Oilwell Perforators: Theoretical Considerations

Brenden Grove

22nd International Symposium on Ballistics

November 17, 2005

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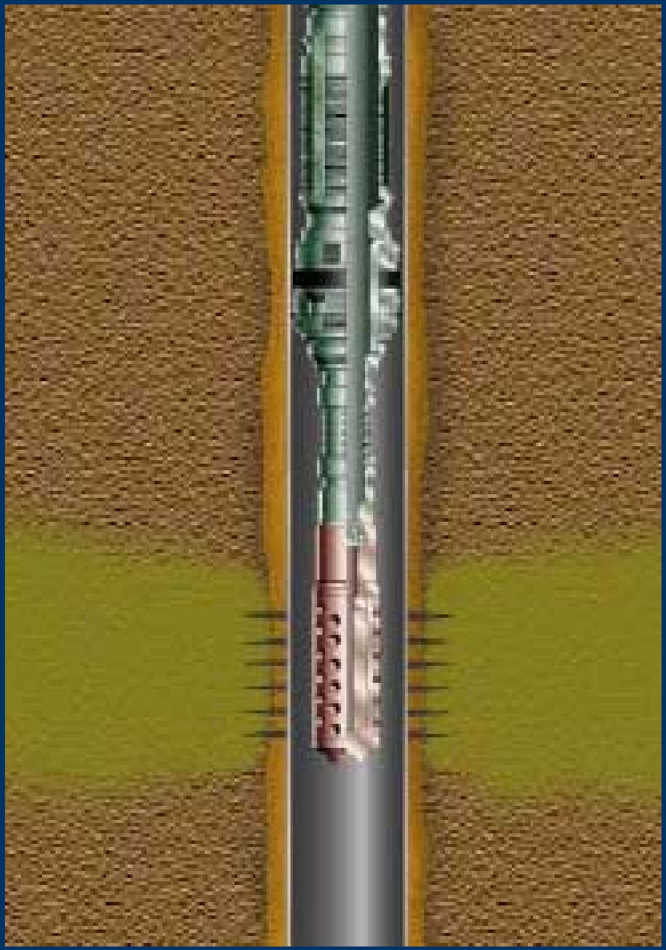
Overview

- Introduction / Background
- Compressible Jet Model
- Implications:
  - Hydrodynamic penetration depth
  - Impact pressure
  - Target strength
- Conclusions

Introduction / Background

- Oilwell perforators → 20-60mm shaped charges
- Perforate casing, cement, formation rock
- Perf tunnels must be clean to allow subsequent fluid flow



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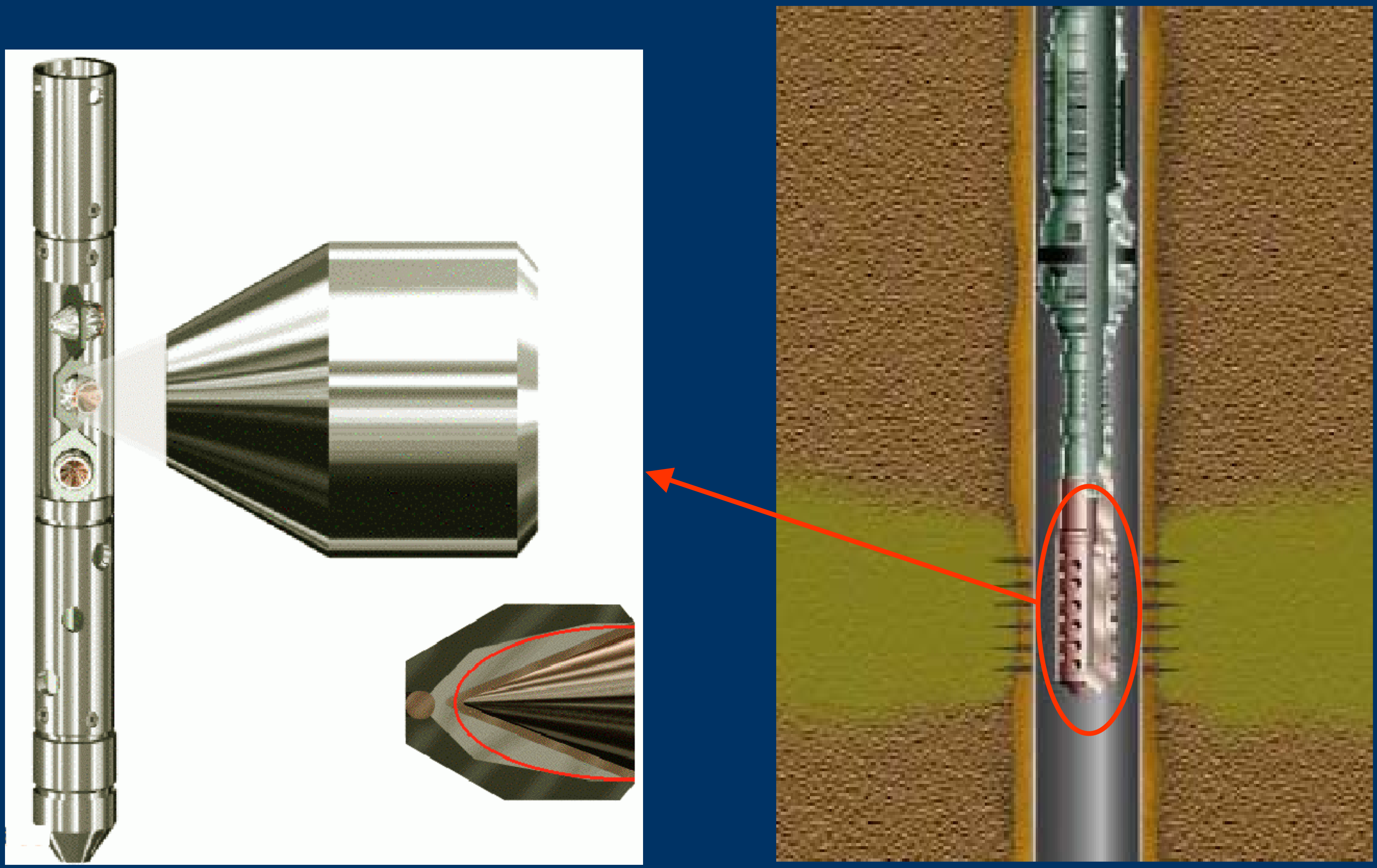
Introduction / Background



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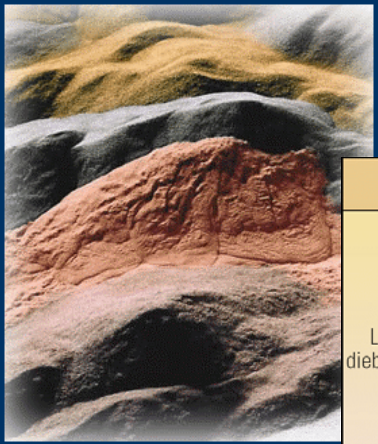
Introduction / Background

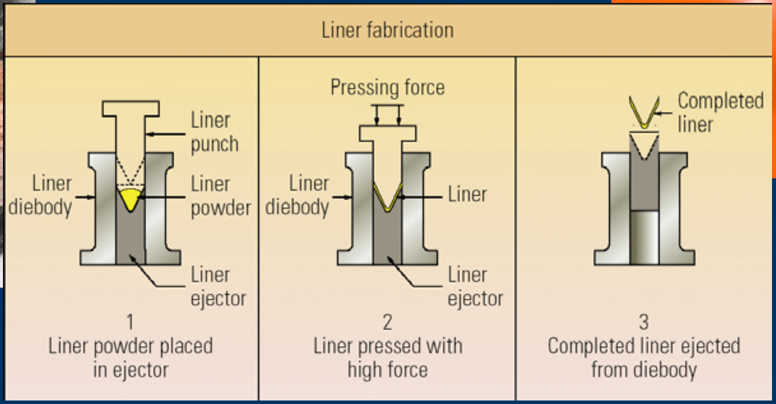
Liner:

– formed by powdered metallurgy (P/M)

– unsintered (green)

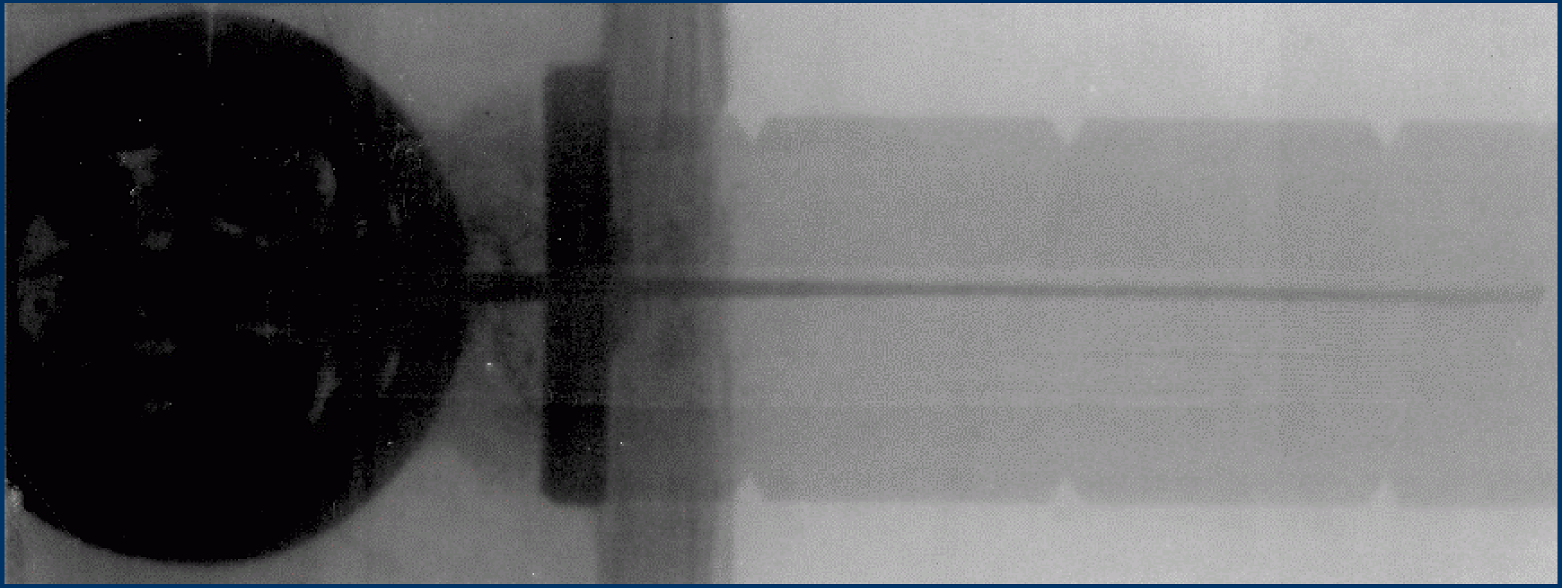


Metal powder photograph: http://www.mpif.org/IntroPM/makepowder.asp?linkid=5



Introduction / Background

- Jet=millions of discrete powder particles
- How to model jet penetration?
  - *Traditional models underpredict penetration*



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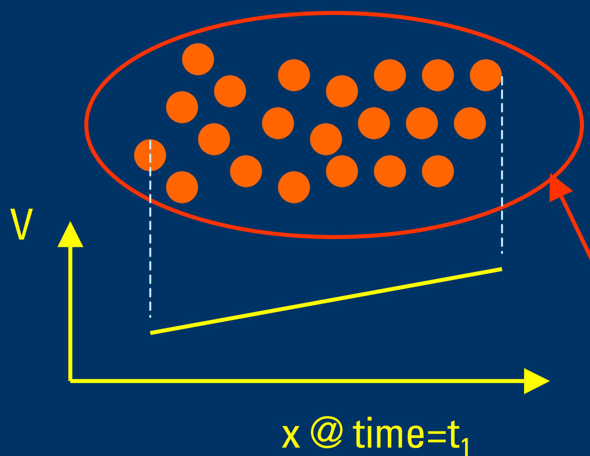
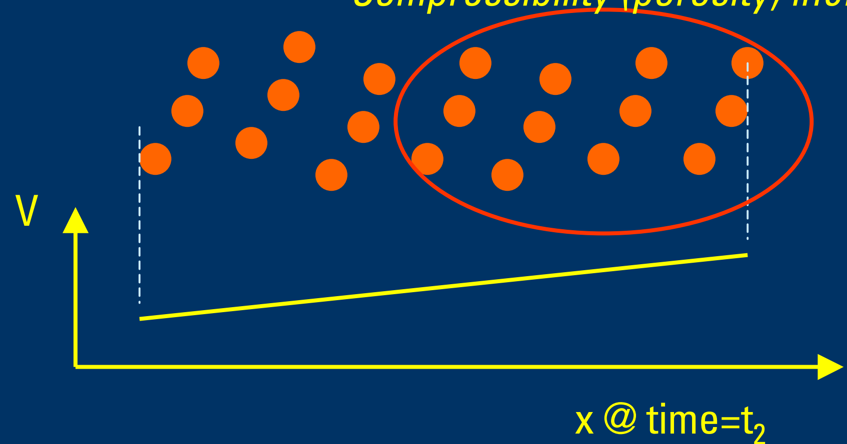
Introduction / Background

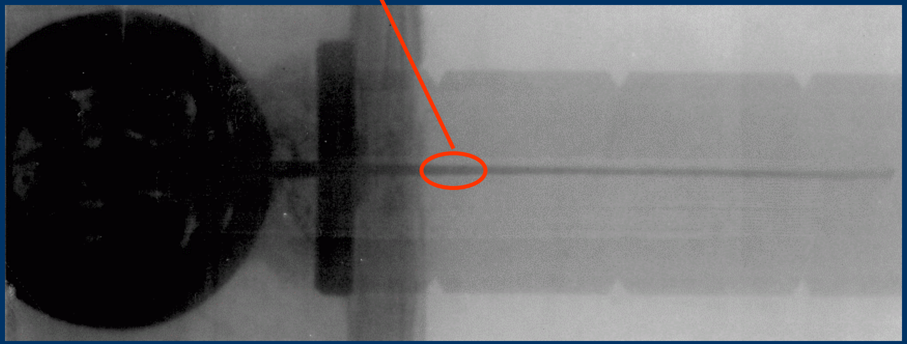
- Jet=millions of discrete powder particles
- How to model jet penetration?

•Density decreases

•Compressibility (porosity) increases







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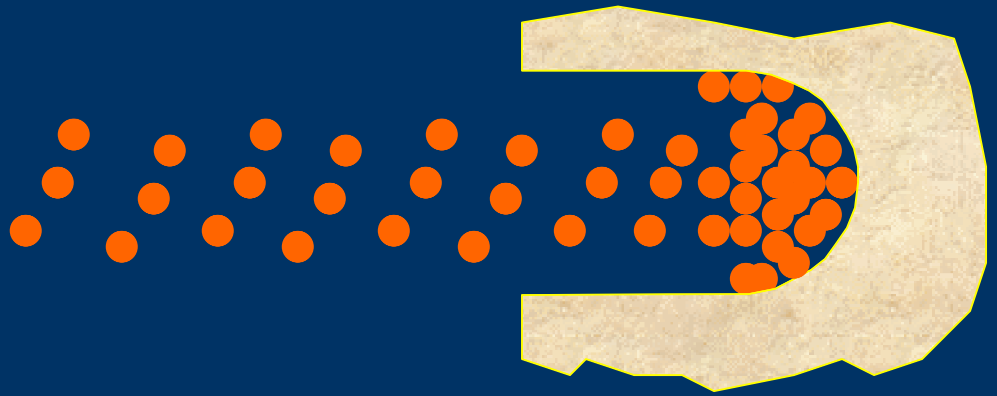
Compressible Jet

Penetration Theory

- Multiple discrete impacts; particles "pile up"?
- Macroscopically – jet compresses
- *Incompressible Bernoulli not applicable*



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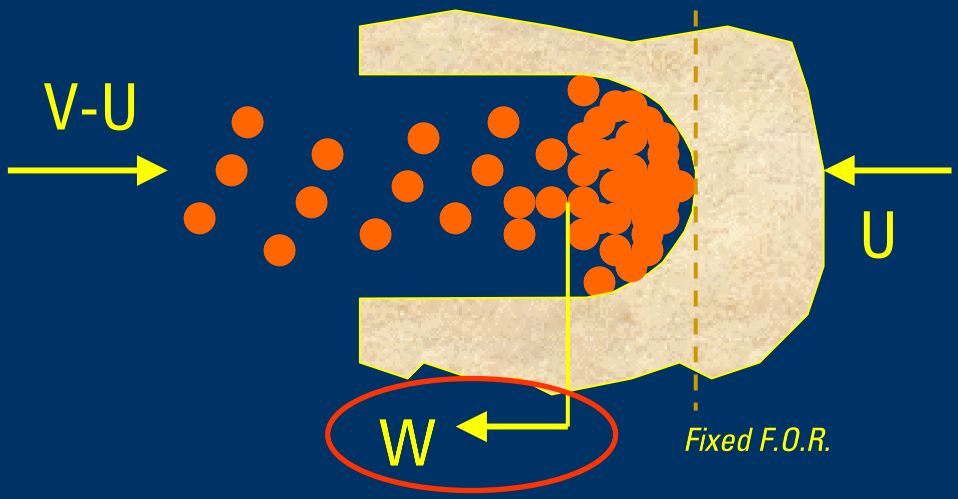
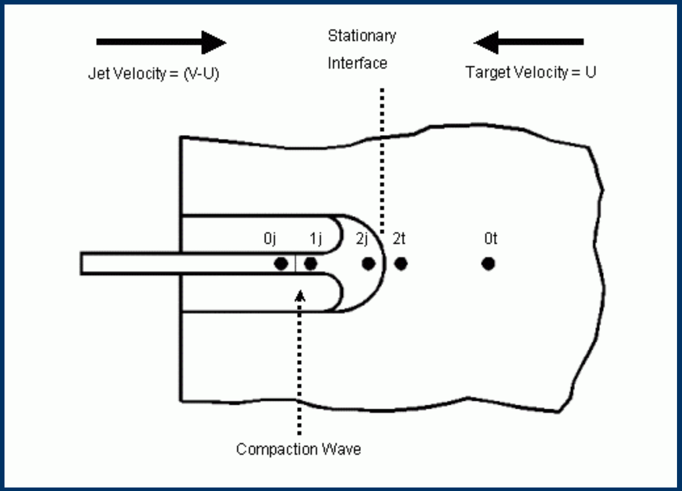
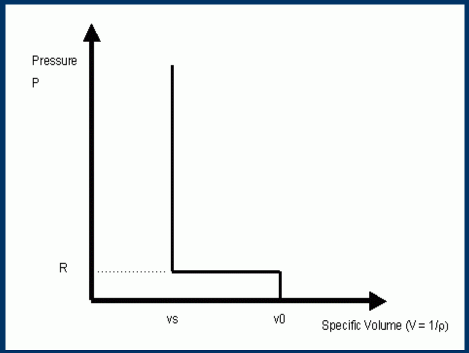
Compressible Jet

Penetration Theory



- Flis & Crilly (18th ISB): compressible target
- Reverse their analysis here





Jet Material Compaction Curve

ρ_0 = initial (distended) jet density
ρ_s = solid (pore-free) jet density
$\phi = 1 - \rho_o / \rho_s$ = jet porosity
R = jet compaction initial resistance

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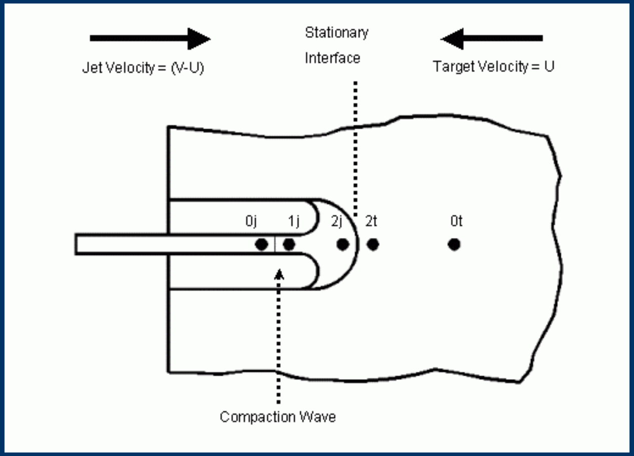
Compressible Jet

Penetration Theory

- Distended jet at ρ_o traveling at (V-U)
- Compacted to ρ_s , decelerated to w_{1j}



mass $\rho_{0j} w_{0j} = \rho_{1j} w_{1j}$ $\quad w_{0j} = V - U$

momentum $P_{0j} + \rho_0 (w_{0j})^2 = P_{1j} + \rho_1 (w_{1j})^2$

full compaction $\rho_{1j} = \rho_{2j} = \rho_c$

- Apply incompressible Bernoulli to compacted jet impact

Compressible Jet

Penetration Theory

Jet pressure

$$P_{2j} = R + \frac{1}{2}\rho_0 (V-U)^2 \underbrace{(1+\phi)}$$

Target pressure

$$P_{2t} = Y_t + \frac{1}{2}\rho_{0t} U^2$$

Compressibility

Effect

PD (hydrodynamic)

$$\frac{PD}{L} = \sqrt{\frac{\rho_0}{\rho_t}(1+\phi)}$$

PD (target strength important)

$$\frac{PD}{L} = \sqrt{\frac{\rho_0}{\rho_t}(1+\phi) - \frac{2\sigma}{\rho_t (V-U)^2}}$$

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Compressible vs. Incompressible Jet

Penetration Theory

	Incompressible	→	Compressible
Jet Pressure	$P_{2j} = Y_j + \frac{\lambda}{2}\rho_0 (V-U)^2$	→	$P_{2j} = R + \frac{1}{2}\rho_0 (V-U)^2 (1+\phi)$
Hydrodynamic Penetration Depth	$\frac{PD}{L} = \sqrt{\frac{\lambda \rho_j}{\rho_t}}$	→	$\frac{PD}{L} = \sqrt{\frac{\rho_0}{\rho_t}(1+\phi)}$

$$\lambda \;\; \text{-->} \;\; (1+\phi)$$

Compressible vs. Incompressible Jet

Penetration Theory

- $(1+\phi) \rightarrow \lambda$
- Porous jet model reduces to incompressible model at limits
- At upper limit ($\phi=1$; $\lambda=2$), $\rho \rightarrow$ zero
- For a given length and macroscopic density, porosity increases the following:
  - *Penetration depth*
  - *Impact pressure*

Jet Density, Length, Porosity

Summary

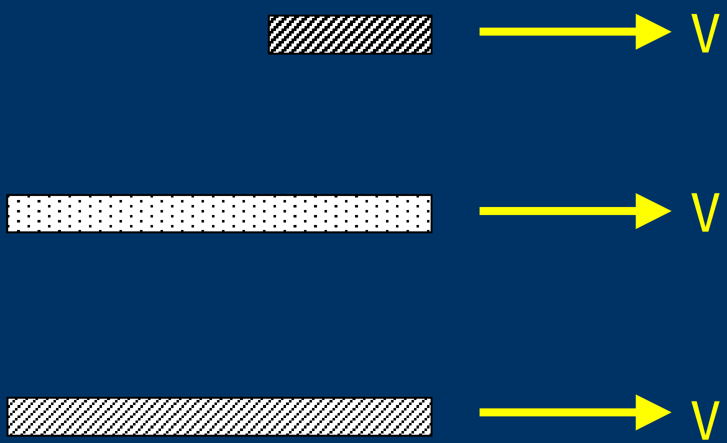
Consider 3 cases: *(Fixed mass, velocity, diameter)*

$$\rho L = constant$$

Case A: ρ_s, incompressible;
length=L_s

Case B: ρ_o, compressible to ρ_s;
length=L_o

Case C: ρ_o, incompressible;
length=L_o



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Jet Density, Length, Porosity

Summary

Hydrodynamic Penetration Depth

Case A:

$$PD_A = L_s \sqrt{\frac{\rho_s}{\rho_t}}$$

Case B:

$$PD_B = L_0 \sqrt{\frac{\rho_0}{\rho_t}(1+\phi)}$$

$$= PD_A \sqrt{\frac{1+\phi}{1-\phi}} \qquad \text{(alternative form)}$$

$$= PD_C \sqrt{1+\phi} \qquad \text{(alternative form)}$$

Case C:

$$PD_C = L_0 \sqrt{\frac{\rho_0}{\rho_t}}$$

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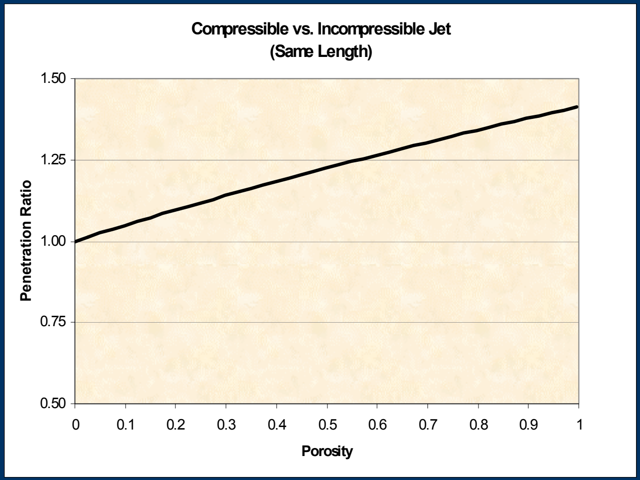
Jet Density, Length, Porosity

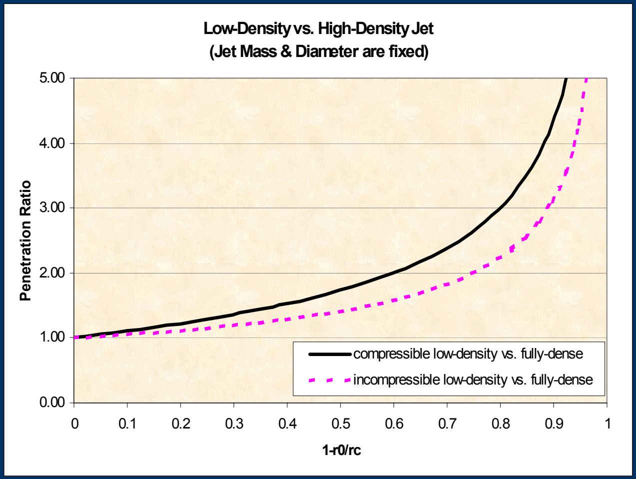
Summary

Hydrodynamic Penetration Depth

$$PD_B > PD_C > PD_A$$

$$PD_B : PD_C : PD_A = \sqrt{\frac{1+\phi}{1-\phi}} : \sqrt{\frac{1}{1-\phi}} : 1$$





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Jet Density, Length, Porosity

Summary

Dynamic Jet Pressure

Case A:

$$P_A = \frac{1}{2}\rho_s (V - U)^2$$

Case B:

$$P_B = \frac{1}{2}\rho_s (V - U)^2 (1 - \phi^2)$$

$$= \frac{1}{2}\rho_0 (V - U)^2 (1 + \phi) \quad \text{(alternative form)}$$

Case C:

$$P_C = \frac{1}{2}\rho_0 (V - U)^2$$

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Jet Density, Length, Porosity

Summary

$$P_A > P_B > P_C$$

Dynamic Jet Pressure

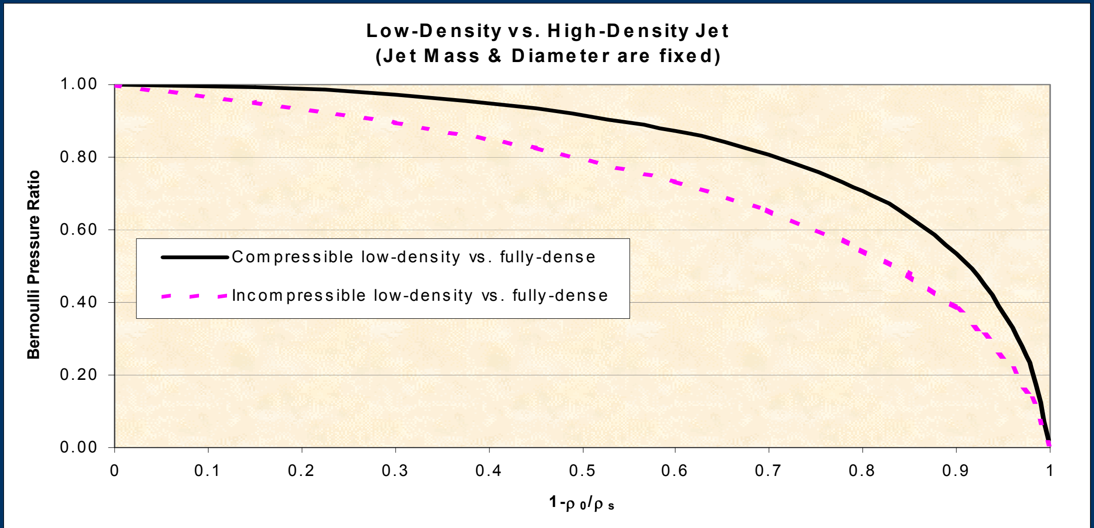
$$U = \frac{V}{1+\gamma}$$

$$\gamma_A = \sqrt{\frac{\rho_t}{\rho_s}}$$

$$\gamma_B = \sqrt{\frac{\rho_t}{\rho_s(1-\phi^2)}} = \frac{\gamma_A}{\sqrt{1-\phi^2}}$$

$$\gamma_C = \sqrt{\frac{\rho_t}{\rho_0}} = \frac{\gamma_A}{\sqrt{1-\phi}}$$

$$P_A : P_B : P_C \quad = \quad 1 \; : \; \left[\frac{1 - \left(\frac{1}{1+\frac{\gamma_A}{\sqrt{1-\phi^2}}} \right)}{1 - \left(\frac{1}{1+\gamma_A} \right)} \right]^2 (1-\phi^2) \; : \; \left[\frac{1 - \left(\frac{1}{1+\frac{\gamma_A}{\sqrt{1-\phi}}} \right)}{1 - \left(\frac{1}{1+\gamma_A} \right)} \right]^2 (1-\phi)$$



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Jet Density, Length, Porosity

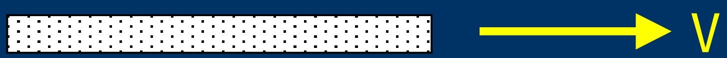
Summary

Consider 3 cases: *(Fixed mass, velocity, diameter)*

$$\rho L = constant$$

Case A: ρ_s, incompressible; length=L_s

Case B: ρ_o, compressible to ρ_s; length=L_o



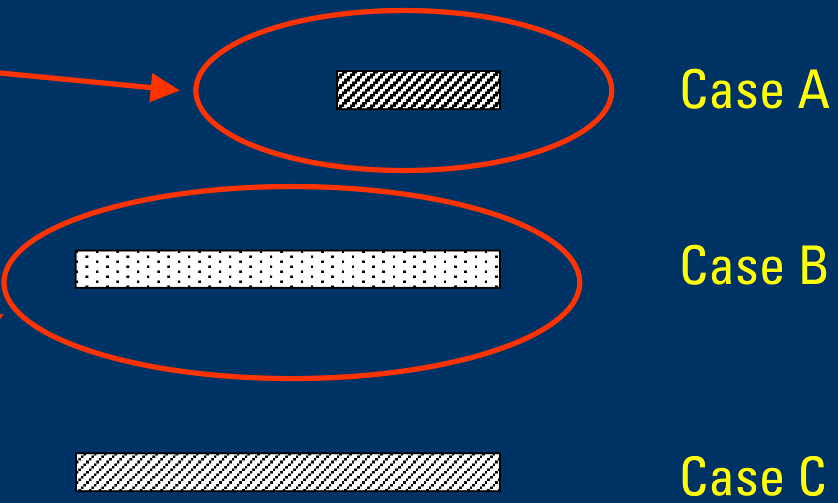
Case C: ρ_o, incompressible; length=L_o

Jet Density, Length, Porosity

Summary

•Greatest impact pressure

•Shallowest hydrodynamic penetration



•Deepest hydrodynamic penetration

•2nd greatest impact pressure

Impact Pressure & Target Strength

What about target strength?

Characteristic target property

Consider some critical point of interest (U_{crit}, P_{crit})

$$U_{crit} = \sqrt{\frac{2(P_{crit} - Y_t)}{\rho_t}}$$

P_{crit} isobars in (ρ_j, V) coordinates

Incompressible; $1 \le \lambda \le 2$

$$\rho_j = \frac{\rho_t U_{crit}^2 + 2\sigma}{\lambda (V - U_{crit})^2}$$

Compressible

$$\rho_j = \rho_s (1-\phi); \qquad \phi = \sqrt{1 - \frac{\rho_t U_{crit}^2 + 2\sigma}{\rho_s (V - U_{crit})^2}}$$

There is no unique V_{min}

Impact Pressure & Target Strength

What do these isobars look like?

Target Material	ρ_t (g/cc)	Y_t (kbar)	P_{crit}	ρ_s (g/cc)	$R=Y_j$ (kbar)
Mild steel	7.86	3 (UTS)	$2Y_t$	16	0
Aluminium	2.7	3 (UTS)	"	"	"
Concrete	2.25	0.3 (UCS)	"	"	"
Sandstone	2.25	0.6 (UCS)	"	"	"

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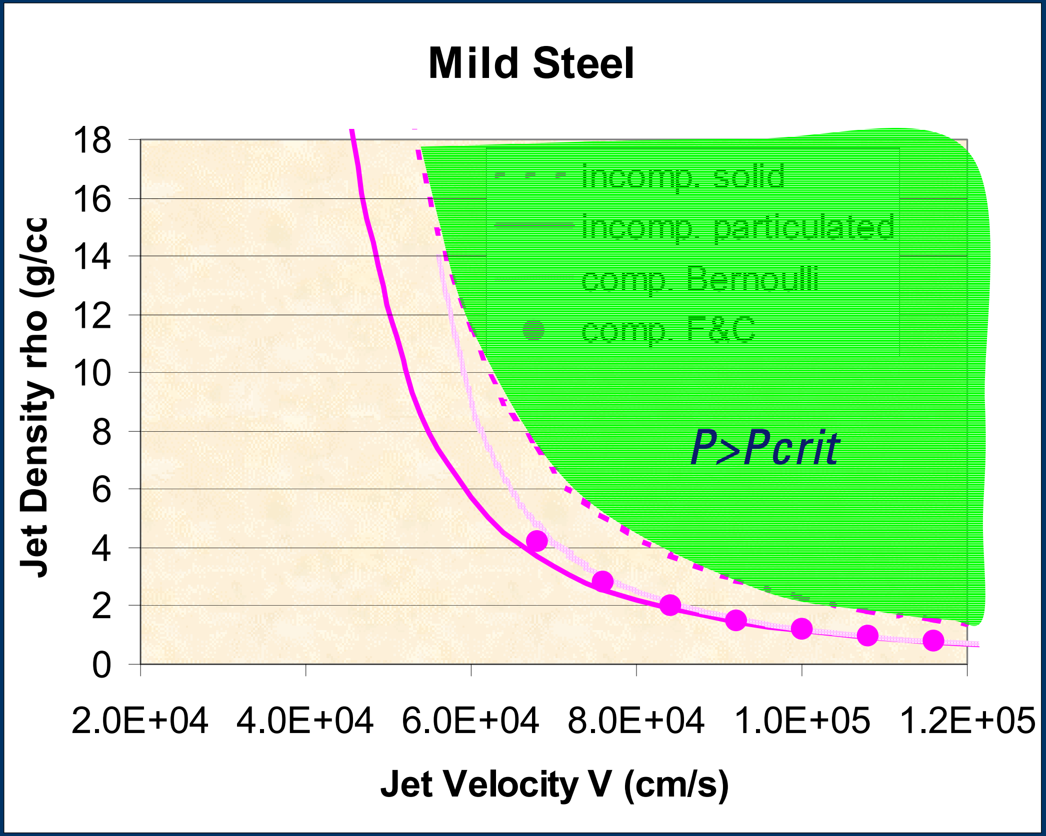
Impact Pressure & Target Strength

Isobars in (ρ_j,V) space



Incompressible Bernoulli

Continuous

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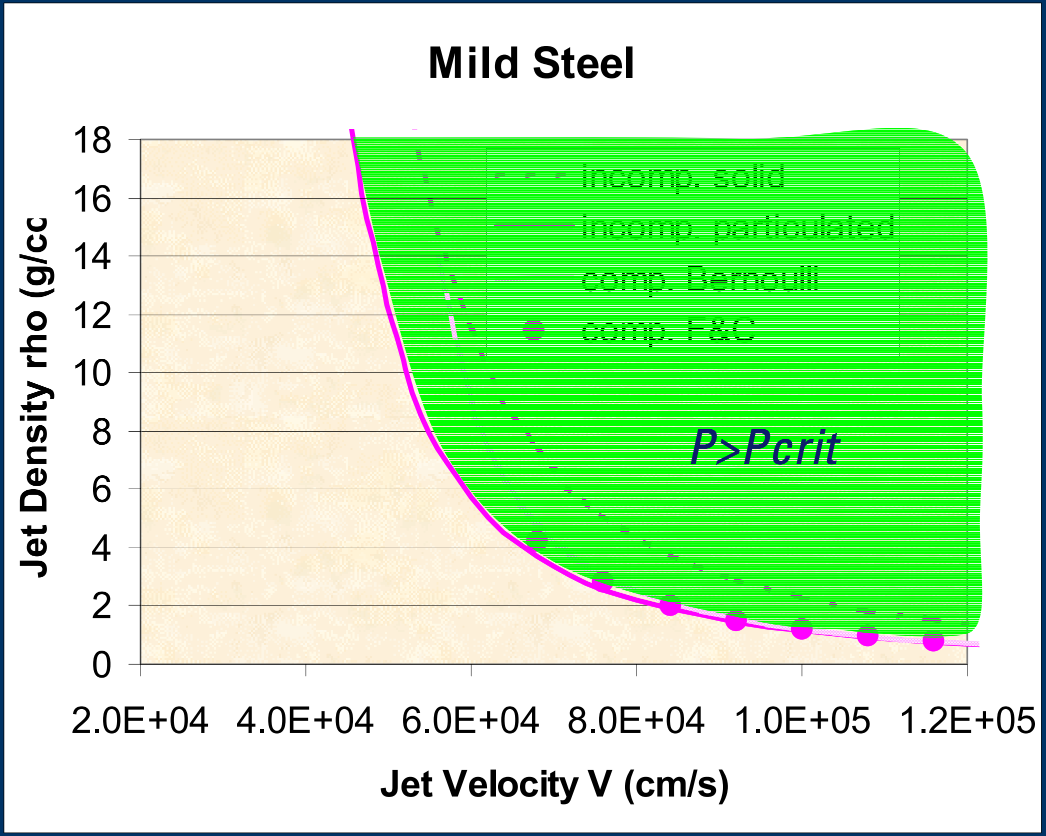
Impact Pressure & Target Strength

Isobars in (ρ_j,V) space



Incompressible Bernoulli

Particulated

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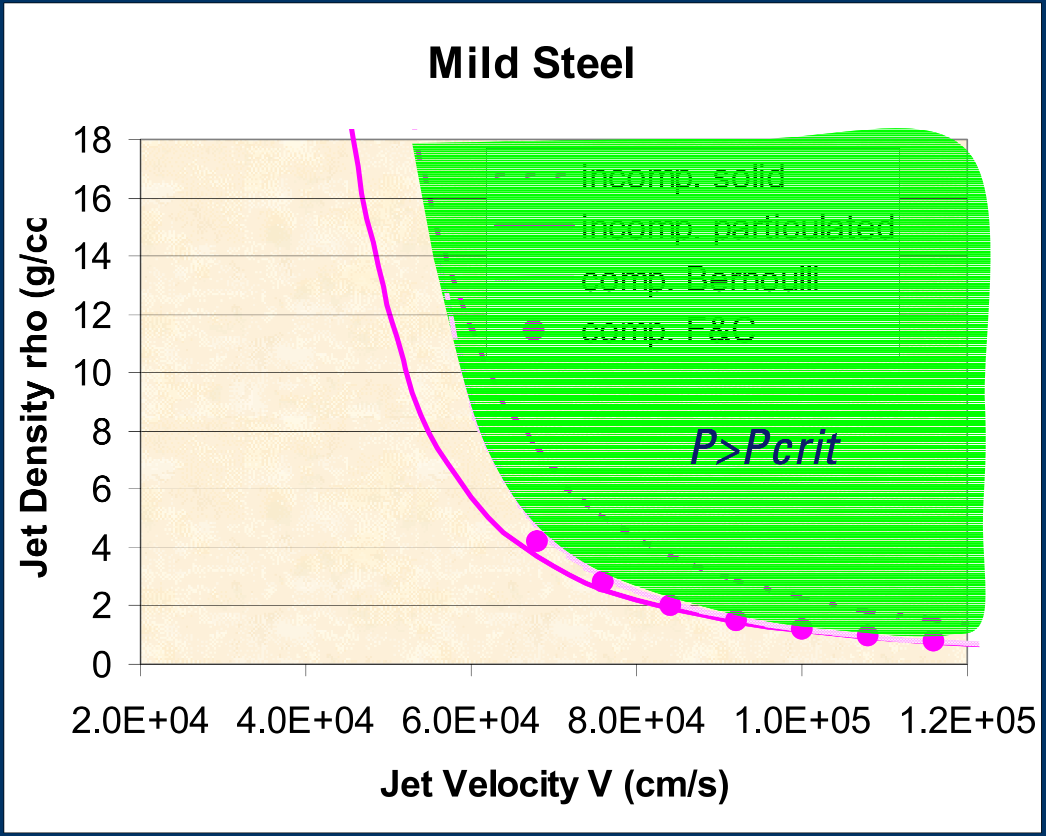
Impact Pressure & Target Strength

Isobars in (ρ_j,V) space



Compressible (porous)

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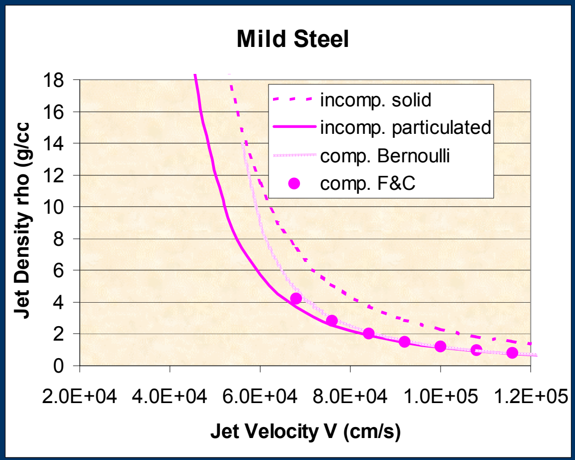
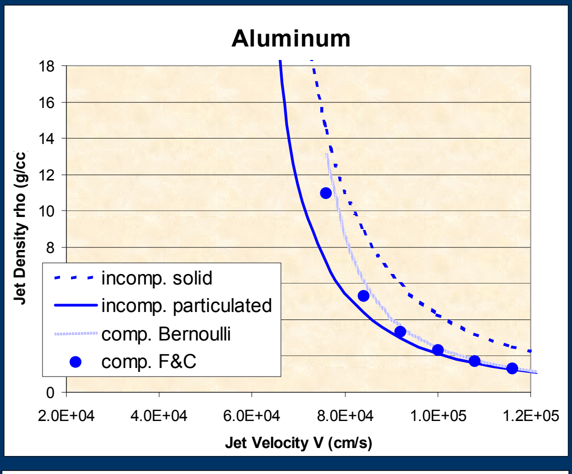
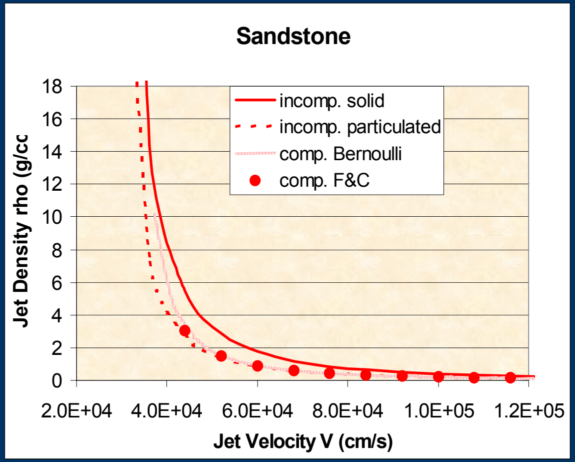
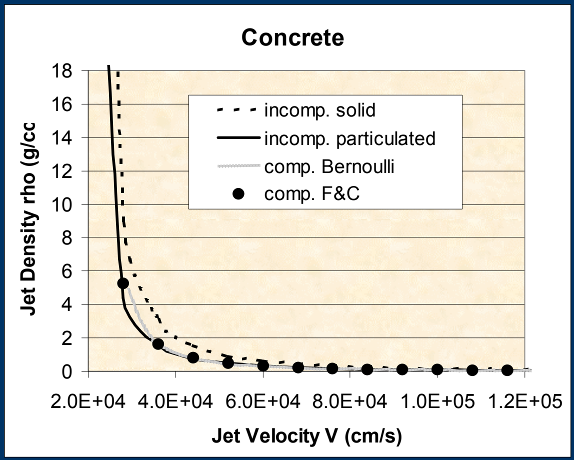
Impact Pressure & Target Strength

Isobars in (ρ_j,V) space



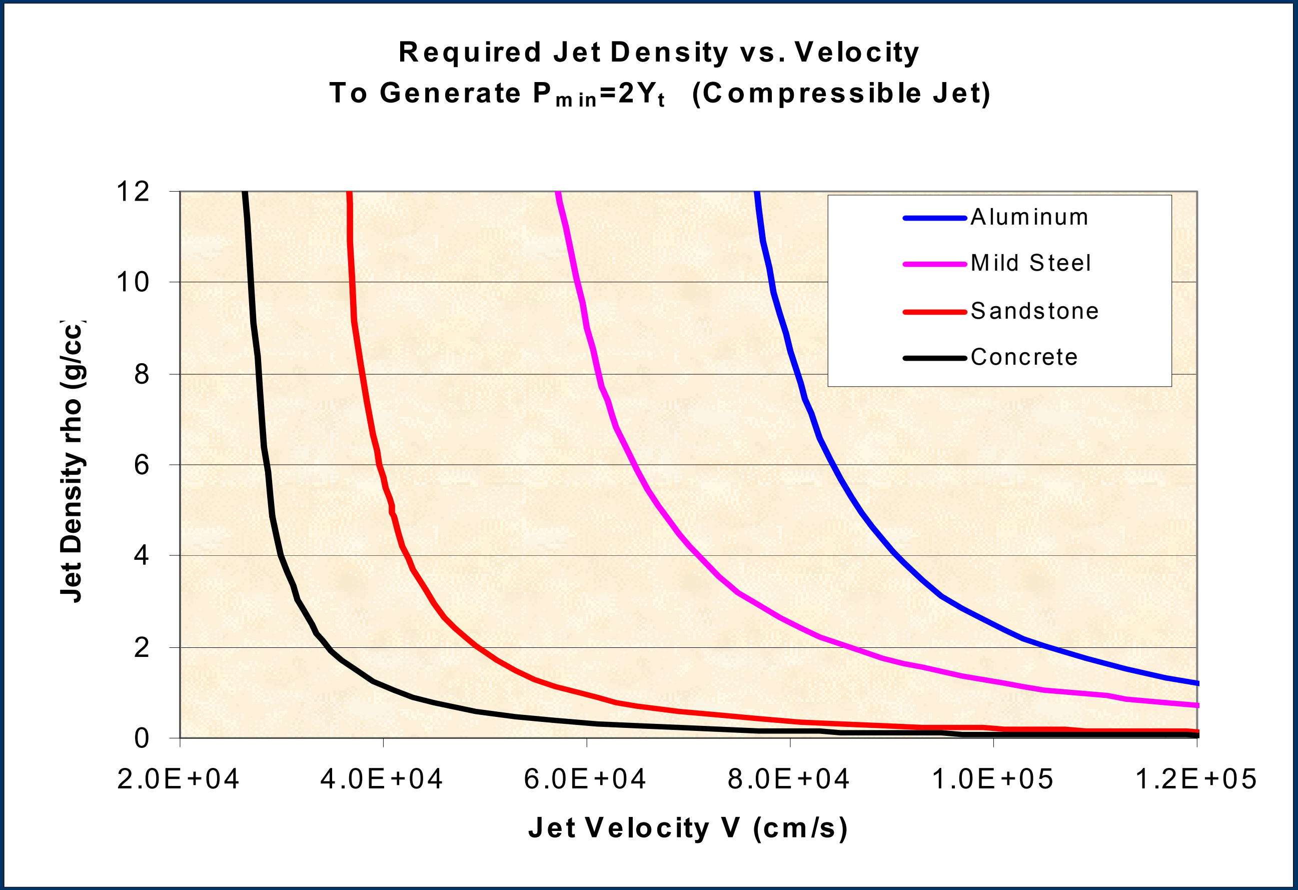






Impact Pressure & Target Strength

Isobars in (ρ_j,V) space



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Conclusions (1)

- Developed treatment of compressible jet
  - Reduces to well-known expressions for solid & fully-particulated jets
  - For a given mass, velocity, diameter:
    - Porous (compressible) penetrator penetrates deeper than incompressible penetrator of same L, ρ
    - …also, deeper than shorter penetrator of higher ρ
    - …produced impact pressure which is intermediate

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Conclusions (2)

- Looked at steady-state impact pressure
  - Presented isobars in (ρ_j,V) coordinates
    - Compressible jet model interpolates between solid & fully-particulated incompressible jet model
  - Highly-distended, low-velocity jets may effectively penetrate moderate-strength geologic targets

- *This approach, so far, neglects transients*

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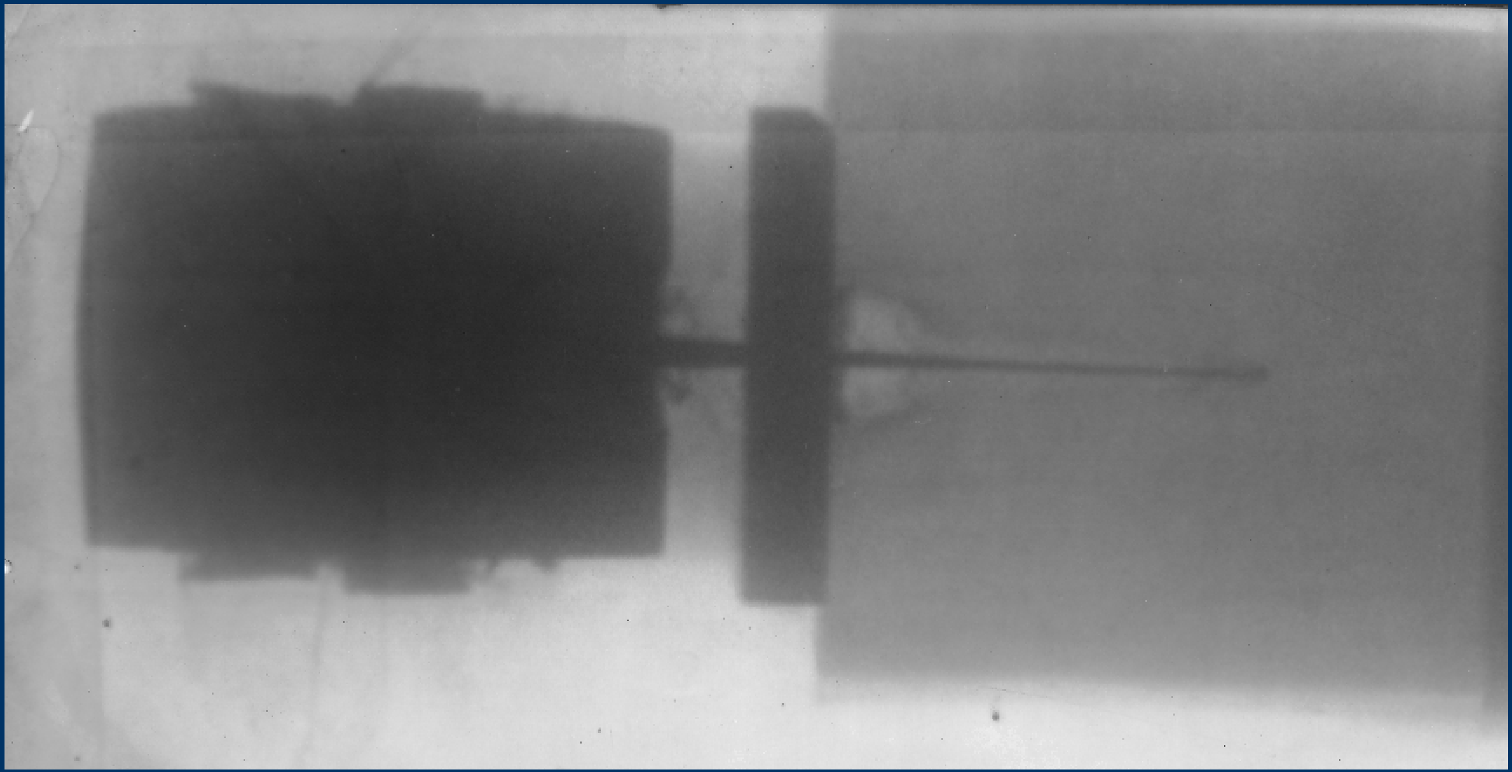
Thank You

Questions??



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