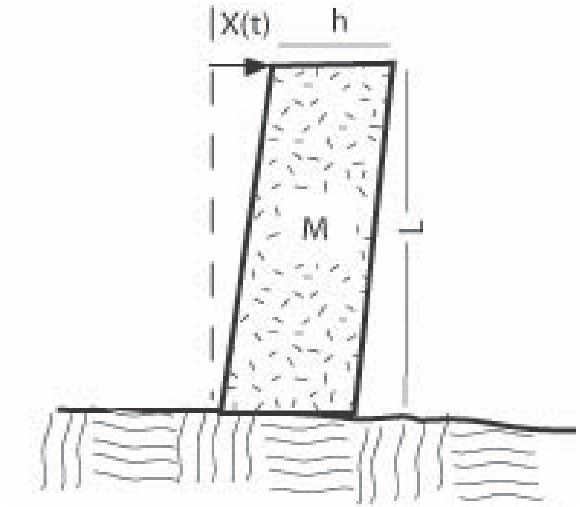
- Radial oscillation of cylinders

$$\frac{d^2x}{dt^2} + \frac{E}{\rho R^2}x = \frac{\Delta P(t)}{\rho h} \qquad \omega = \frac{1}{R}\sqrt{\frac{E}{\rho}}$$



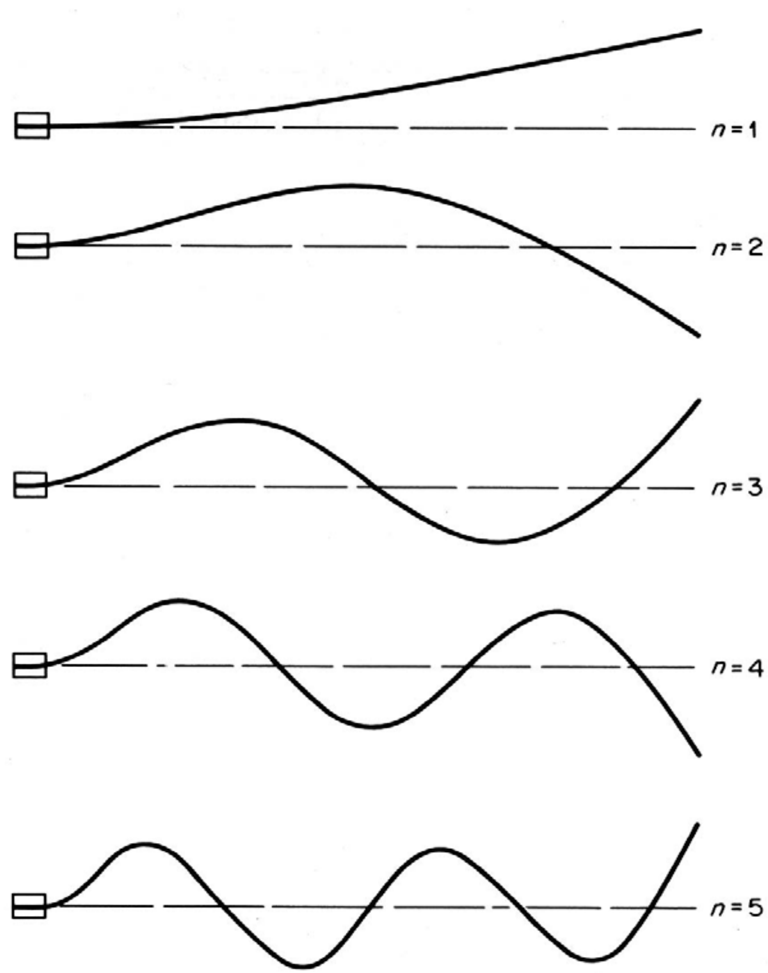
- Bending of beams or columns

$$M' = \frac{6}{15}M \qquad K = \frac{EI8}{L^3} \qquad \omega = 3.5\sqrt{\frac{EI}{ML^3}}$$



Frequencies are "lowest or fundamental mode" – these are usually the most important modes for structural response to explosions.

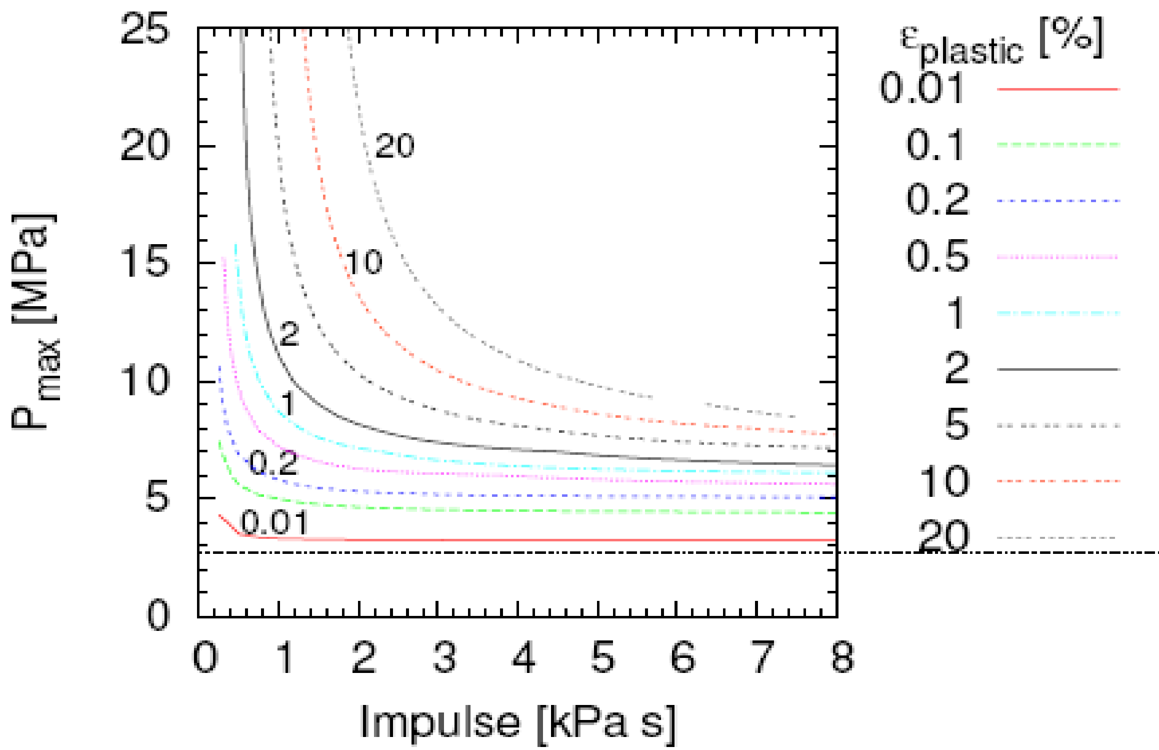
Modes of Beam Oscillation



Morse and Ingard – Theoretical Acoustics

Pressure-Impulse (P-I) Structure Response

- More realistic representation of response
- For fixed X_{max} and pulse shape, unique relation between peak pressure (P) and impulse (I)

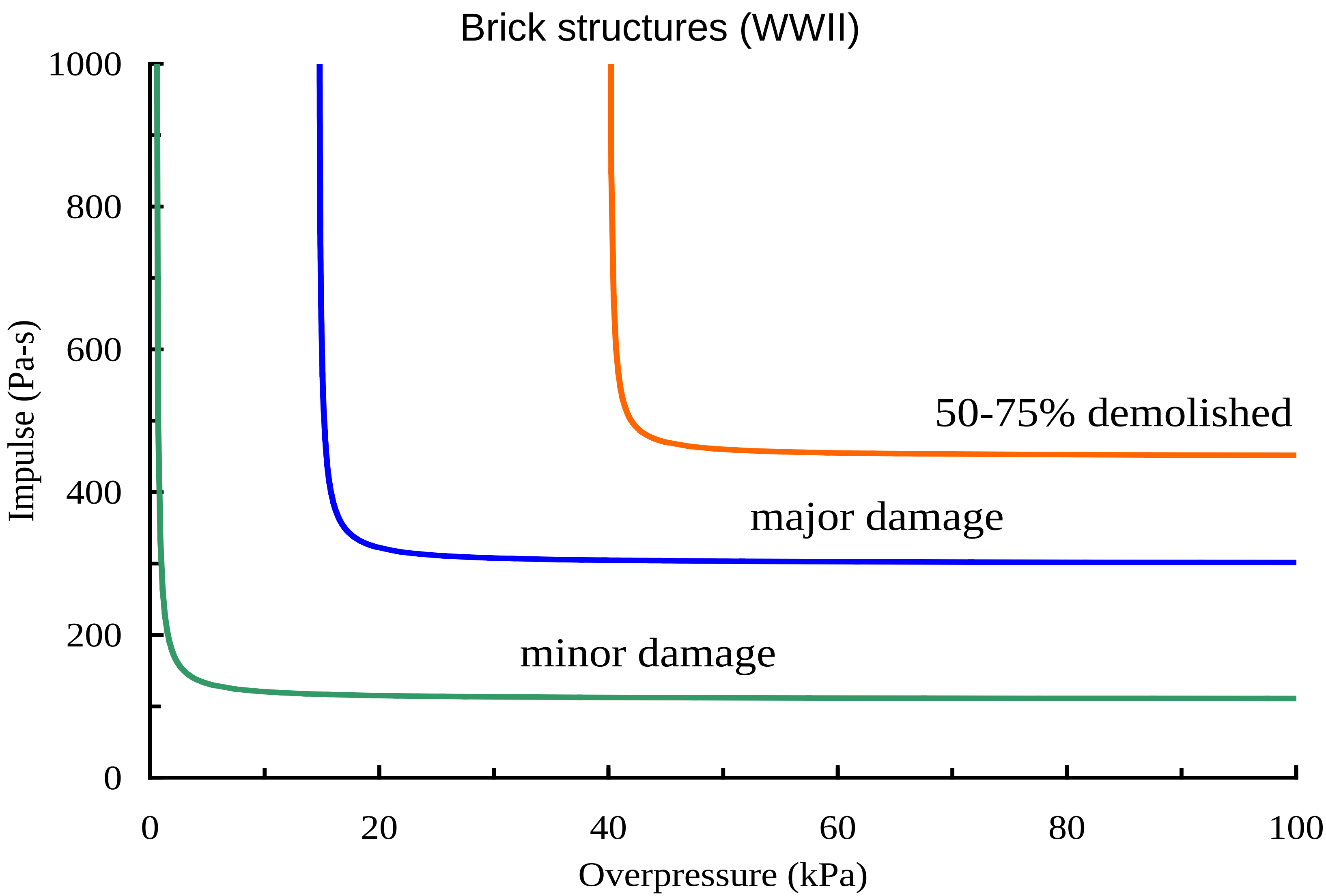


Shock wave with exponential tail

Limiting cases:

1. Short pulse – impulse determines damage
2. Long pulse – peak pressure determines

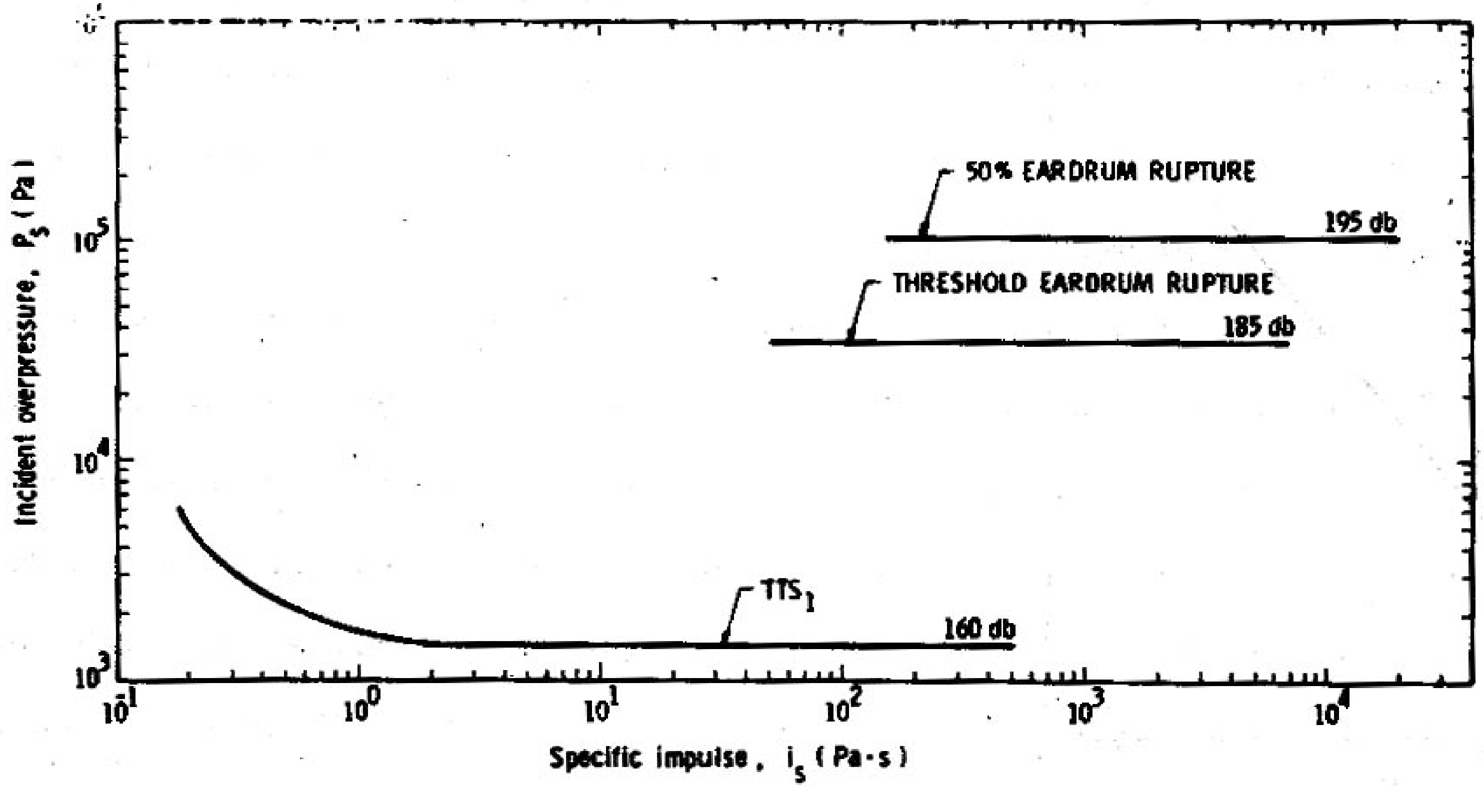
P-I Damage thresholds II



From Baker et al.

P-I Damage Thresholds II

Ear drums



Example

- Blast wave from 50 lbs TNT equivalent at 100 ft range
- Use charts or correlations from Dorofeev

$$P_1^* = 0.34/(R^*)^{4/3} + 0.062/(R^*)^2 + 0.0033/(R^*)^3$$

$$I_1^* = 0.0353/(R^*)^{0.968}$$

E = 4.52x50/2.2 = 103 MJ R_s = $(1 \times 10^8 / 10^5)^{1/3}$ = 10 m or 33 ft

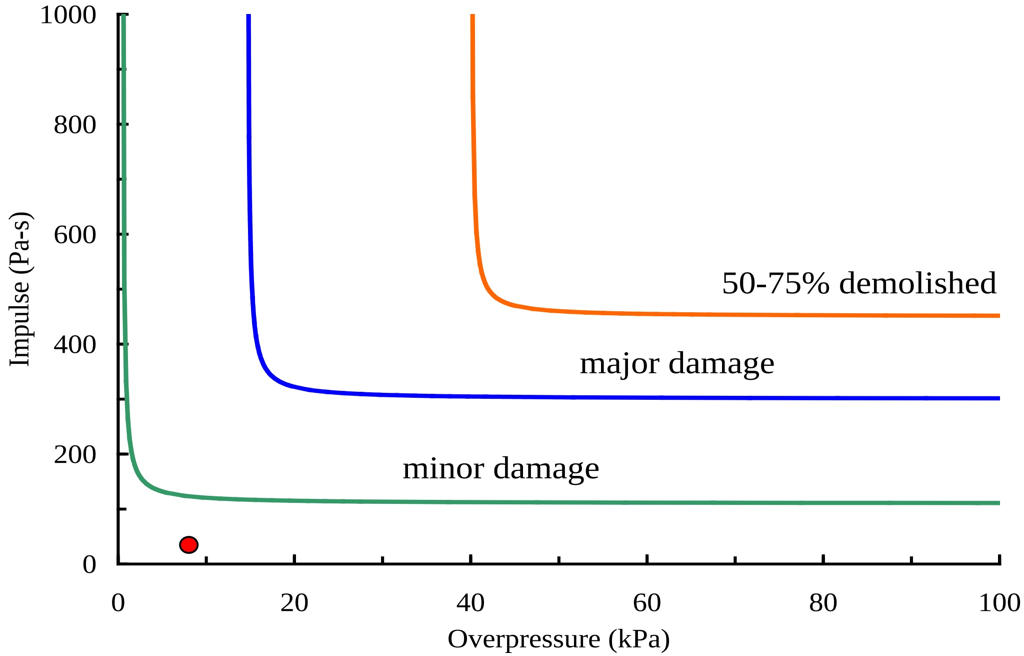
R* = 30.5/10 = 3 P* = 0.085 or DP = 1.25 psi (8.5 kPa)

I* = 0.012 T = 3/340 = 8.8 ms I = 10 Pa s

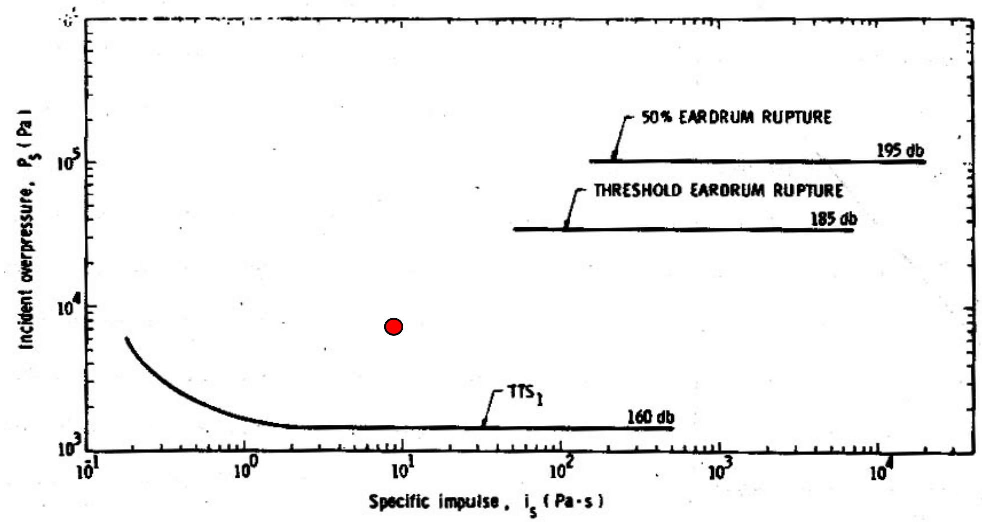
These are “side-on” parameters, normal reflection will approximately double overpressure and impulse in this regime.

P-I Results

Brick structures



Ear drums



Your ears will be ringing but the building is undamaged!

Numerical simulation

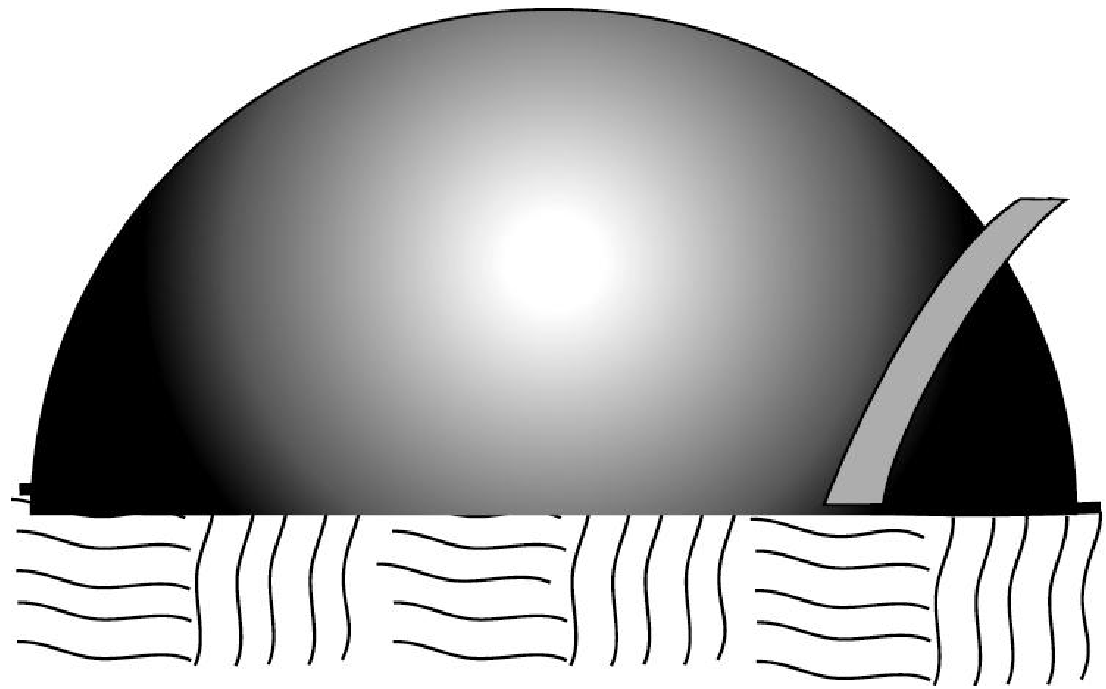
- Finite element models
  - static
  - vibration: mode shape and frequencies
  - dynamic
    - transient response to specified loading
    - elastic
    - plastic/fracture
- Numerical integration of simple models with complex loading histories
  - spring-mass systems
  - Elasticity with assumed mode shape

Blast Loading Dynamic Response

Example: Cantilever Beam

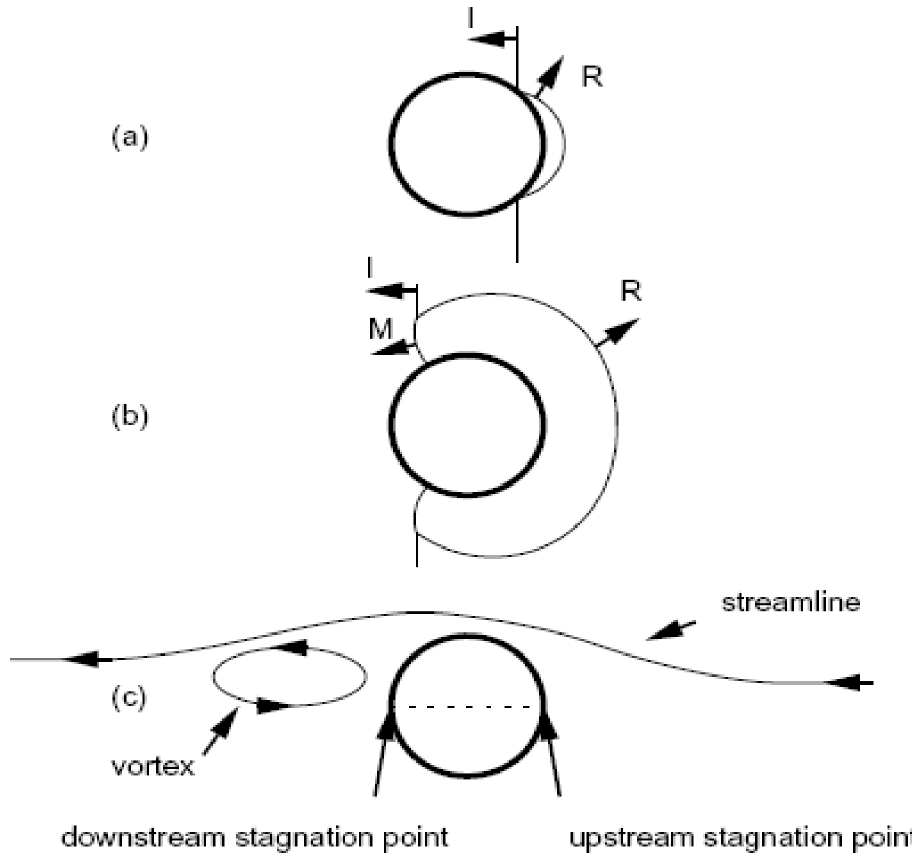
Blast Incident on a Cantilever Beam

- Blast loading of a cantilever beam
- Forces
  - Initial impulse of shock
  - Flow and drag
- Elastic response
  - Giordona et al
- plastic response
  - Van Netton and Dewey



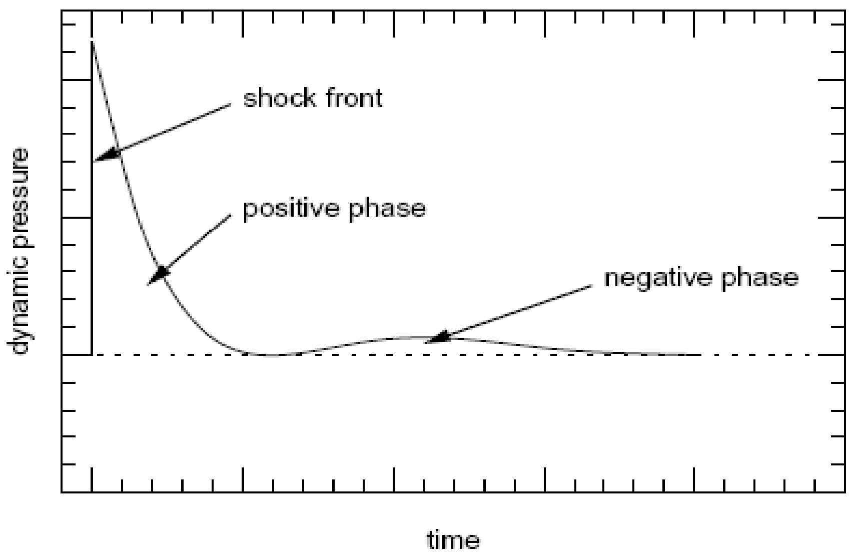
Forces on Blast-loaded Cantilever

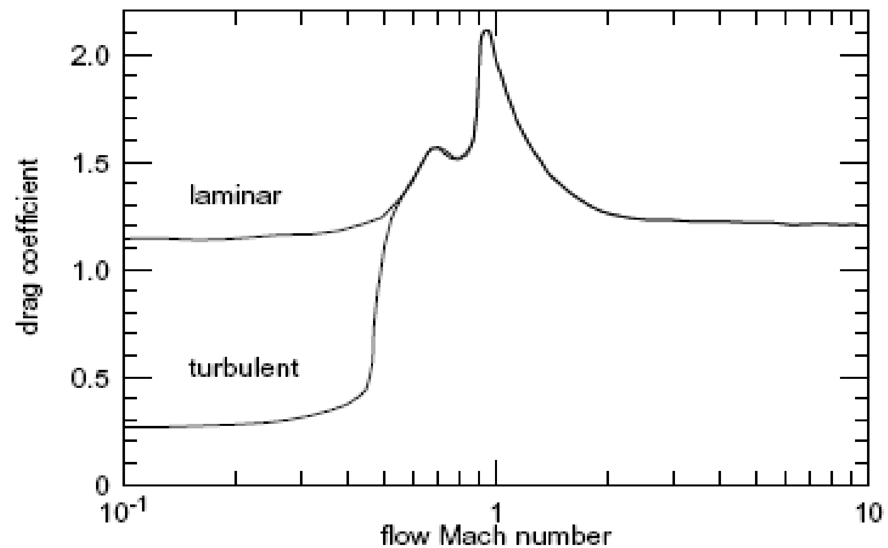
- Shock wave interaction
  - Sudden load to arrival of shock and propagation around cylinder
  - Usually impulsive
- Following flow
  - Continuous load due to separated flow around cylinder.
  - Transient drag loading



Van Netten and Dewey, Shock Waves (1997) 7: 175–190

Force due to flow induced by blast wave



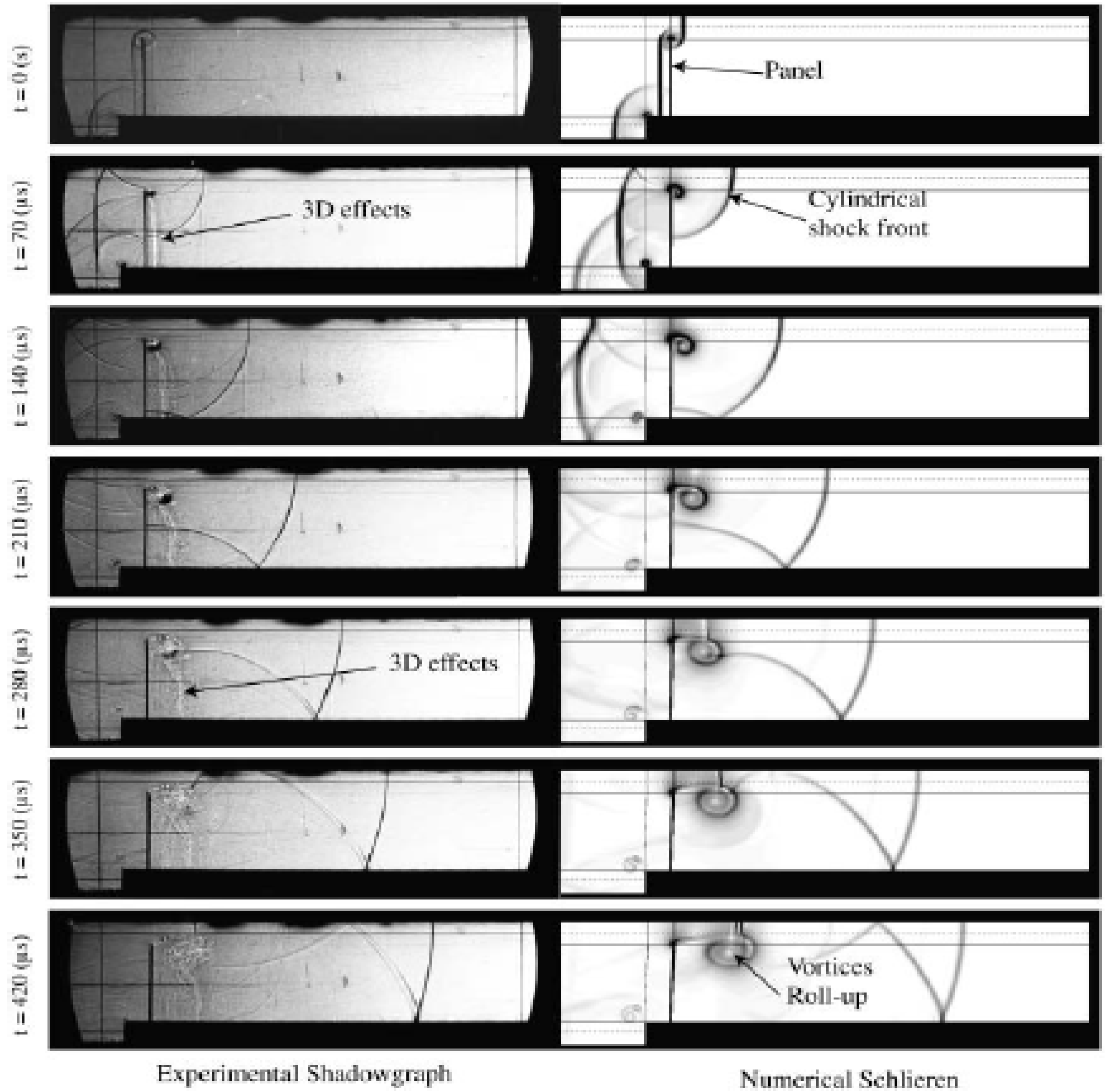


Dynamic Pressure $\frac{1}{2}\rho u^2$

Drag coefficient $C_D(Ma, Re) = \dfrac{F}{\frac{1}{2}\rho u^2 A}$

Van Netten and Dewey, Shock Waves (1997) 7: 175–190

Initial stages of shock diffraction over a cantilever beam



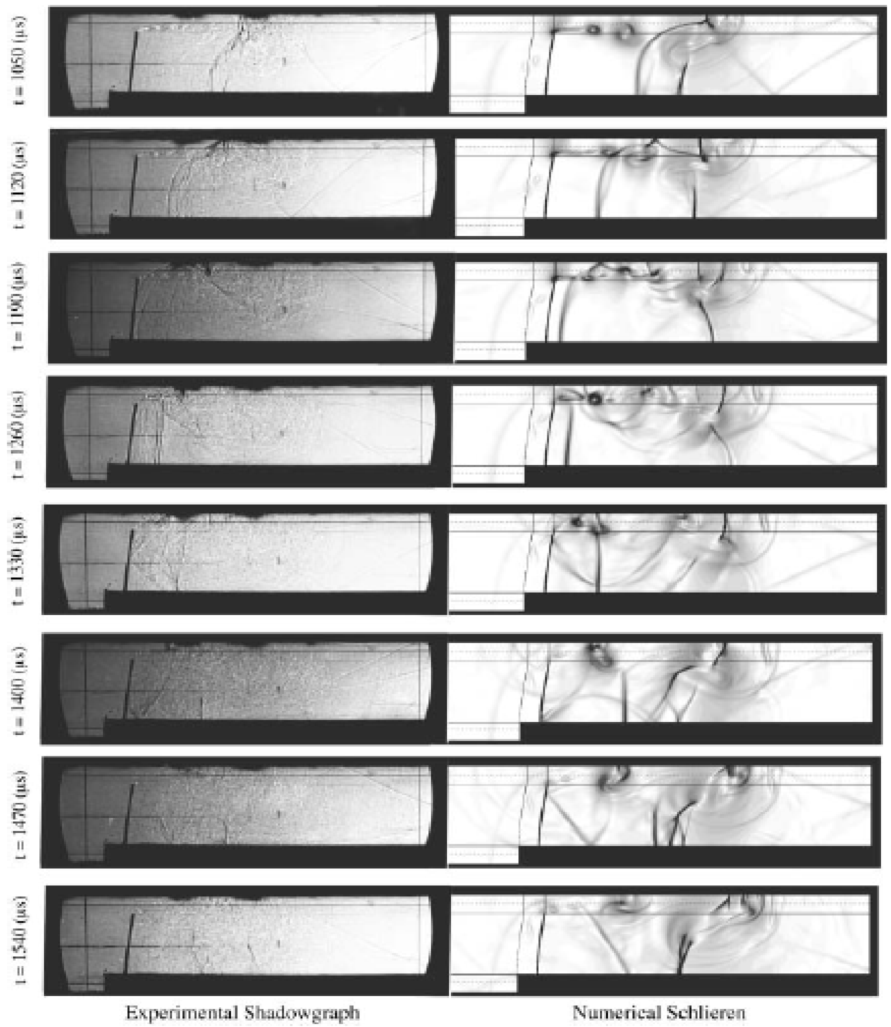
Giordano et al, Shock Waves 14 (1-2), 103-110, 2005.

Immediately after the shock wave passes over the beam there is no deflection.

Purely elastic case.

Experiment (left)
Computation (right)

Later stages of diffraction over a cantilever beam



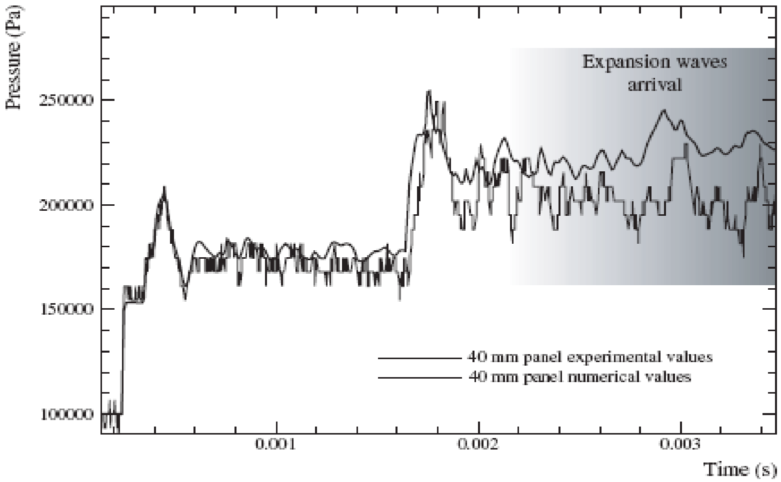
After some time, the beam starts to deform. Dynamic response of beam and inertia are important physical effects.

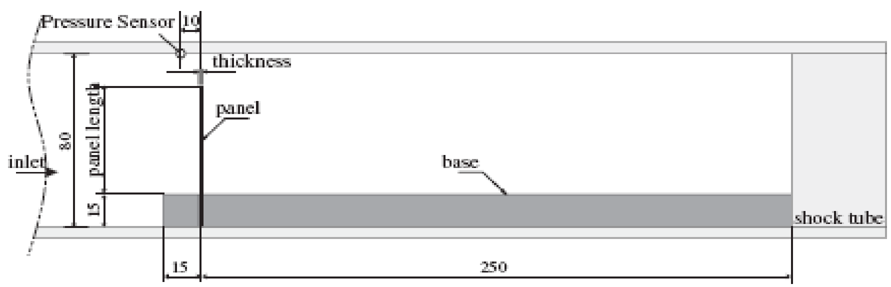
Purely elastic case.

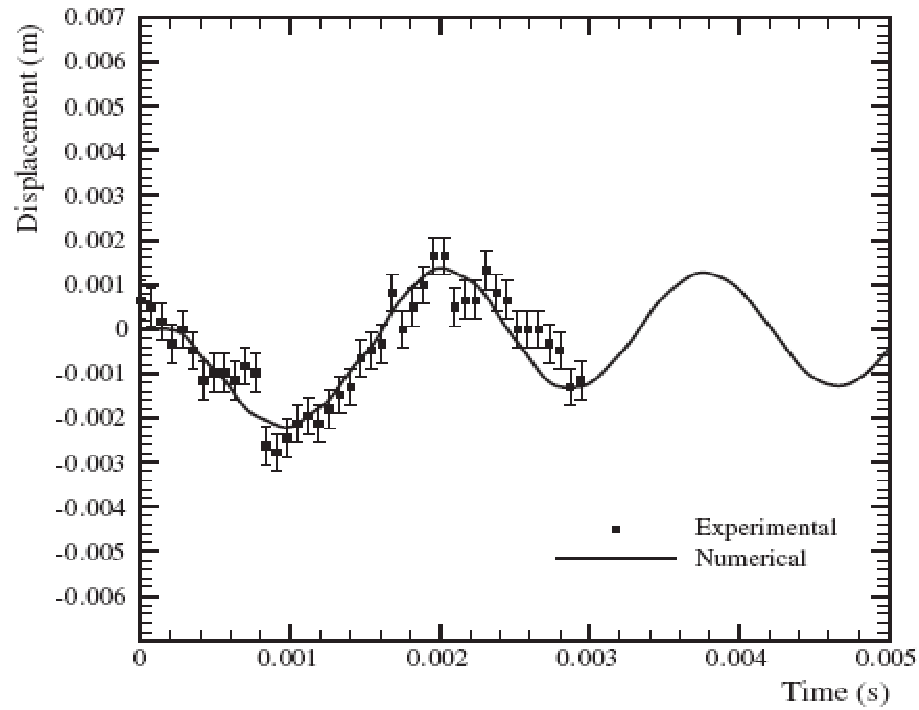
Experiment (left)
Computation (right)

Giordano et al, Shock Waves 14 (1-2), 103-110, 2005.

Applied Load and Oscillations of Beam



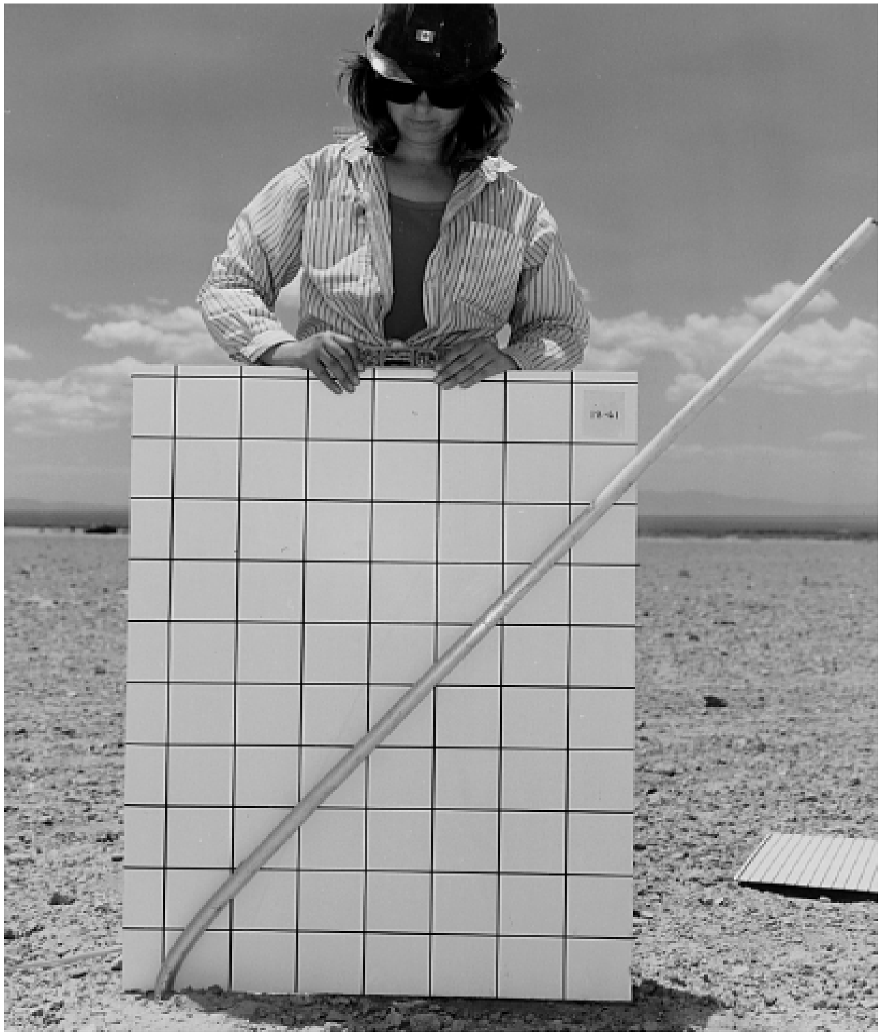




Note the harmonic motion of the beam after incident and reflected shock.

Giordano et al, Shock Waves 14 (1-2), 103-110, 2005.

Plastic Deformation of Blast loaded Cantilever



Permanent deformation of beam due to formation of a "plastic hinge" at the base. Stresses exceed the yield strength of the material and beam remains permanently bent over. Deflection depends on loading history.

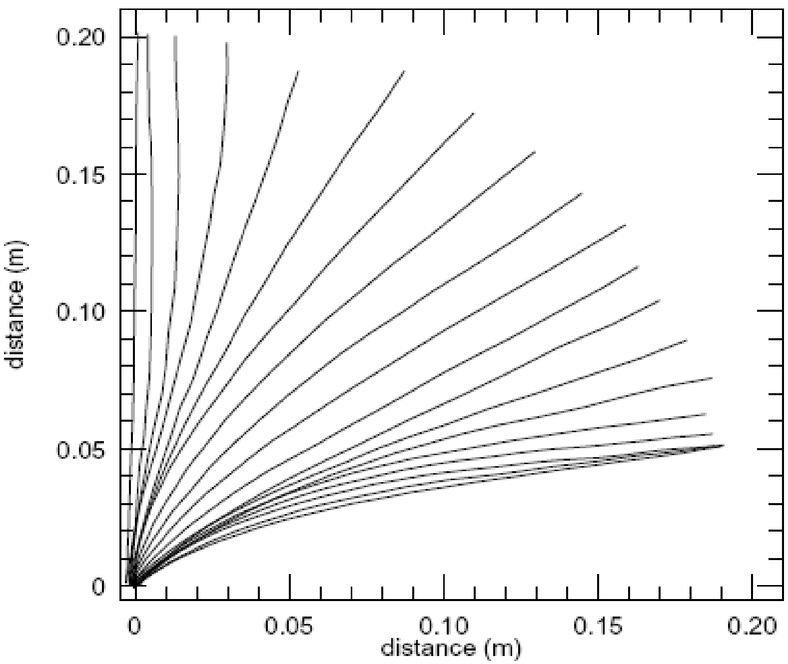
Can be used as a "blast gage" for ideal explosives.

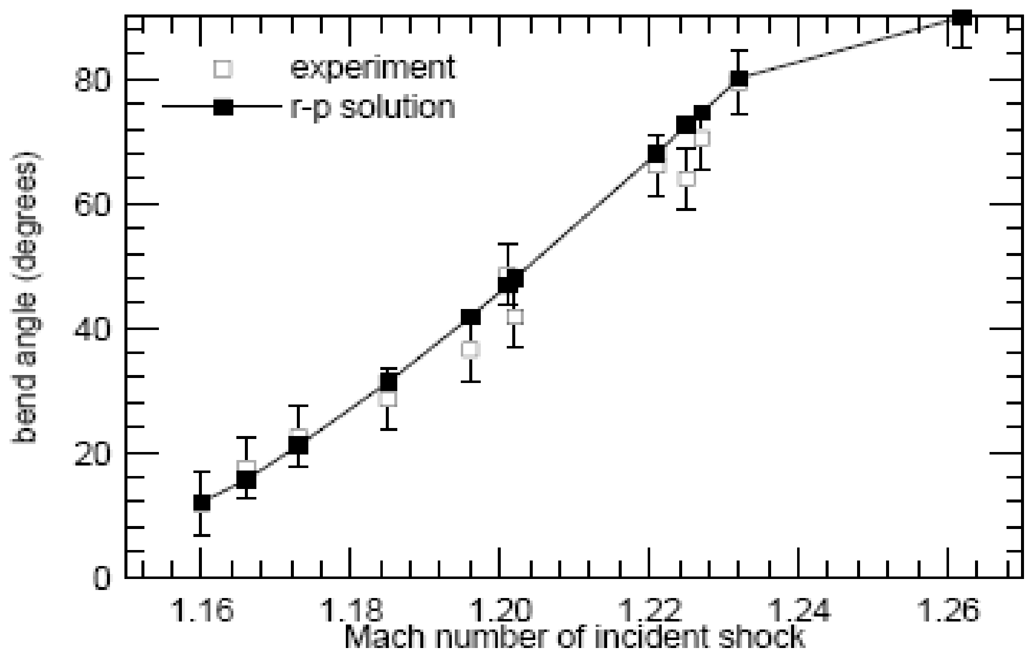
Van Netten and Dewey, Shock Waves (1997) 7: 175–190

Shock tube experiments

Deformation of a 200 mm long, 1.55 mm dia aluminum rod due to a M = 1.23 shock, 1 ms intervals

Final angle of deformation for 50 mm long, 1 mm dia solder rods.





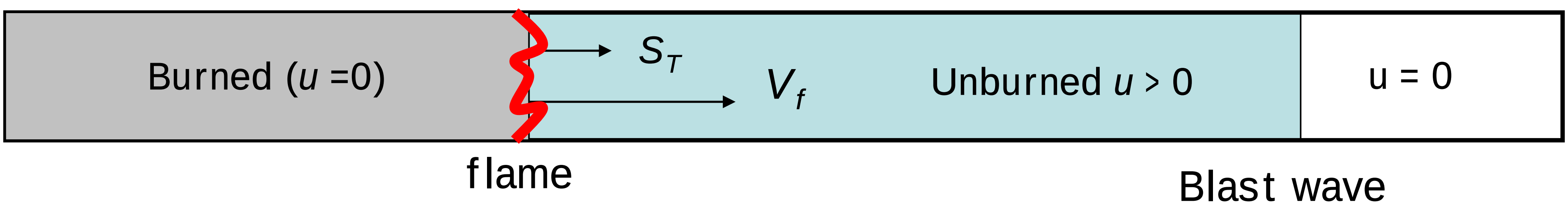
Van Netten and Dewey, Shock Waves (1997) 7: 175–190

Internal Explosions

Deflagrations and Detonations in Vessels

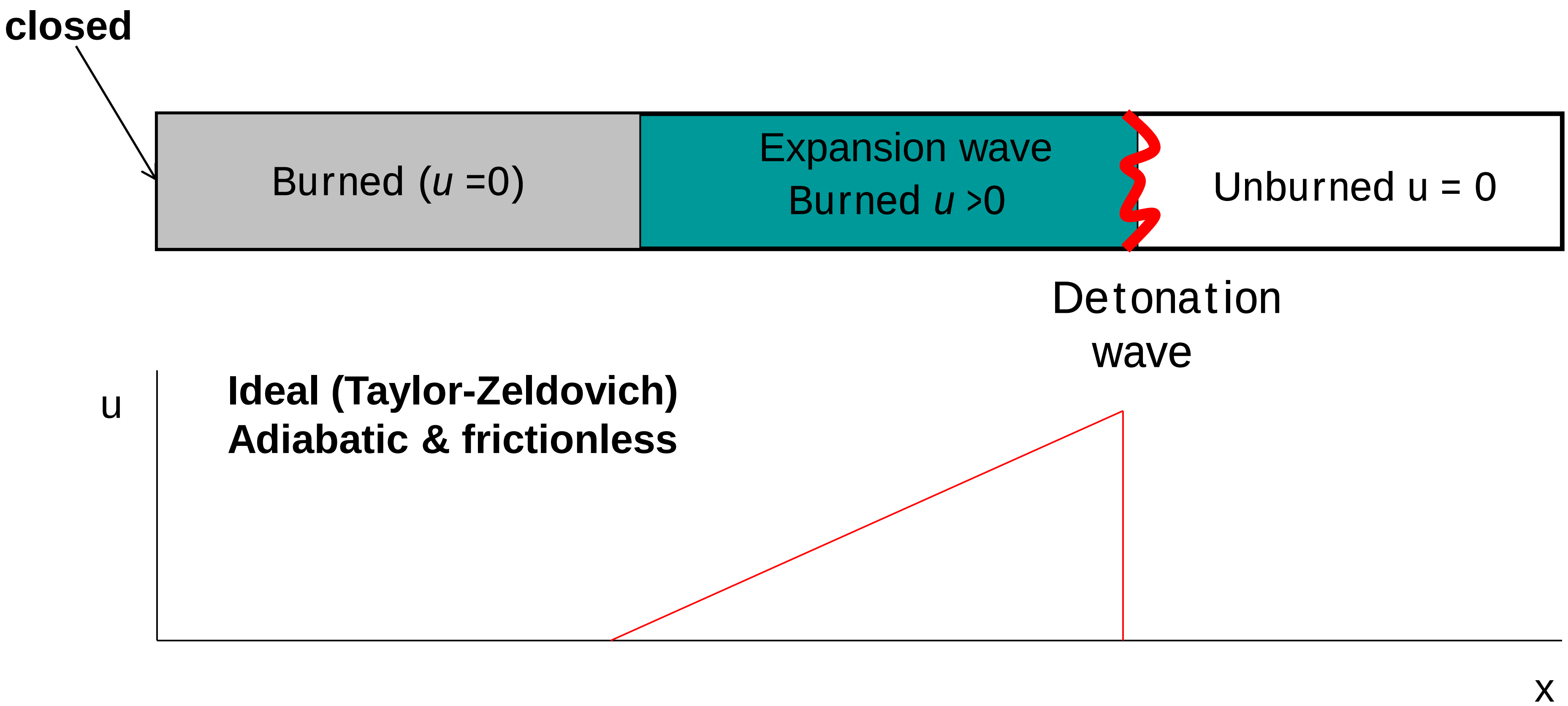
Creation of flow by Explosions I.

- Flames create flow due to expansion of products pushing against confining surfaces
- Consider ignition at the closed-end of a tube
  - Expansion ratio $$\sigma = \rho_u / \rho_b$$
  - Flame velocity $$V_f = \sigma S_T A_f / A = \sigma S_T^{eff}$$
  - Flow velocity $$U = V_f - S_T^{eff} = (\sigma - 1) S_T^{eff}$$



Creation of flow by Explosions II

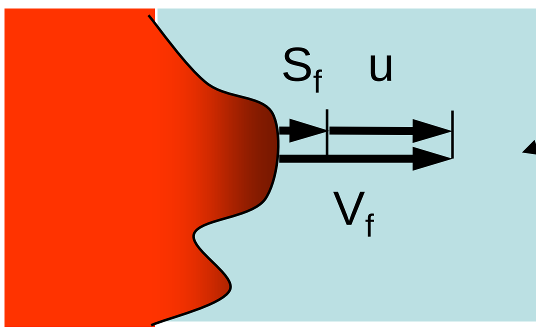
- Detonations and shock waves create flow due to acceleration by pressure gradients in waves
- Consider ignition of detonation at the closed-end of a tube

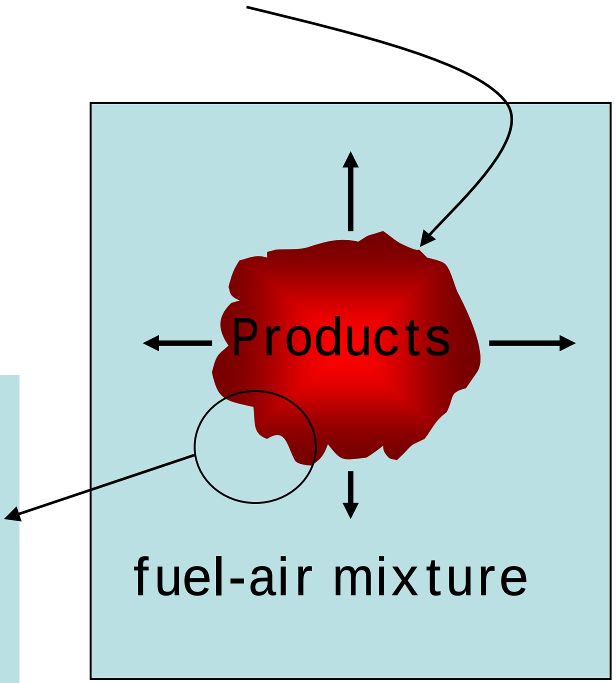


Internal Explosion - Deflagration

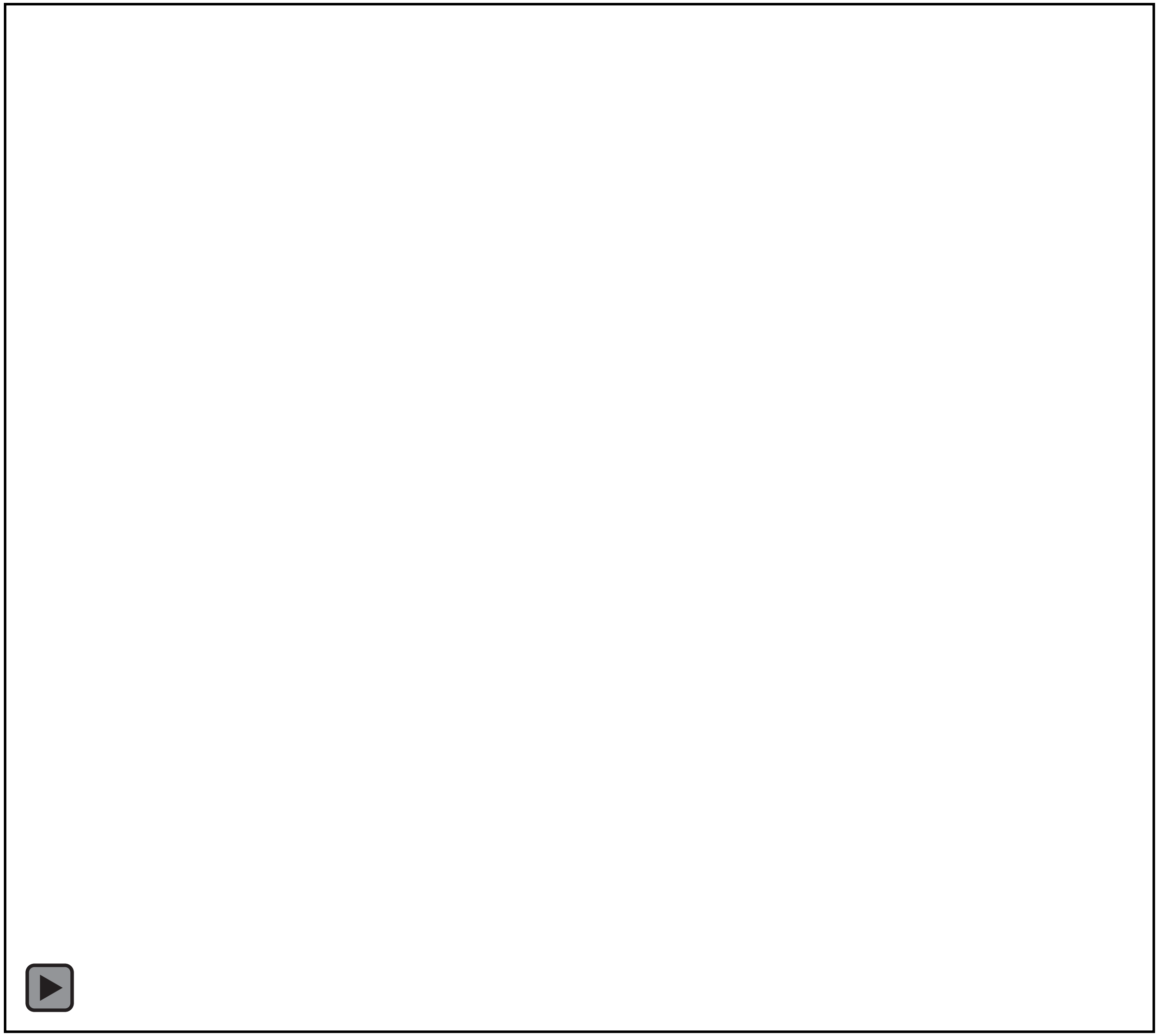
- Limiting pressure determined by thermodynamic considerations
  - Adiabatic combustion process
  - Chemical equilibrium in products
  - Constant volume
- Initial pressure-time history determined by flame speed

$V_f = S_f + u$

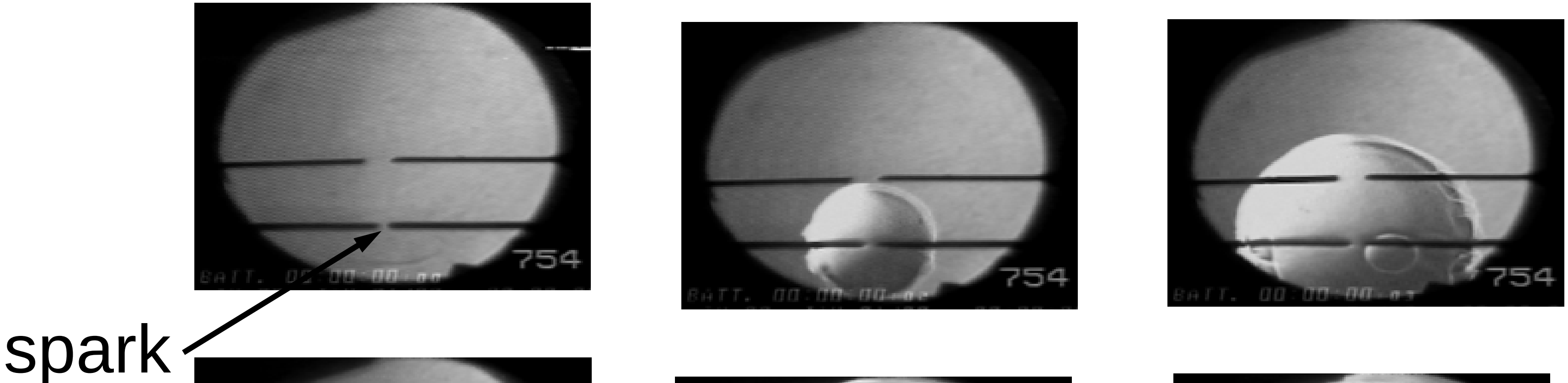


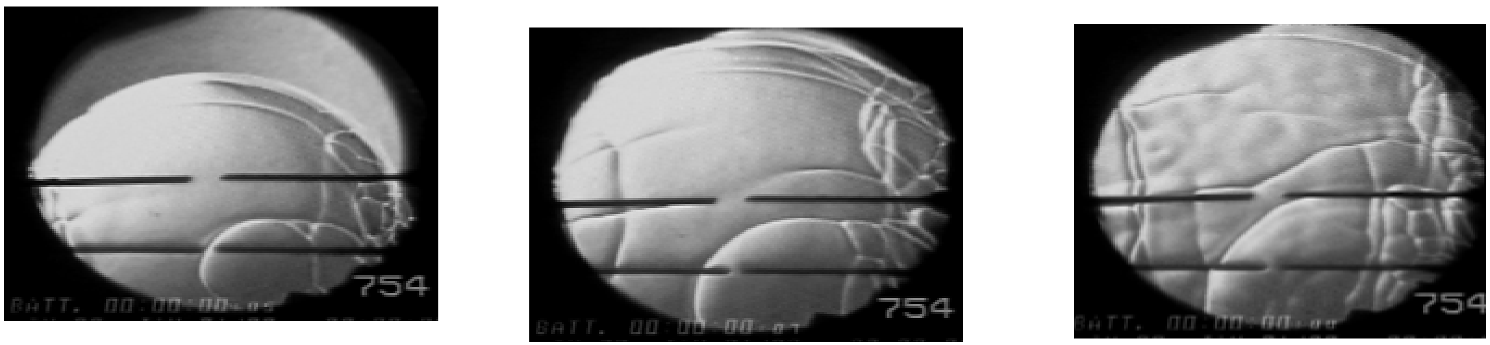


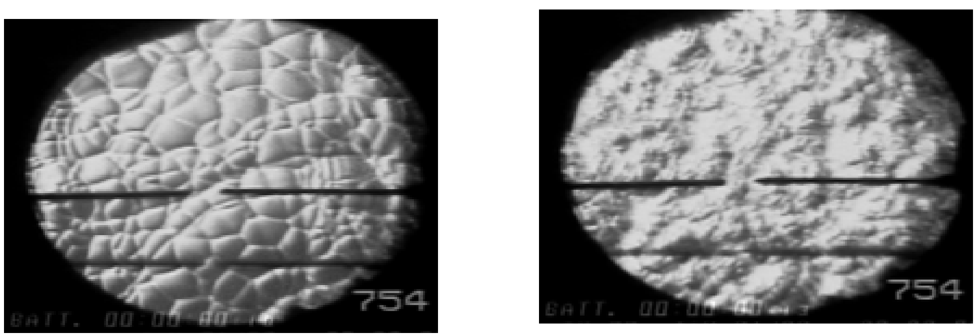
Laminar Flame Propagation



Breakdown of Initially Laminar Flame





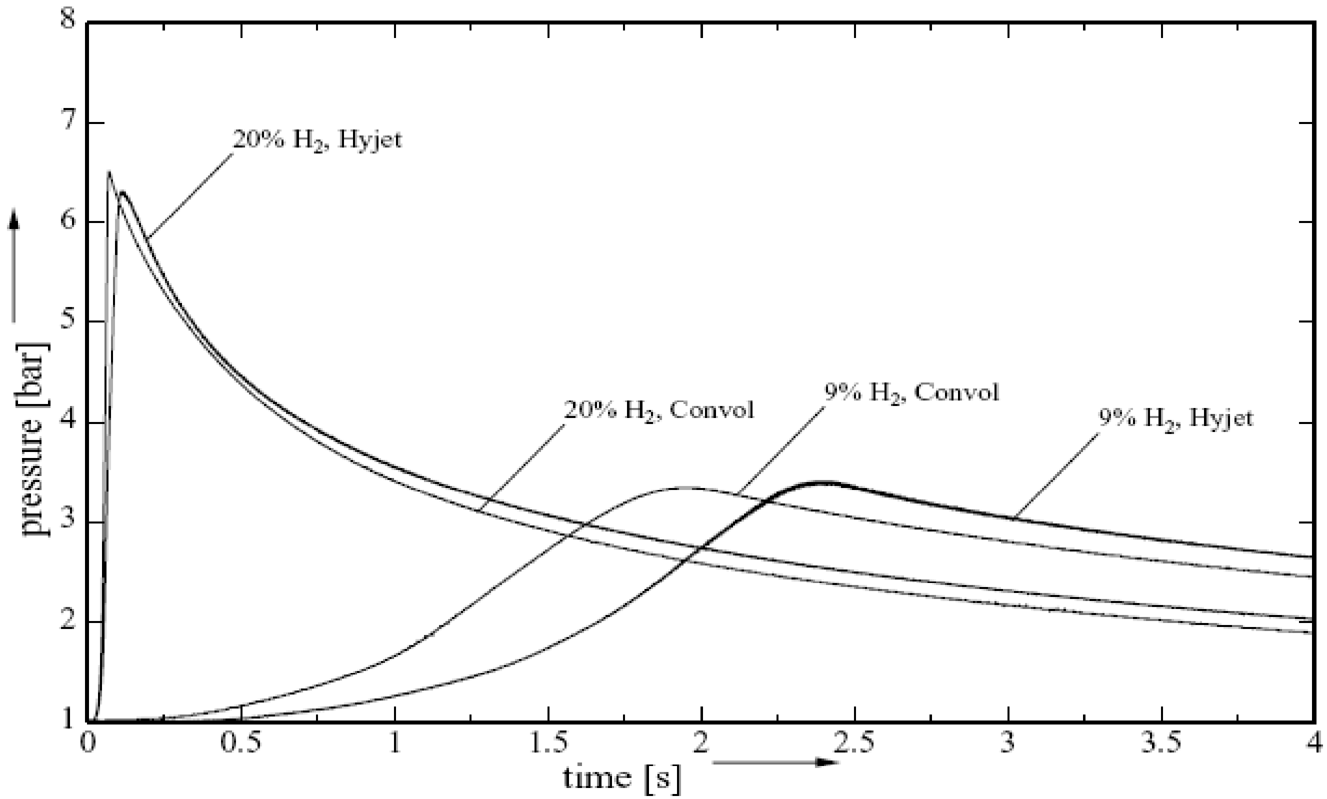


Mixture of H2-propane that simulates Jet A

Flame growth and pressure rise

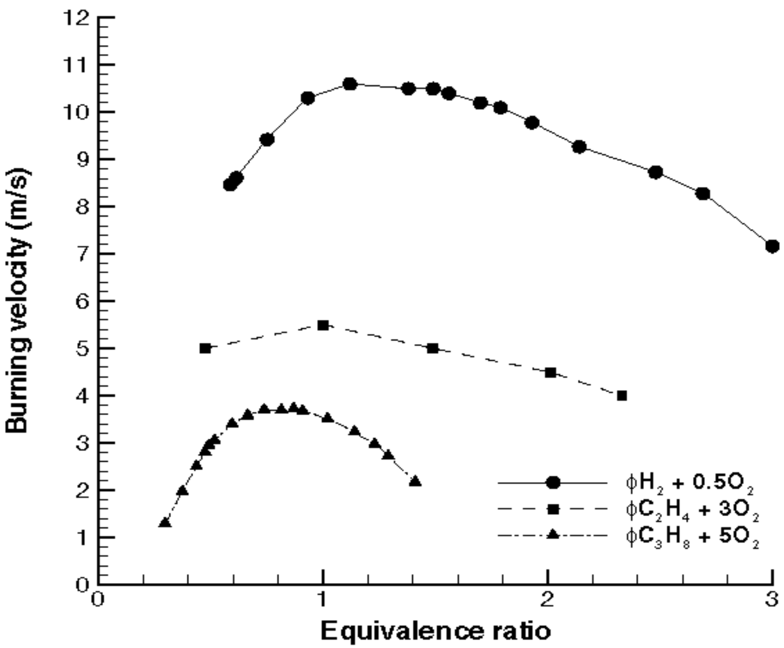
Pressure in Closed Vessel Explosion

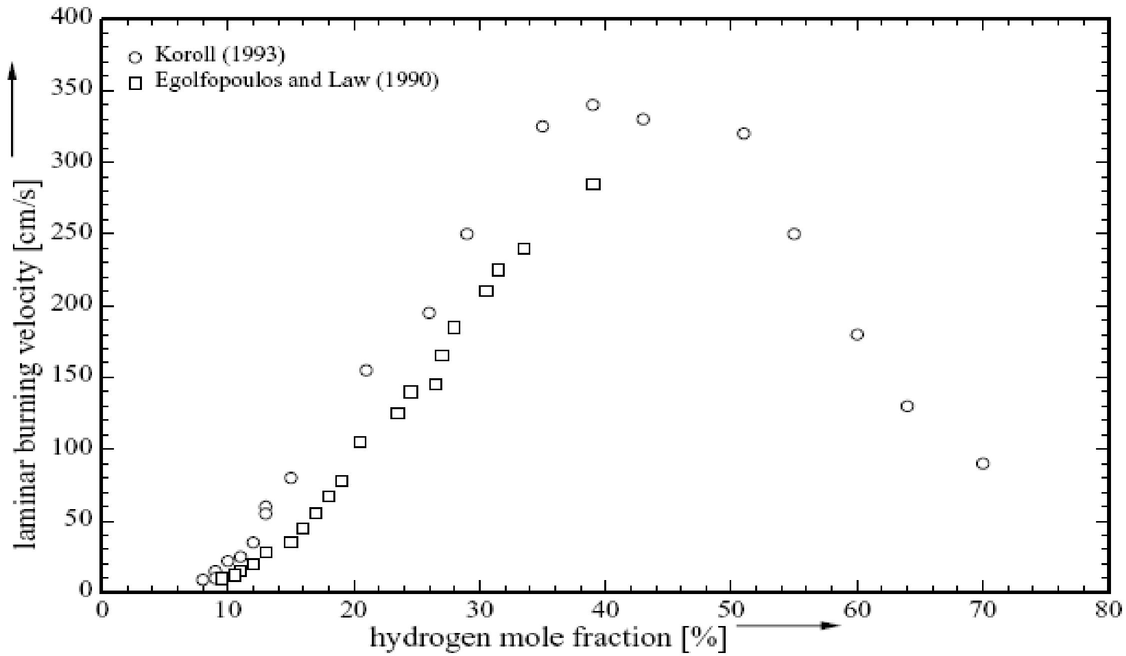
Peak pressure limited by heat transfer during burn and any Venting that takes place due to openings or structural failure



Burning Velocity

- Laminar burning speed depends on substance, composition, pressure, temperature
- Flames in explosions are turbulent, effective burning speed much higher





Adiabatic Explosion Pressure

- Pressure of products if there are no heat losses and complete reaction occurs
- Energy balance at constant volume

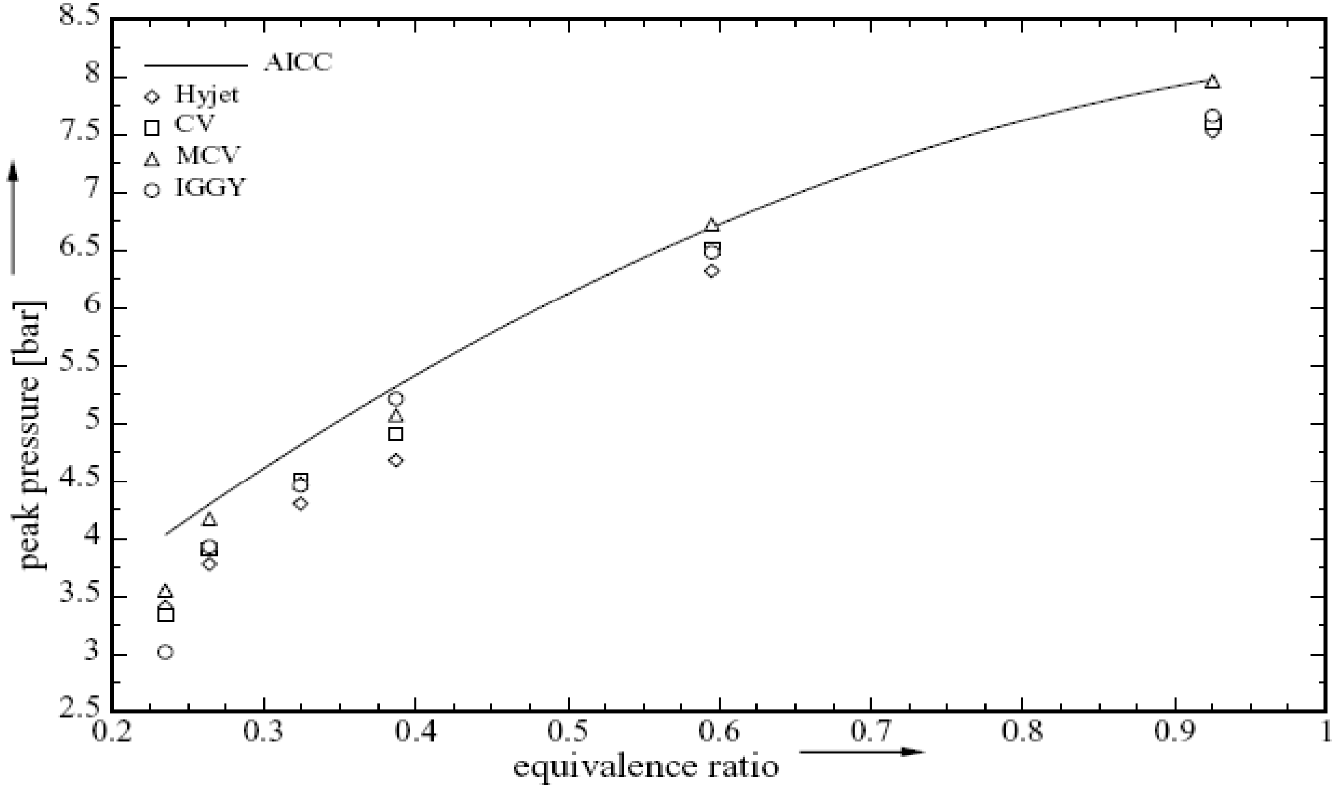
$$E_{reactants}(T_{reactants}) = E_{products}(T_{products})$$

$$V_{reactants} = V_{products}$$

$$P_p = P_r\ (N_p T_p / N_r T_r)$$

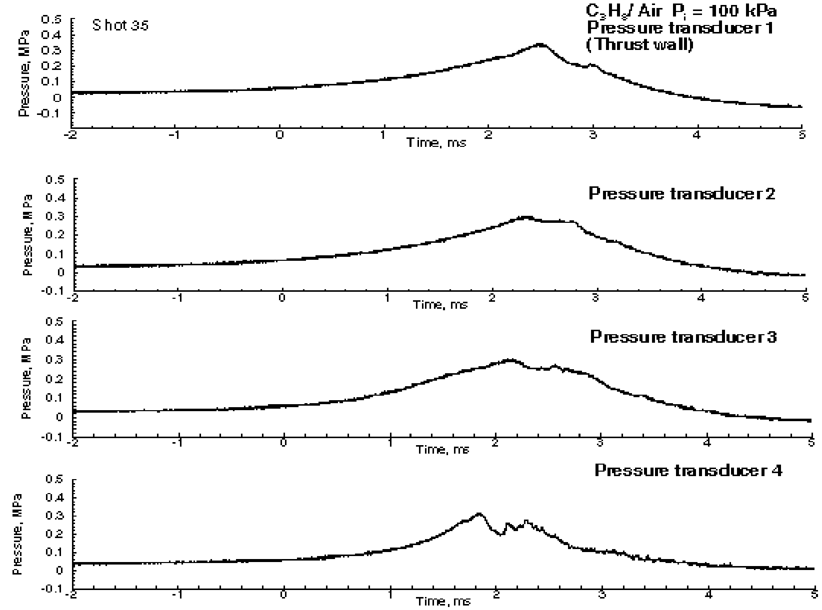
- Products in thermodynamic equilibrium
- For stoichiometric HC fuel-air mixtures: $P_p \sim 8\text{-}10\ P_r$
- Decreases for off-stoichiometric, and diluted mixtures,
- Values are similar for all HC fuels when expressed in terms of equivalence ratio.
- Upper bound for peak pressure as long as no significant flame acceleration occurs

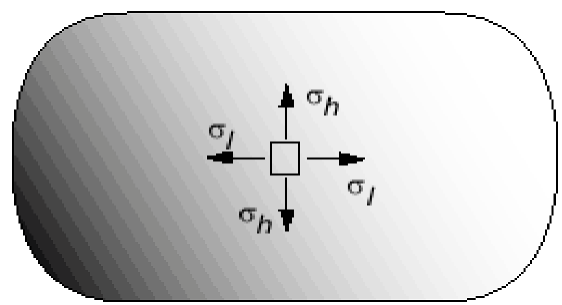
Measured Peak Pressure vs Calculated



Structural Response to Deflagration

- Quasi-static pressurization
  - Spatially uniform
- Structure response can be easily bounded with
  - Thermochemical computations
  - Static structural analysis
    - Internal pressure
    - Thermal stress

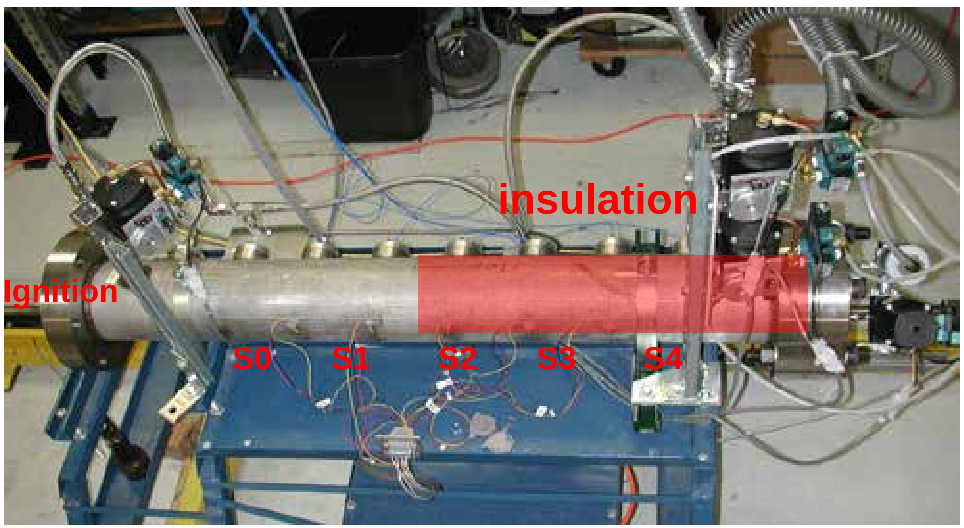


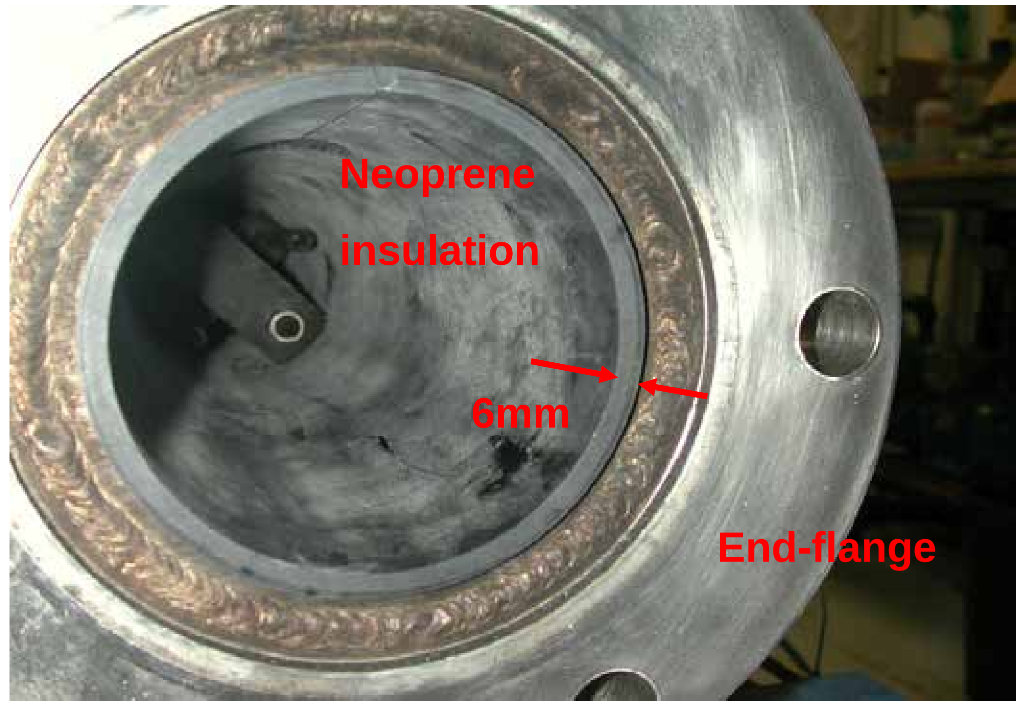


$$\sigma_h = \frac{R}{h}\Delta P \qquad \sigma_l = \frac{R}{2h}\Delta P$$

Thermal Stress from Deflagrations

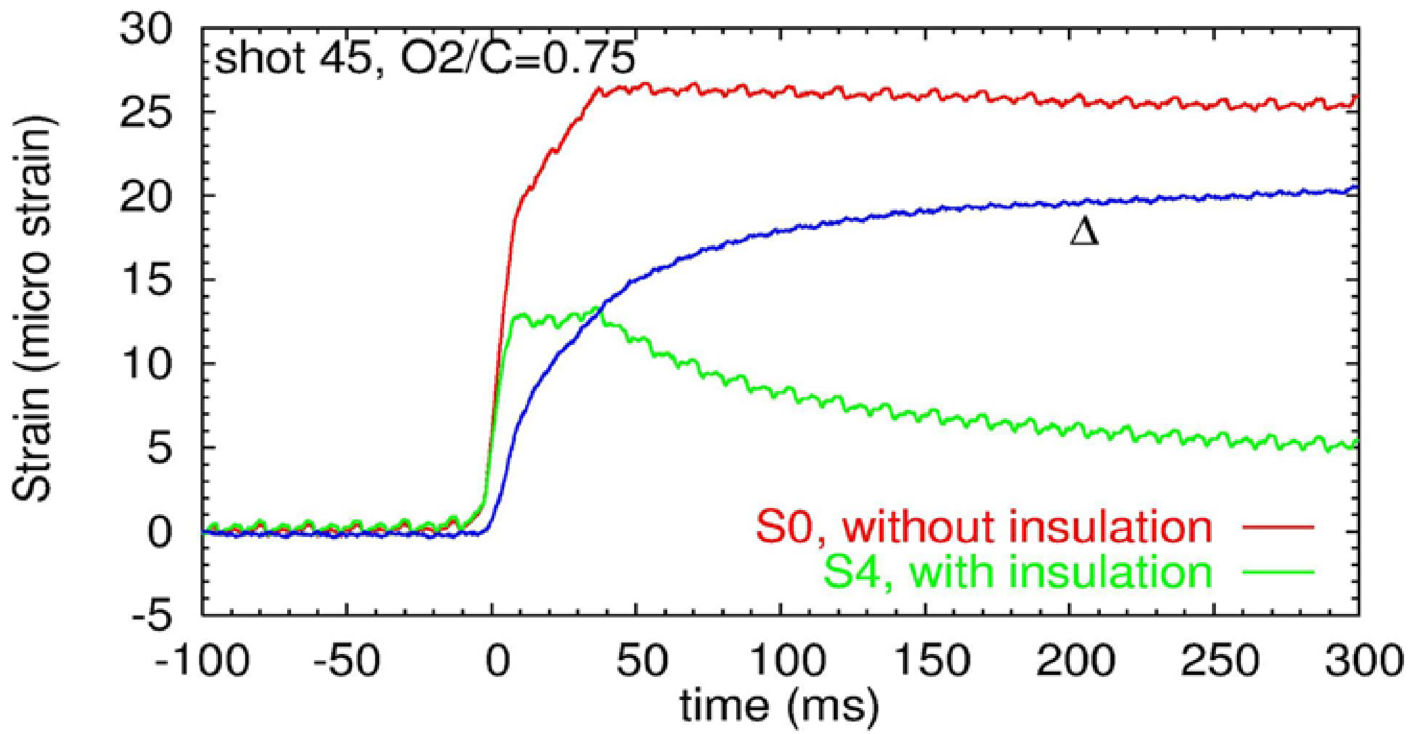
- **Downstream 0.6 m of tube was insulated on the inside with 6 mm of neoprene.**



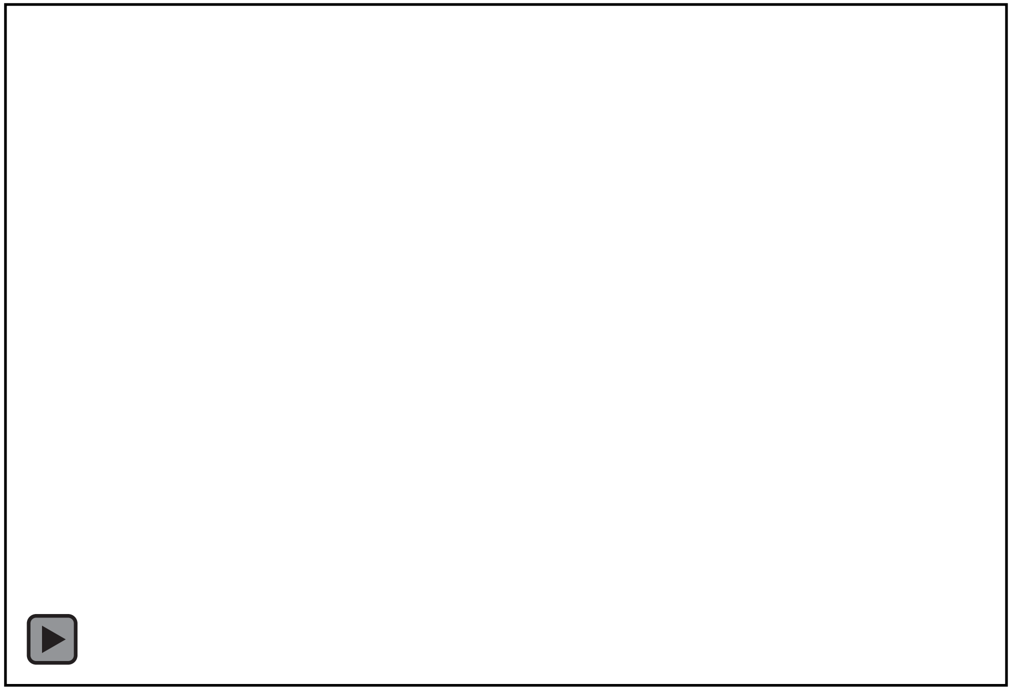


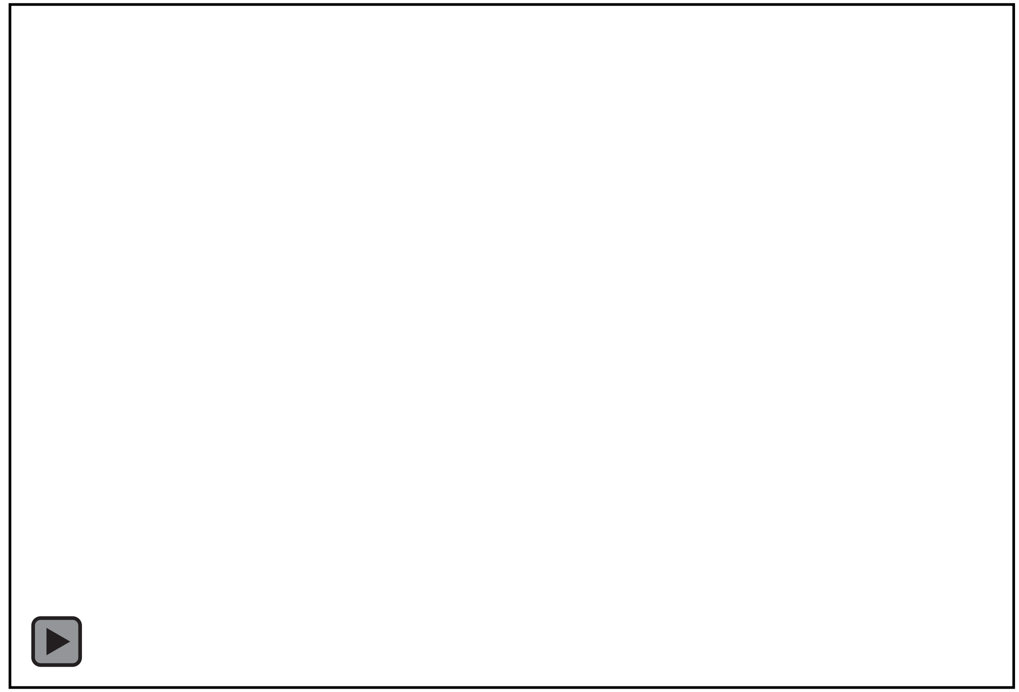
Thermal stress component of strain

- **Characteristic rise time of 50 ms**
- **Contribution to hoop strain is about 125% of peak value due to mechanical loading alone.**
- **Dominates long-time (> 100-200 ms) observations**



Structural failure due to deflagration





Aviation kerosene (Jet A) at 40 C, pressure of .58 bar (14 kft pressure altitude)

Detonations in Piping

- Accidental explosions
- Potential hazard in
  - Chemical processing plants
  - Nuclear facilities
    - Waste processing
    - Fuel and waste storage
    - Power plants
- Test facilities
  - Detonation tubes used in laboratory facilities
  - Field test installations (vapor recovery systems)

Recent Accidental Detonations in NPP

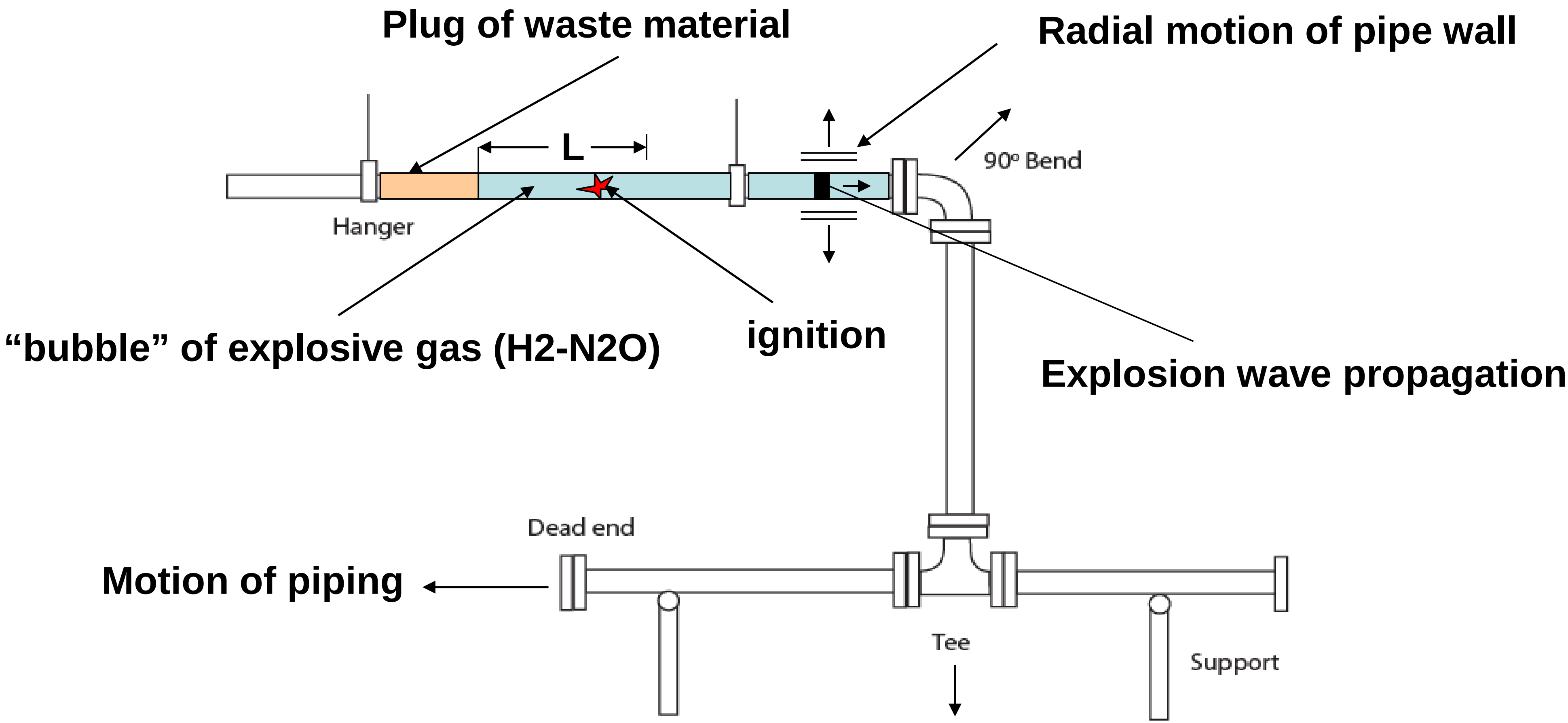
(a)

Hamaoka-1 NPP

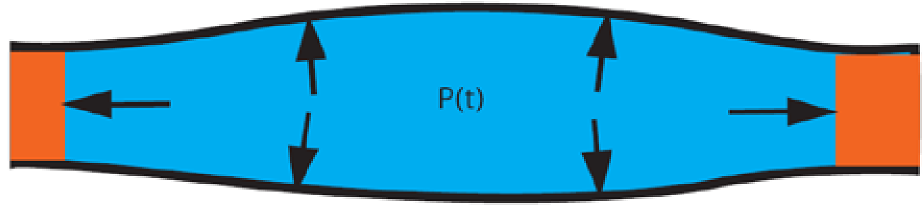
Brunsbuettel KBB

Both due to generation of H_2+1/2O_2 by radiolysis and accumulation in stagnant pipe legs without high-point vents or off-gas systems.

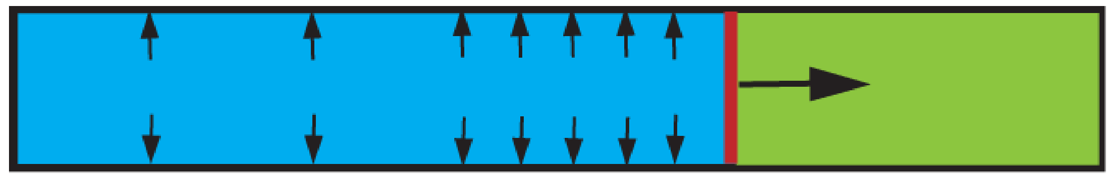
Explosion Scenario



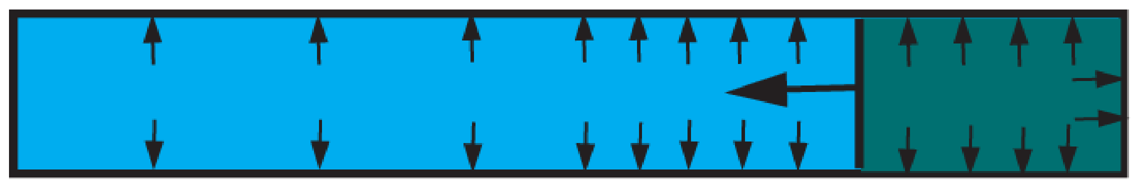
Bubble



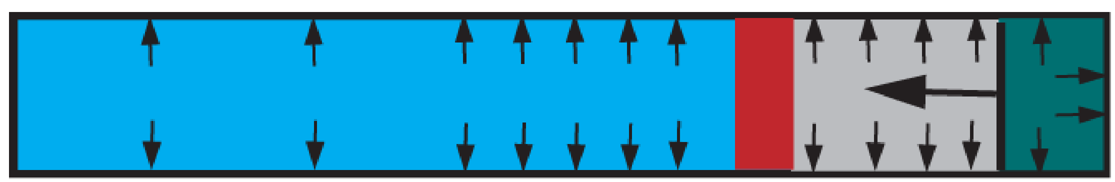
Propagating detonation



Reflected detonation

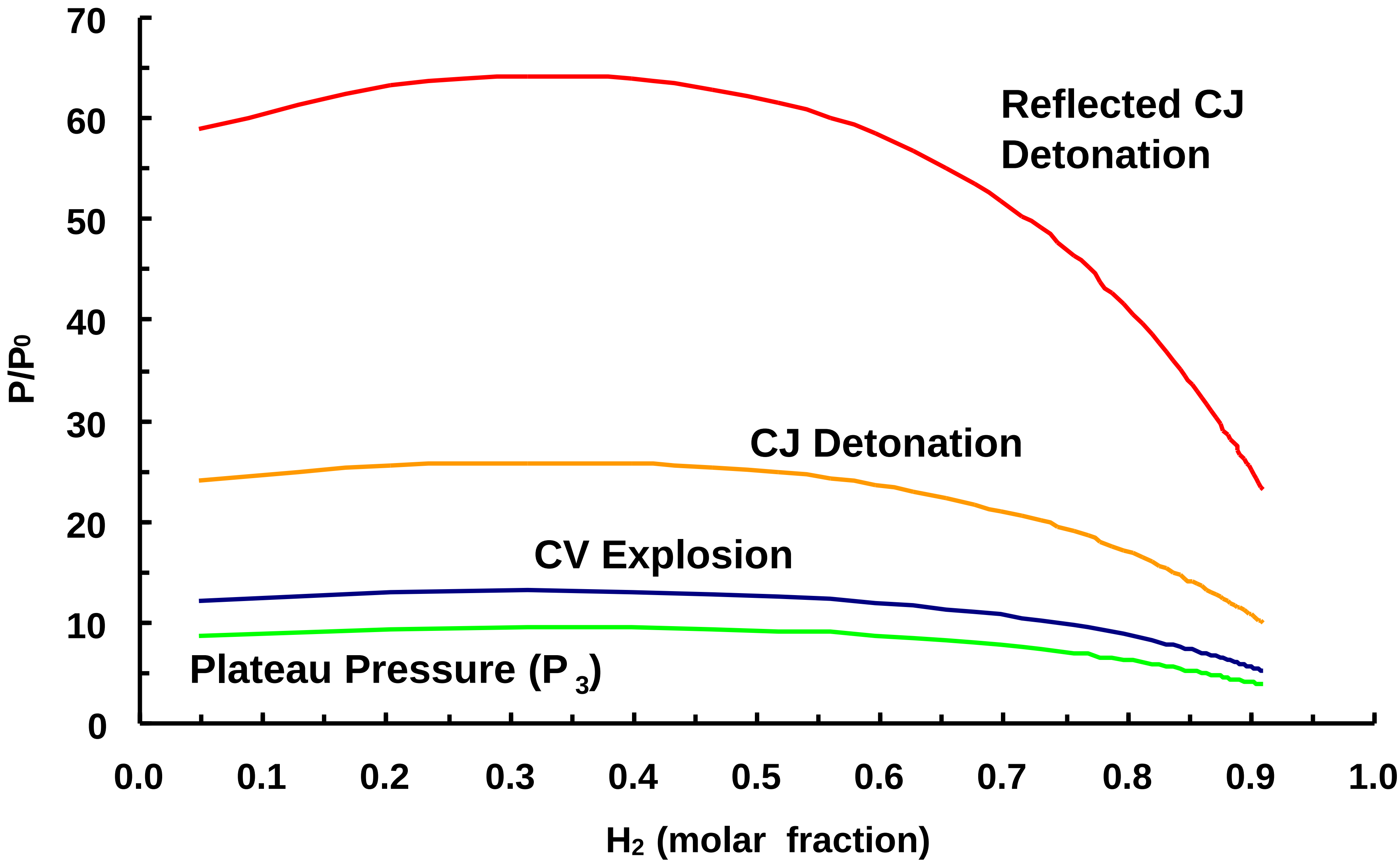


Deflagration-to-Detonation Transition followed by reflection (DDT/Pressure Piling)



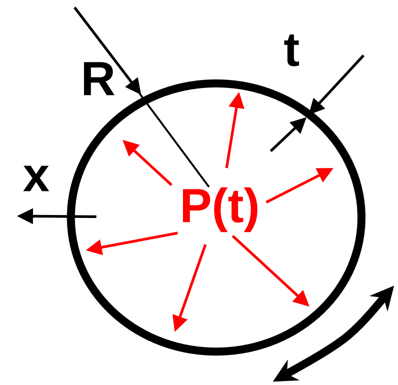
Example of Bubble Explosion

H2-N2O Explosion Pressure Estimates



Radial (Hoop) motion of Pipes: SDOF Model

Allow only for radial displacement x of tube surface



Assumes radial and axial symmetry of load

Stress in hoop direction is restoring force

$$\sigma_{hoop} = \varepsilon_{hoop} E$$

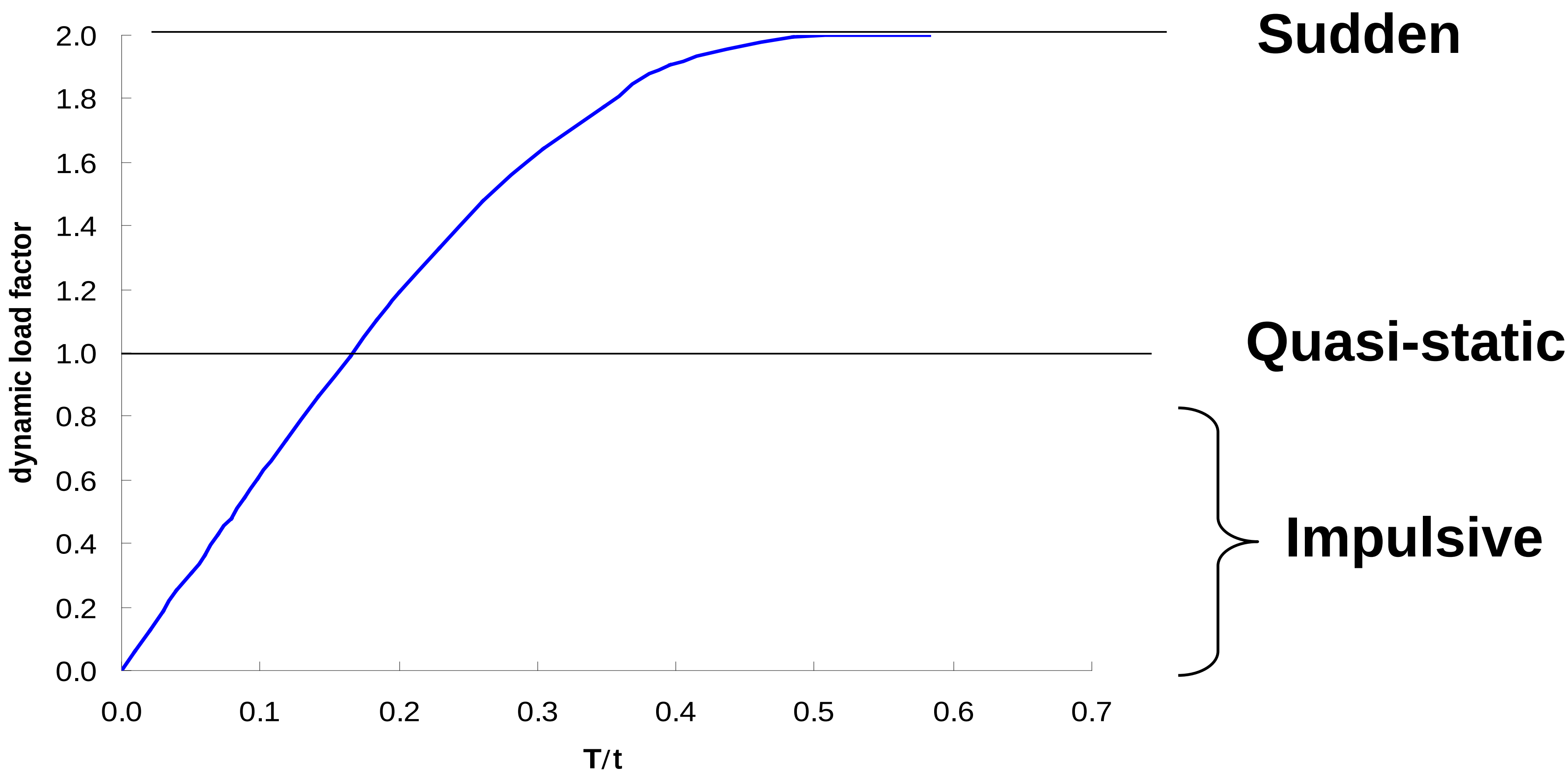
Results in harmonic oscillator equation (no damping)

$$\ddot{x} + \omega^2 x = F(t)$$

for tube →

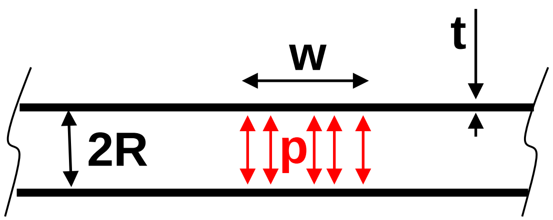
$$\ddot{x} + \underbrace{\frac{E}{\varrho R^2}}_{\text{reduced frequency}} x = \underbrace{\frac{P(t)}{\varrho t}}_{\text{reduced driving force}}$$

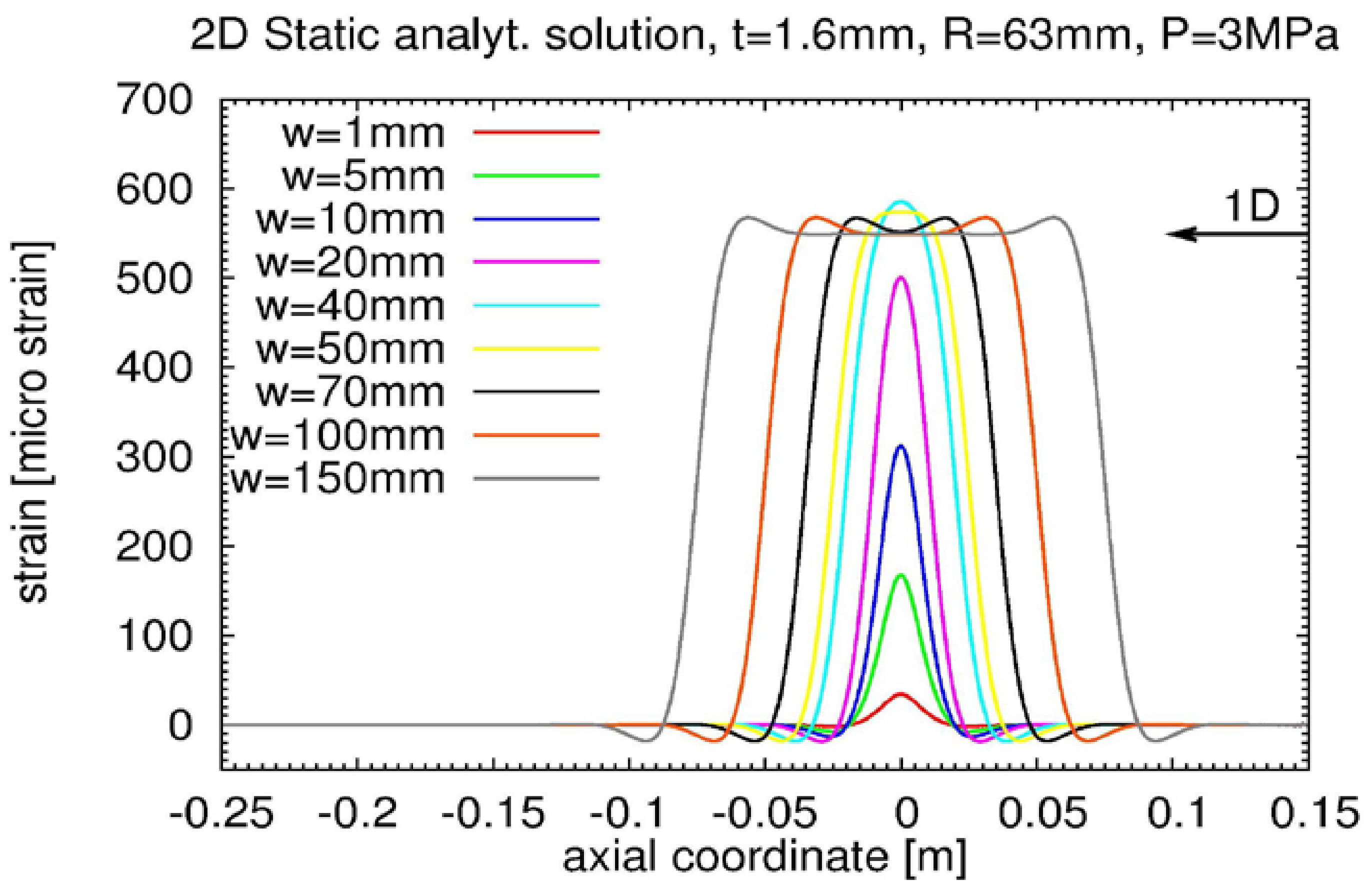
Dynamic Loading Factor



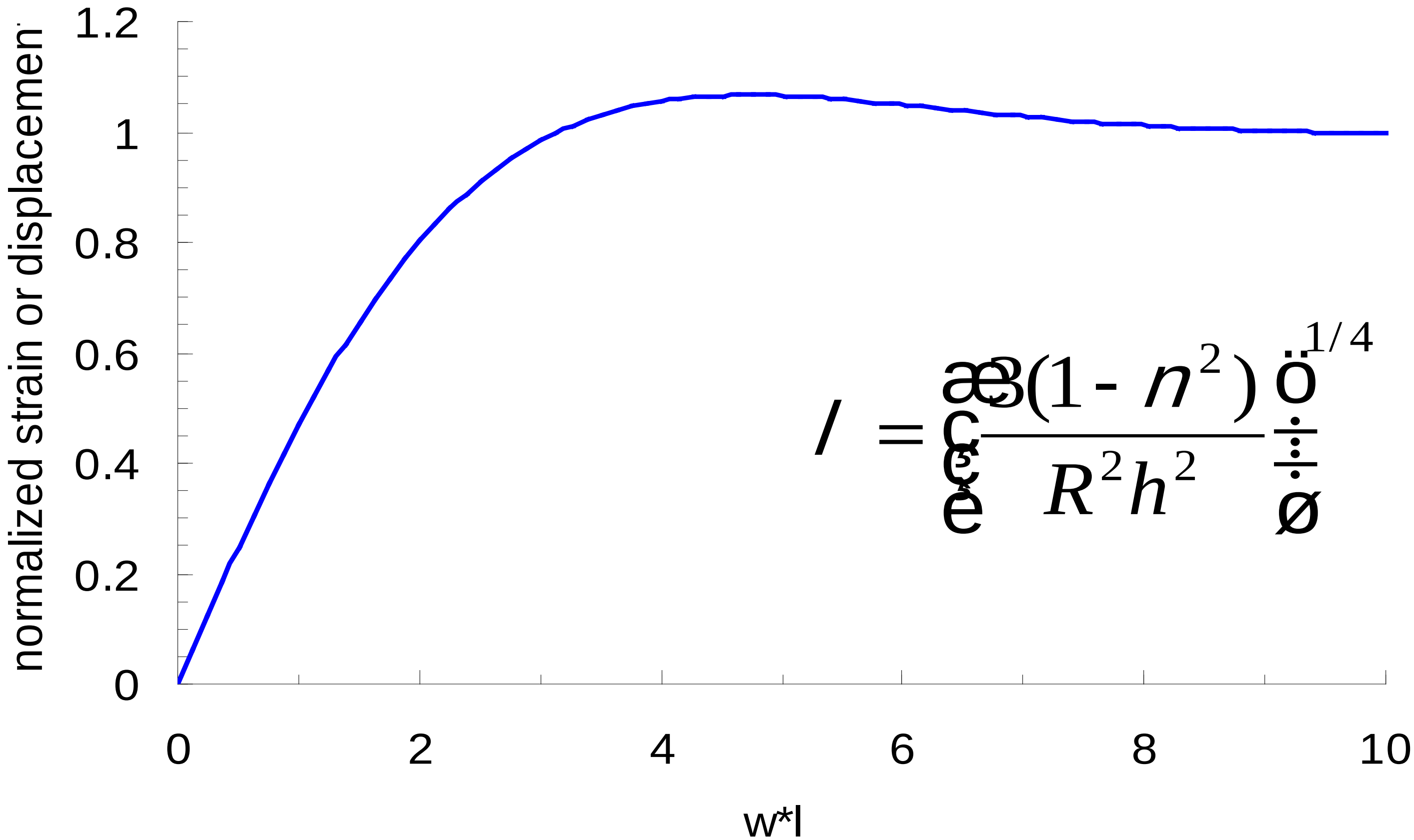
Effect of load localization

Infinite thin-walled (R/t>10) cylinder of radius R under uniform radial pressure p over length w.





Load Length Factor



$$\lambda = \left(\frac{3(1-\nu^2)}{R^2 h^2} \right)^{1/4}$$

BOC Methodology

- Estimate loading using SDOF model and acc
  for finite length of load.

Yield stress

$$\sigma_{hoop,\max} = P_0 \times \frac{\Delta P_{\max}}{P_0} \times \frac{R}{h} \times \Phi\left(\frac{t}{T}\right) \times F(w/\ ) < \sigma_Y$$

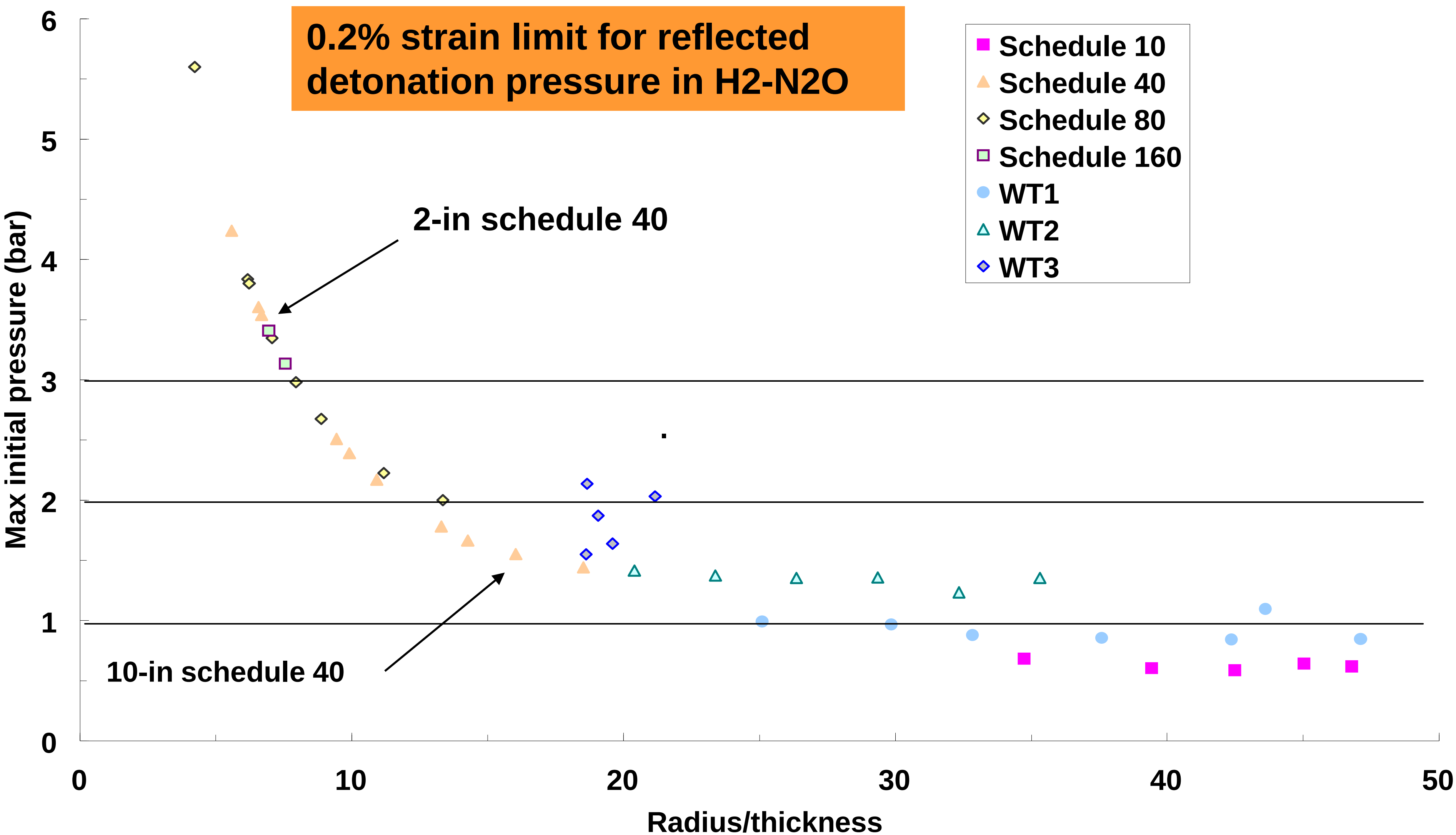
From explosion pressure estimate

Diameter and Schedule of pipe

Dynamic Load Factor

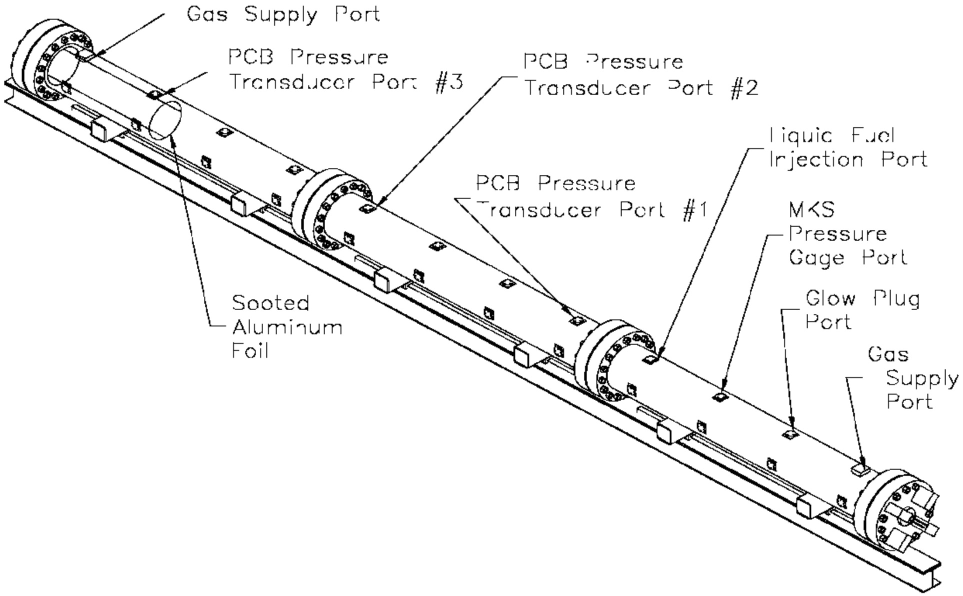
Load length factor

Hazard larger for bigger, thinner pipes

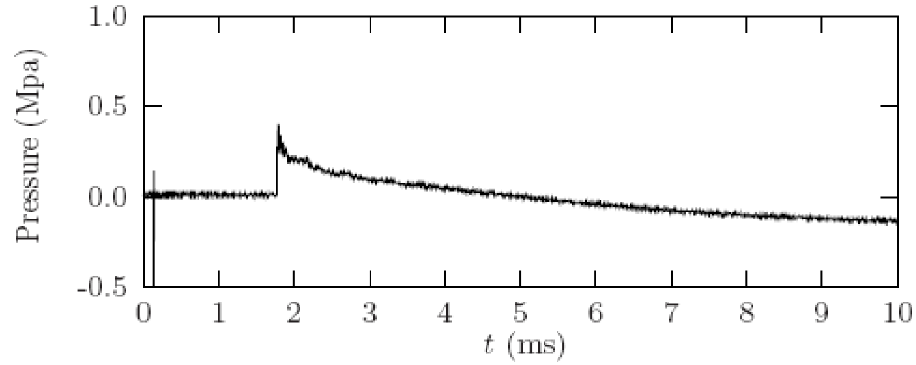


Detonations

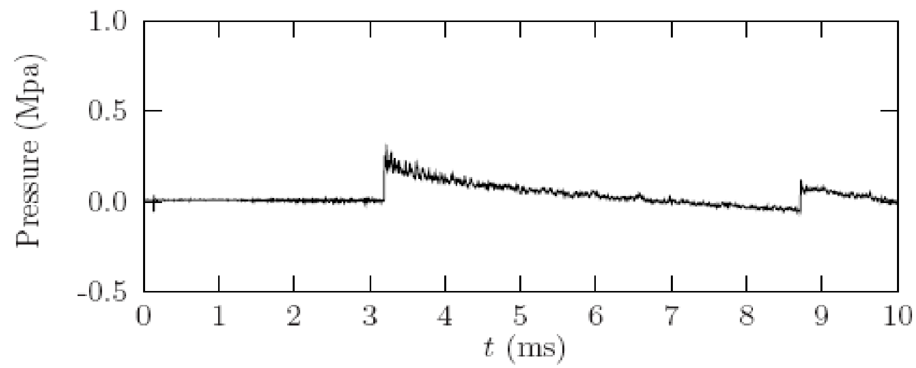
Detonations are pressure waves



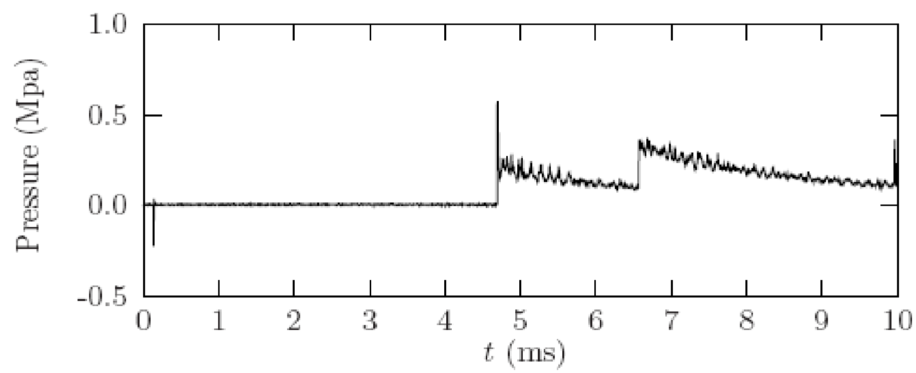
Austin & Shepherd 2003



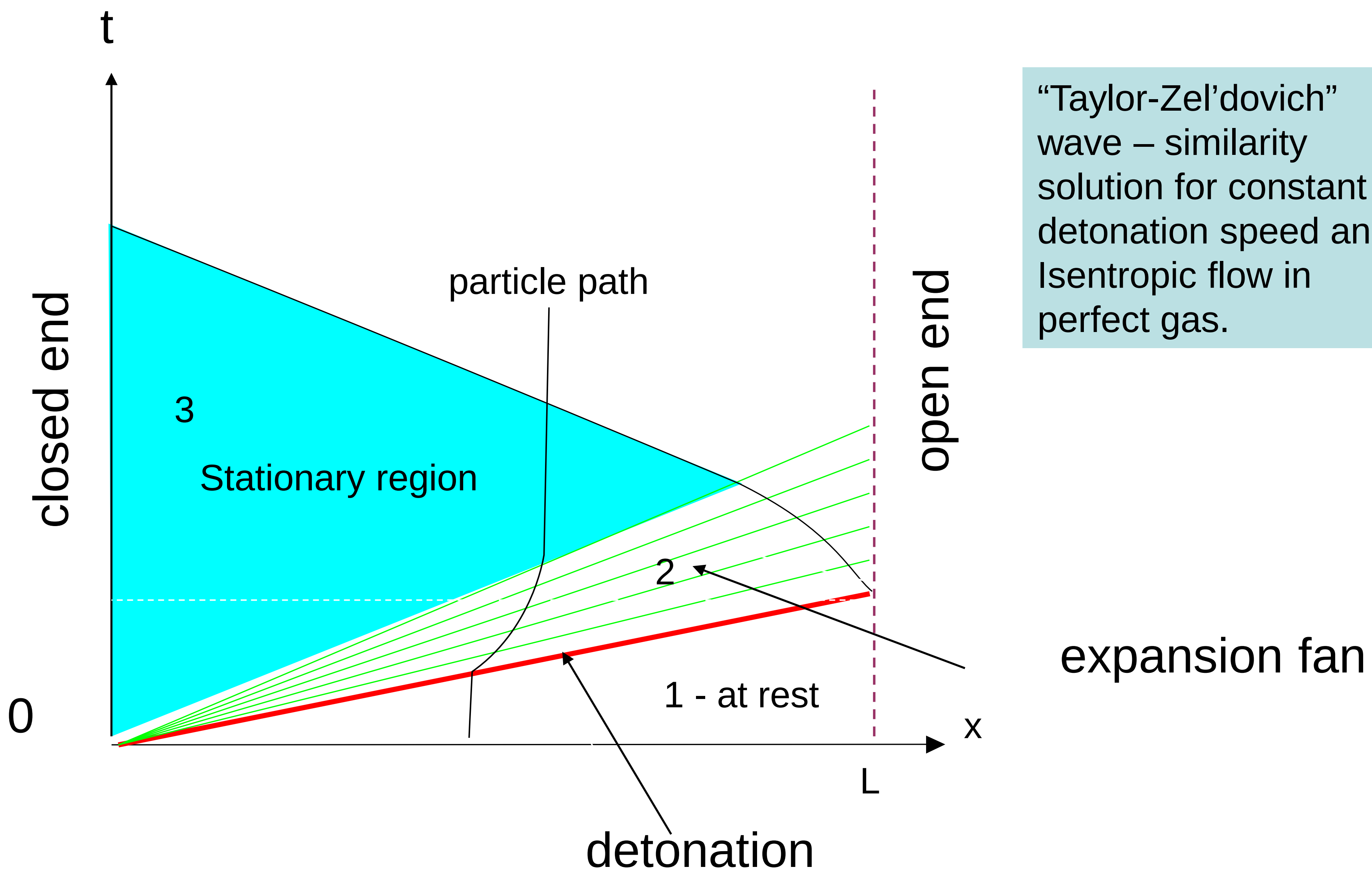
(a)



(b)



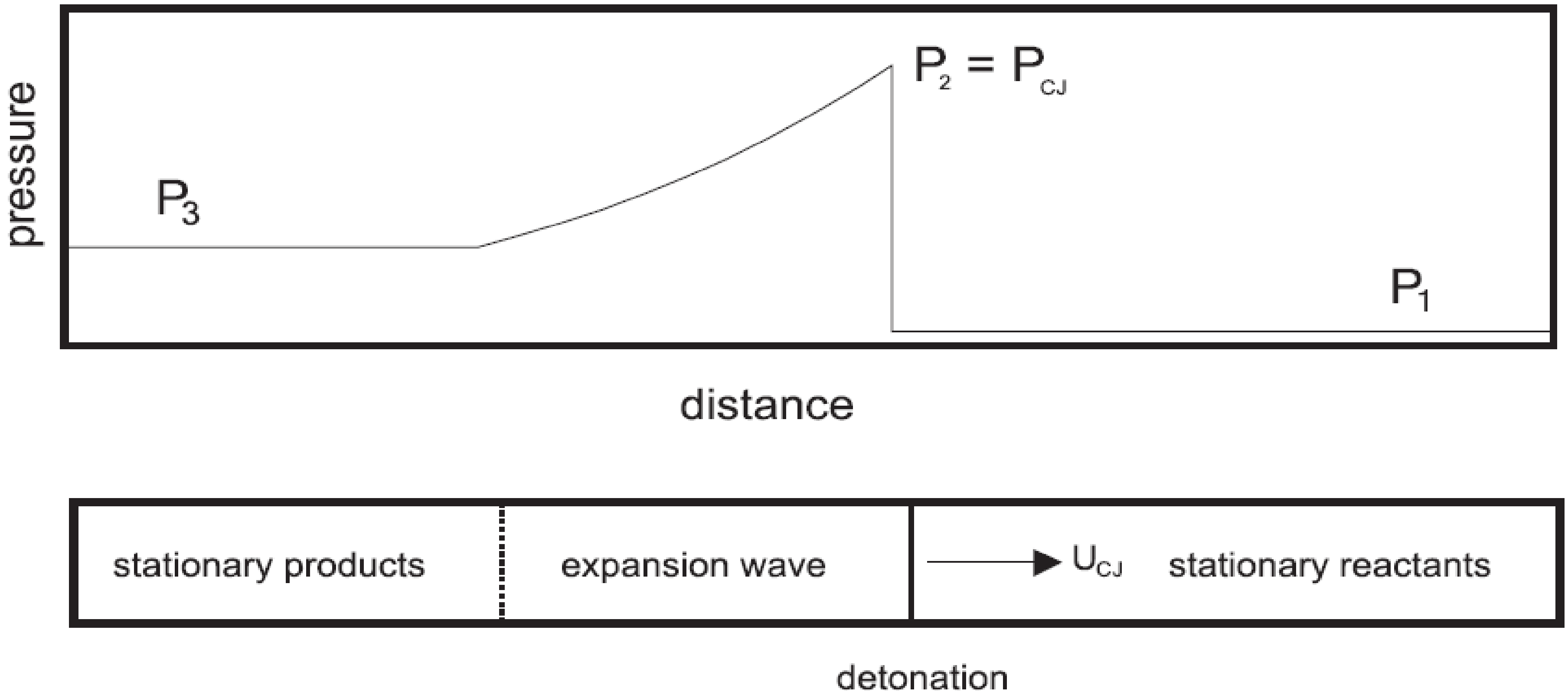
Detonation Followed by an Expansion Wave



“Taylor-Zel’dovich” wave – similarity solution for constant detonation speed and Isentropic flow in perfect gas.

Spatial distribution of Pressure

Spreads linearly with increasing time.

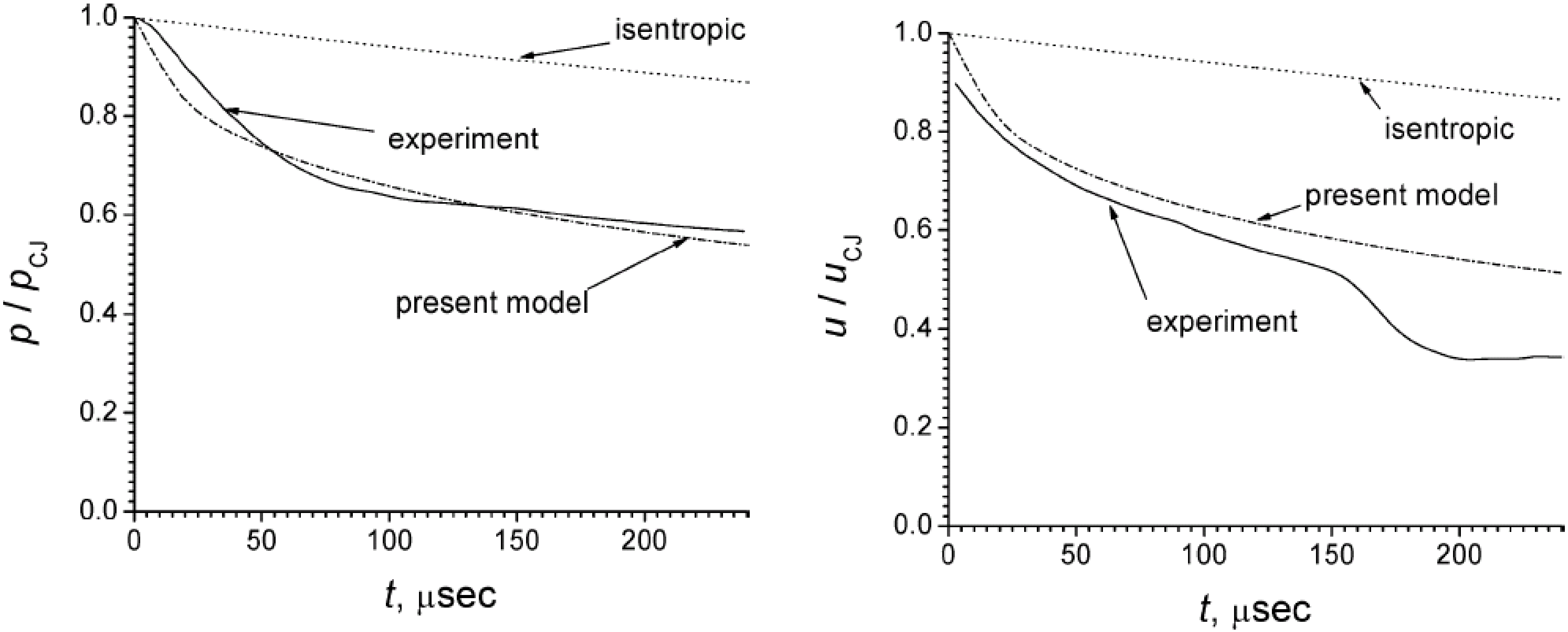


What is actual situation?

- Real gases
  - Viscous flow
  - Heat conduction
  - Turbulence (Re > 10^6)
- Expansion flow reaches fixed duration
  - L/D > 100-200 => finite length of expansion wave
  - Impulse behind wave stops growing with increased length
- Heat and momentum transfer to tube
  - Alters velocity profile
  - Drops temperature and pressure

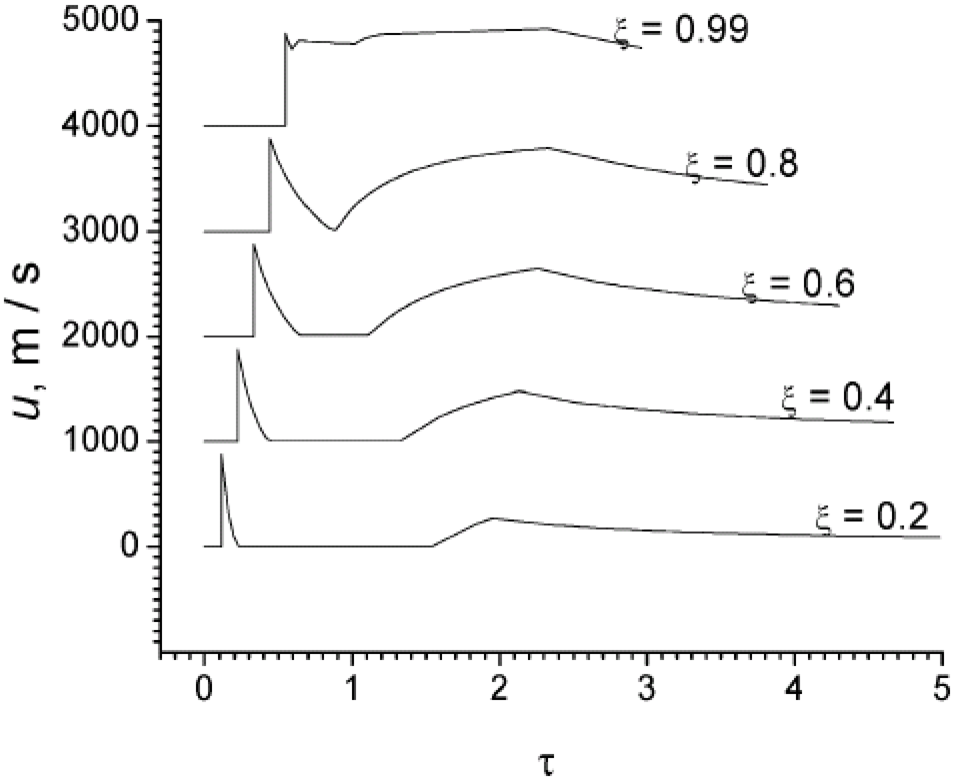
Experimental Results and Quasi-1D Models

$$Q_{\text{loss}} = \frac{2C_{\text{f}}}{Pr^{2/3}D_{\text{h}}}\rho\,|u|\,\left(h_{\text{w,eq}} - h_{\text{aw}}\right).$$

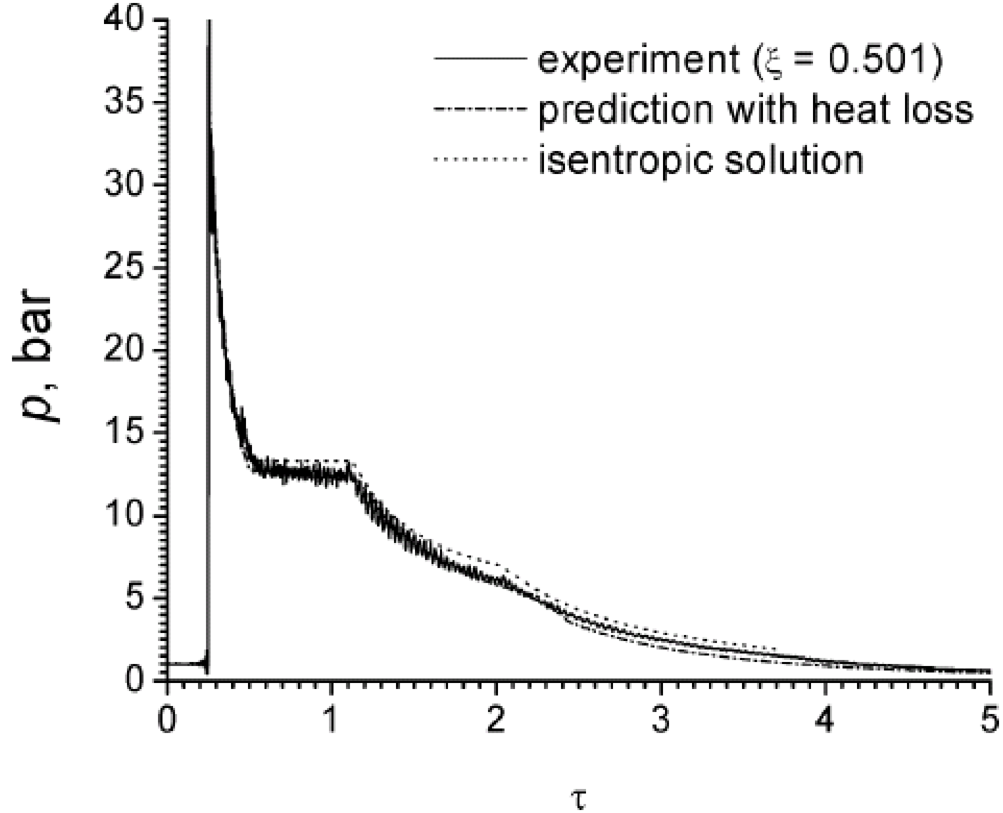


L/d = 550, H2+1/2O2 Edwards et al 1970, Hanson and Radulescu 2005

Ideal Model good for Short Tubes



L/d = 18, H2+Air, Hanson and Radulescu 2005



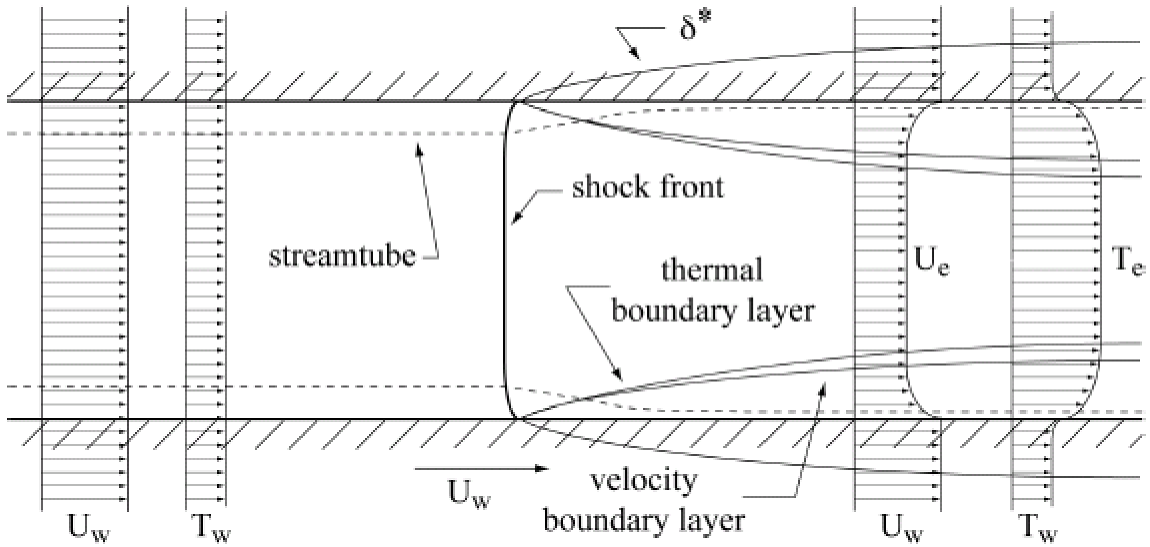
L/d = 50, C3H8+5O2 Harris et al 2001, Hanson and Radulescu 2005

Heat and Momentum Transfer – Real Flows

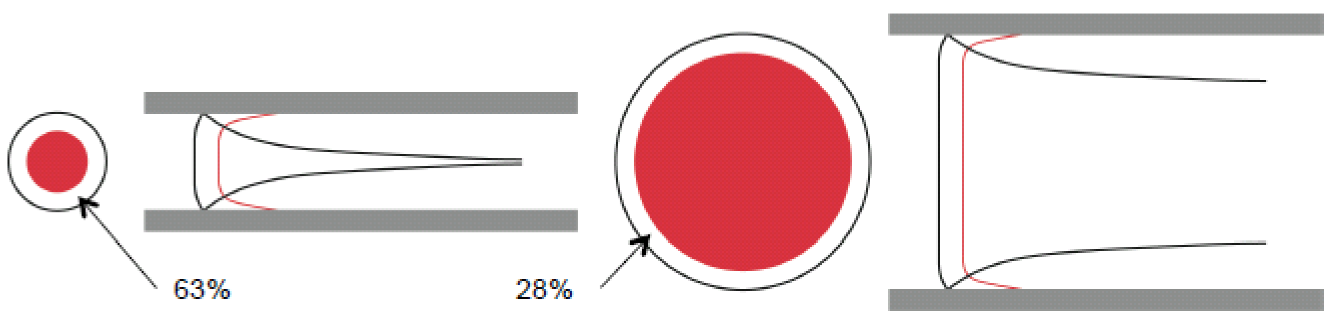
Boundary layer - thermal and momentum

Near wall:

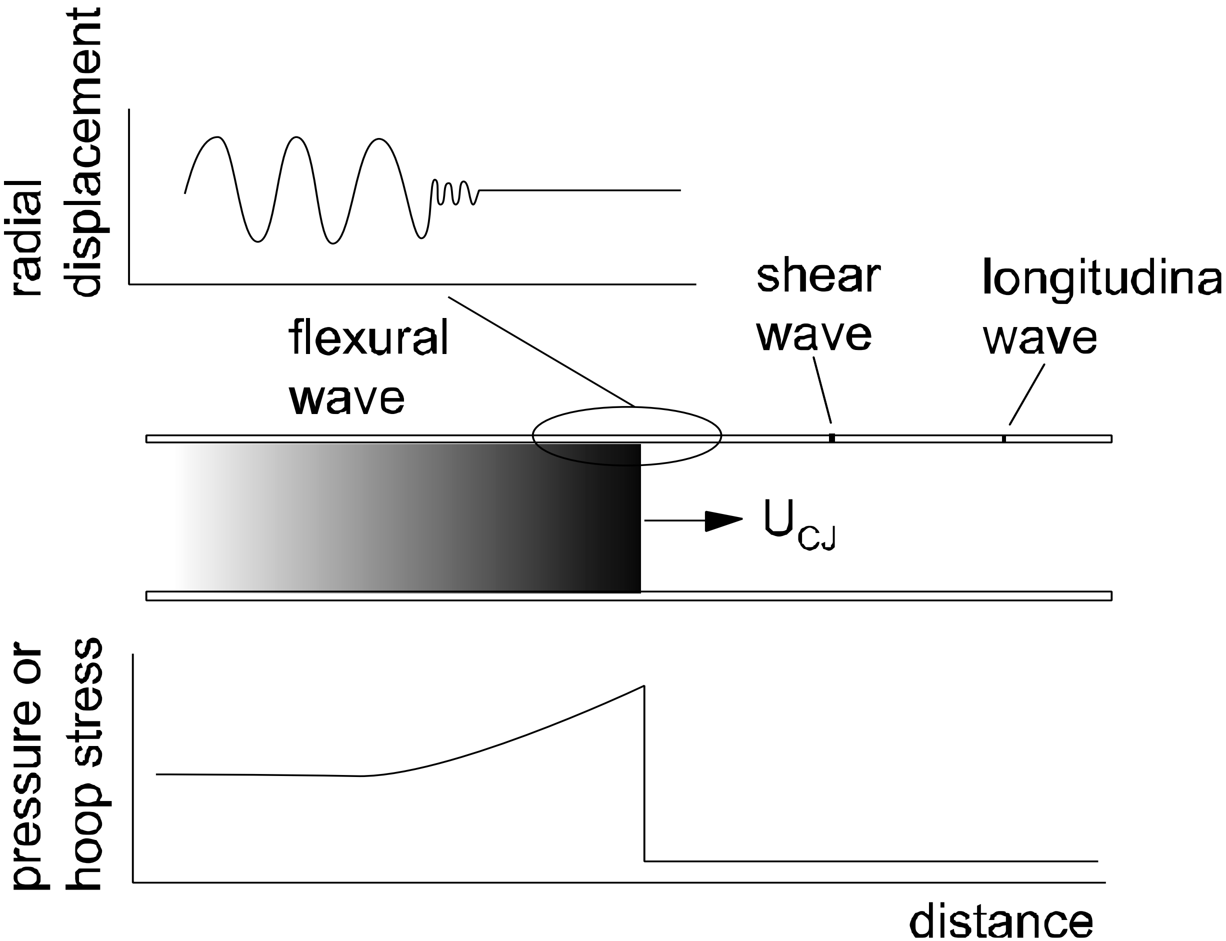
- Negative δ* curves shock
- Decreases ω_1
- Decreases T_2
- Increases Δ or quenches



Effect of tube size

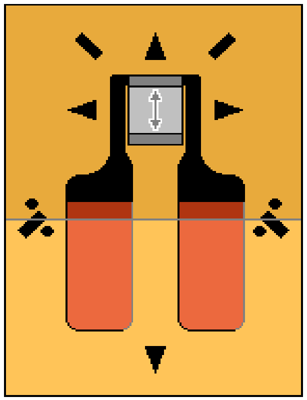


Detonations Excite Flexural Waves in Piping

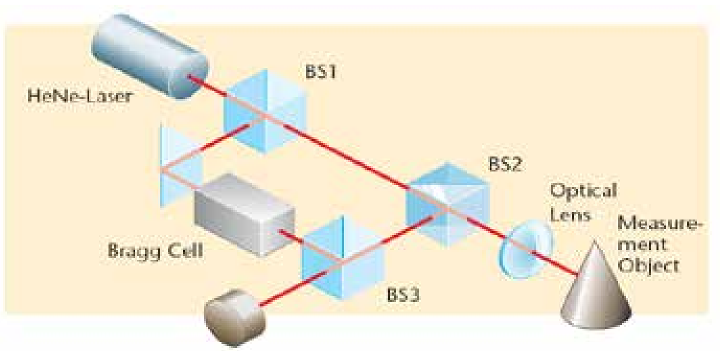


Measuring Elastic Vibration

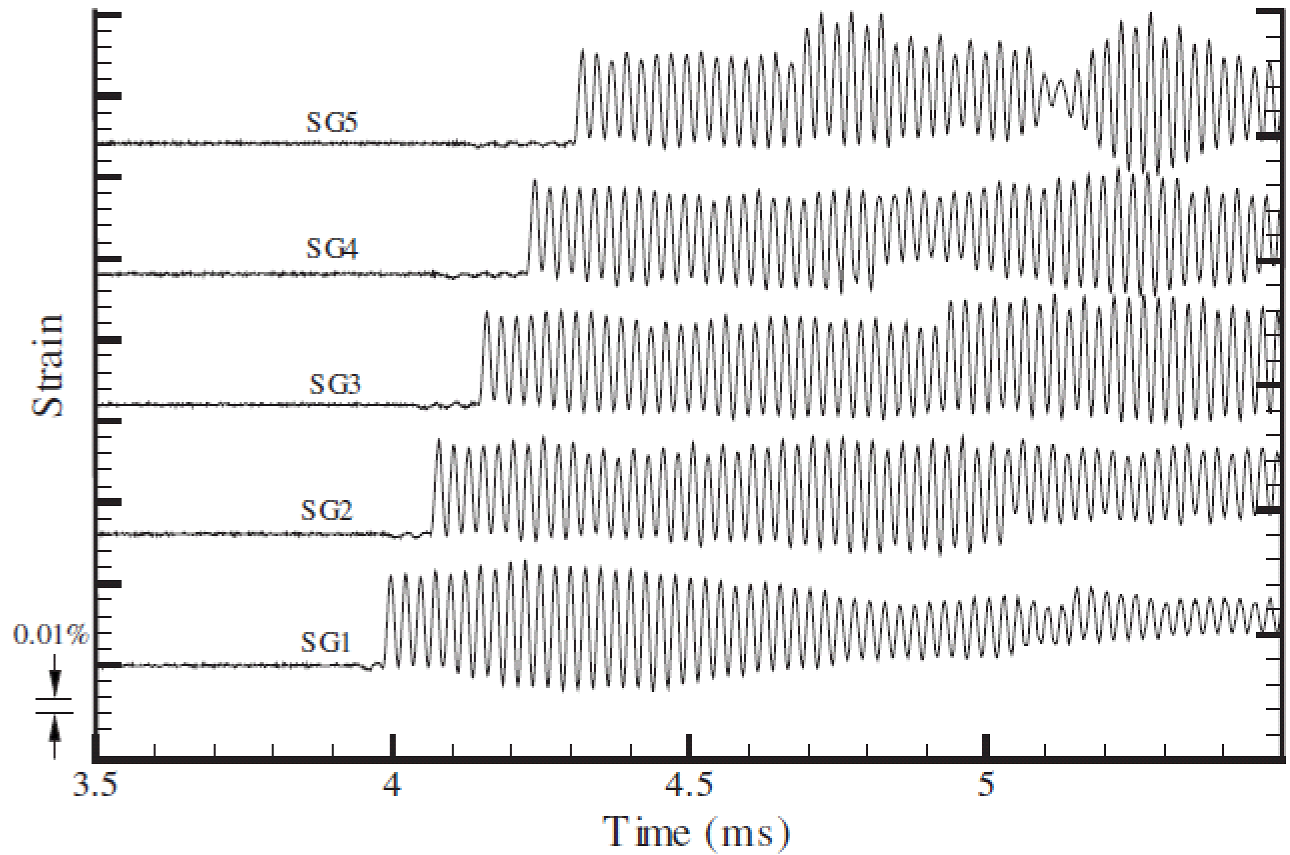
Strain gage



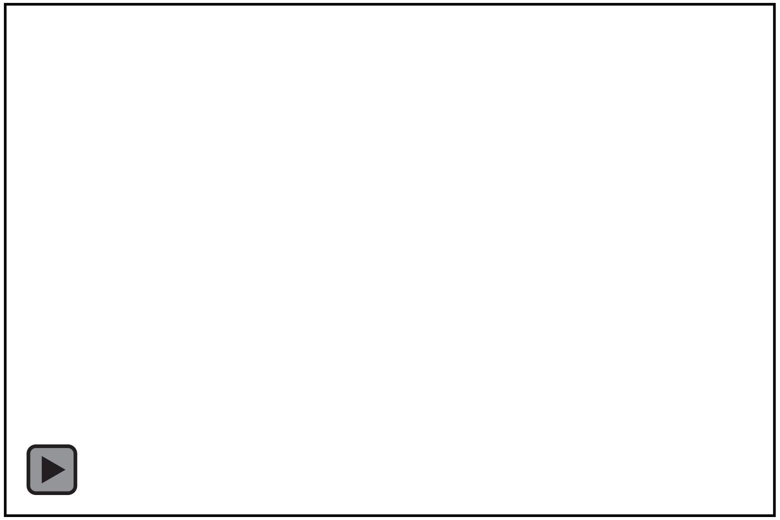
Optical Vibrometer



Chao 2004



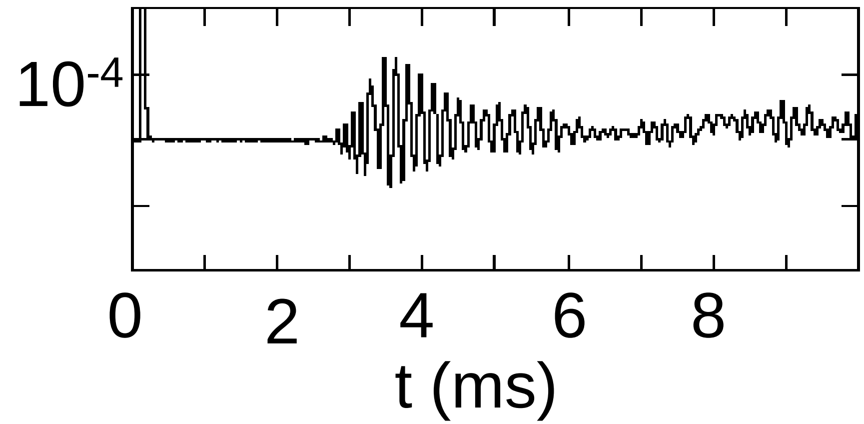
Flexural Wave Resonance in Tubes



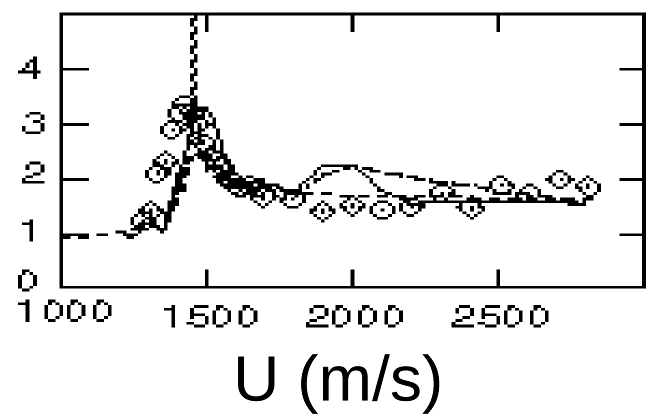
- Coupled response due to hoop oscillations and bending
- Traveling load can excite resonance when flexural wave group velocity matches wave speed
- Can be treated with analytical and FEM models

Beltman and Shepherd 2002

Measured strain (hoop)



Amplification factor



Detonation-Induced Failure of Piping Systems

- Initiation of cracks at flaws
- Plastic deformation at
  - Location of transition from deflagration to detonation
  - Reflection from bends, tees, dead ends
- Rupture
  - Plastic instability to to prolonged application of high pressure
- Bending pipes or support structures
  - Forces created by detonation wave changing direction

Detonation-Induced Fracture

External Blast

Fracture

Chao 2004

Fracture Behavior is a Strong Function of Initial Flaw Length

Outer diameter: 41.28 mm, Wall thickness: 0.89 mm, Length: 0.914 m
Surface notch dimensions: Width: 0.25 mm, Notch depth: 0.56 mm
Chao 2004

Post-test Al 6061-T6 Specimens (Pcj = 6.2 MPa)

Surface Notch Length = 1.27 cm

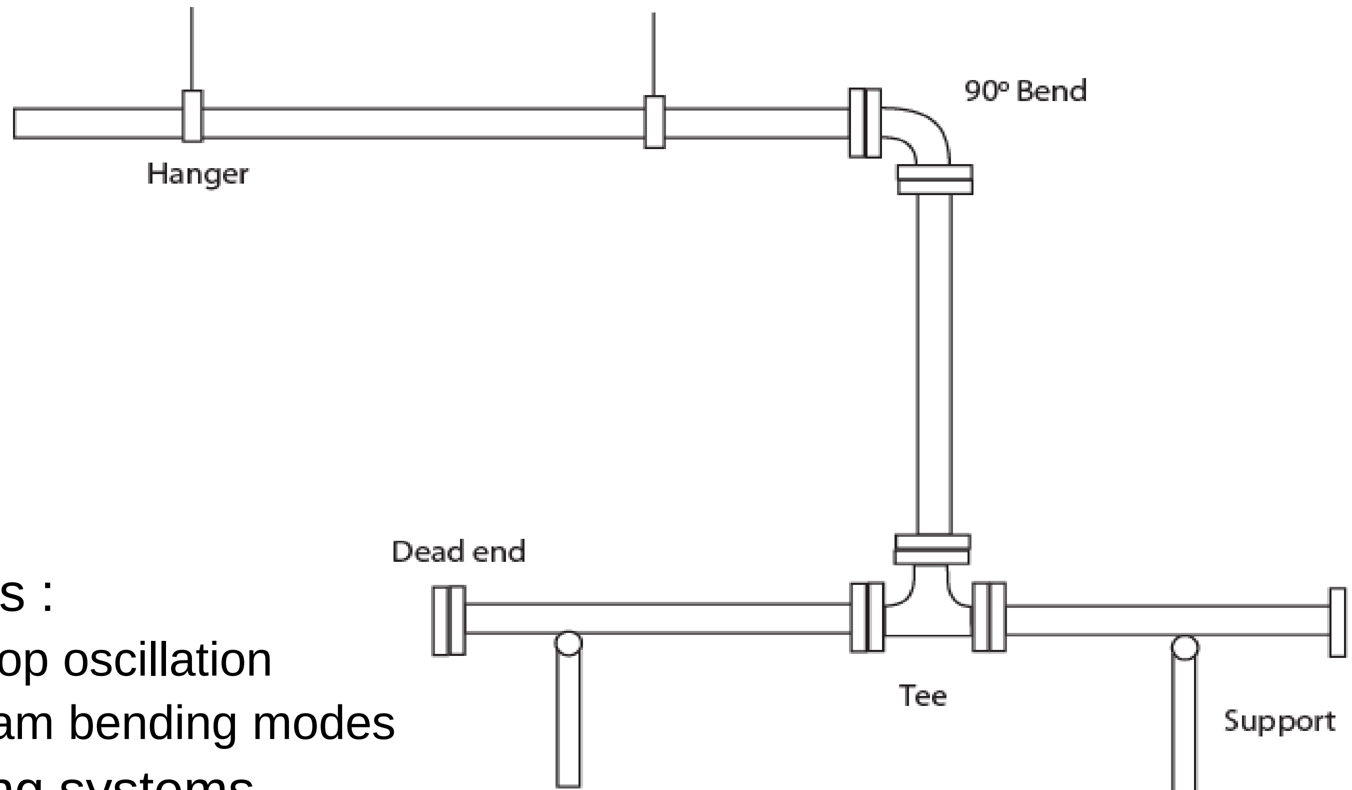
Surface Notch Length = 2.54 cm

Surface Notch Length = 5.08 cm

Surface Notch Length = 7.62 cm

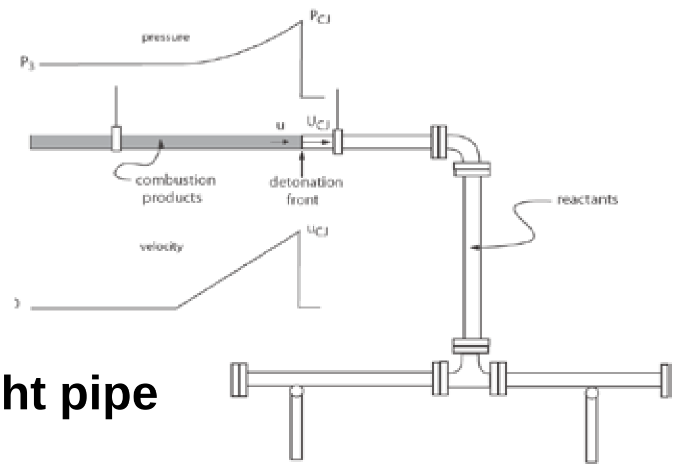
Detonation wave direction

Special Issues in Piping Systems

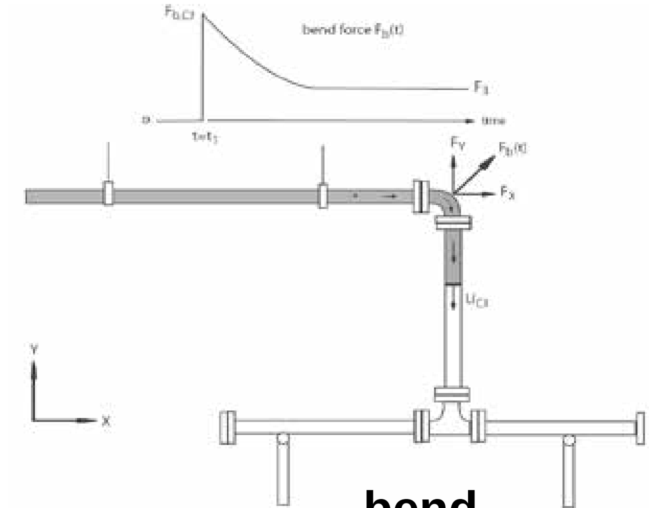


- Two types of loads :
  - Short period hoop oscillation
  - Long period beam bending modes
- Significant in piping systems
  - Traveling load creates series of impulses at bends, tees and closed ends
  - Dynamic pressure must be accounted for in computing magnitude of impulse
  - Strains due to bending comparable or larger than hoop strains

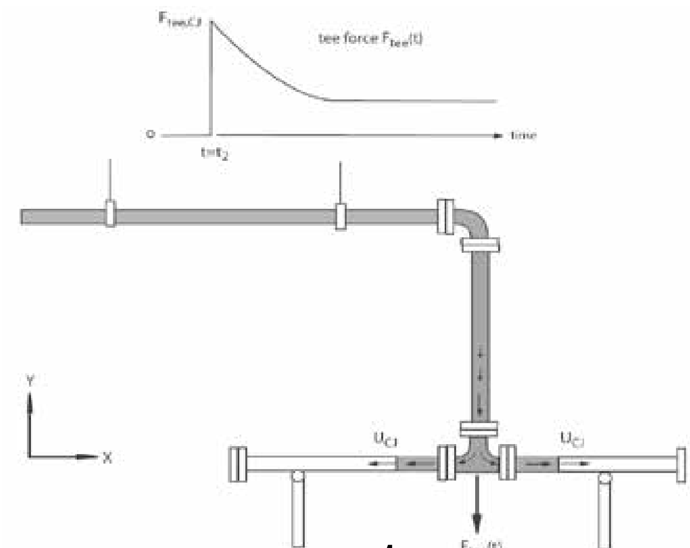
Piping System Response



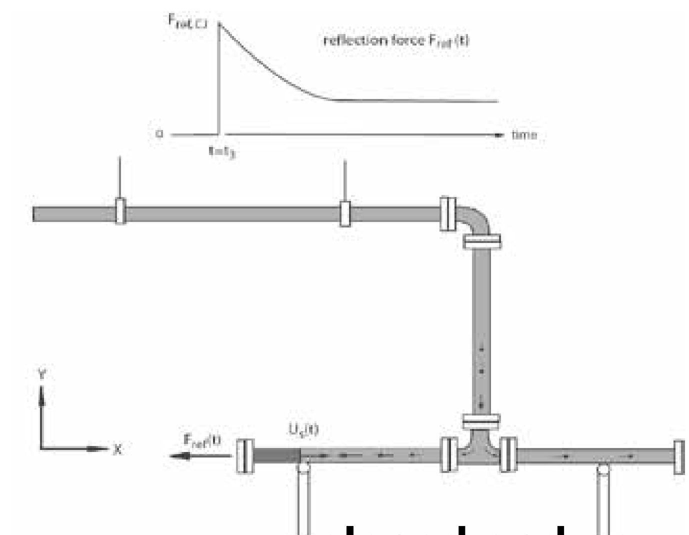
Straight pipe



bend



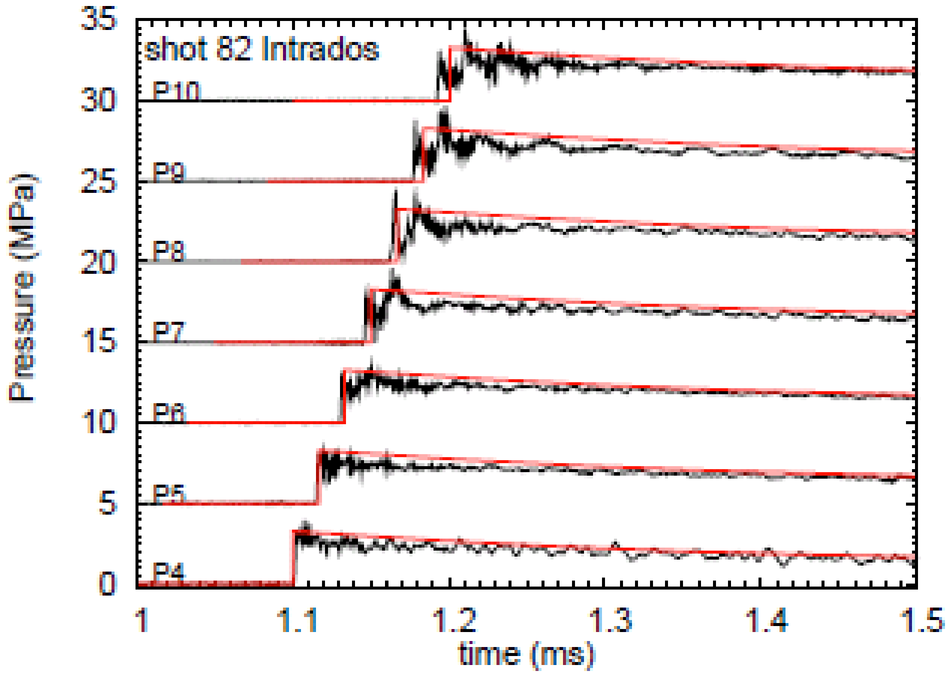
tee

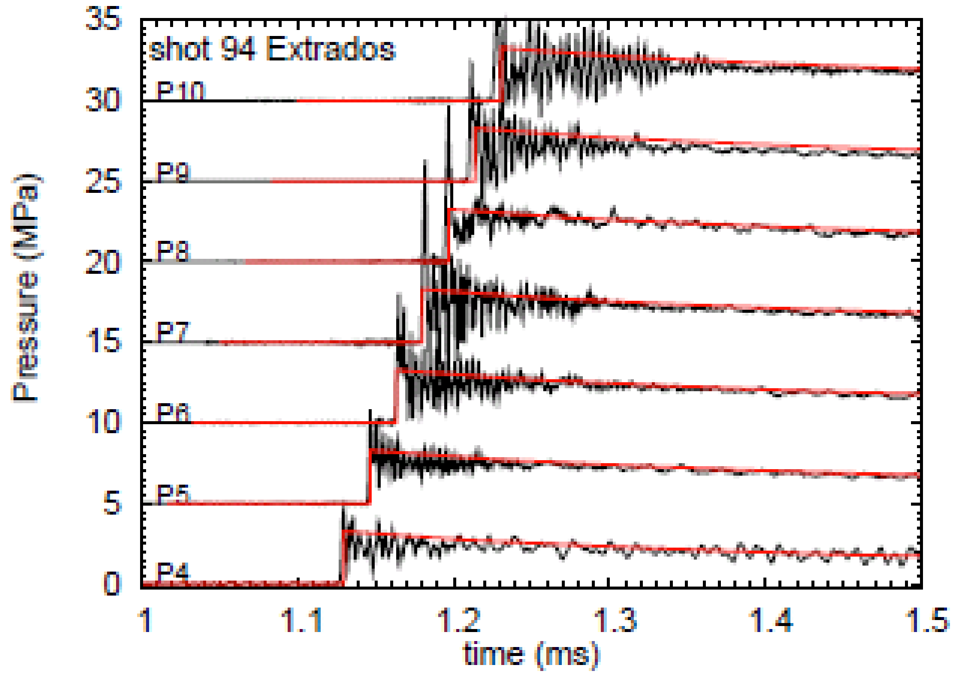


closed end

Simulation (R. Dieterding ORNL)

Pressure Waves on 90º Bend



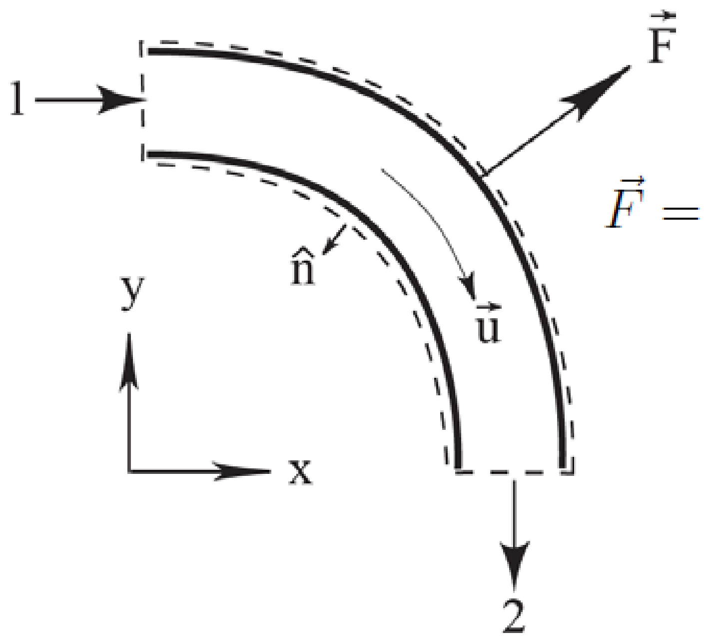


Liang, Curran and Shepherd 2007

Transverse Flow Forces in a 90º Bend

Momentum equation (general case):

$$\vec{F} = \int_{\partial\Omega_1} \left[\rho \vec{u}\vec{u}\cdot\hat{x} + (P - P_a)\hat{x}\right]\, dA + \int_{\partial\Omega_2} \left[\rho \vec{u}\vec{u}\cdot\hat{y} + (P - P_a)\hat{y}\right]\, dA - \frac{d}{dt}\int_{\Omega_O} \rho\vec{u}\, dV$$



Simplification for uniform, steady flow:

$$\vec{F} = \hat{x}A_1\left[(P_1 - P_a) + \rho_1 u_1^2\right] + \hat{y}A_2\left[(P_2 - P_a) + \rho_2 u_2^2\right]$$

General unsteady case:

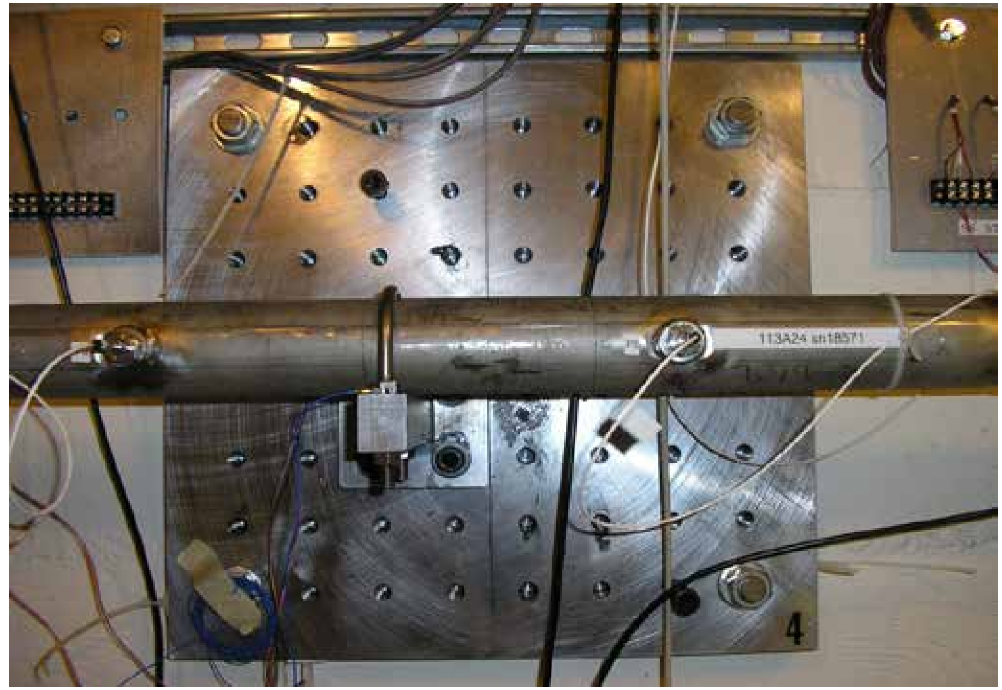
$$\vec{F} = \hat{x}F_x(t) + \hat{y}F_y(t)$$

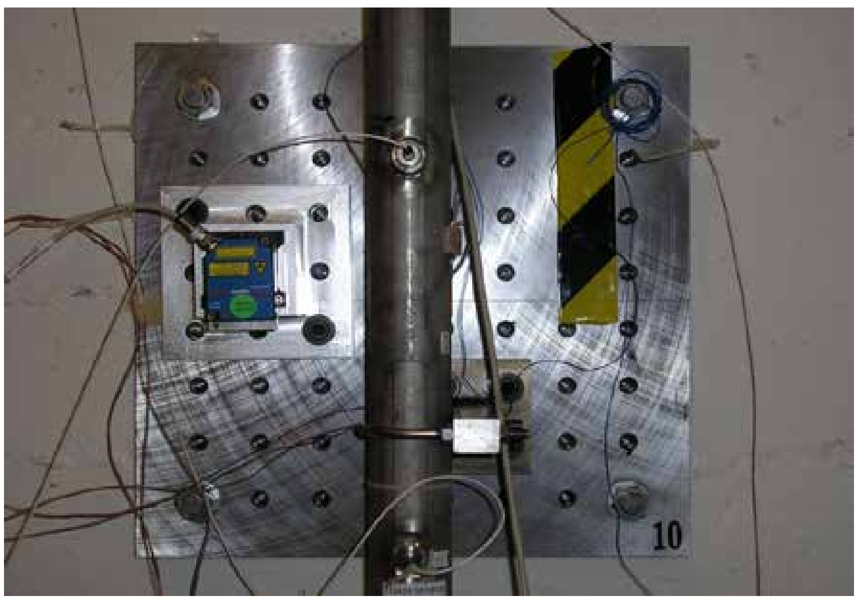
Dynamic pressure within Taylor wave $\rho u^2 \sim P - P_3$

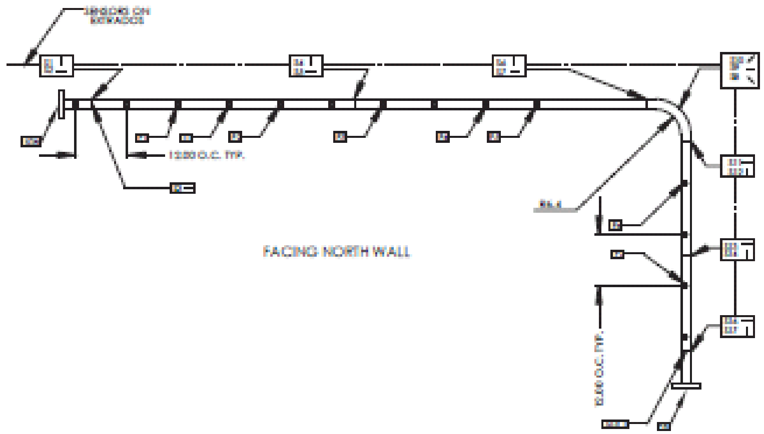
Approximate transverse force

Shepherd and Akbar 2009 FM2008.002

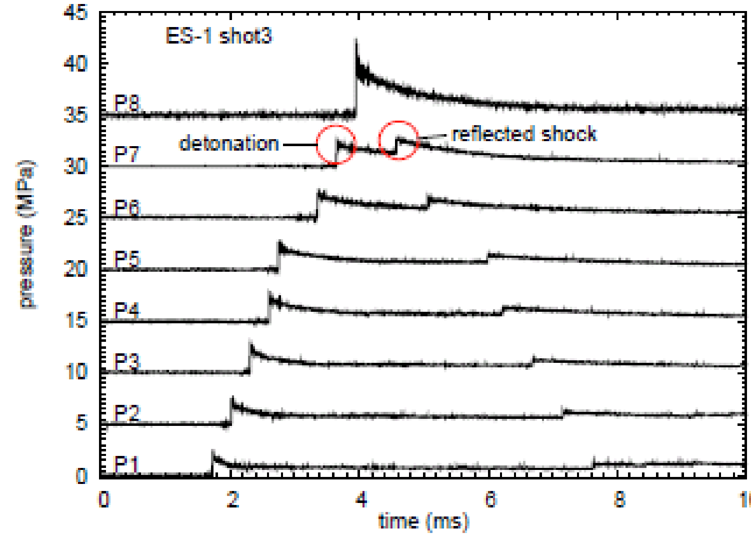
$$F(t) \propto A \times \left[2(P(t) - P_3) + P_3\right]$$


113A24 sn18571
4

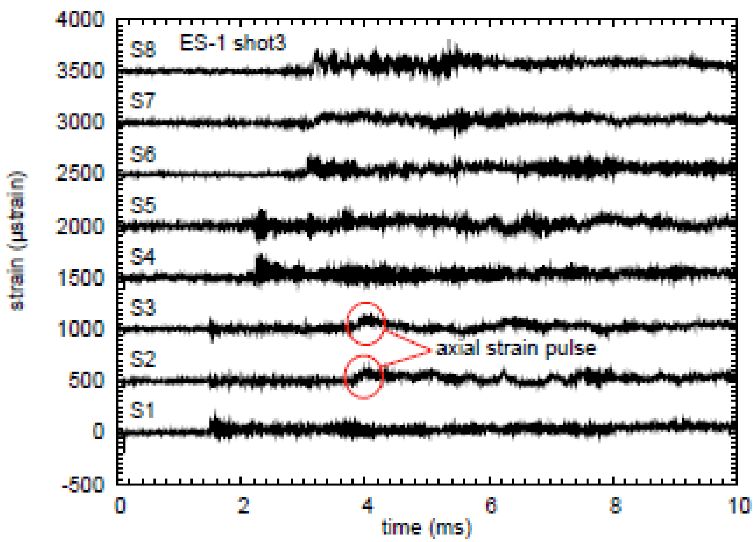

10


FACING NORTH WALL

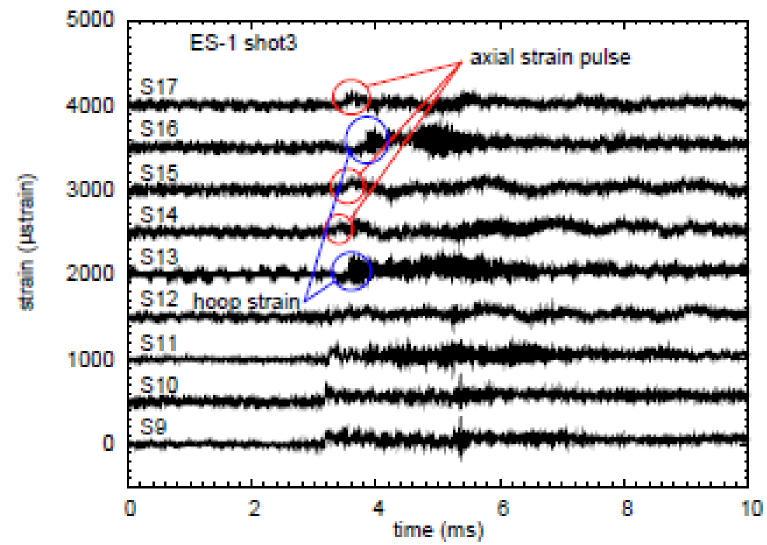
a)


ES-1 shot3
P8
P7
P6
P5
P4
P3
P2
P1
detonation
reflected shock
pressure (MPa)
time (ms)
0
5
10
15
20
25
30
35
40
45
0
2
4
6
8
10

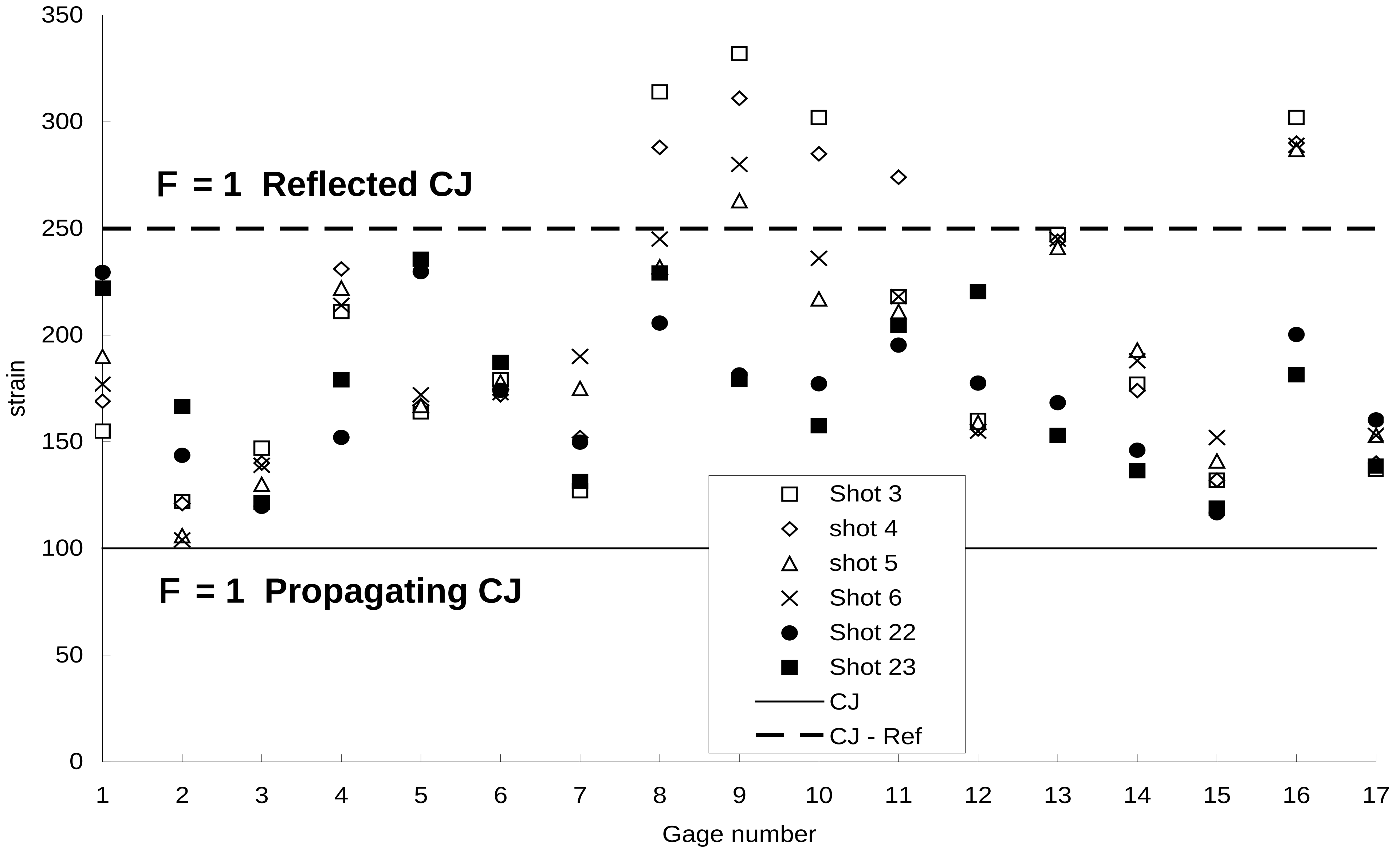
b)


ES-1 shot3
S8
S7
S6
S5
S4
S3
S2
S1
axial strain pulse
strain (μstrain)
time (ms)
-500
0
500
1000
1500
2000
2500
3000
3500
4000
0
2
4
6
8
10

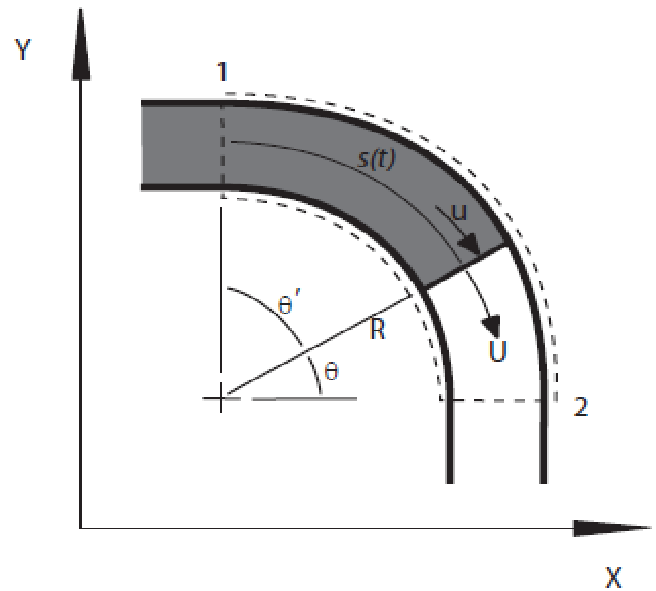
d)


ES-1 shot3
S17
S16
S15
S14
S13
S12
S11
S10
S9
axial strain pulse
hoop strain
strain (μstrain)
time (ms)
0
1000
2000
3000
4000
5000
0
2
4
6
8
10

e)


F = 1 Reflected CJ
F = 1 Propagating CJ
strain
Gage number
350
300
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
Shot 3
shot 4
shot 5
Shot 6
Shot 22
Shot 23
CJ
CJ - Ref

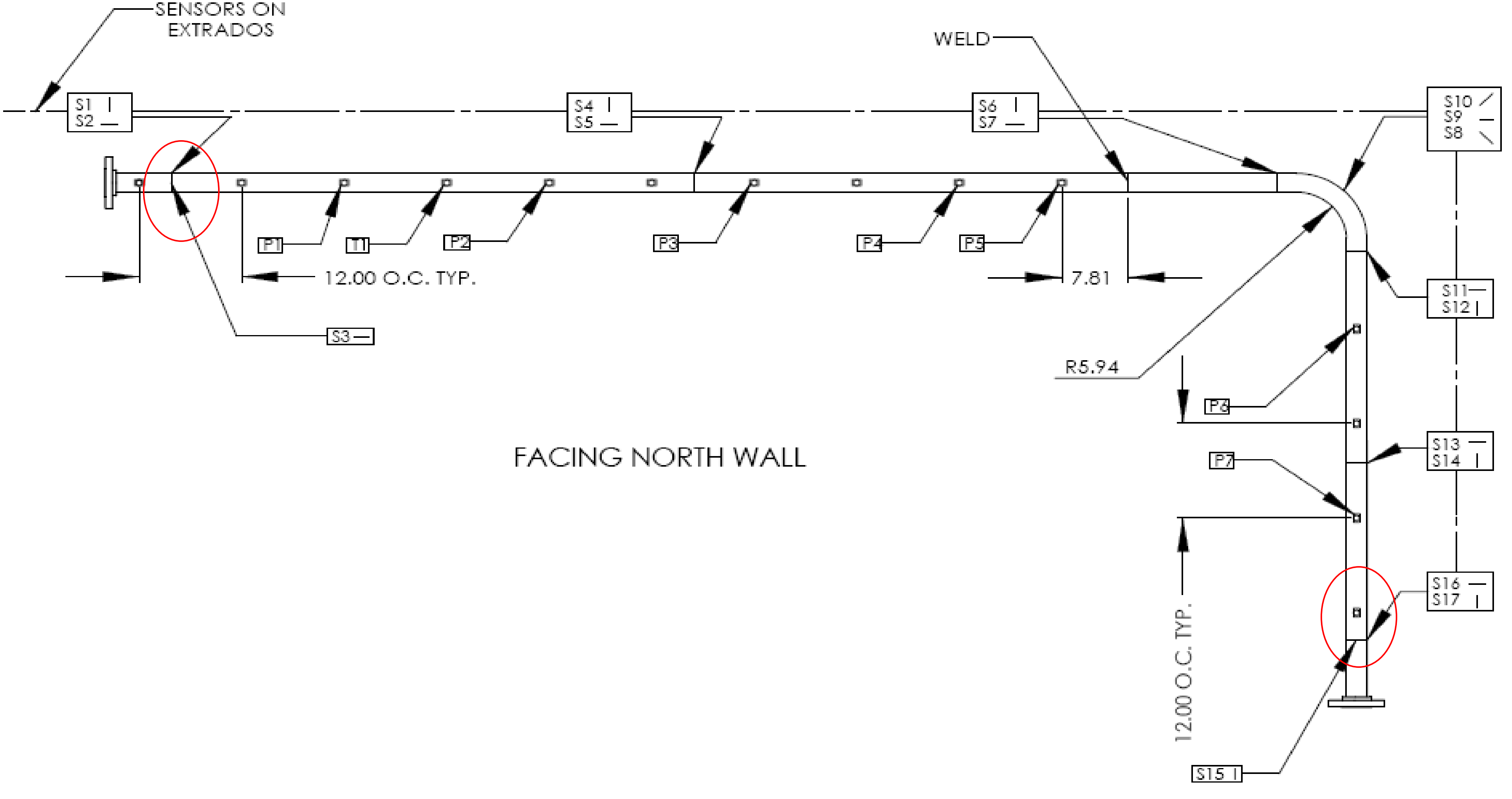
Control Volume Bend Force Model



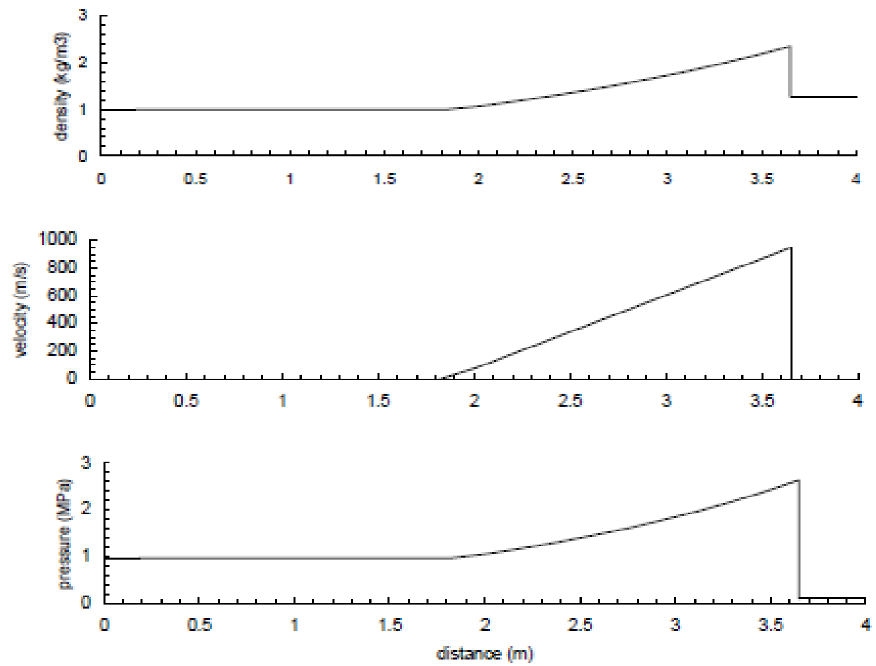
$$\vec{F} = \int_{\partial\Omega_1} \left[\rho\vec{u}\vec{u}\cdot\hat{x} + (P - P_a)\hat{x}\right]\, dA + \int_{\partial\Omega_2} \left[\rho\vec{u}\vec{u}\cdot\hat{y} + (P - P_a)\hat{y}\right]\, dA - \frac{d}{dt}\int_{\Omega_O} \rho\vec{u}\, dV \quad (22)$$

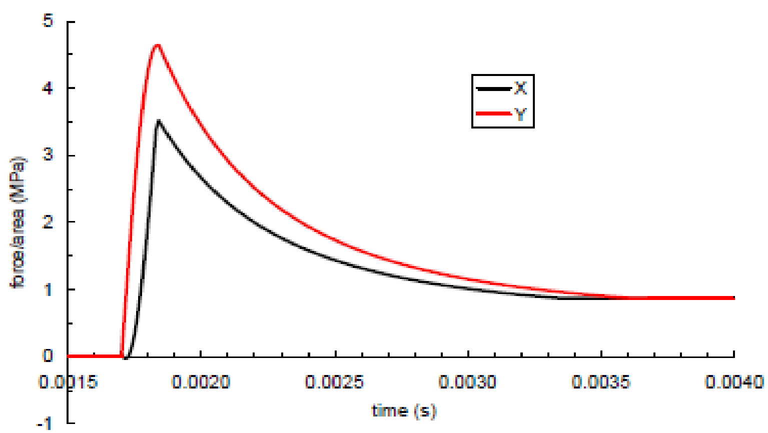
$$\begin{aligned}\vec{F}(t) = \hat{x}A\left[(P_1(t) - P_a) + \rho_1(t)u_1^2(t)\right] + \hat{y}A\left[(P_2(t) - P_a) + \rho_2(t)u_2^2(t)\right] \\ + \rho_{CJ}u_{CJ}U_{CJ}A\left[-\hat{x}\cos\left(\frac{U(t-t_1)}{R}\right) + \hat{y}\sin\left(\frac{U(t-t_1)}{R}\right)\right]\end{aligned}$$

Measuring Axial Strains



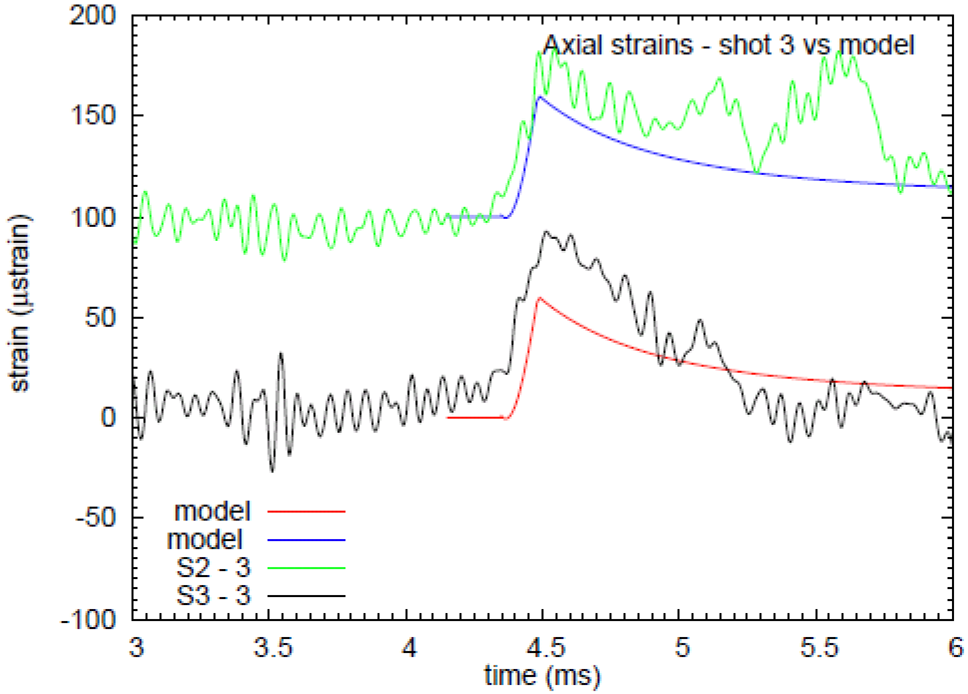
Bend Force Estimation for CJ Detonation

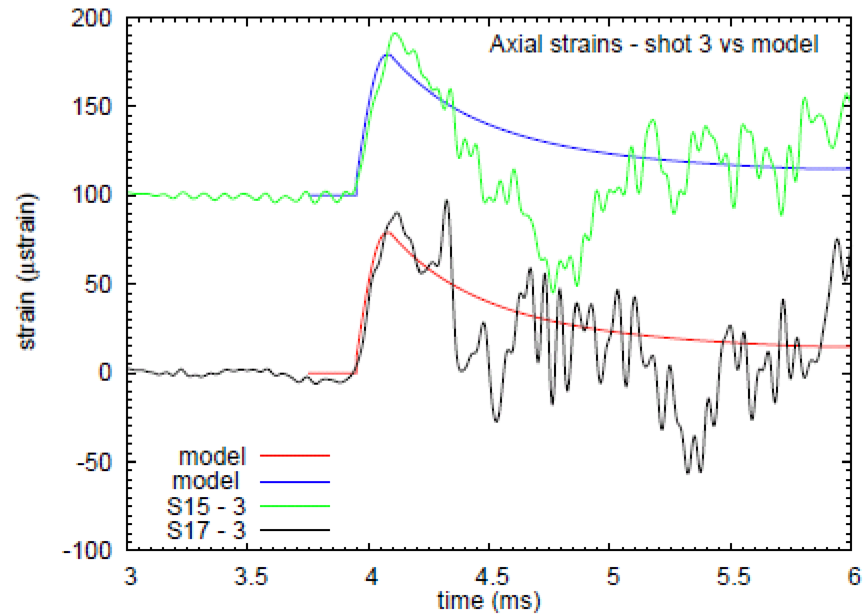




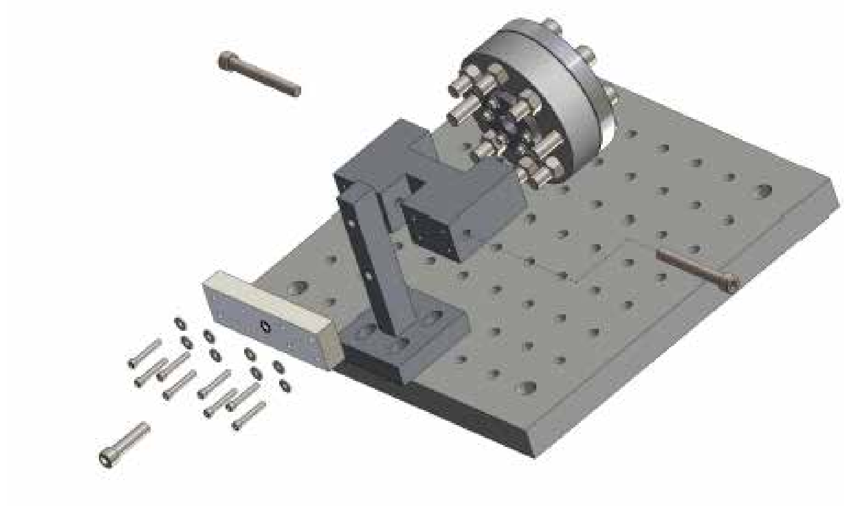
Axial Strain Pulses – Measured vs Predicted

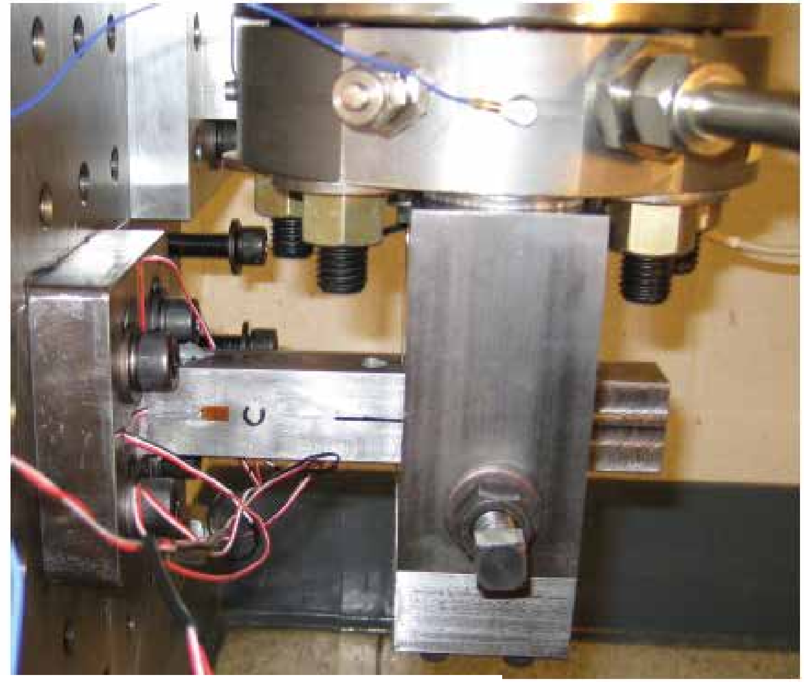
$$\frac{\partial \sigma}{\partial x} = \frac{\rho}{E}\frac{\partial^2 u}{\partial t^2}$$

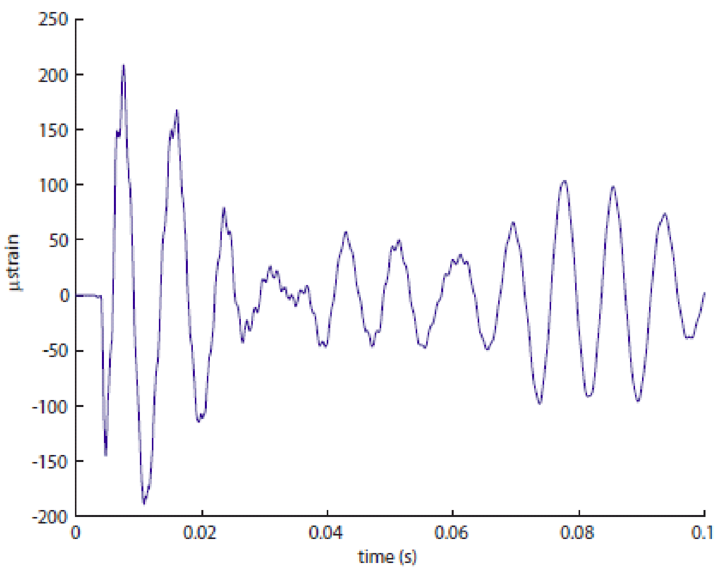


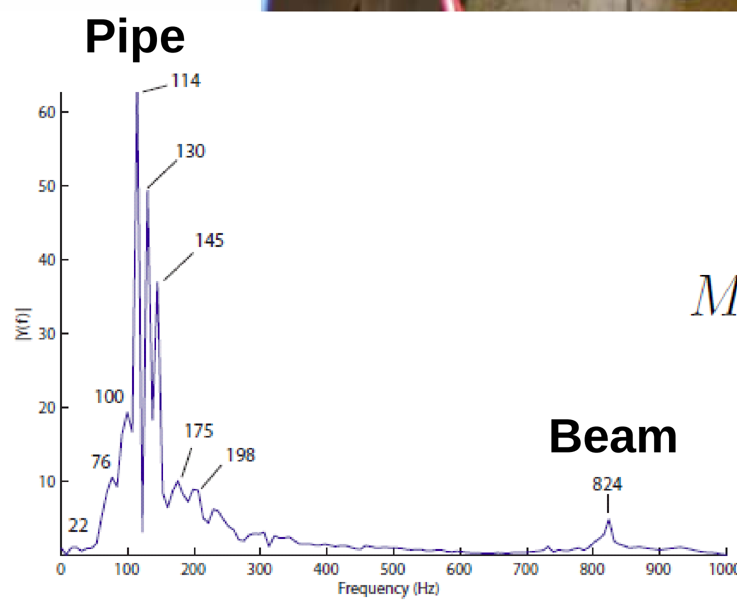


Direct Force Measurement









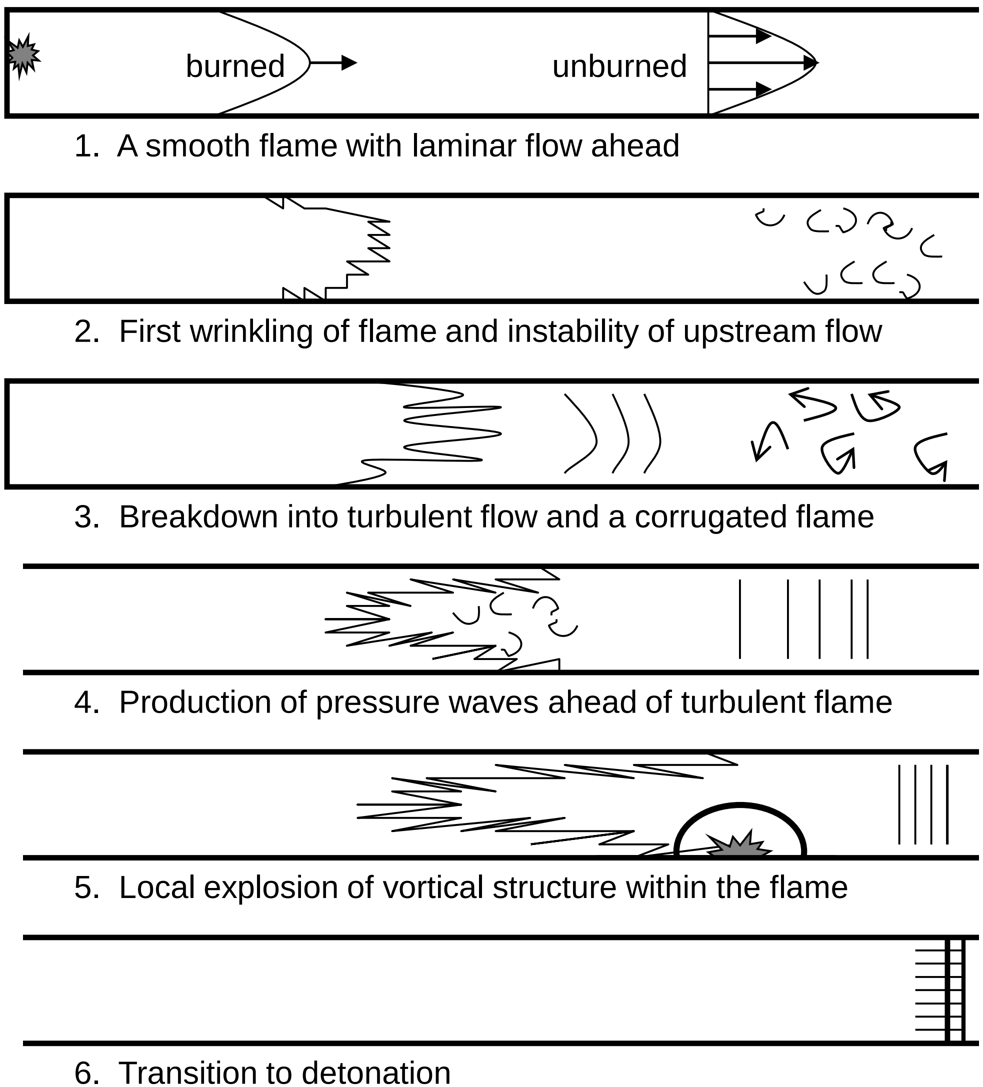
$$M\frac{d^2Y}{dt^2} + k_y Y = F(t)$$

Deflagration-to-Detonation Transition (DDT)

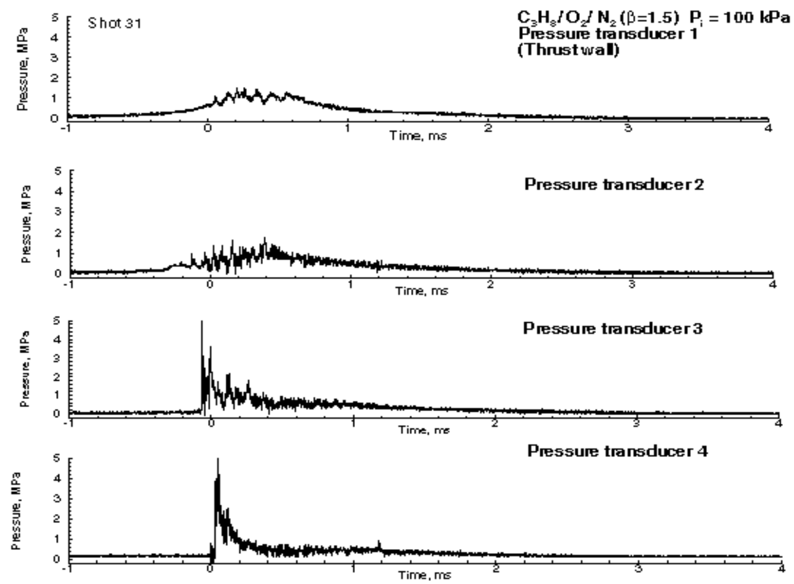
DDT

- Deflagration to detonation transition is a common industrial hazard with gaseous explosions
- Compression of gas by flame increases pressure when detonation finally occurs “pressure piling”.
- Represents upper bound in severity of pressure loading.

Deflagration to Detonation Transition

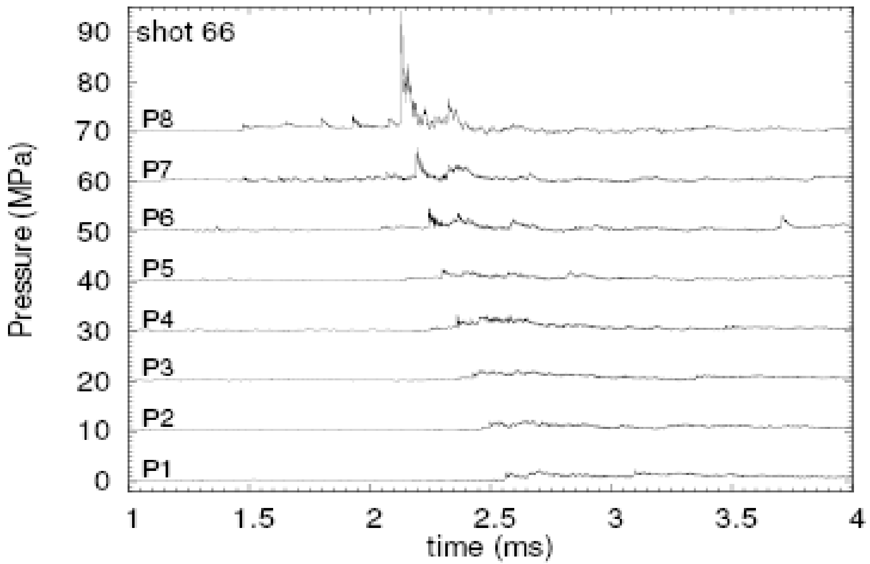


- Flame creates flow
  - Pressure build-up
- Detonation onset
  - Localized

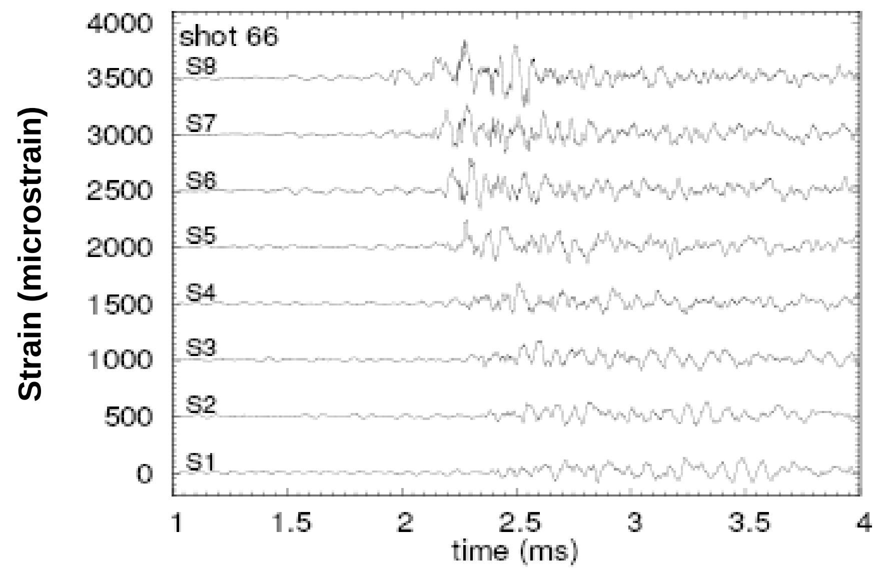


DDT Near End Flange

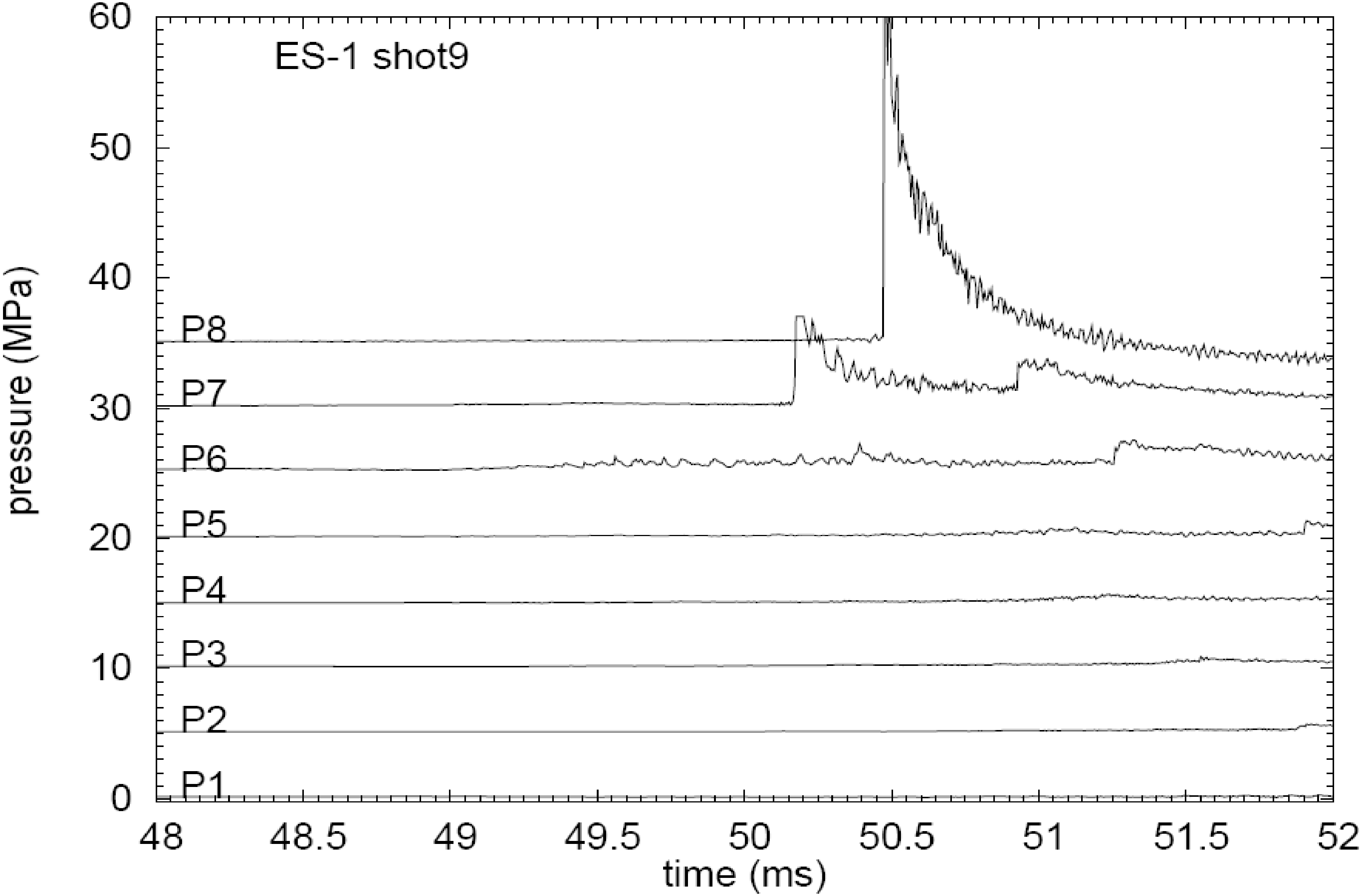
Pressure History

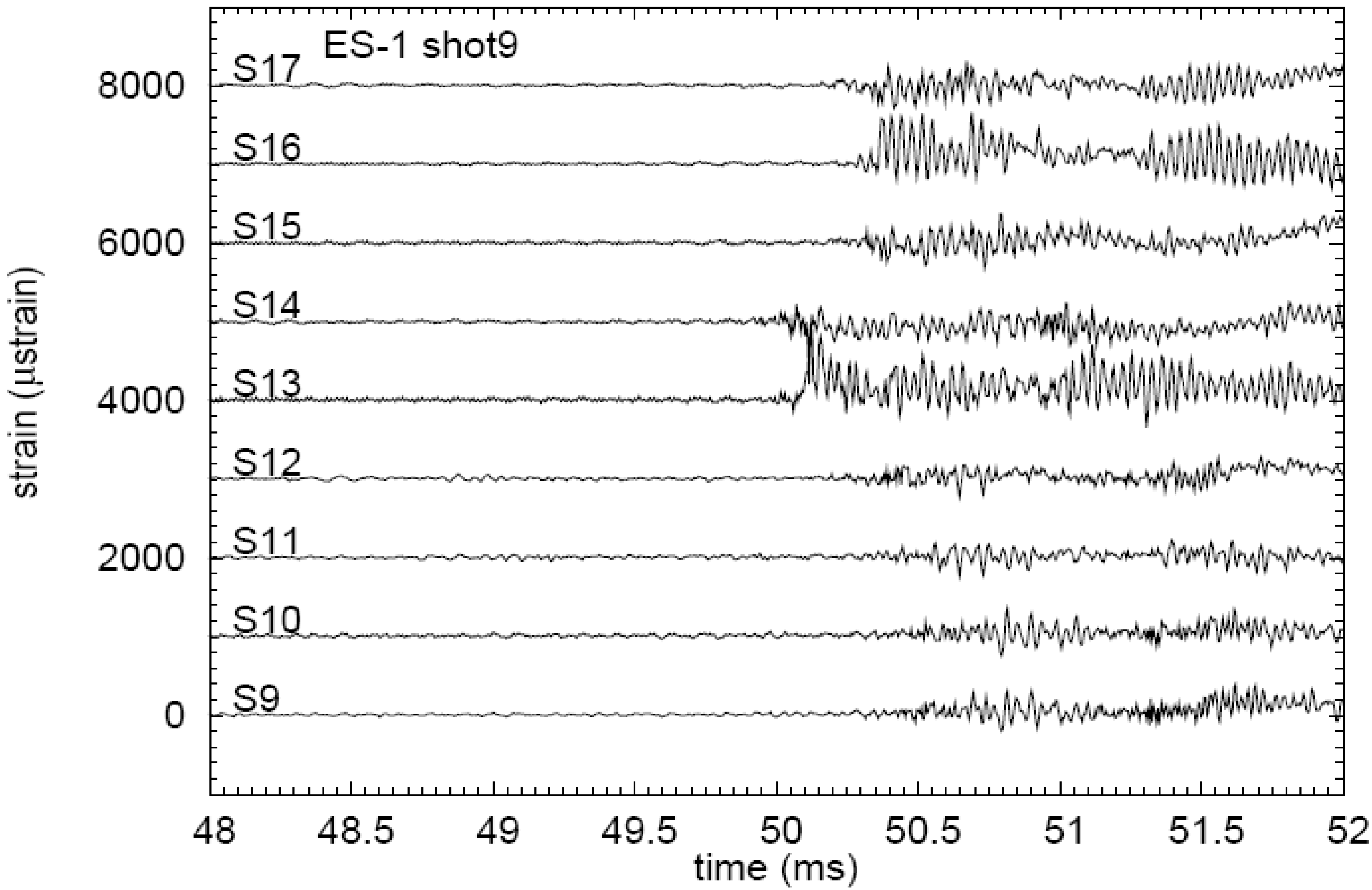


Strain History



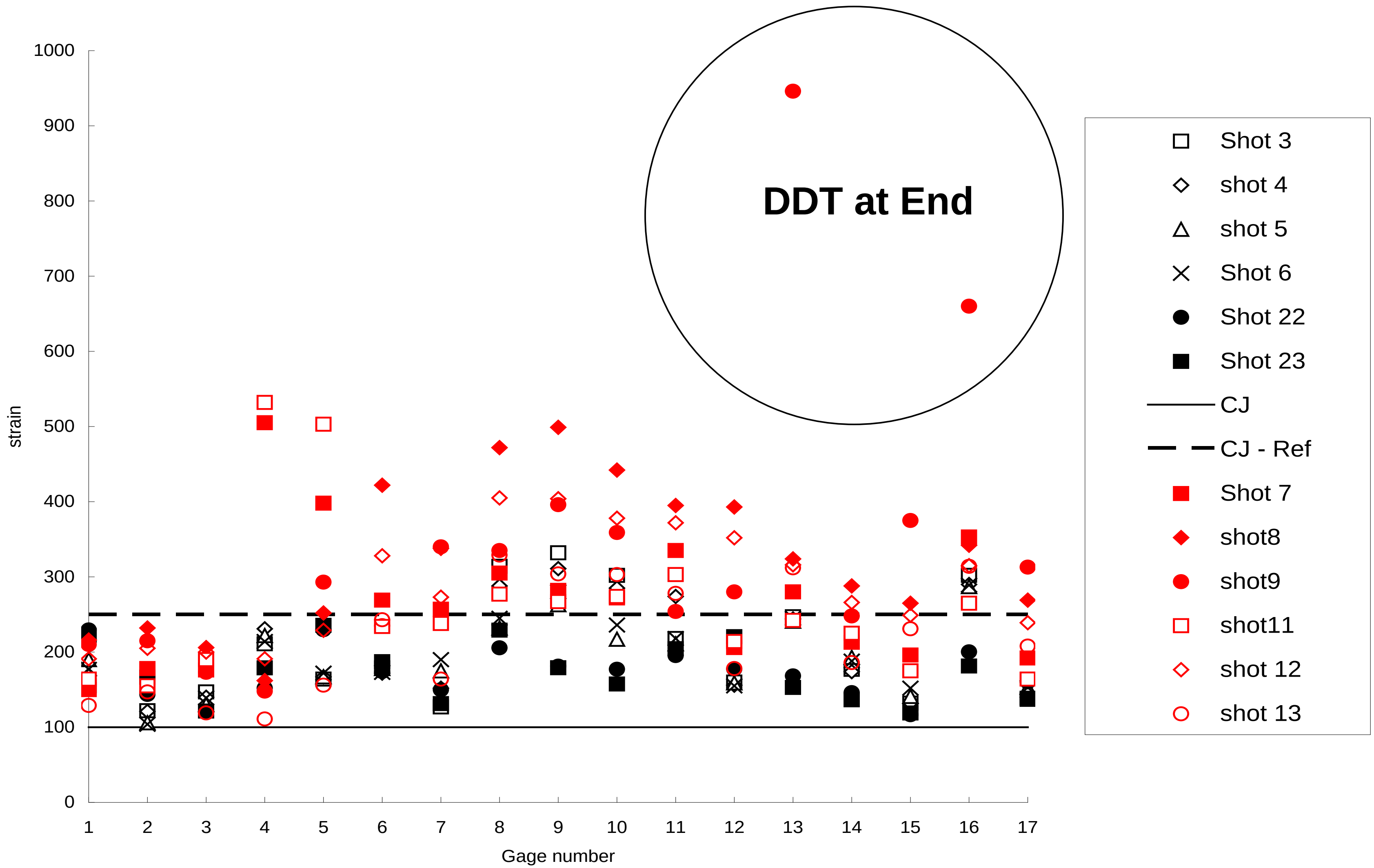
- **15% H2 in H2-N2O at 1 atm initial pressure**
- **Thermal ignition**
- **Tab obstacles inside 5' long tube**


ES-1 shot9
pressure (MPa)
time (ms)
P8
P7
P6
P5
P4
P3
P2
P1
60
50
40
30
20
10
0
48
48.5
49
49.5
50
50.5
51
51.5
52



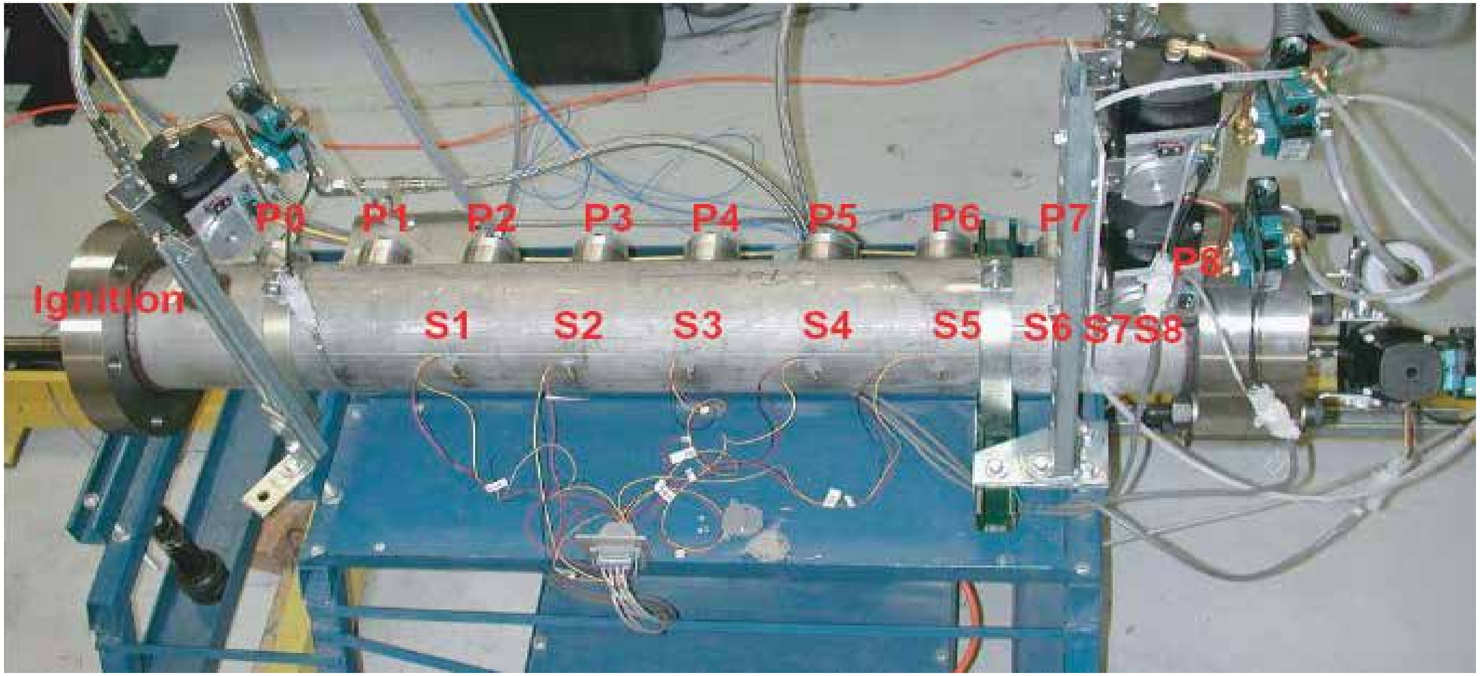
ES-1 shot9
S17
S16
S15
S14
S13
S12
S11
S10
S9
8000
6000
4000
2000
0
strain (μstrain)
48
48.5
49
49.5
50
50.5
51
51.5
52
time (ms)

DDT Structural Loading CIT ES1 Testing

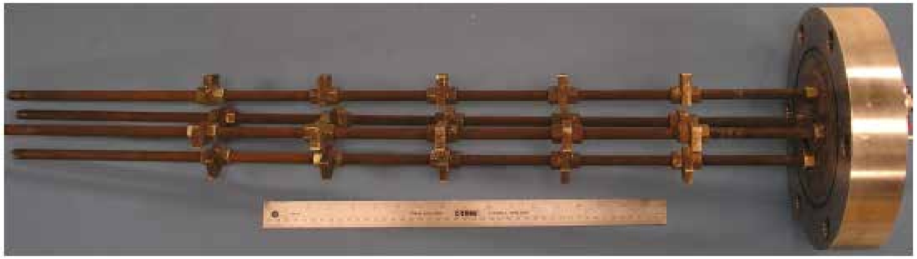


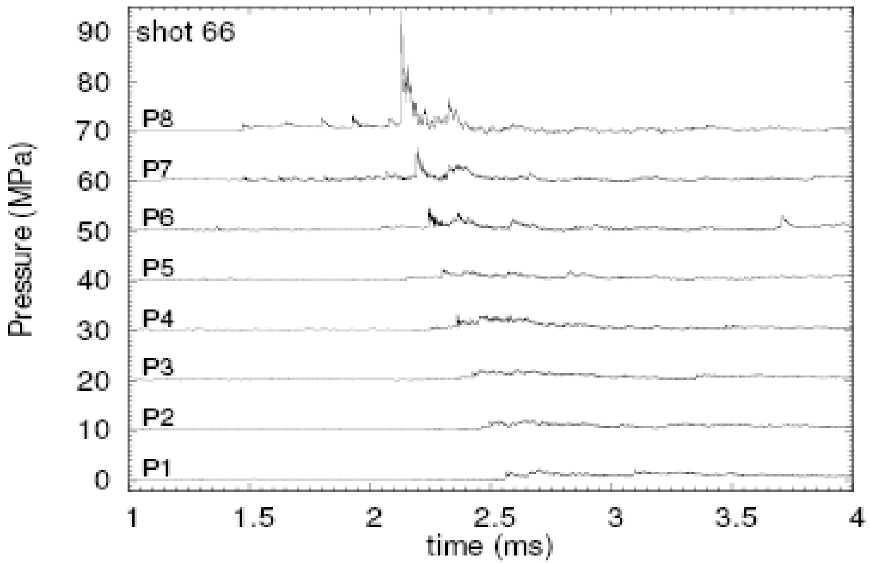
Other DDT Testing

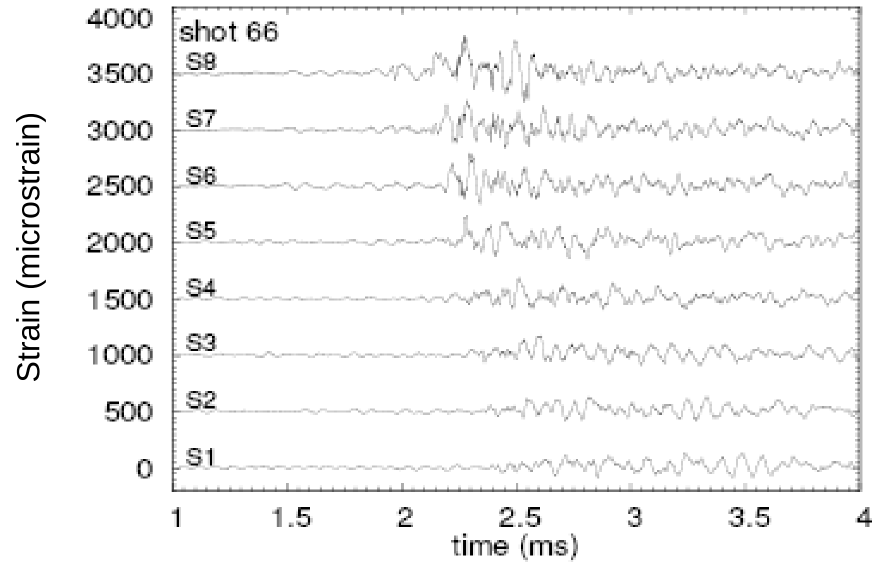
- Thick walled vessels for elastic response
- Thin-walled vessels for plastic response and failure
- Use bars or tabs as “obstacles” to cause flame acceleration
- Range of mixtures studied H2-N2O, H2-O2, CH4, C2H4, C3H8-O2
- Measurement of strain and pressure



DDT Near End Flange



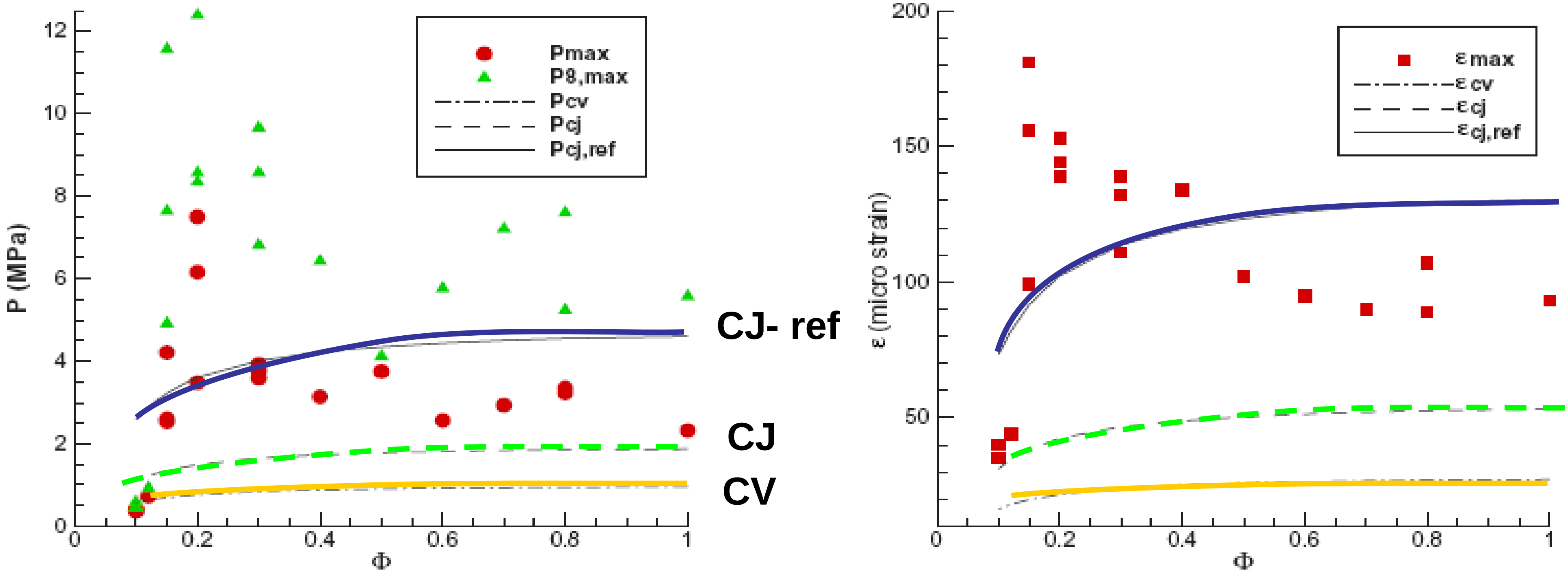




- 15% H2 in H2-N2O at 1 atm initial pressure
- Thermal ignition
- Tab obstacles inside tube

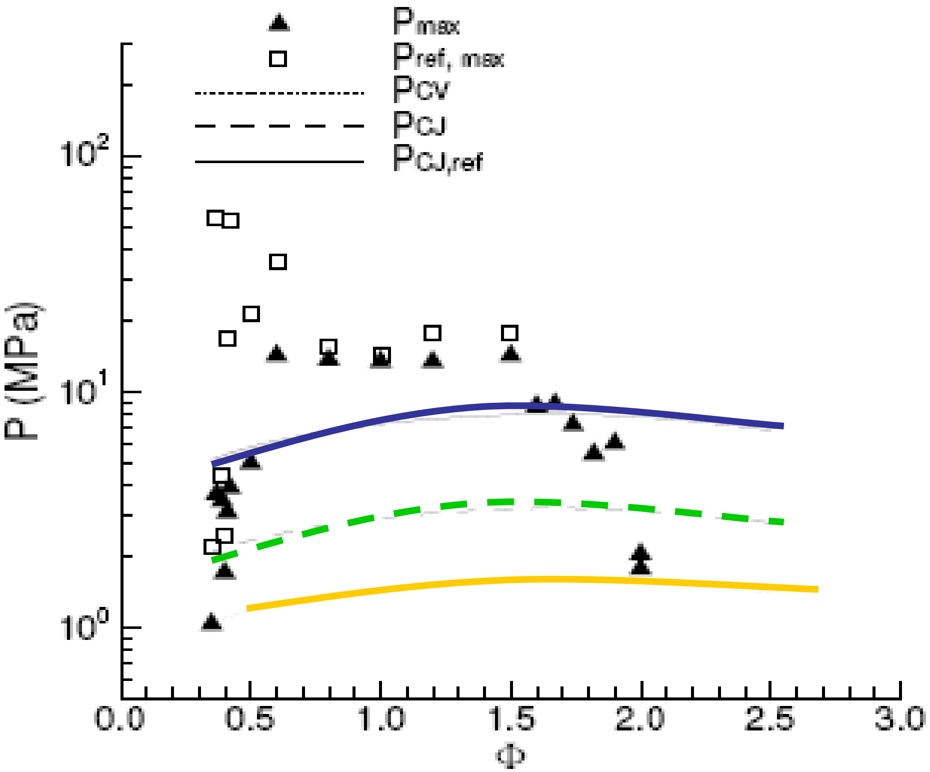
Liang, Karnesky & Shepherd 2006

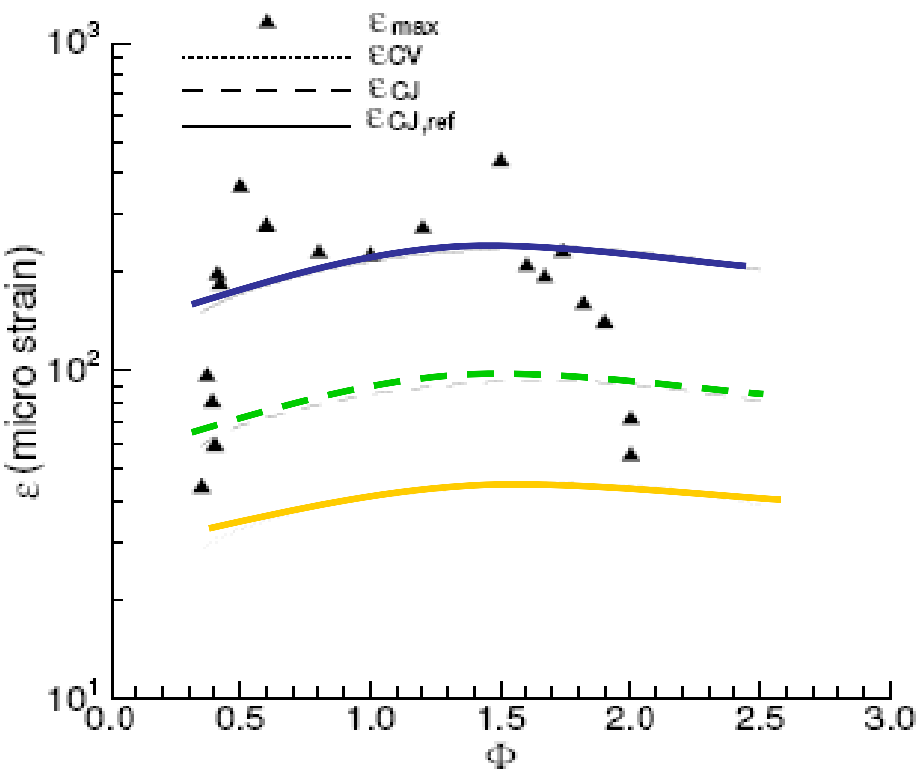
H2-O2



Pintgen, Liang, & Shepherd 2007

CH4-O2



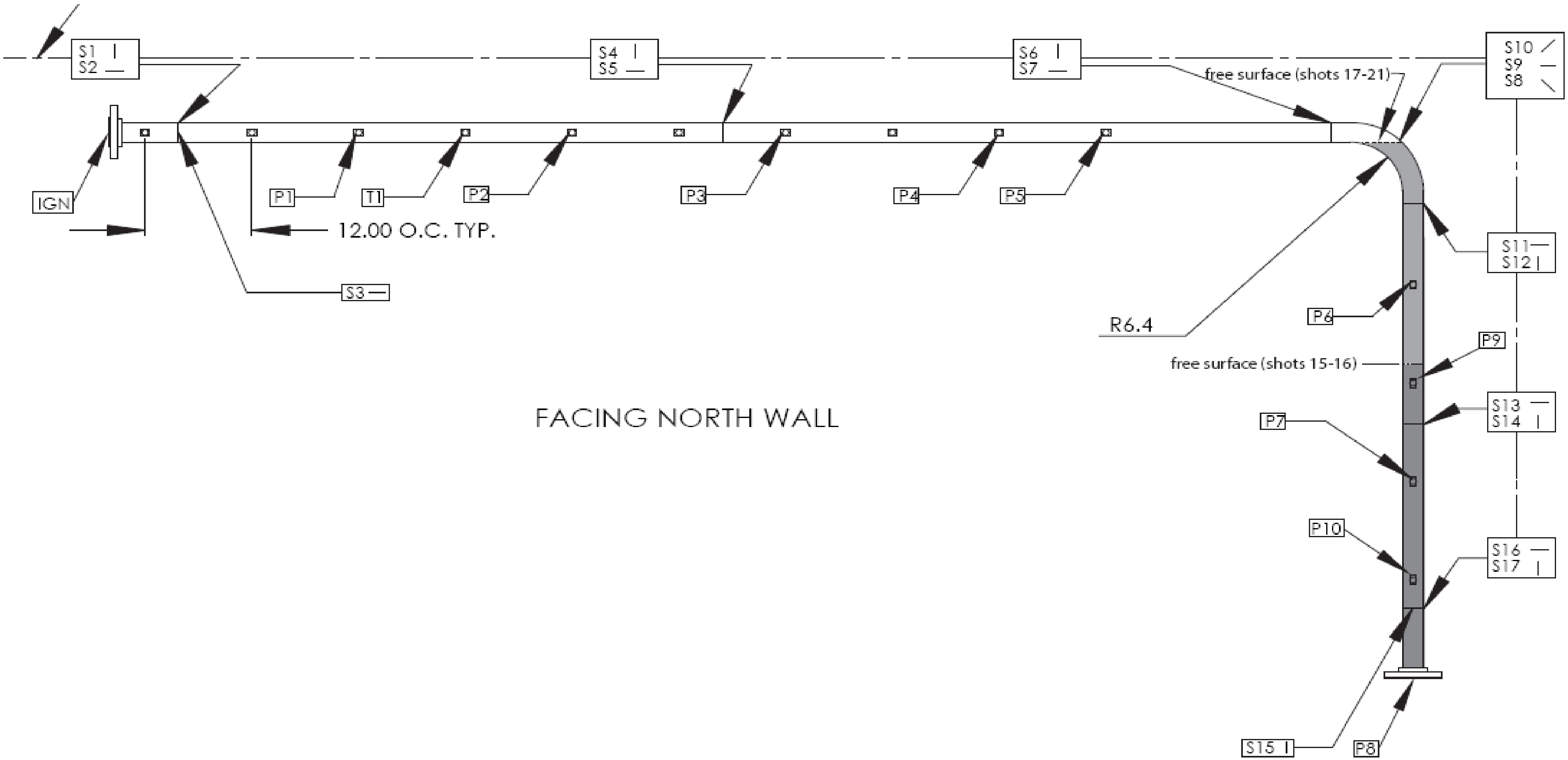


Pintgen, Liang, & Shepherd 2007

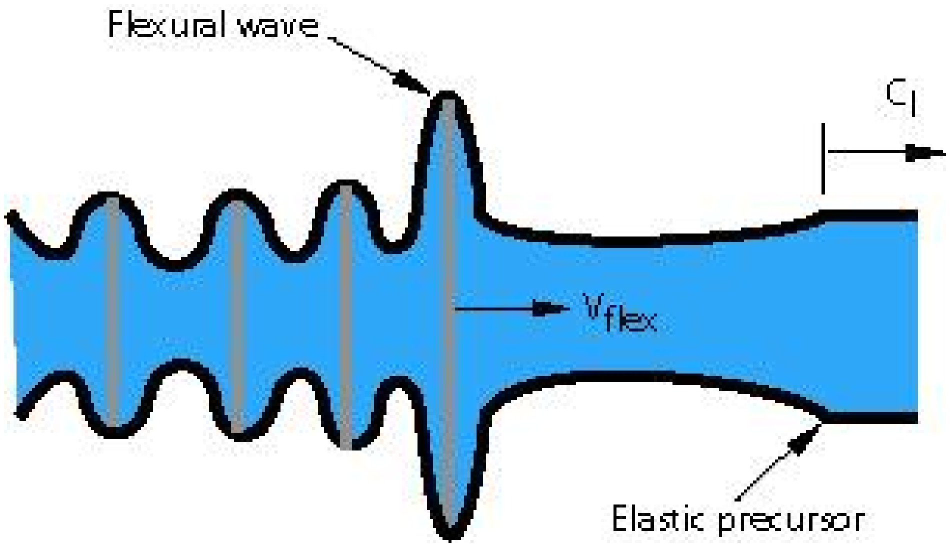
Conclusions of DDT Testing

- Peak pressures in DDT up to 10 X CJ-ref
  - White 1957, Kogarko 1958, Craven and Grieg 1967, etc.
- Load is in impulsive regime
- Peak strain is comparable to 2.5 x static strain of reflected detonation
- Results for four fuel-oxygen systems comparable (H_2, CH_4, C_2H_4, C_3H_8)

Water-Hammer Induced by Detonation



Elementary Theory



$$V_{flex} = \frac{c_f}{\sqrt{1 + \frac{D}{h}\frac{E_f}{E_s}}}$$

≈ 950 m/s **(Al tube)**

- Elastic tension precursor

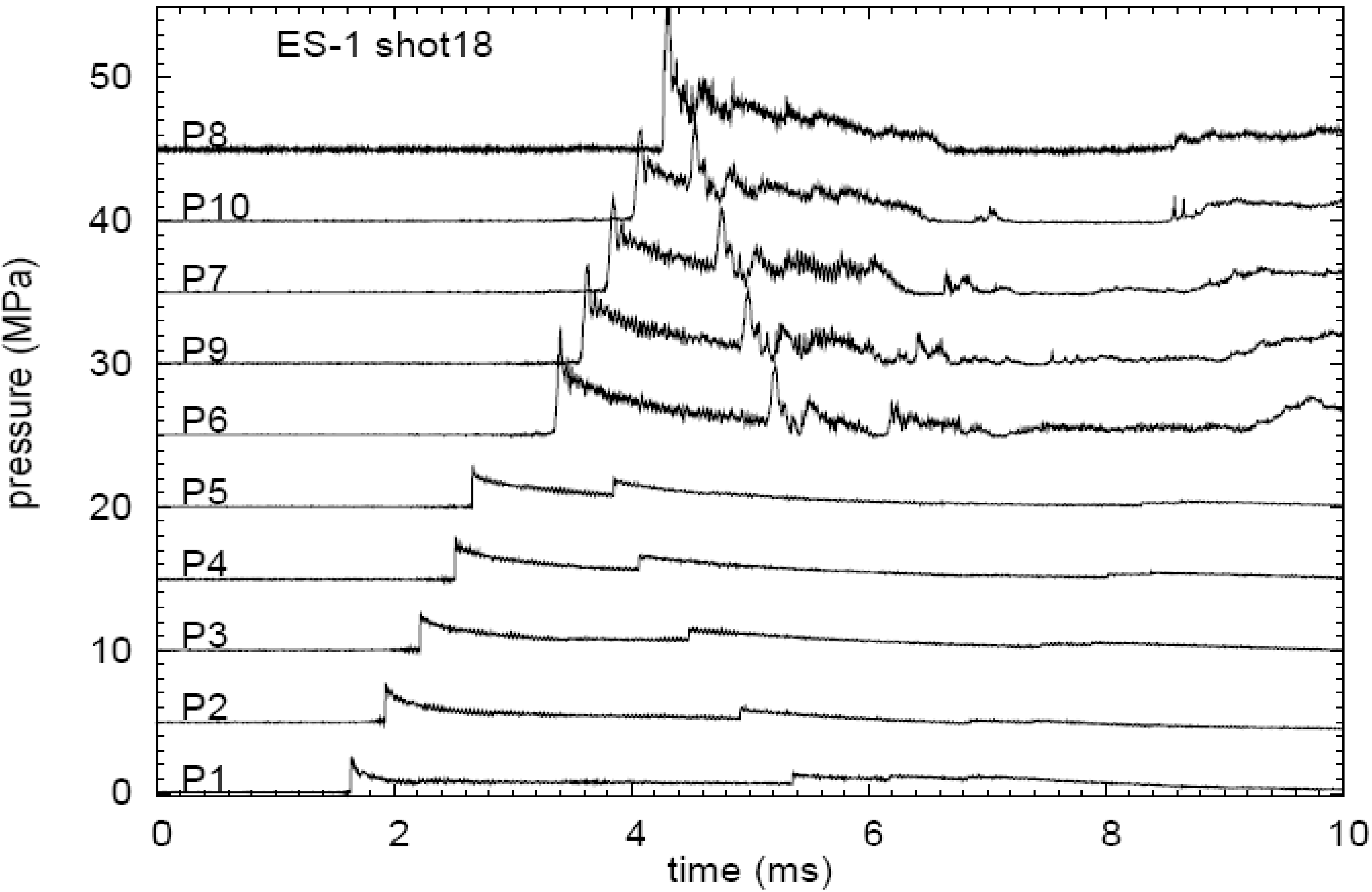
  $c_l = \sqrt{E_s/\rho_s} = 5100$ m/s

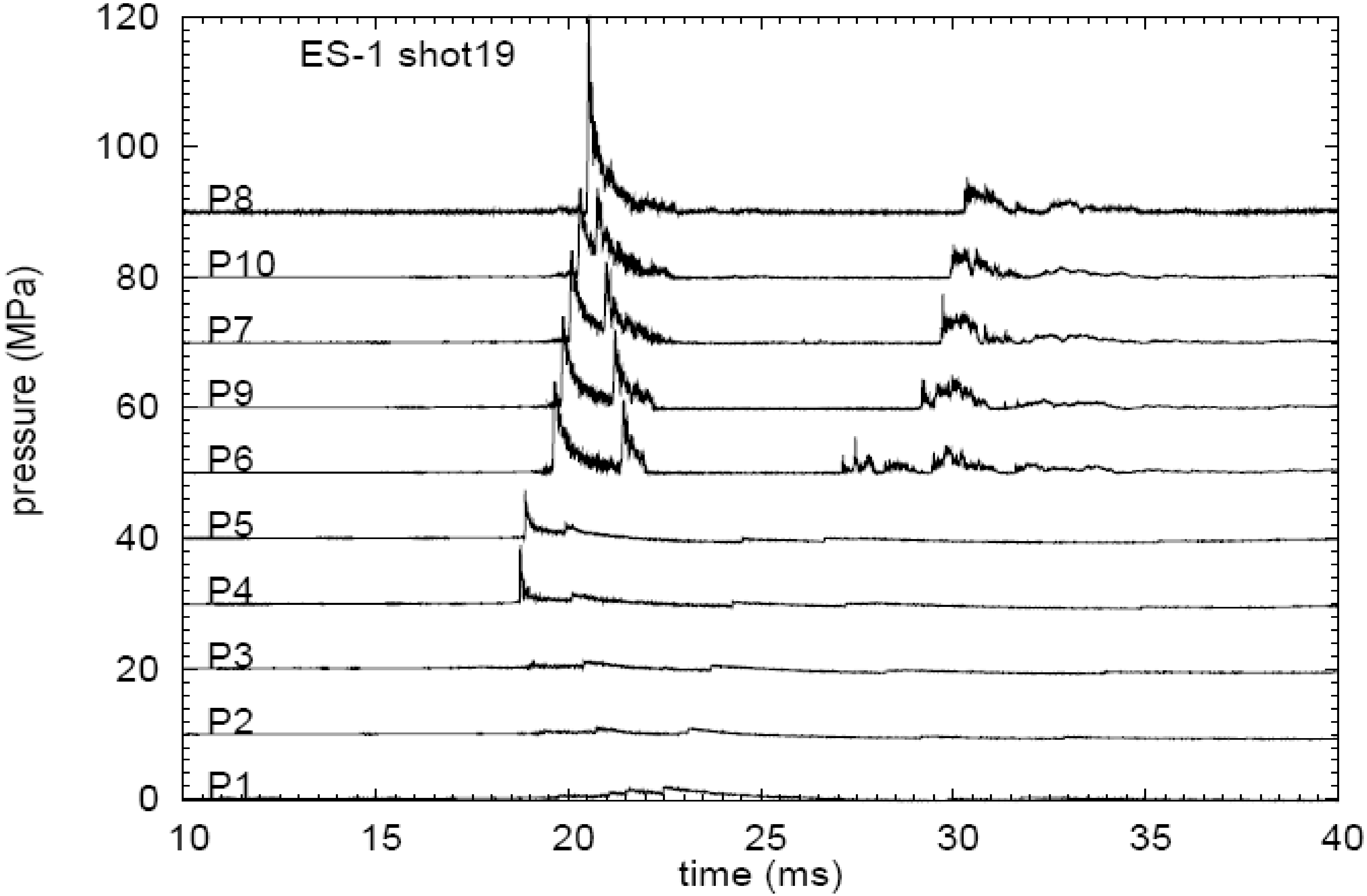
- sound speed in water

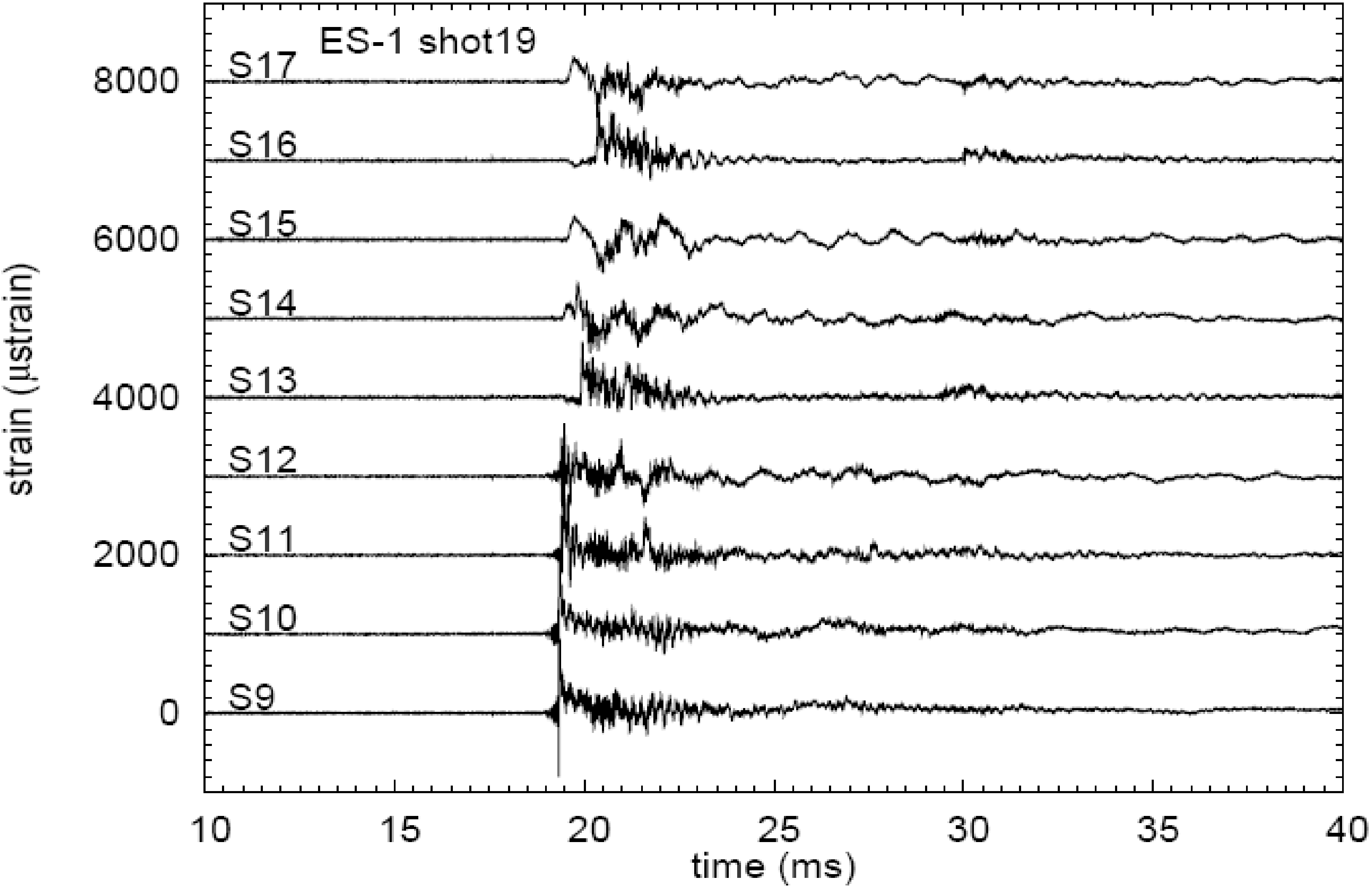
  $c_f = \sqrt{E_f/\rho_f} = 1500$ m/s

- Flexural wave in tube coupled to water compression wave
- ”water hammer”

Joukowsky 1898, von Karman 1911, Skalak 1956, Tijsseling 1996


ES-1 shot18
P8
P10
P7
P9
P6
P5
P4
P3
P2
P1
pressure (MPa)
0
10
20
30
40
50
0
2
4
6
8
10
time (ms)


ES-1 shot19
pressure (MPa)
time (ms)
P8
P10
P7
P9
P6
P5
P4
P3
P2
P1
120
100
80
60
40
20
0
10
15
20
25
30
35
40


ES-1 shot19
S17
S16
S15
S14
S13
S12
S11
S10
S9
8000
6000
4000
2000
0
strain (μstrain)
10
15
20
25
30
35
40
time (ms)

Modeling Piping Response To Detonations

- SDOF model for hoop oscillations
- Simplified traveling wave model
  - Beam on an elastic foundation
- Analytical shell models
  - (Tang) with rotary inertia
- Numerical simulation
  - Shell models (Cirak)
  - FEM models (LS-Dyna)
- Structural models for piping systems with bends, tees, supports, and nozzles.

Reference Books

References on Gaseous Explosions

1. W. E. Baker, P. A. Cox, P. S.Westine, J. J. Kulesz, and R. A. Strehlow. *Explosion Hazards and Evaluation*. Elsevier, 1983. This is the classic monograph with an extensive discussion of all aspects of explosion and structural response. It is intended to be a detailed technical reference and guide for engineers involved in safety assessments. The book emphasizes hand calculation methods and is approximately evenly divided between the topics of characterizing explosion loading, and models of structural response. There are chapters on fragment and thermal effects, and also a discussion on damage criteria.

2. Anon. *Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs*. AIChE, 1994. Center for Chemical Process Safety. This monograph is one of the series of publications by the Center for Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers http://www.aiche.org/ccps/. The emphasis is on pressure wave and thermal radiation from uncon¯ned vapor clouds and boiling liquid expanding vapor explosions (BLEVE). Oriented toward chemical process plant safety.

References on Gaseous Explosions (cont)

3. J. M. Kuchta. Investigation of ¯re and explosion accidents in chemical, mining, and fuel-related industries - a manual. Bulletin 680, Bureau of Mines, 1985. The Bureau of Mines carried out an extensive research program on gaseous explosions and this publication summarizes much of the data on °ammability and explosion phenomena obtained by this group through the mid 1980s.

4. Dag Bjerketvedt, Jan Roar Bakke, and Kees van Wingerden. Gas explosion handbook. *Journal Of Hazardous Materials*, 52(1):1{150, January 1997. See the most recent online version at http://www.gexcon.com/. The group at GEXCON AS has been very actively involved in explosion incident investigation and explosion protection studies. Their FLACS program is one of the most widely used tools for evaluating pressure wave generation by vapor cloud explosions in industrial facilities. This handbook (now online) provides a relatively easy to read introduction to all aspects of explosions with Chapter 8 providing an introduction to structural response.

5. K. Gugan. *Unconfined Vapor Cloud Explosions*. Gulf Publishing Company, 1978. Incidents of unconfined vapor cloud explosions from 1921 through 1979 are reviewed and detailed observations of structural damage are given for selected cases. Analysis is now dated but the factual material is very useful.

References on Blast Waves

1. S. Glasstone and P. J. Dolan. *The Effects of Nuclear Weapons*. United States Department of Defense and Department of Energy, 3rd edition, 1977. As title indicates, the focus is on nuclear weapons. Air blasts are a significant aspect of nuclear weapons effects and provided the motivation for the large body of work carried out on blast waves during the cold war era. Glasstone provides a detailed description of blast wave phenomena and the effect of nuclear blasts on structures.
2. W. E. Baker. *Explosions in Air*. University of Texas Press, Austin, Texas, 1973. Substantially overlaps material in Engineering Design Handbook. Explosions in Air. Volume 1. US Army Materiel Command, 1974. AMCP 706-181. This is the classic monograph on blast waves and is more oriented to conventional high explosives than Glasstone.
3. G. F. Kinney and K. J. Graham. *Explosive Shocks in Air*. 2nd Ed. Springer, 1985. Covers similar topics as both Baker and Glasstone but more oriented to classroom study. Some limited discussion of structural effects.
4. Anon. Estimating air blast characteristics for single point explosions in air, with a guide to evaluation of atmospheric propagation and effects. Technical Report ANSI S2.20-1983 (ASA20-1983), American National Standards Institute, 1983. Discusses standardized approach for scaling air blasts from an ideal (point) explosion. Discusses long range propagation in the atmosphere and effect of various weather features. Some discussion about structural effects such as window breakage.

References on Structural Response

1. W. E. Baker, P. A. Cox, P. S. Westine, J. J. Kulesz, and R. A. Strehlow. *Explosion Hazards and Evaluation*. Elsevier, 1983. This is probably still the best single reference on analytical methods of structural response to explosion.
2. P.D. Smith and J.G. Hetherington. *Blast and Ballistic Loading of Structures*. Butter-worth/Heinemann, 1994. An alternative to Baker et al., covers much of same material, much less detail so that it is easier to grasp the concepts.
3. M. Paz and W. Leigh. *Structural Dynamics*. Springer, ¯fth edition, 2004. Modern all-around text on structural response, oriented to civil engineers that are interested in earthquake response of structures. Integrates use of computer simulation (SAP2000) intothe text.
4. J. Biggs. *Introduction to structural dynamics*. McGraw-Hill, Inc., 1964. ISBN 07-005255-7. This is the classic textbook on single degree of freedom modeling.
5. N. Jones. *Structural Impact*. Cambridge University Press, 1989. ISBN 0-521-30180-7. Jones has a detailed discussion of plastic deformation which applications to both impact and impulsive pressure loading.
6. Anon. *Structures to Resist the Effects of Accident Explosions*. Departments of the Army, the Navy, and the Air Force, 1990. Design guide for concrete-reinforced structures. Very comprehensive but oriented to military installations.

References on Mechanics

1. M. F. Ashby and D. R. H. Jones. *Engineering Materials I*. Butterworth Heinemann, second edition, 1996. Elementary discussion of the material properties relevant to mechanics with formulas and data that are useful for order of magnitude computations.
2. W. Nash. *Strength of Materials*. Schaum's Outlines, McGraw Hill, fourth edition, 1998. A tutorial approach to the theory of the strength of materials that concentrations on beams.
3. A.C. Ugural and S.K. Fenster. *Advanced Strength and Applied Elasticity*. Elsevier, 2nd SI edition, 1987. An all-around text of elasticity, plasticity and applications to static problems in the strength of materials.
4. S.P. Timoshenko and J. N. Goodier. *Theory of Elasticity*. McGraw-HIll Publishing Company, third edition, 1970. This is the classic text on elasticity. Emphasizes analytical solutions.
5. N. Noda, R.B. Hetnarski, and Y. Tanigawa. *Thermal Stresses*. Taylor and Francis, 2002. ISBN 1-56032-971-8. If you need to solve a problem that involves thermal stresses, this is the book to go to.
6. D. Broek. *Elementary Engineering Fracture Mechanics*. Kluwer Academic Publishers, fourth revised edition, 1991. Fracture mechanics is a key part of the modern approach to designing pressure vessels and piping.
7. W. Johnson and P. B. Mellor. *Engineering Plasticity*. Ellis Horwood Limited, 1983.
8. C. R. Callidine. *Plasticity for Engineers*. Horwood Publishing Limited, 2000.

Handbooks

1. W. Young and R. Budynas. *Roark's formulas for stress and strain*. McGraw-Hill, 2002. ISBN 0-07-072542-X. Seventh Edition. Roarks is an essential compendium of solutions for static problems in elasticity. Formulas for stress and strain for many shapes, boundary conditions, and loading problems are tabulated.

2. R. D. Blevins. *Formulas for natural frequency and mode shape*. van Nostrand Reinhold Company, 1979. Blevins compilation is similar in philosophy to Roark's but focuses on dynamic solutions, speci¯cally elastic vibrations of structures. He tabulates mode shapes and vibrational frequencies for many structural elements and boundary conditions.

3. A. S. Kobayashi, editor. *Handbook on Experimental Mechanics*. Society of Experimental Mechanics, second revised edition, 1993. If you have to perform or interpret experiments, Kobayashi's handbook is an excellent guide to various experimental methods.

4. J.R. Davis. *Carbon and Alloy Steels*. ASM international, 1996. ISBN 0-87170-557-5. Data on the most common construction material for piping and pressure vessels.

5. C. Moosbrugger. *Atlas of stress-strain curves*. Materials Park, OH : ASM international, 2002. Measured stress-strain curves for a wide range of materials.

Books on Related Subjects are Useful

- Earthquake engineering
  - Strong ground motion excites building motion
- Terminal ballistics
  - Projectile impact creates stress waves and vibration
- Crashworthiness
  - Vehicle crash mitigation
- Weapons effects
  - Conventional (High explosive and FAE)
  - Nuclear and nuclear simulation testing

TIP – Many recent studies on structural response to blasts have been sponsored to counter terrorism – the results are often restricted to government agencies or official use only.

Web Resources

- For more resources, preprints, and reports from Caltech Explosion Dynamics Lab, see

  http://shepherd.caltech.edu/EDL