Flow and Storage of Powders

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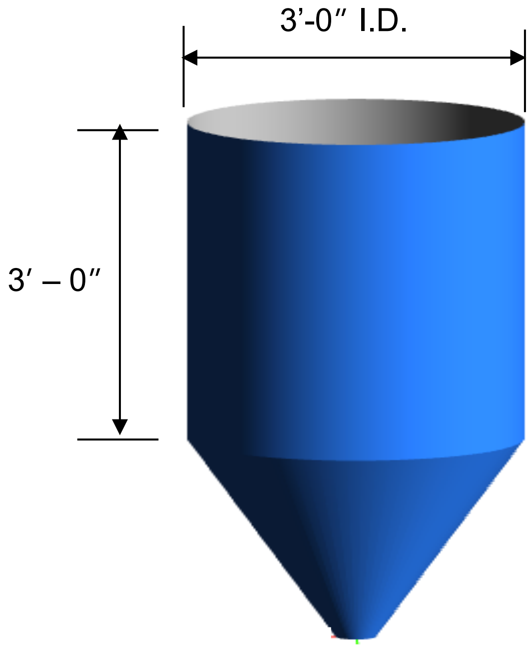
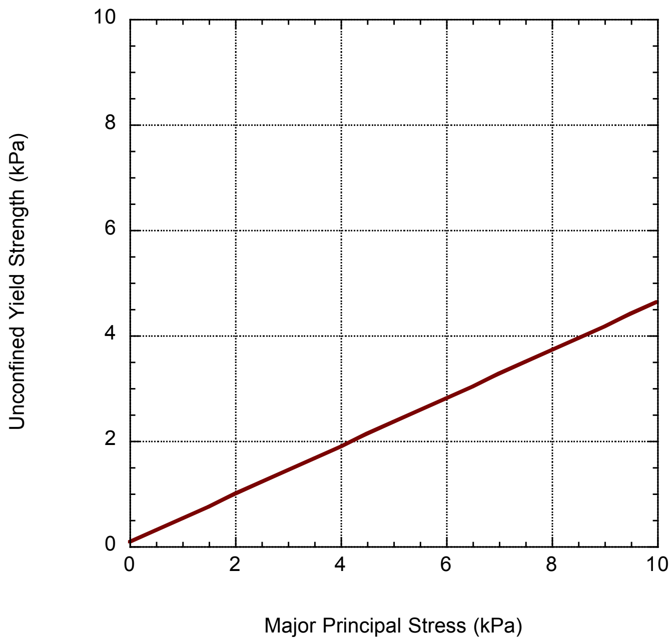
978-799-7311

Funnel flow hopper design

Critical rathole diameter depends on dimensions of cylinder section

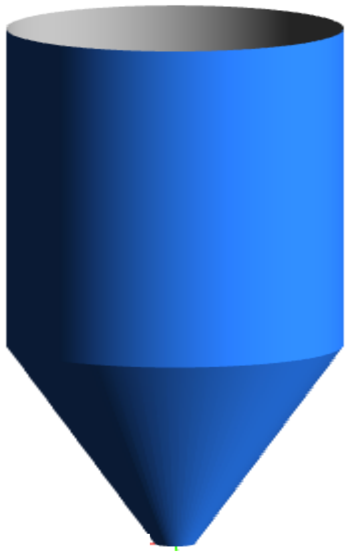


Funnel flow hopper design

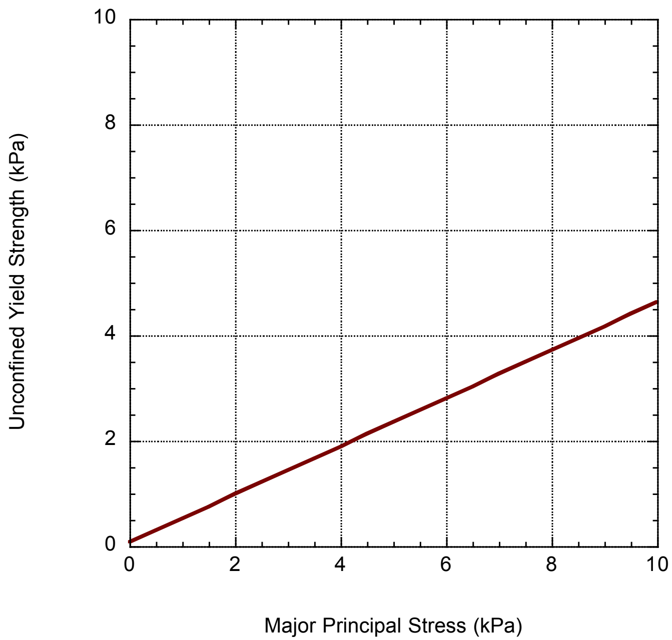


$$D_F = \frac{G(\phi_t) f_C}{\rho_b g}$$

$$\sigma_1 = \frac{\overline{\rho}_b g R_H}{k \tan\phi'}\left[1 - \exp\left(\frac{-k(\tan\phi')h}{R_H}\right)\right]$$



Funnel flow hopper design



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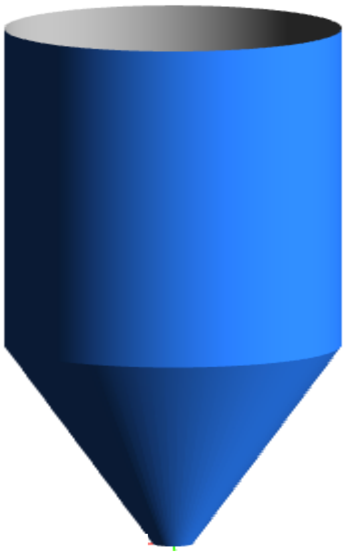
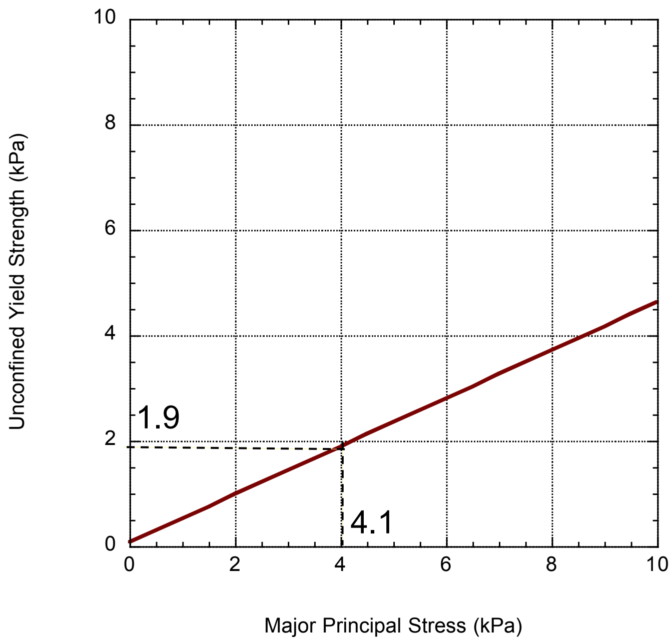


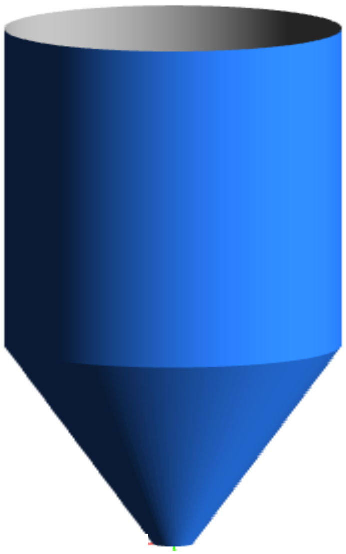
$$\sigma_1 = \frac{(615)(9.8)(0.914/4)}{(0.4)\tan(21^\circ)}\left[1 - \exp\left(\frac{-(0.4)\tan(21^\circ)(0.914)}{0.914/4}\right)\right] = 4100 \text{ Pa}$$

Funnel flow hopper design

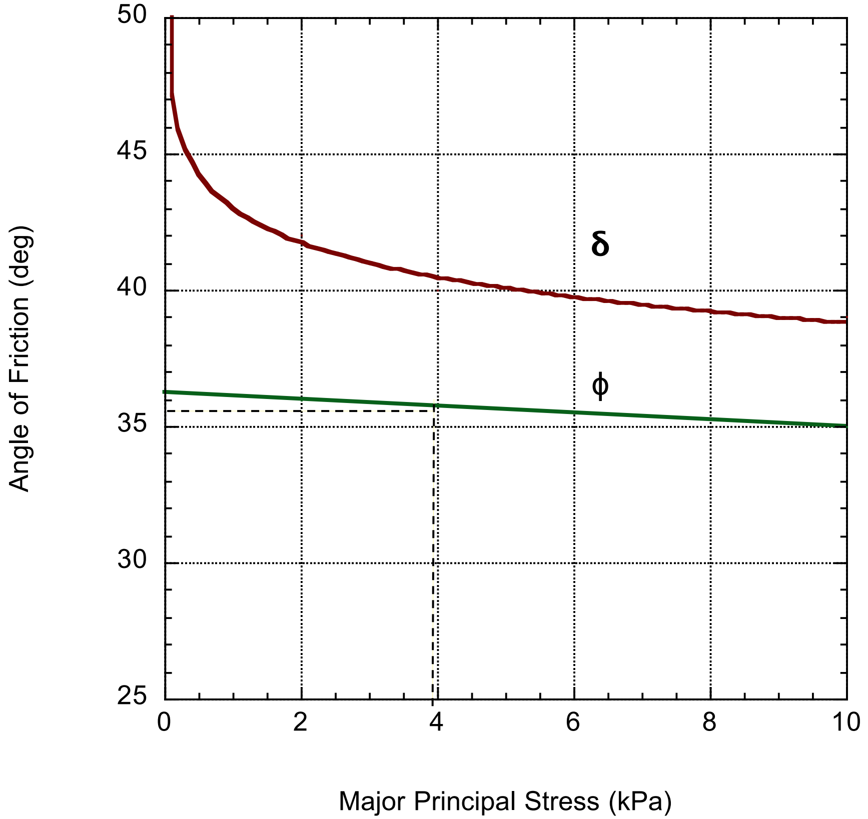


$$D_F = \frac{G(\phi_t) f_C}{\rho_b g}$$

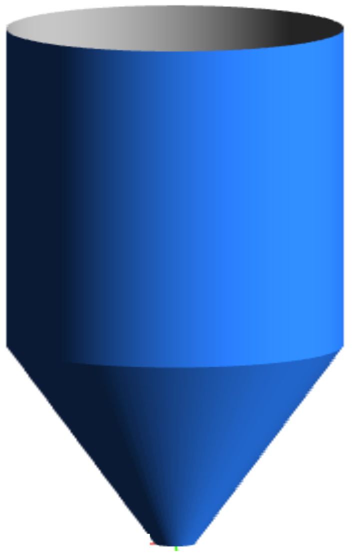
$$f_C = 1.9 \text{ kPa}$$



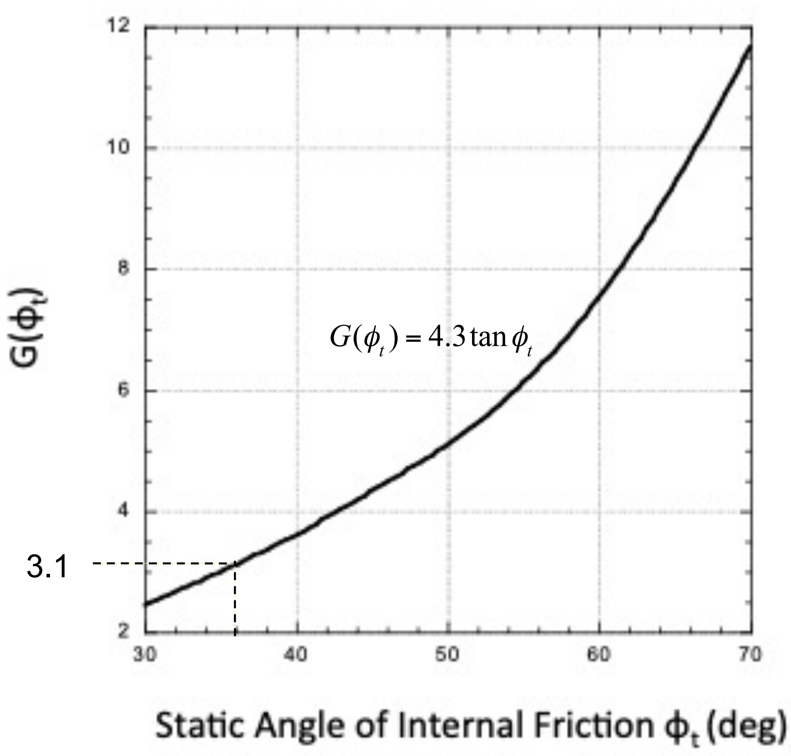
Funnel flow hopper design



$$D_F = \frac{G(\phi_t) f_C}{\rho_b g}$$



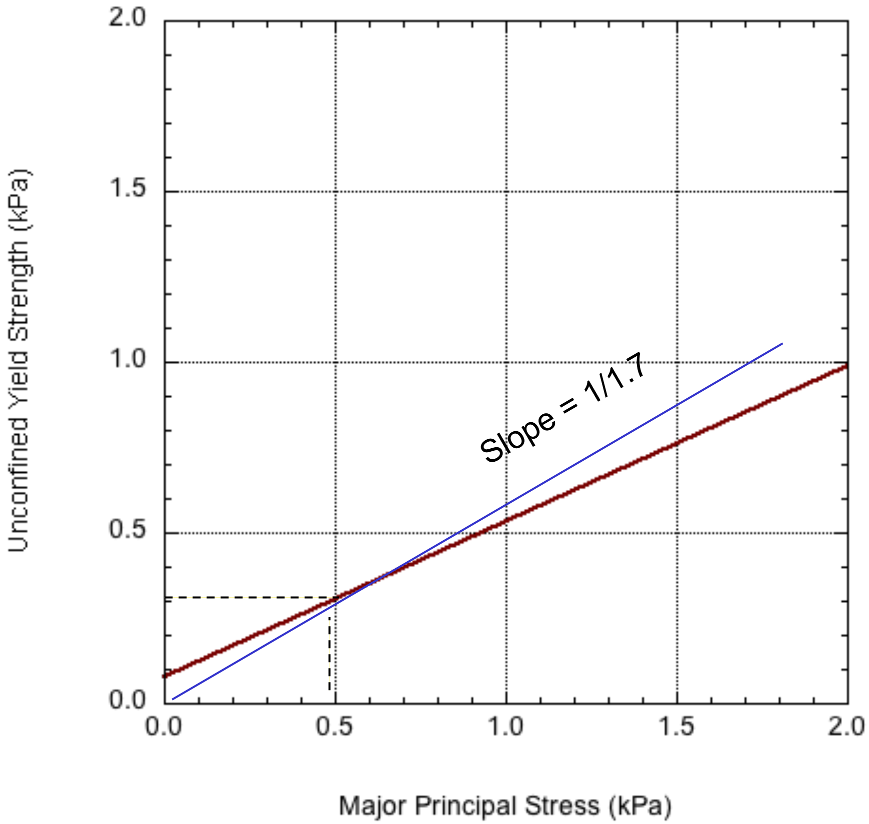
Funnel flow hopper design

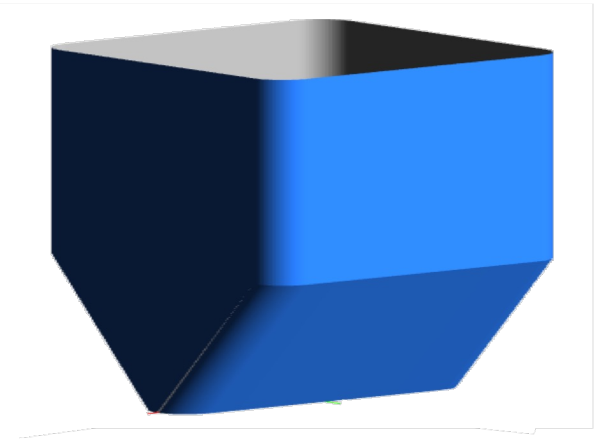


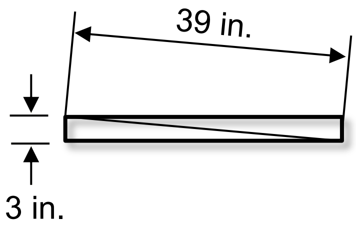
$$D_F = \frac{G(\phi_t) f_C}{\rho_b g}$$

$$= \frac{(3.1)(1.9)}{(618)(9.8)} = 1.0 \text{ m} = 39 \text{ in.}$$

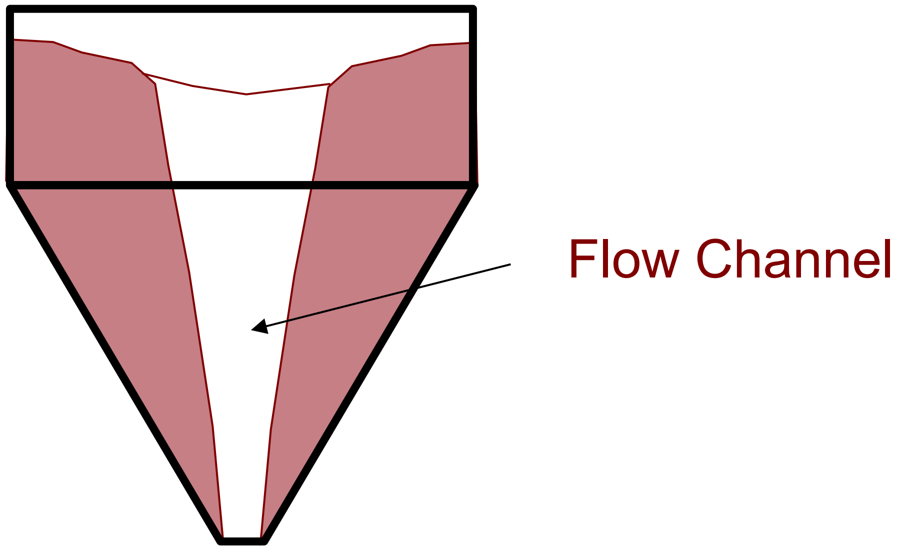
Funnel flow hopper design





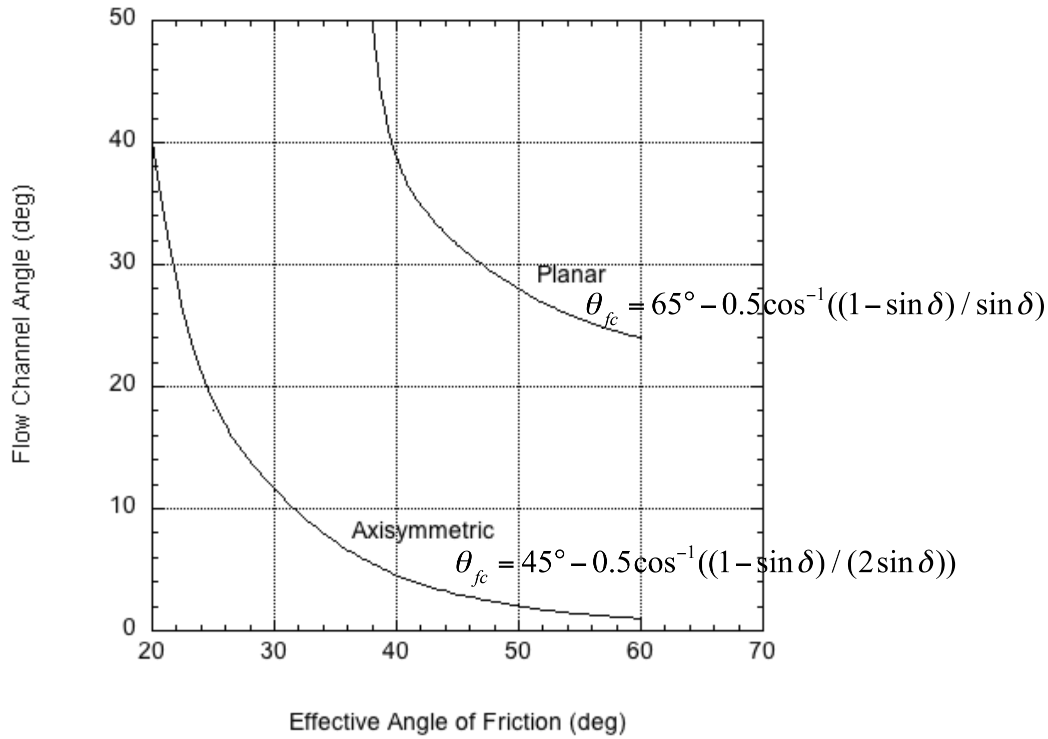


Flow channel

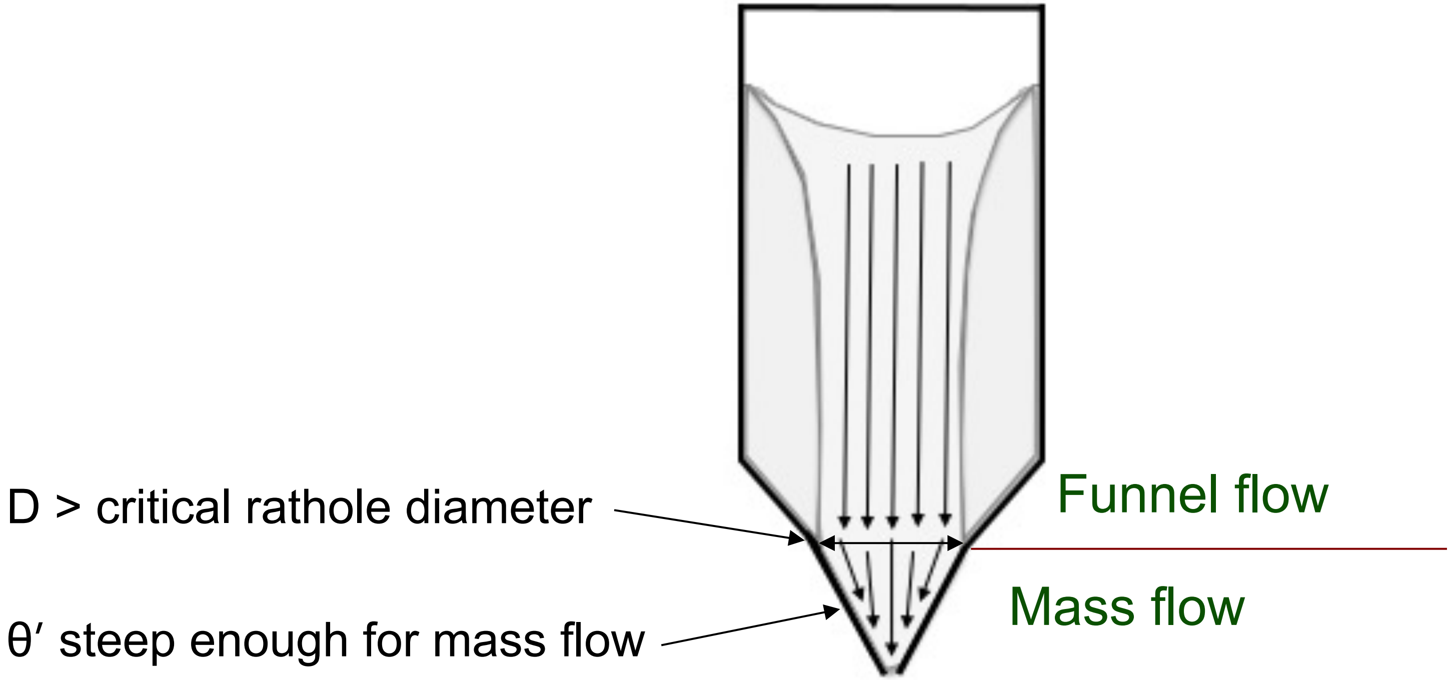


Flow channel

Flow channel

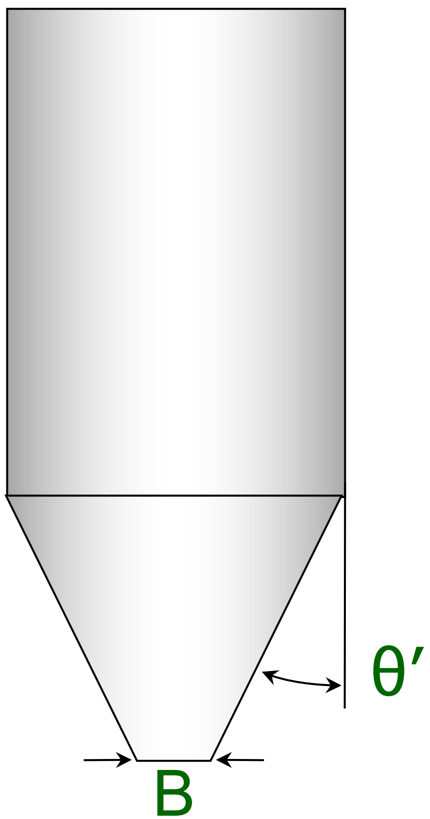


Expanded flow



Solids discharge rates

Coarse powders, mass flow hopper:



$$a = -g$$

$$v_o = \sqrt{\frac{Bg}{2(m+1)\tan(\theta')}}$$

m = 1 for cone; 0 for slot

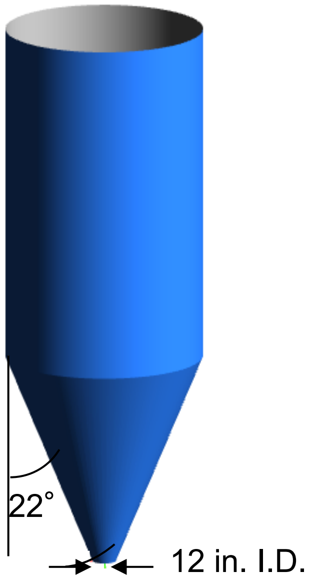
Solids discharge rates

$$v_o = \sqrt{\frac{Bg}{2(m+1)\tan(\theta')}}$$

$$v_o = \sqrt{\frac{(0.304)(9.8)}{4\tan(22°)}}$$

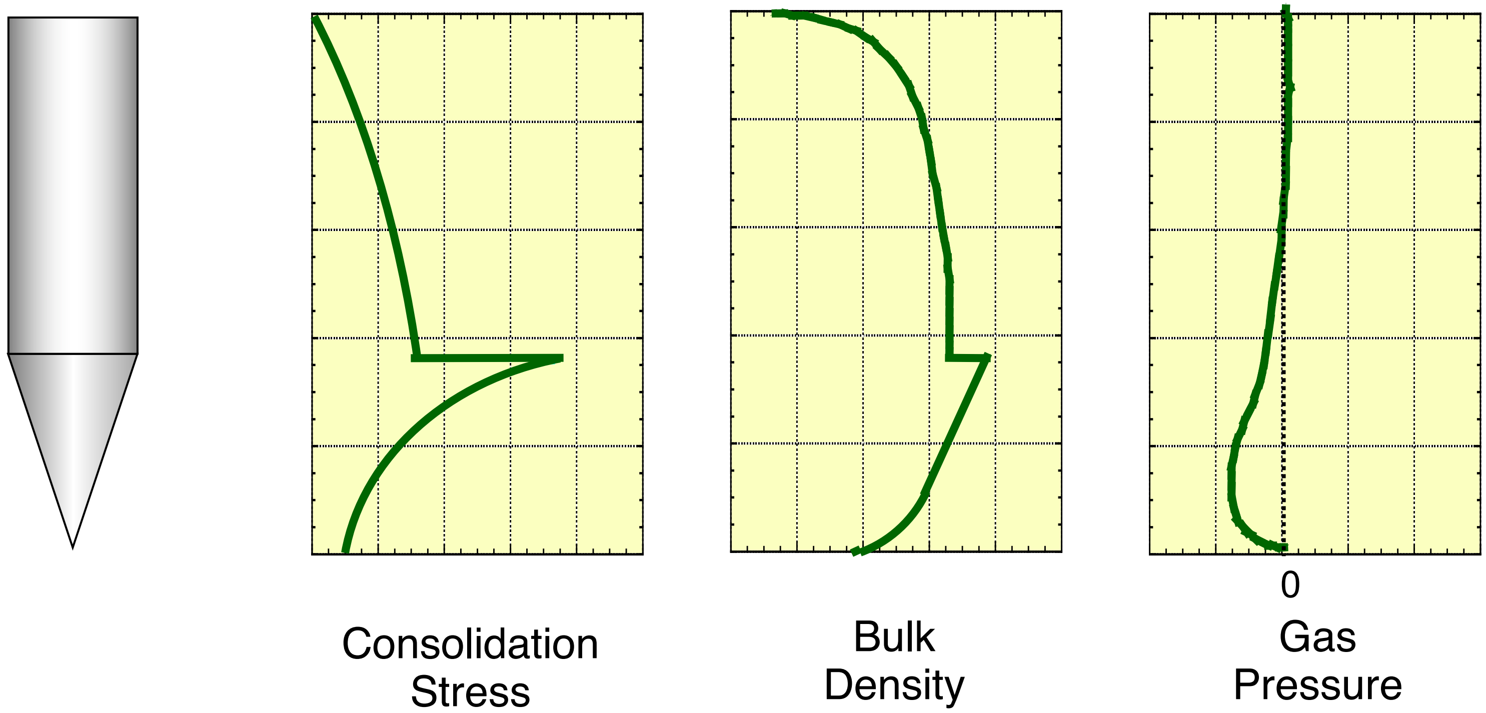
$$v_o = 1.4\ \text{m/s}$$

$$\dot{m} = \rho_{bo} A_o v_o = \ 210\ \text{tonne/hr}$$



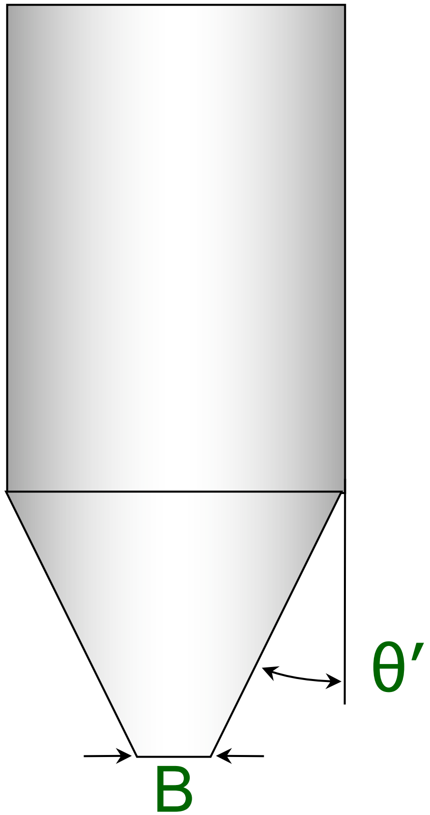
Solids discharge rates

Fine powders



Solids discharge rates

Fine powders, mass flow hopper:

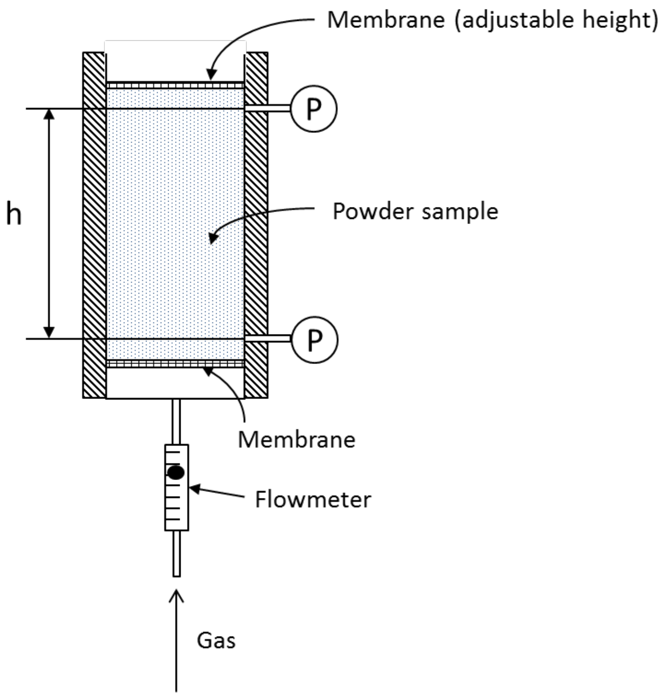


$$\rho_b a = -\rho_b g - \frac{dP}{dz}$$

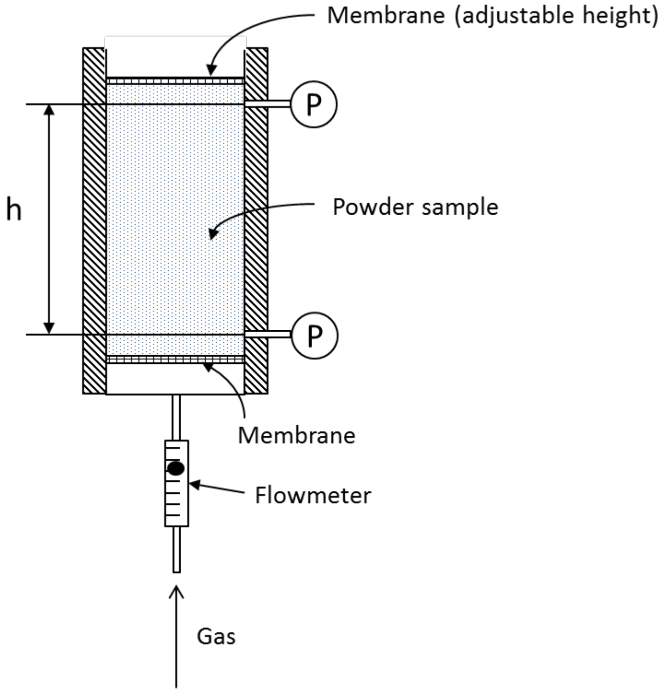
Note: pressure gradient = $\frac{dp}{dz} < 0$

$$\boxed{v_o = \sqrt{\frac{Bg}{2(m+1)\tan(\theta')}\left(1 + \frac{1}{\rho_b g}\frac{dP}{dz}\right)}}$$

Permeability testing

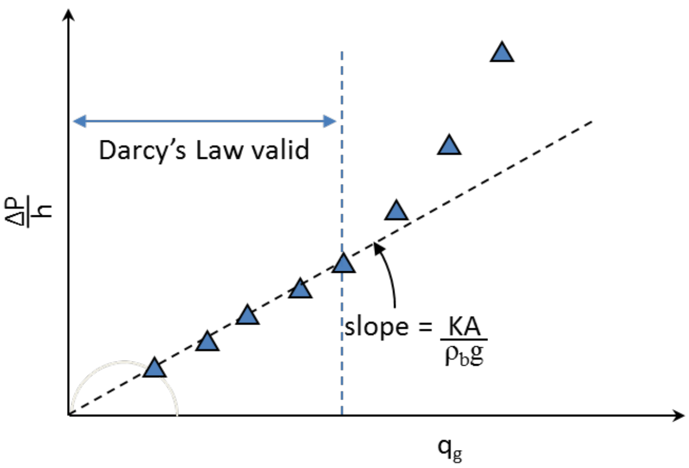


Permeability testing



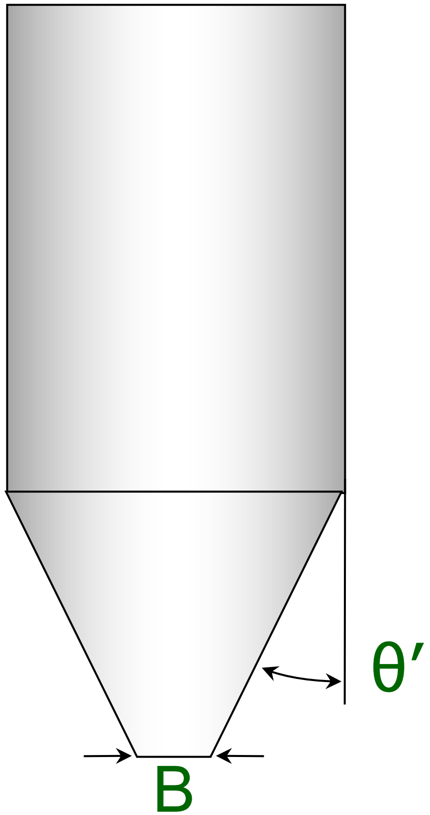
Darcy's Law:

$$q_g = \frac{KA}{\rho_b g}\frac{\Delta P}{h}$$



Solids discharge rates

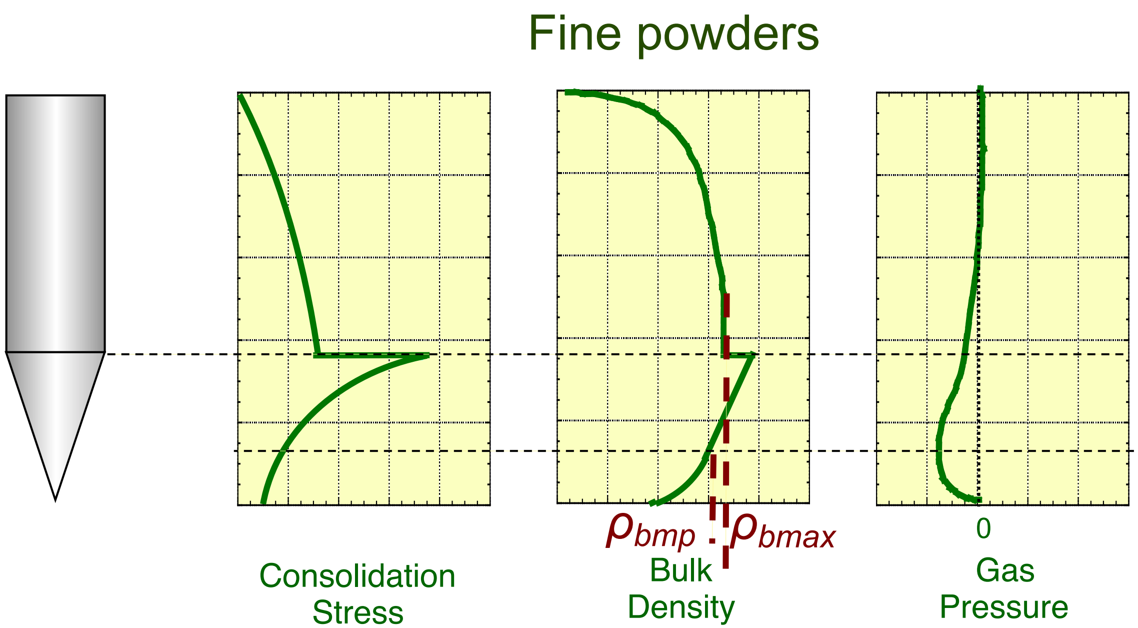
Fine powders, mass flow hopper:



$$\rho_b a = -\rho_b g - \frac{dP}{dz}$$

$$\boxed{\left[\frac{2(m+1)\tan\theta'}{Bg}\right]v_o^2 + \left[\frac{1}{K_o}\left(1-\frac{\rho_{bo}}{\rho_{bmp}}\right)\right]v_o - 1 = 0}$$

Bulk density at minimum gas pressure



$$\left[\frac{2(m+1)\tan\theta'}{Bg}\right]v_o^2+\left[\frac{1}{K_o}\left(1-\frac{\rho_{bo}}{\rho_{bmp}}\right)\right]v_o-1=0$$

Discharge rate calculation

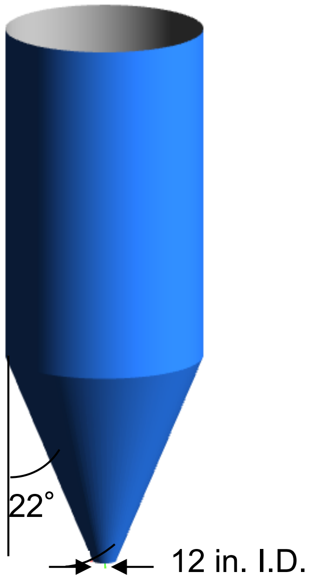
$$K_o = 0.0024 \text{ m/s}$$

$$\left[\frac{2(m+1)\tan\theta'}{Bg}\right]v_o^2 + \left[\frac{1}{K_o}\left(1-\frac{\rho_{bo}}{\rho_{bmp}}\right)\right]v_o - 1 = 0$$

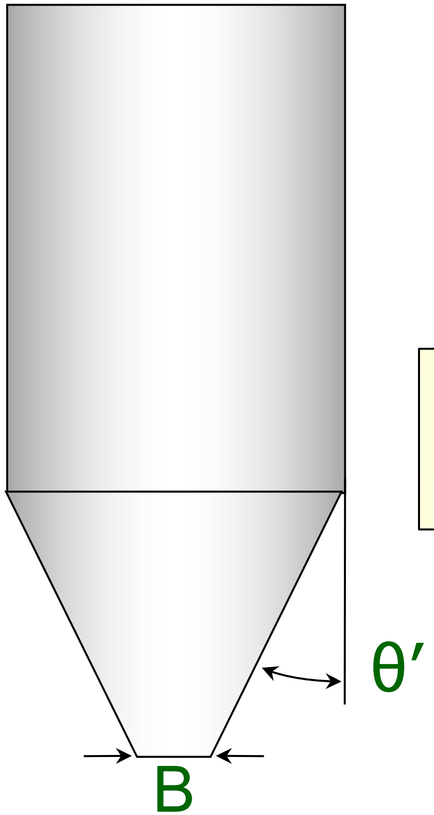
$$\left[\frac{4\tan(22°)}{(0.304)(9.8)}\right]v_o^2 + \left[\frac{1}{0.0024}\left(1-618\right)\right]v_o - 1 = 0$$

$$v_o = 0.10 \text{ m/s}$$

$$\dot{m} = \rho_{bo} A_o v_o = \text{ 16 tonne/hr}$$



Fine, cohesive powders



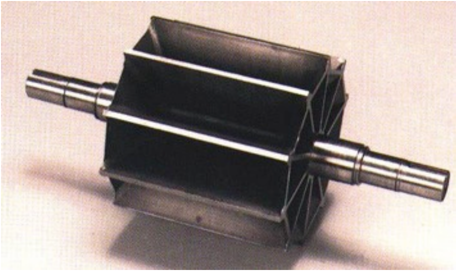
$$\frac{2(m+1)\tan\theta'}{Bg}v_o^2 = 1 - \frac{2(m+1)\cos\theta'\sin(\beta+\theta')f_C}{\rho_b gB} + \frac{1}{\rho_{bo}g}\left.\frac{dP}{dz}\right|_o$$

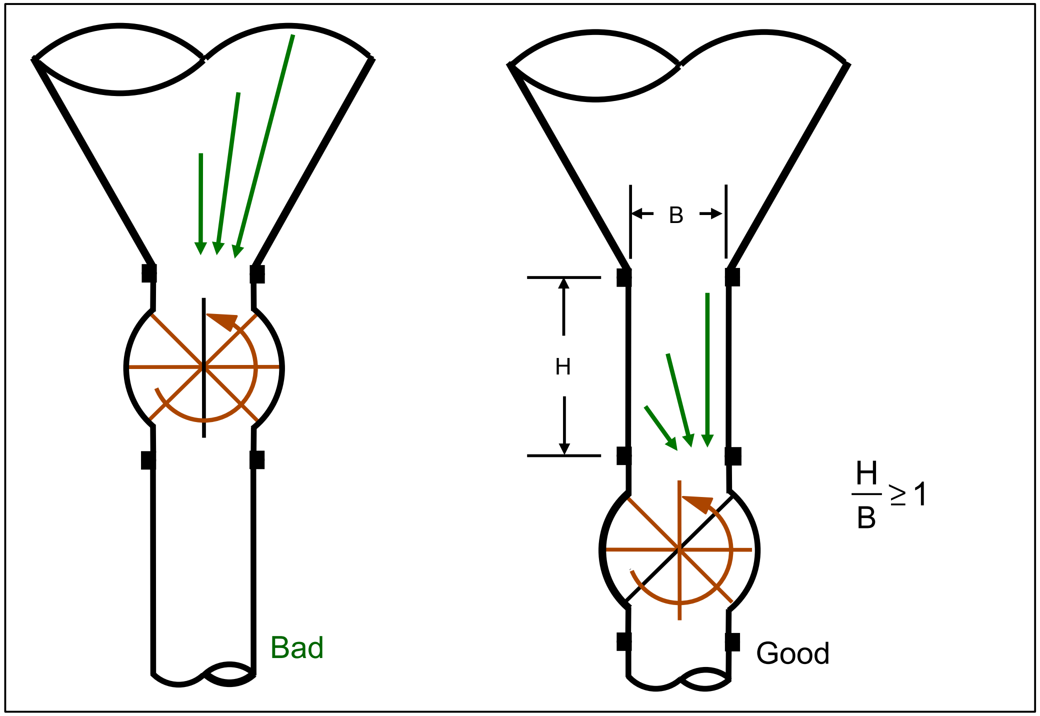
$$\boxed{\left[\frac{2(m+1)\tan\theta'}{Bg}\right]v_o^2 + \left[\frac{1}{K_o}\left(1-\frac{\rho_{bo}}{\rho_{bmp}}\right)\right]v_o + \frac{2(m+1)\cos\theta'\sin(\beta+\theta')f_C}{\rho_b gB} - 1 = 0}$$

Feeders

- Used to modulate the discharge rate of a powder from a hopper, bin, or silo
- Outlet must be large enough to prevent flow obstruction and allow desired discharge rate
- Slide gates should never be used to control discharge rates

Rotary valves



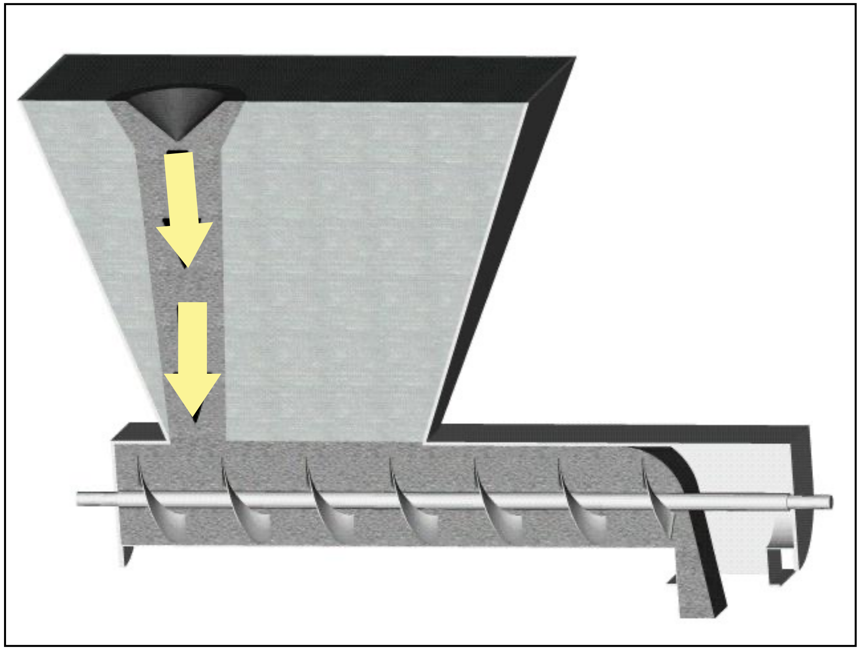


Rotary valves

- Typical speed: 15-25 rpm
- Maximum speed: 35-40 rpm

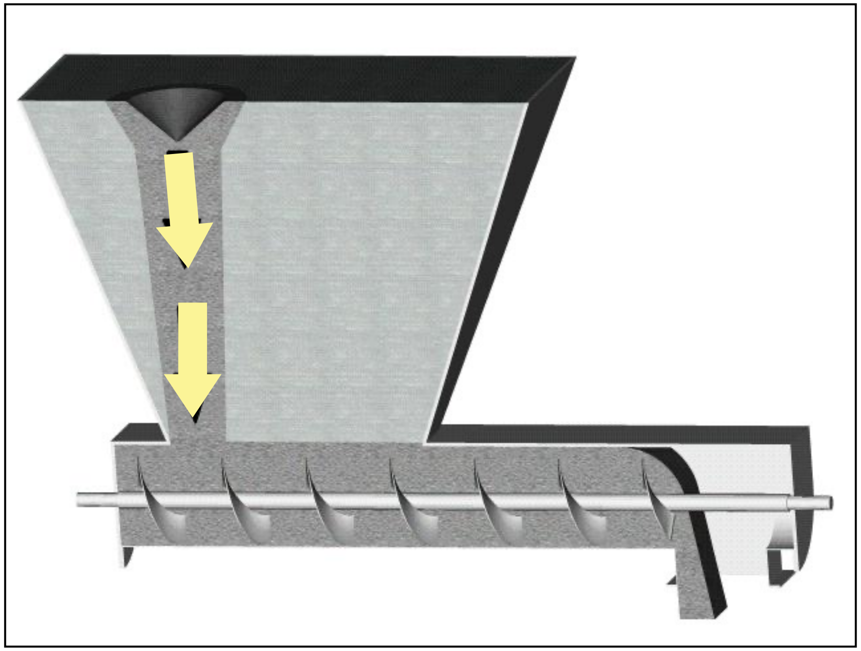
Screw feeders

Screw feeders

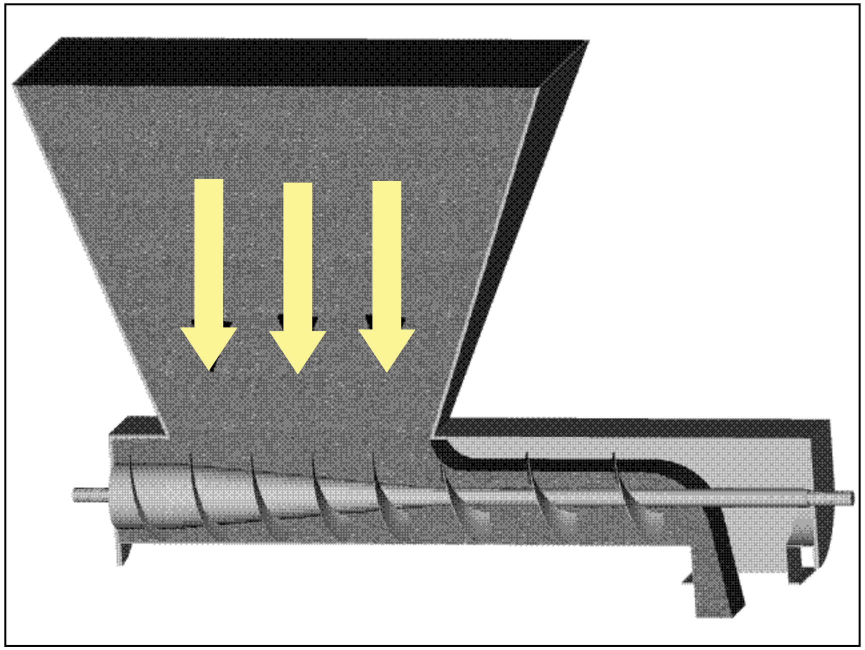


Constant diameter, constant pitch

Screw feeders

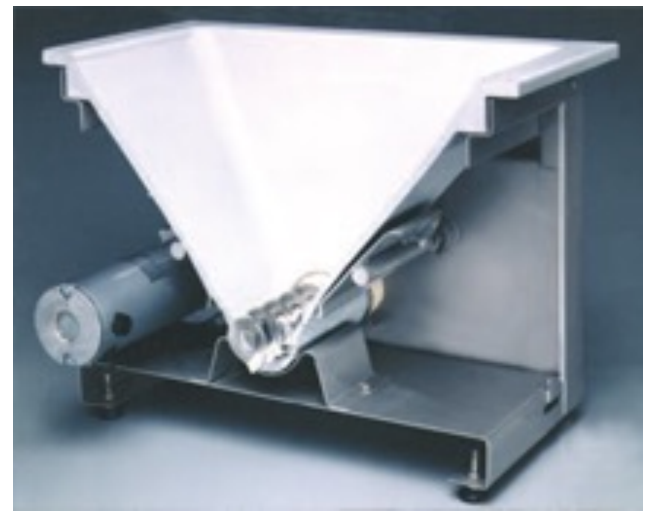


Constant diameter, constant pitch



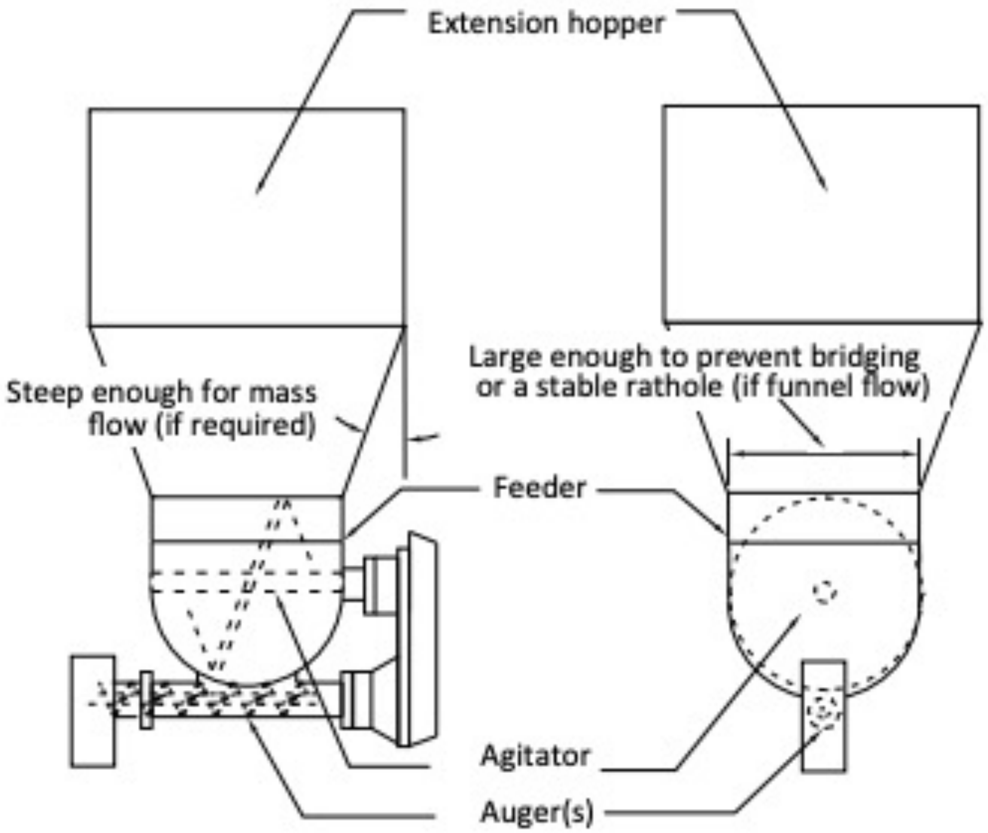
Tapered shaft diameter, increasing pitch

LIW and volumetric screw feeders

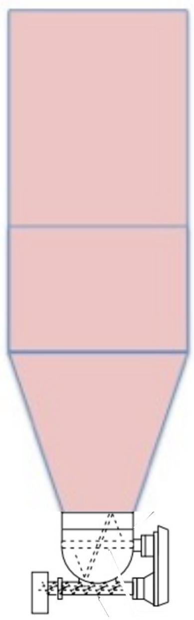


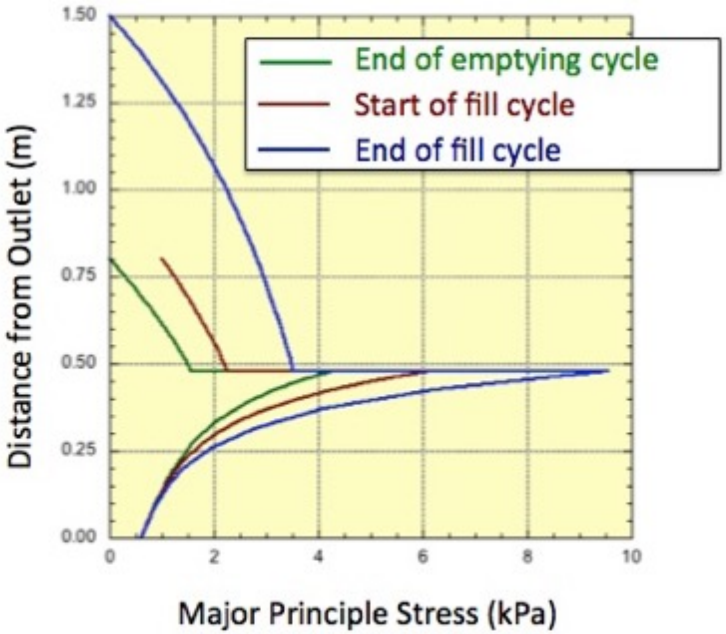
- Consider hopper design!
- Inlet to feeder should be large enough to prevent arching/stable rathole if hopper has sloping walls

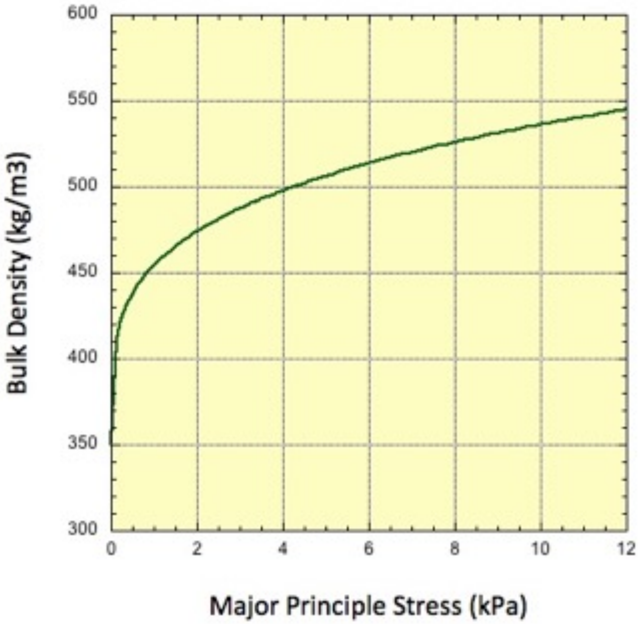
Screw feeder w/agitator



Gravimetric feeders

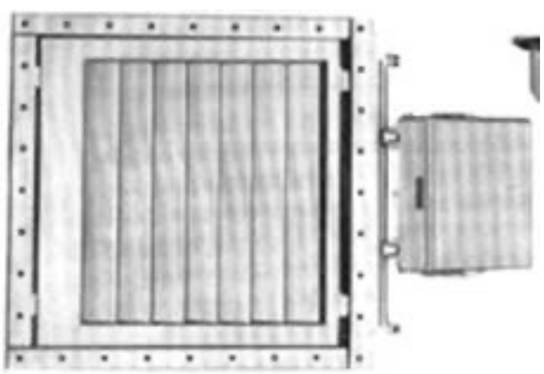




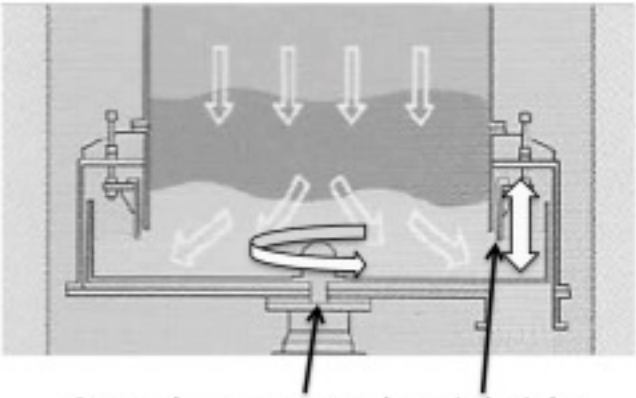


Vibratory feeder

- Pan feeder – hopper interface important
- Stilleta – vibrating louvers

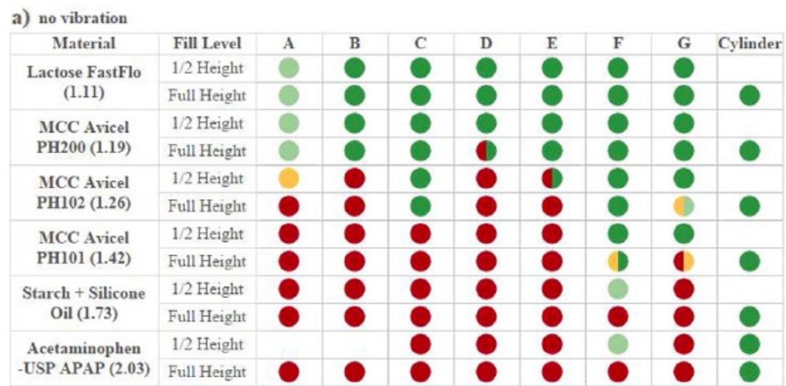


Circle feeder



Controls: rotor speed, weir height

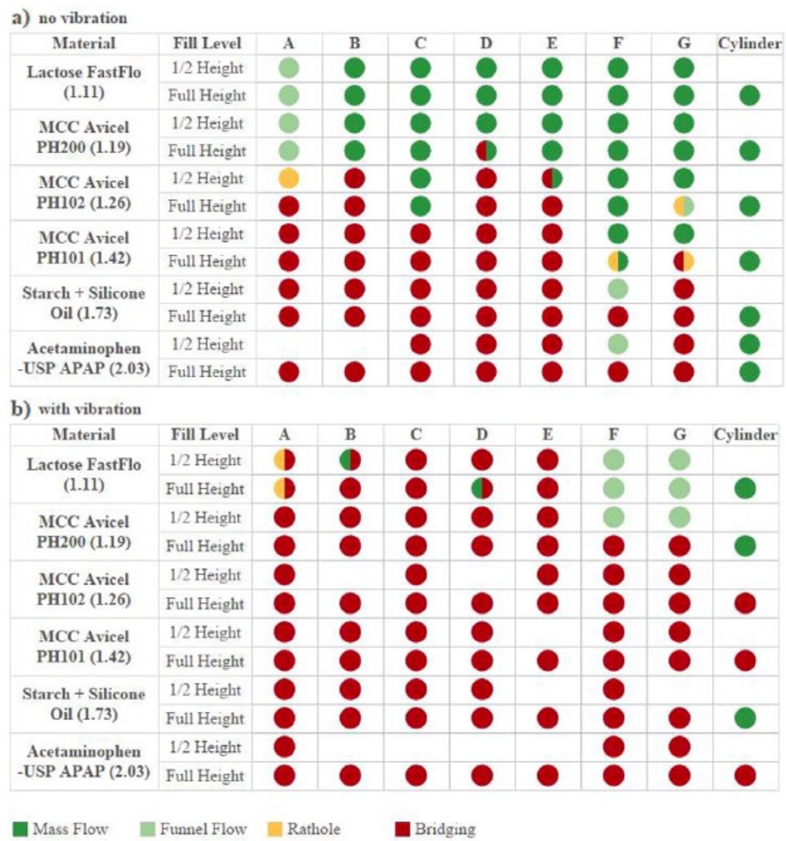
Vibrators



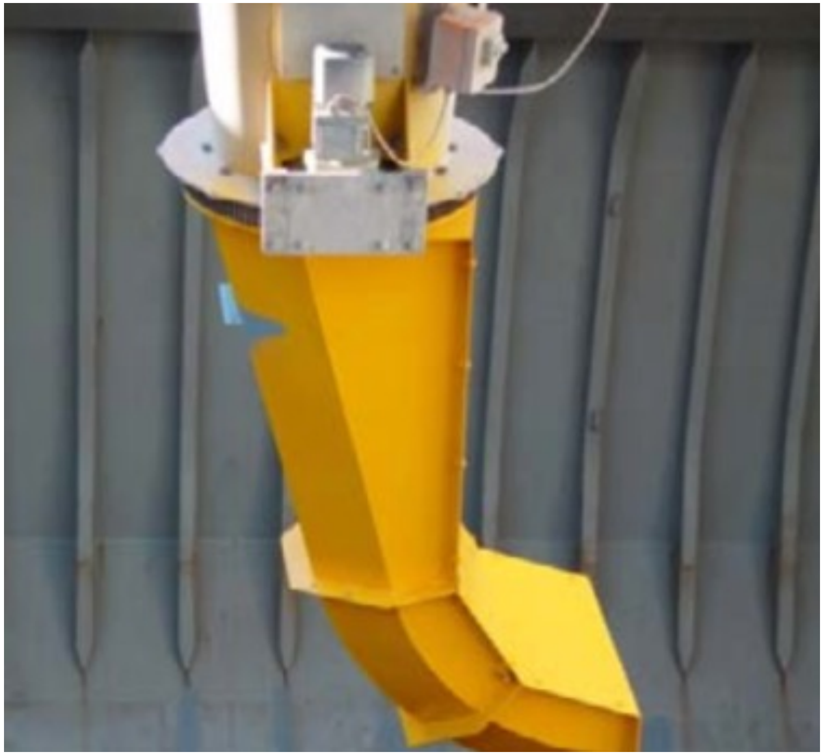
a) no vibration

Material	Fill Level	A	B	C	D	E	F	G	Cylinder
Lactose FastFlo (1.11)	1/2 Height	●	●	●	●	●	●	●	
	Full Height	●	●	●	●	●	●	●	●
MCC Avicel PH200 (1.19)	1/2 Height	●	●	●	●	●	●	●	
	Full Height	●	●	●	●	●	●	●	●
MCC Avicel PH102 (1.26)	1/2 Height	●	●	●	●	●	●	●	
	Full Height	●	●	●	●	●	●	●	●
MCC Avicel PH101 (1.42)	1/2 Height	●	●	●	●	●	●	●	
	Full Height	●	●	●	●	●	●	●	●
Starch + Silicone Oil (1.73)	1/2 Height	●	●	●	●	●	●	●	
	Full Height	●	●	●	●	●	●	●	●
Acetaminophen -USP APAP (2.03)	1/2 Height			●	●	●	●	●	●
	Full Height	●	●	●	●	●	●	●	●

Vibrators


a) no vibration
Material
Fill Level
A
B
C
D
E
F
G
Cylinder
Lactose FastFlo (1.11)
MCC Avicel PH200 (1.19)
MCC Avicel PH102 (1.26)
MCC Avicel PH101 (1.42)
Starch + Silicone Oil (1.73)
Acetaminophen -USP APAP (2.03)
1/2 Height
Full Height
b) with vibration
Mass Flow
Funnel Flow
Rathole
Bridging

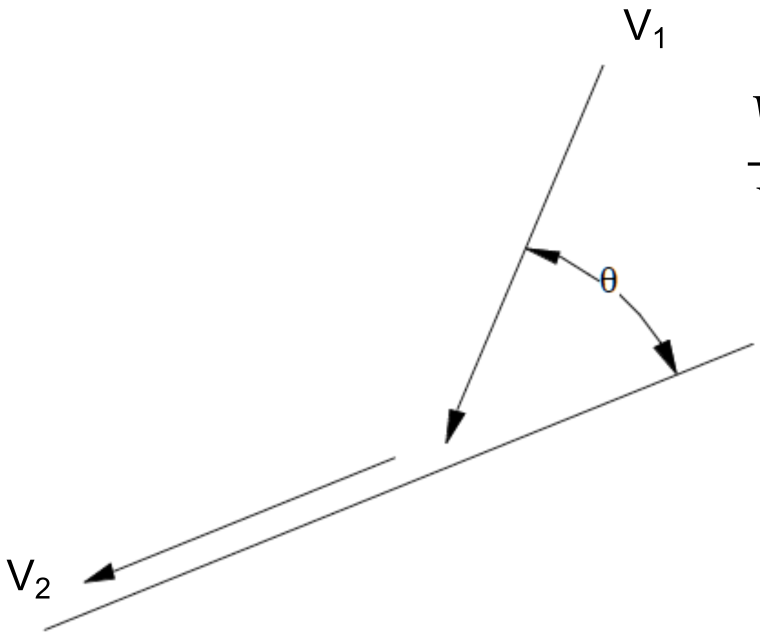
Transfer chutes



Transfer chutes

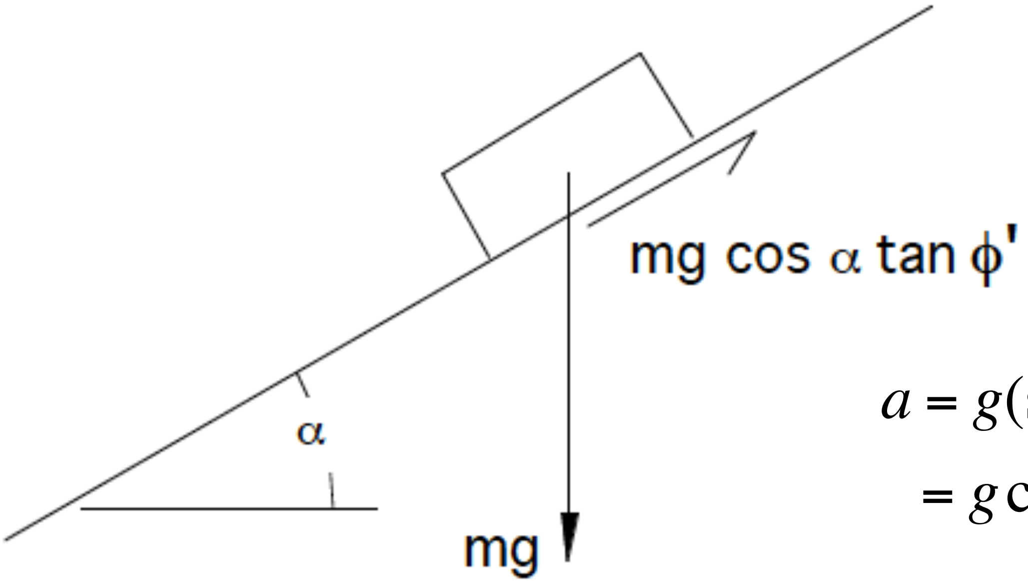
- Prevent plugging at impact points
- Ensure sufficient cross-section area
- Control the stream of particles

Transfer chutes



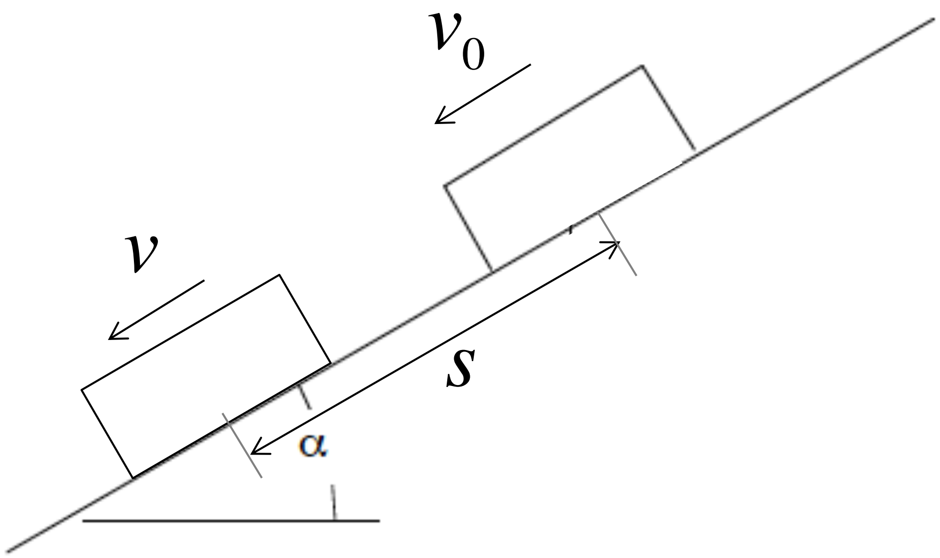
$$\frac{V_2}{V_1} = \cos\theta - \sin\theta\tan\phi'$$

Transfer chutes



$$a = g(\sin\alpha - \cos\alpha\tan\phi')$$
$$= g\cos\alpha(\tan\alpha - \tan\phi')$$

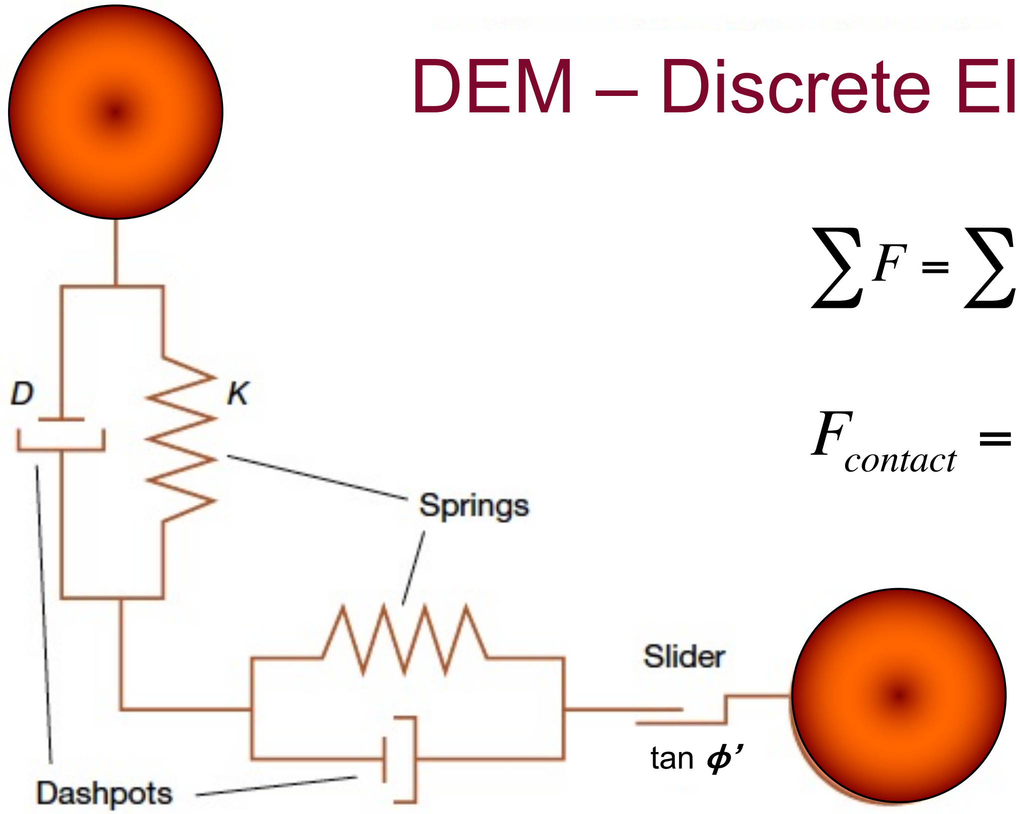
Transfer chutes



$$v = \sqrt{v_0^2 + 2as}$$

$$\dot{m} = \rho_b v A$$

Transfer chutes

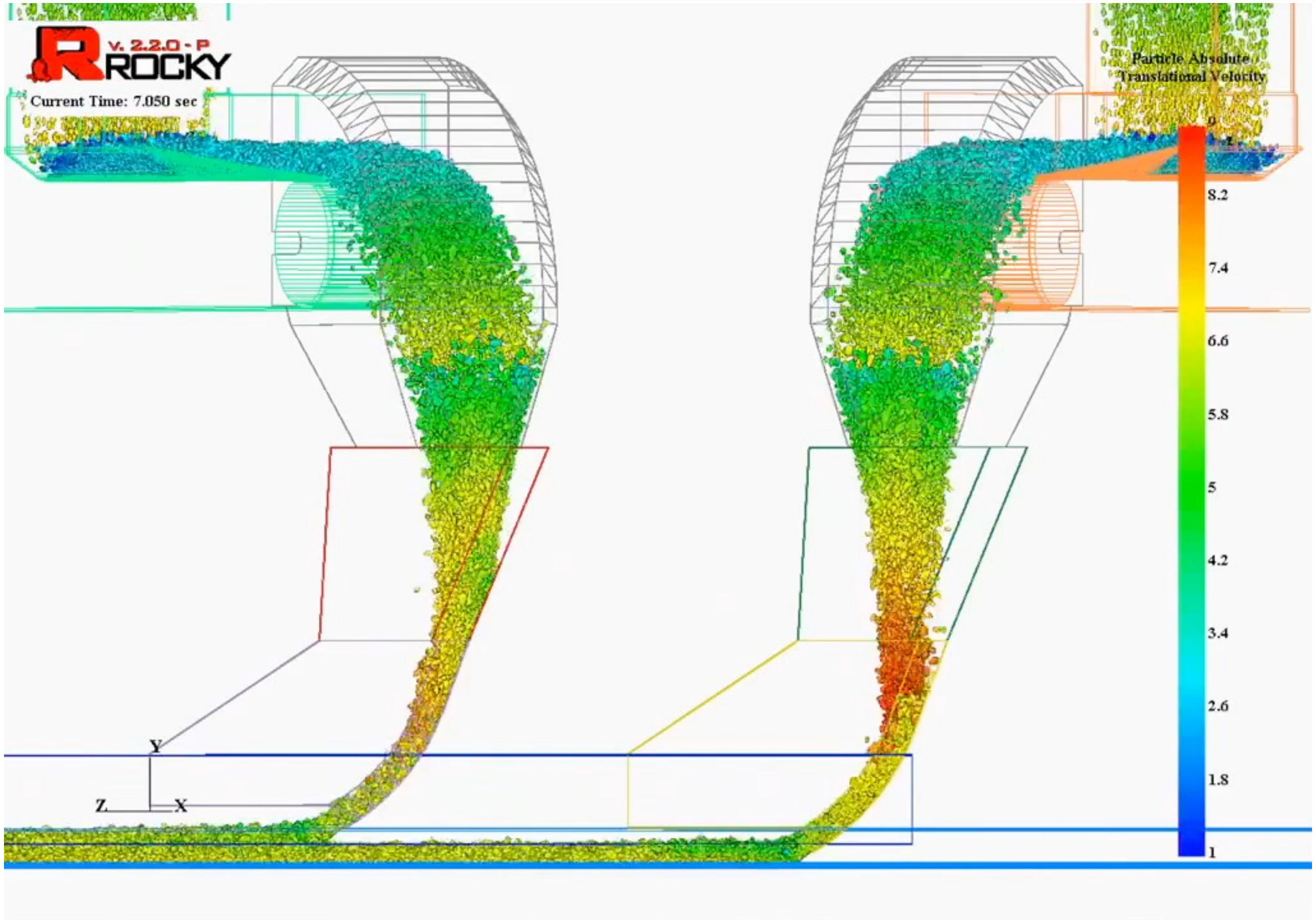


DEM – Discrete Element Method

$$\sum F = \sum (F_{contact} + F_{body})$$

$$F_{contact} = -K\delta^{n} - D\delta^{l}\delta'^{m}$$

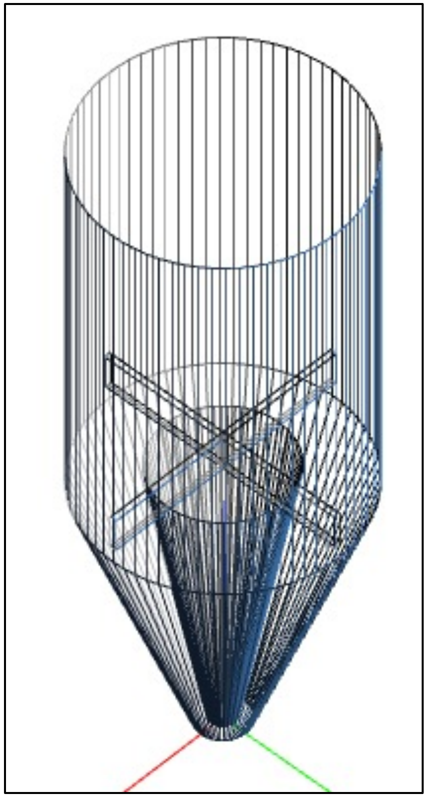
Transfer chutes

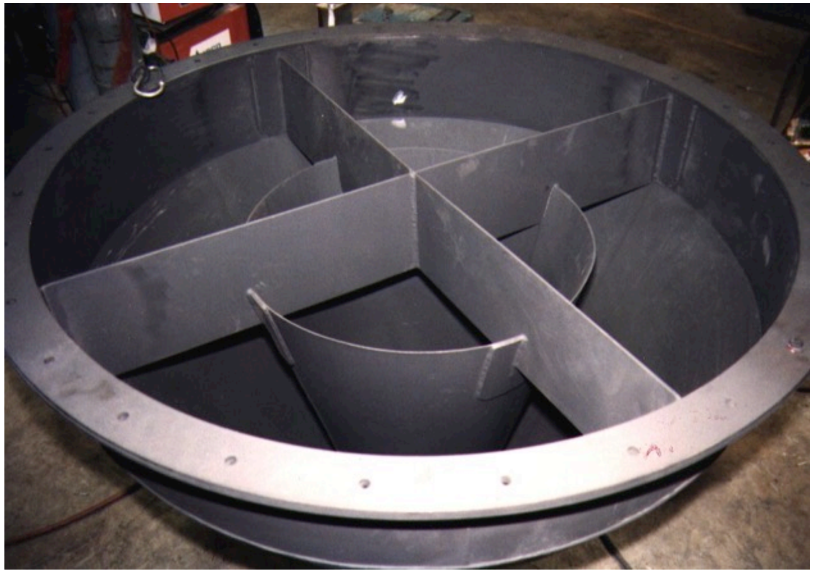


Tricks

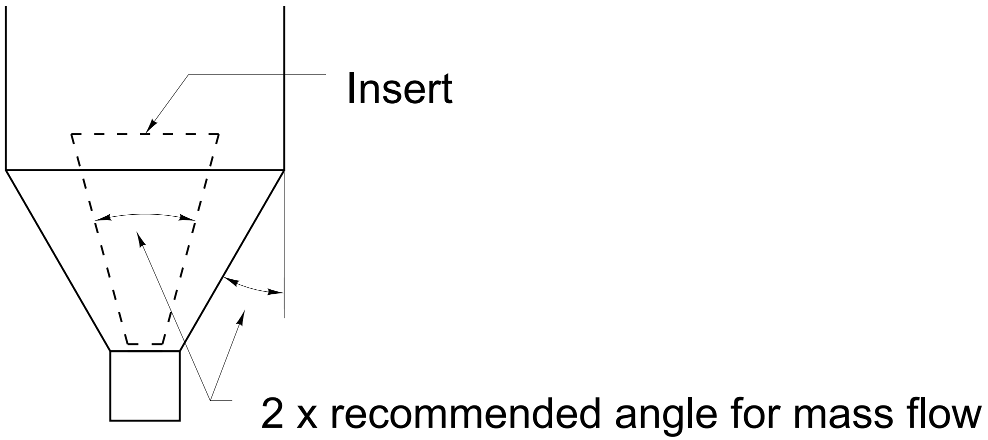
- Inserts
- Diverging walls

Inserts

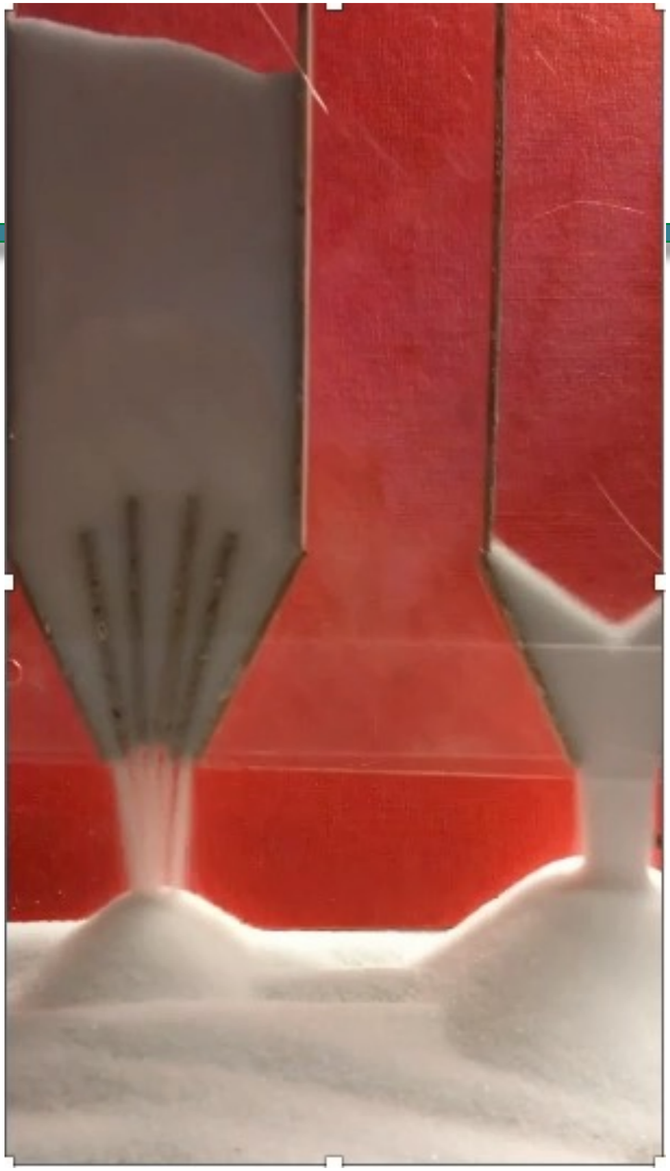




Inserts



Inserts



Converging/diverging

Diamondback

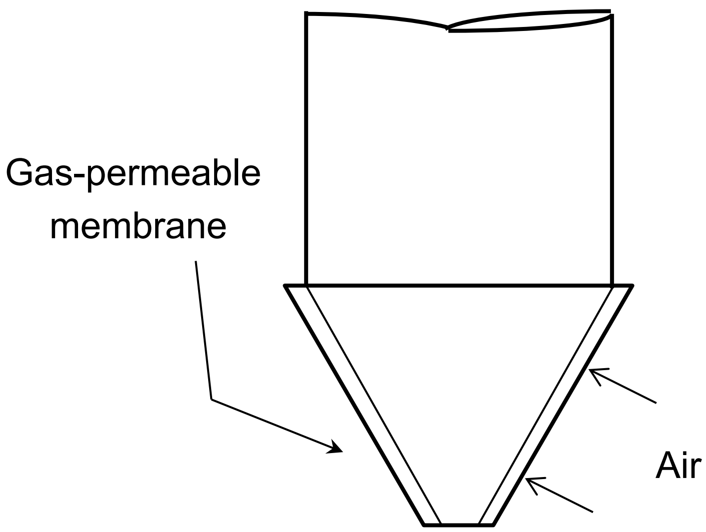
Stacked wedges

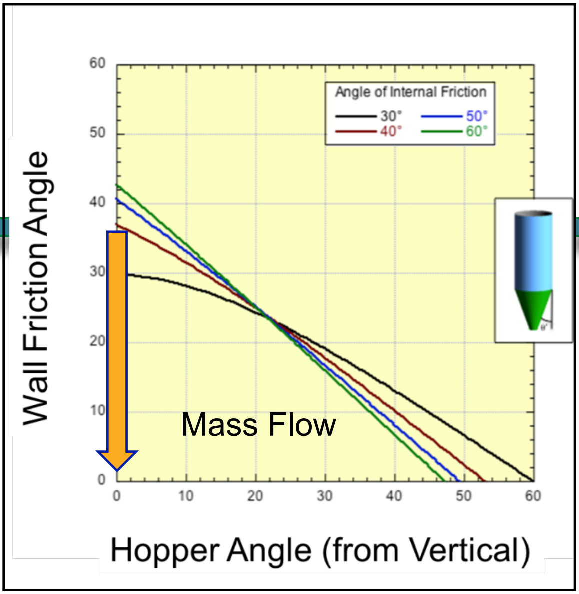
Converging/diverging

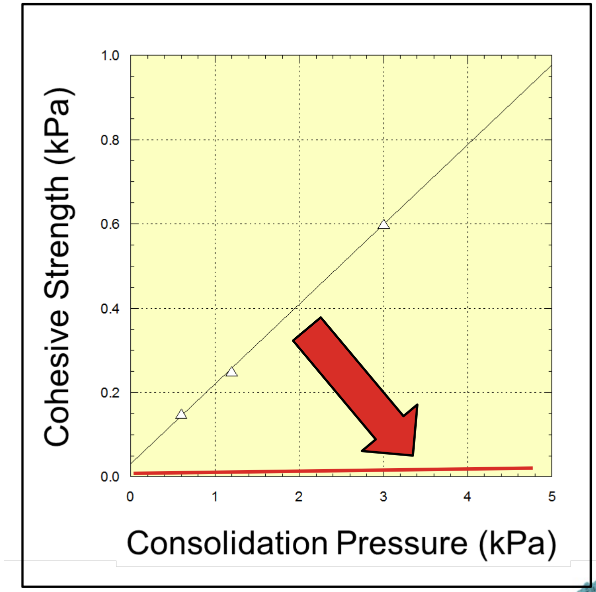
“D-tron”

Air assistance

Air assistance



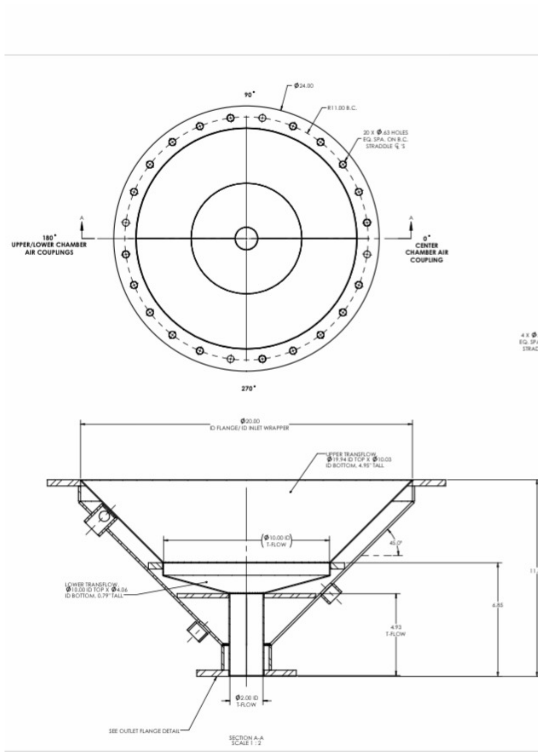




Air assistance

Air assistance

Air assistance

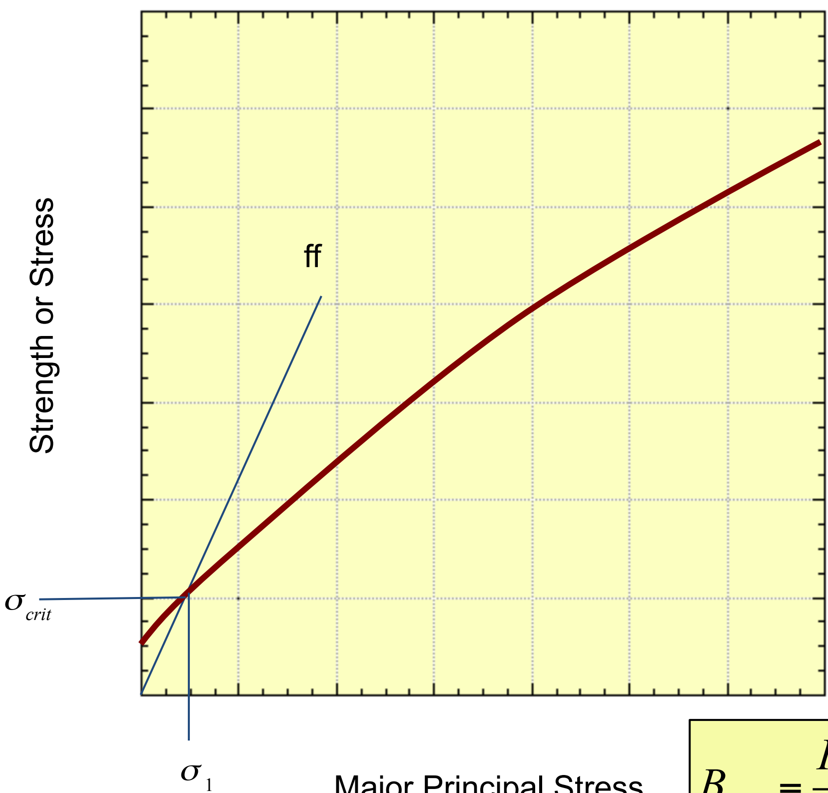


Air assistance

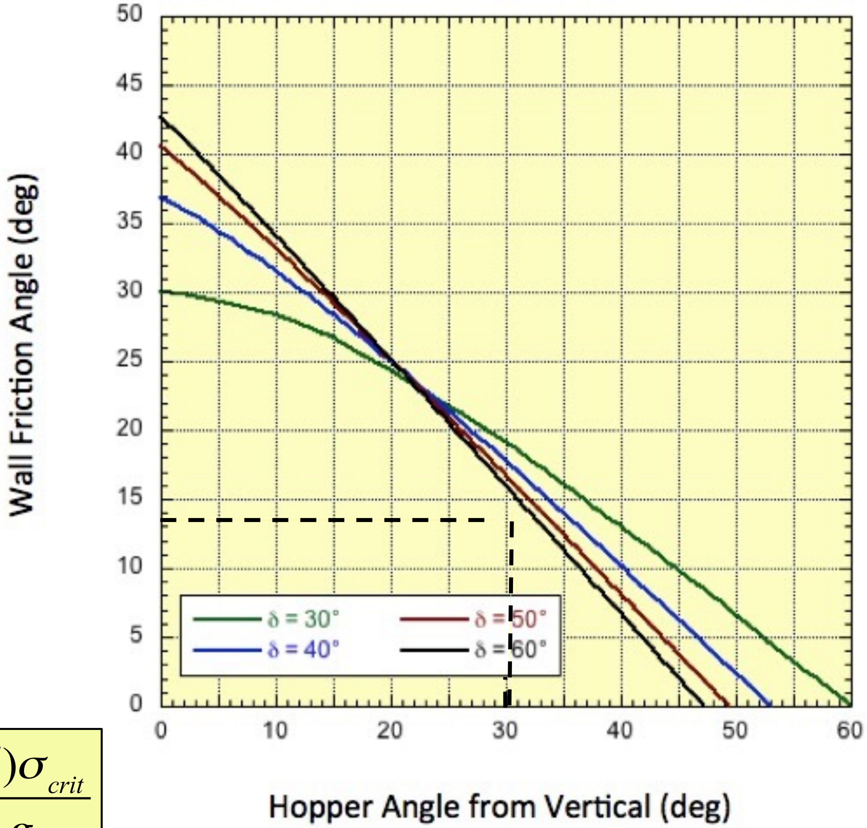
Solving powder handling problems

- Change the equipment
  - Modify to allow mass flow
  - Use proper feeder
- Change the product
  - Particle size
  - Moisture content
  - Surface character
  - Composition

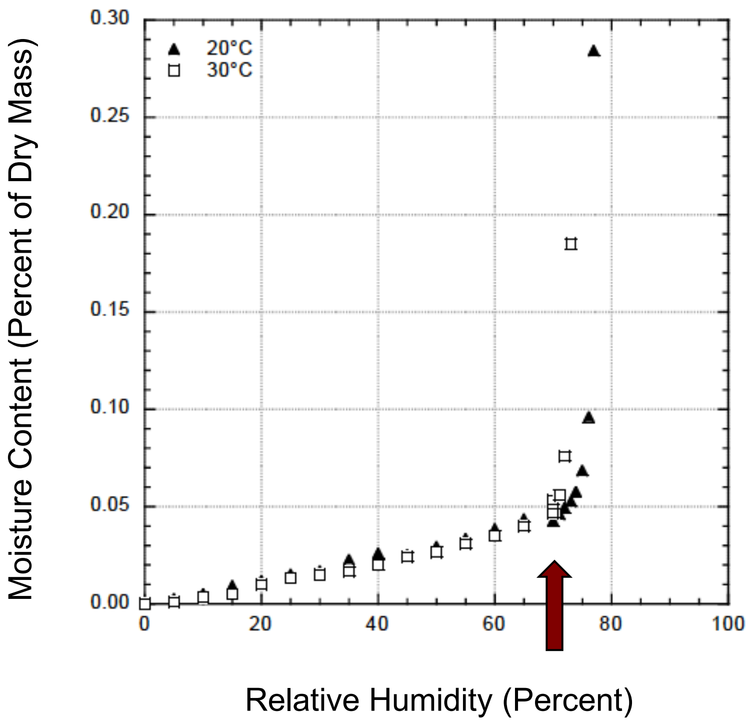
Product specs

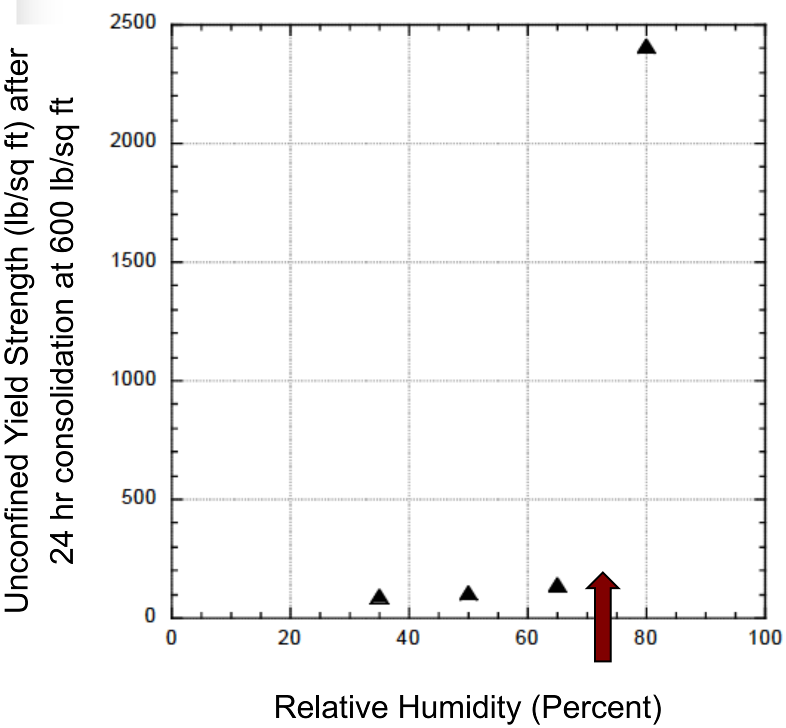


$$B_{\min} = \frac{H(\theta')\sigma_{crit}}{\rho_b g}$$

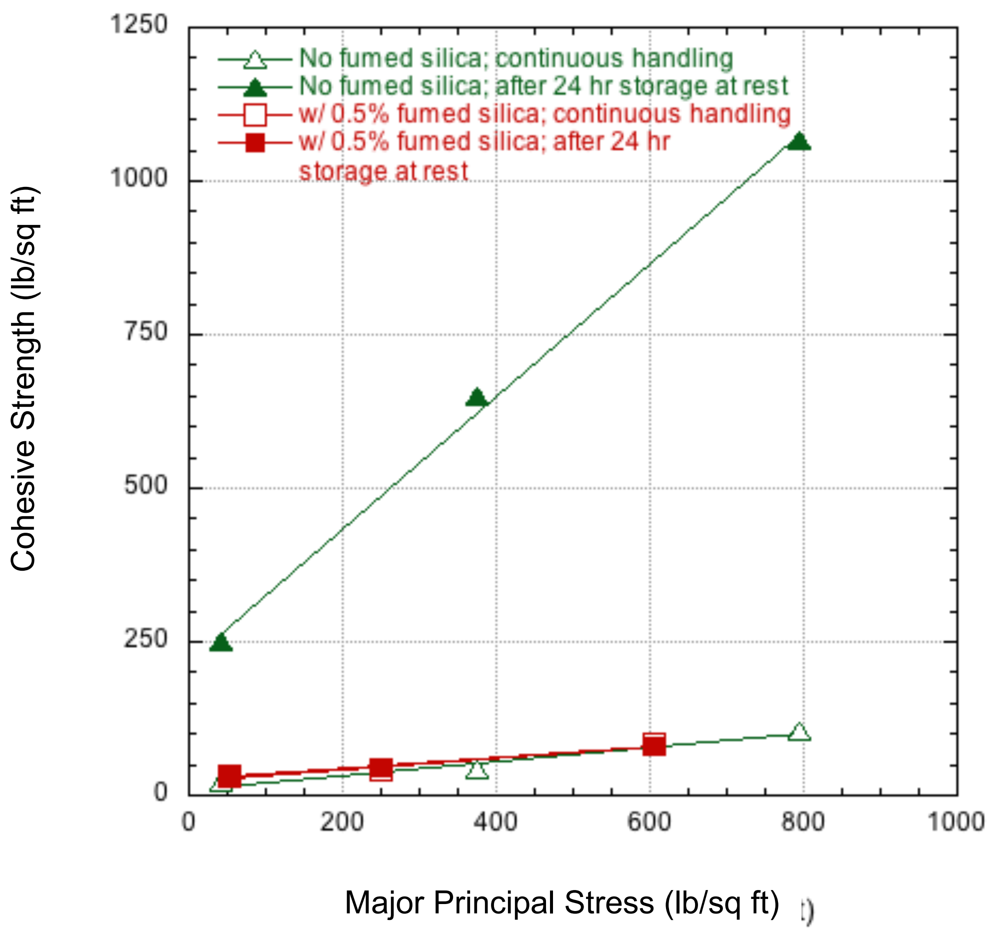


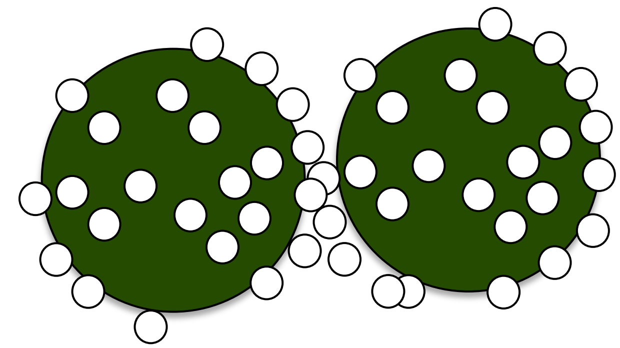
Sorption isotherm





Parting agents





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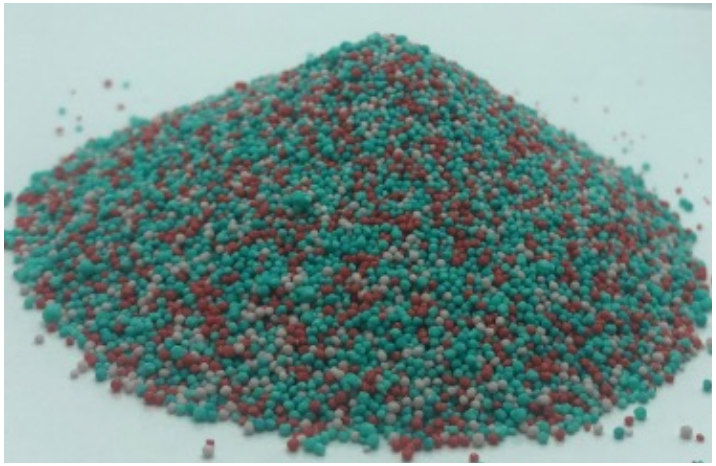
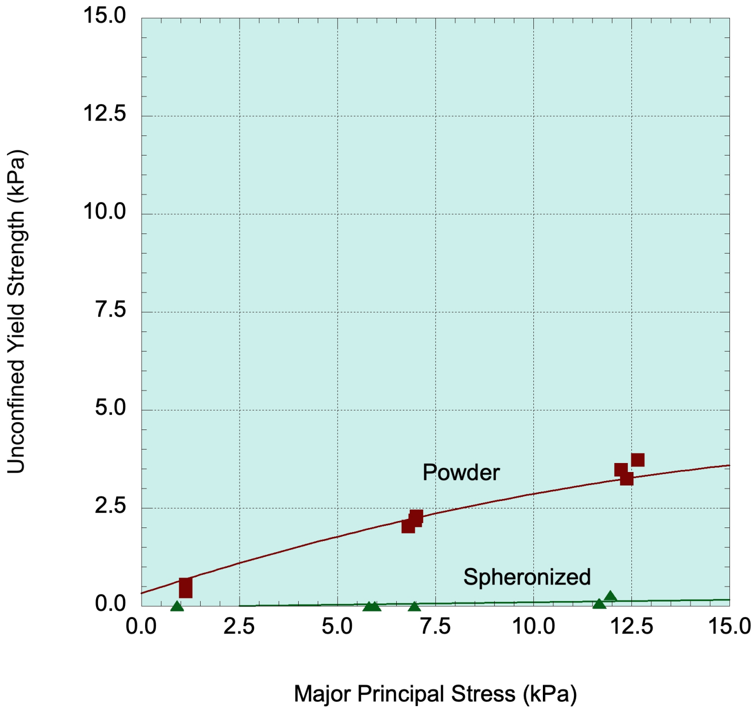
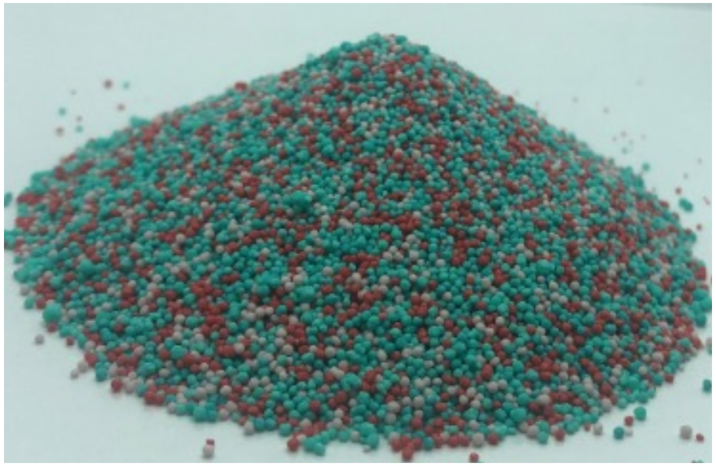
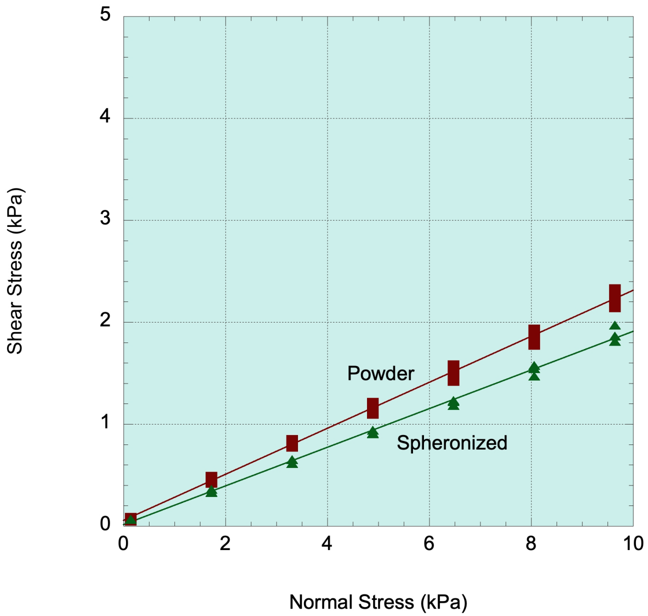
Granulation

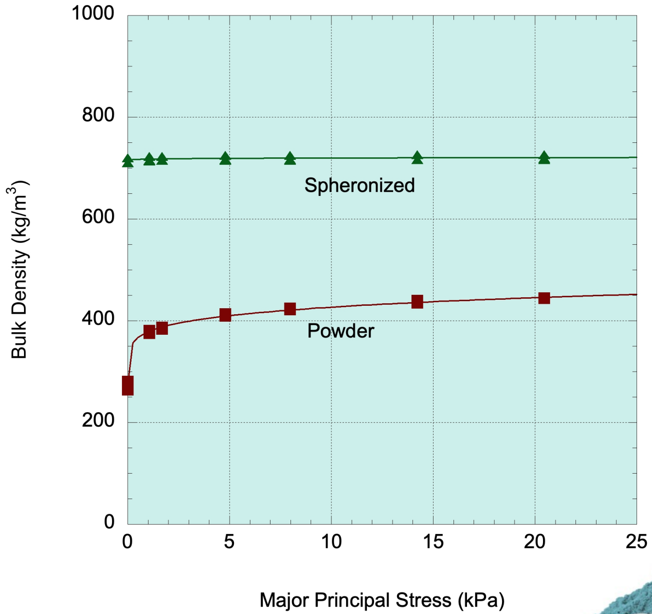




Granulation





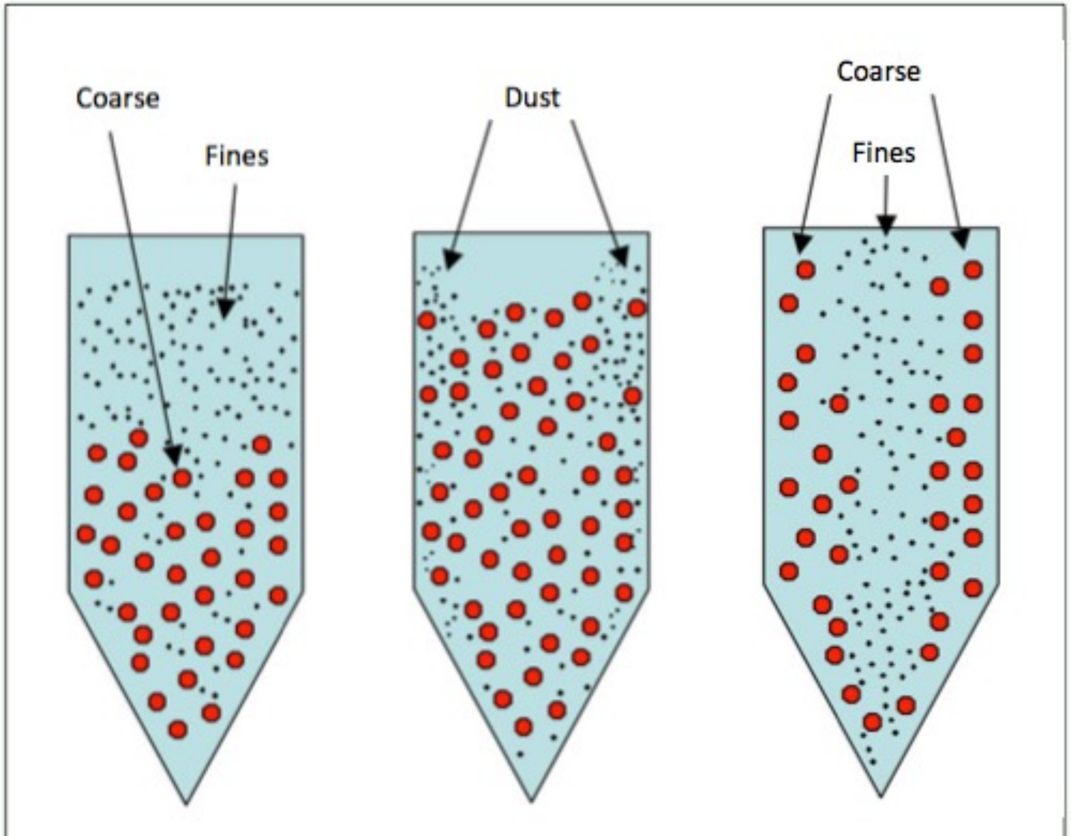


Granulation

Segregation

- Change in particle size, composition, or other properties of a powder when handled
- Causes variability in potency, dissolution, dosage weight, stability, color, *etc.*

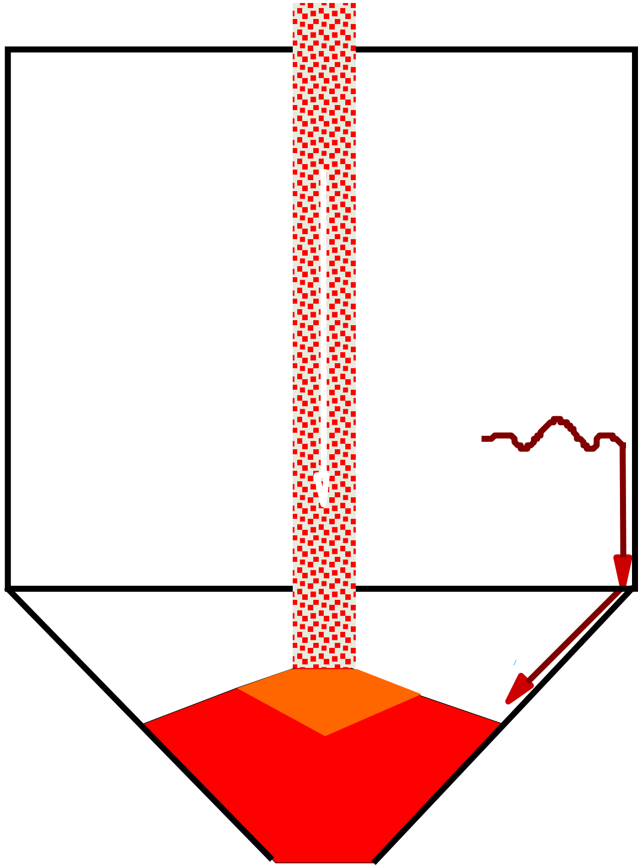
Seg'n mechanisms



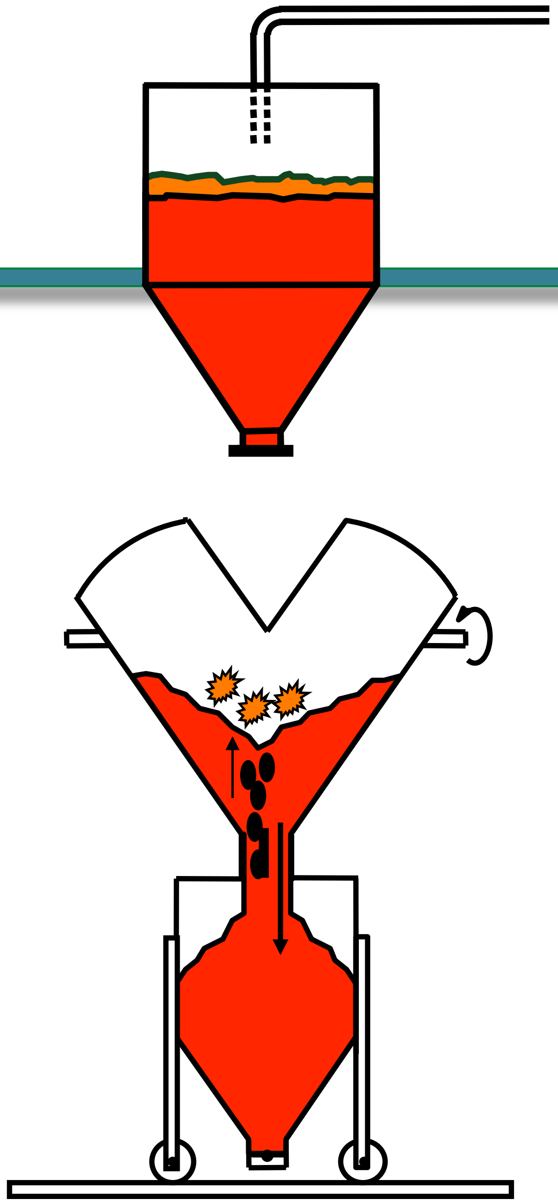
Fluidization Dusting Sifting

Dusting

- Requirements
  - Particle entrainment into air
  - Air currents
- Results in thin layer at walls, significantly different than bulk



Fluidization



- Requirements
  - Particle entrainment into air
  - Differences in settling velocities
  - Air currents
- Results in separation by particle size and density, top to bottom

Sifting

"Christmas Tree Segregation" – Lyn Bates

Sifting

- Requirements
  - Differences in particle size
  - Sufficiently large particles (50-100 μm)
  - Free-flowing, relatively non-cohesive
  - Interparticle motion
- Results in side-to-side differences in particle size

Preventing segregation

- Change the material
- Change the process

Preventing segregation

- Modify particle
  - Surface energy
  - Shape, texture

Preventing segregation

- Modify particle
  - Surface energy
  - Shape, texture
- Reduce particle size difference
  - Agglomerate
  - Extract and return fines

Preventing segregation

- Modify particle
  - Surface energy
  - Shape, texture
- Reduce particle size difference
  - Agglomerate
  - Extract and return fines
- Adjust ratio of fines to coarse
  - Critical ratio where voids formed by coarse particles are filled with fines

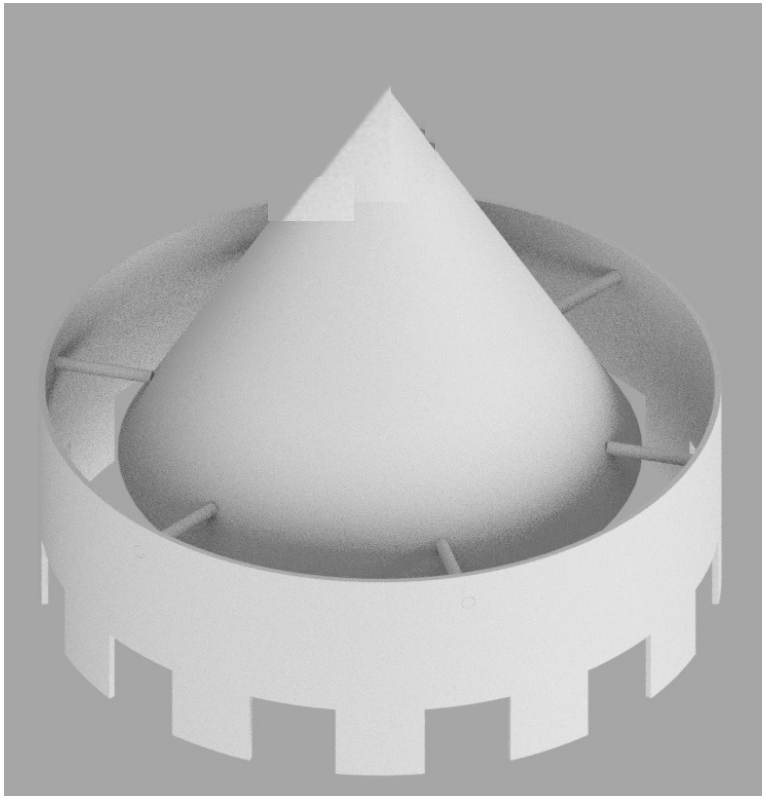
Preventing segregation

- Reduce particle size
  - Particles less likely to separate if they are cohesive
  - (But more likely to bridge)
- Adjust moisture content
  - Water can make powder more cohesive
  - (But more likely to bridge)

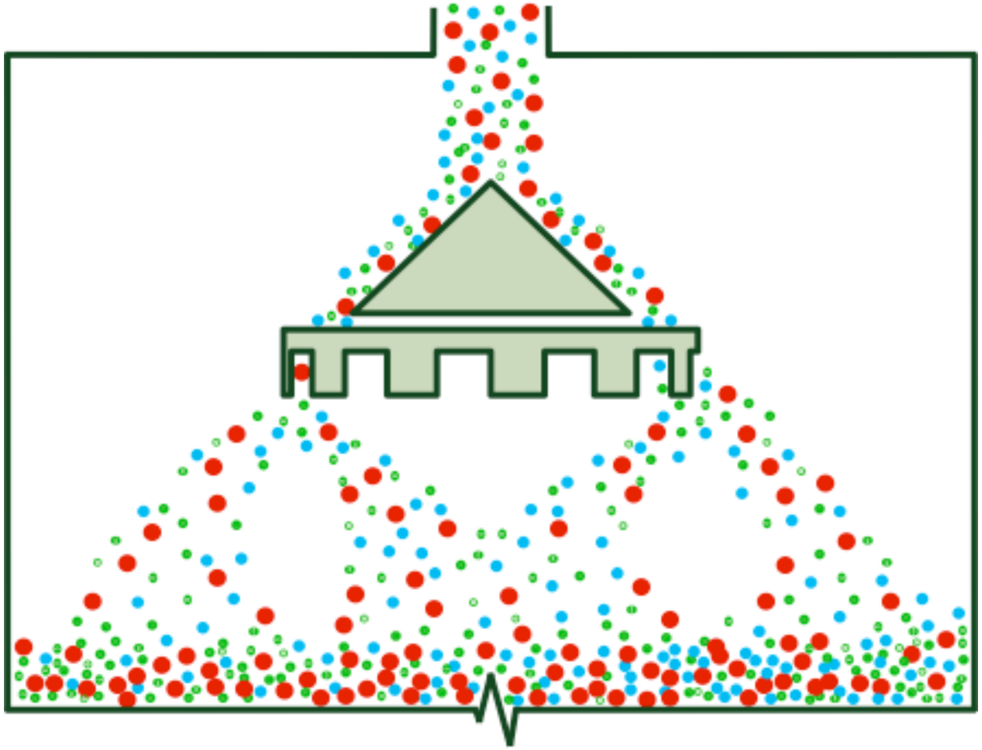
Preventing segregation

- Handle blends in mass flow bins
- Reduce batch size(s)
- Defer mixing to later stage of production

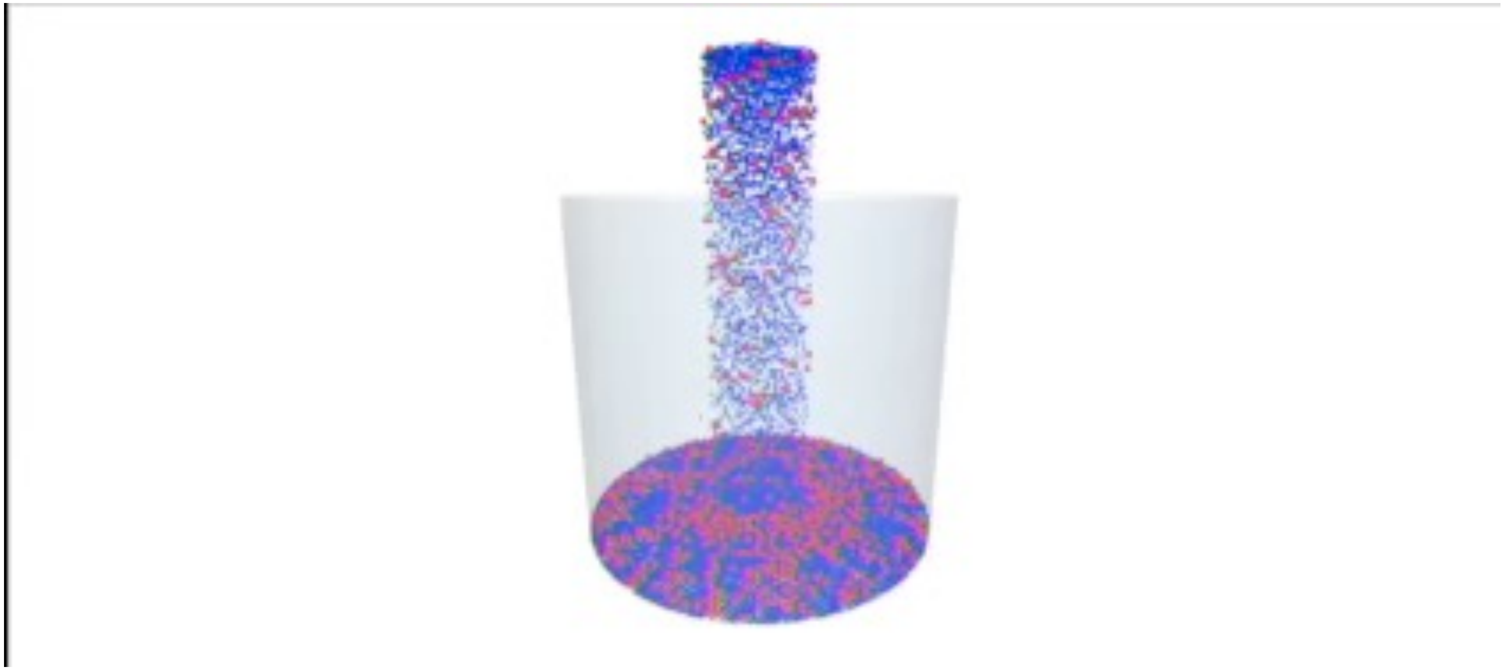
Dispersion cones



Dispersion cones

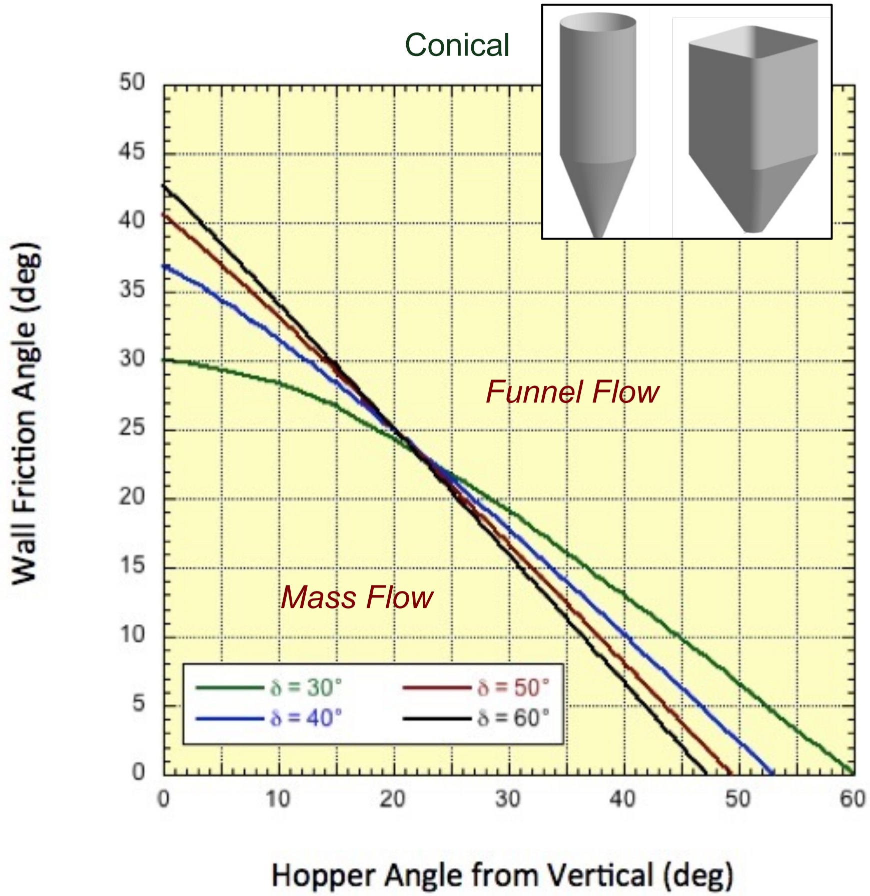


Dispersion cones



Dispersion cones

Mass flow hopper angle



Solids velocity profiles

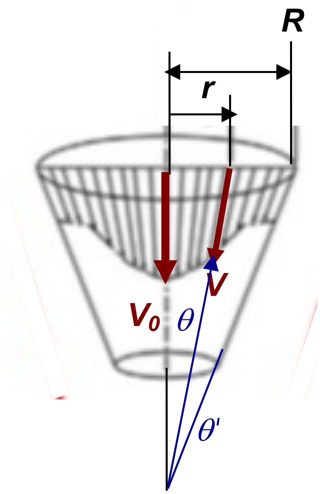
$$\frac{d\psi}{d\theta} = -1 - [ms\sin\delta(1+\sin\delta)(\cot\theta\sin 2\psi + \cos 2\psi - 1)$$
$$+\cos\theta - \sin\delta\cos(\theta + 2\psi) + s\cos^2\delta] / [2s\sin\delta(\cos 2\psi - \sin\delta)]$$

$$\frac{ds}{d\theta} = \frac{s\sin 2\psi + \sin(\theta+2\psi) + ms\sin\delta[\cot\theta(1+\cos 2\psi) - \sin 2\psi]}{\cos 2\psi - \sin\delta}$$

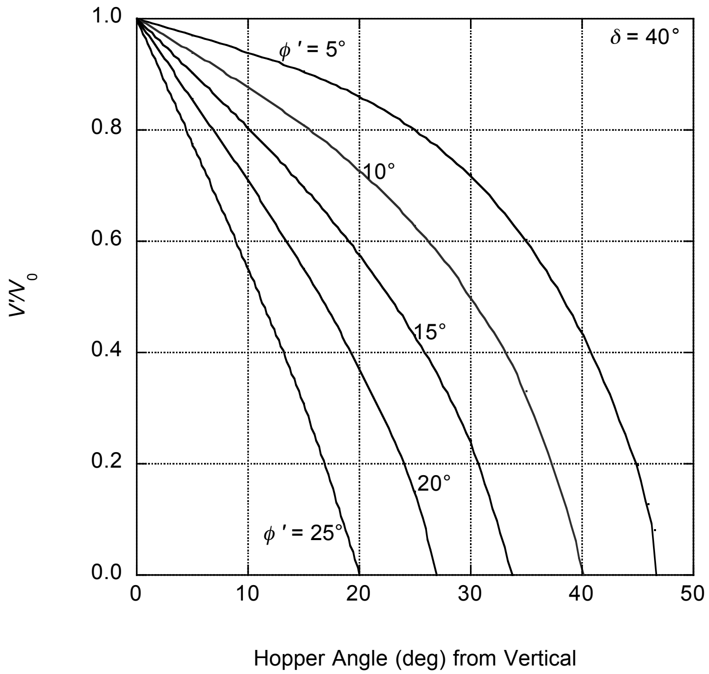
$$\psi(\theta') = \frac{1}{2}\left[\phi' + \sin^{-1}\left(\frac{\sin\phi'}{\sin\delta}\right)\right] + 90°$$

$$\psi(90°) = 90°$$

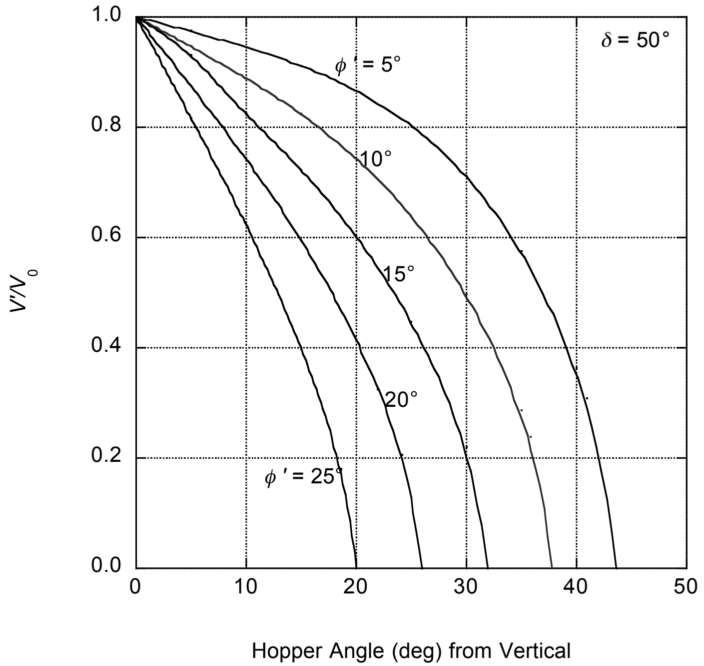
$$\frac{V}{V_0} = \exp\left[-(2+m)\int_0^{\theta'}\tan(2\psi)\,d\theta\right]$$



V'/V_0



1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
V'/V0
δ = 40°
ϕ ' = 5°
10°
15°
20°
ϕ ' = 25°
Hopper Angle (deg) from Vertical



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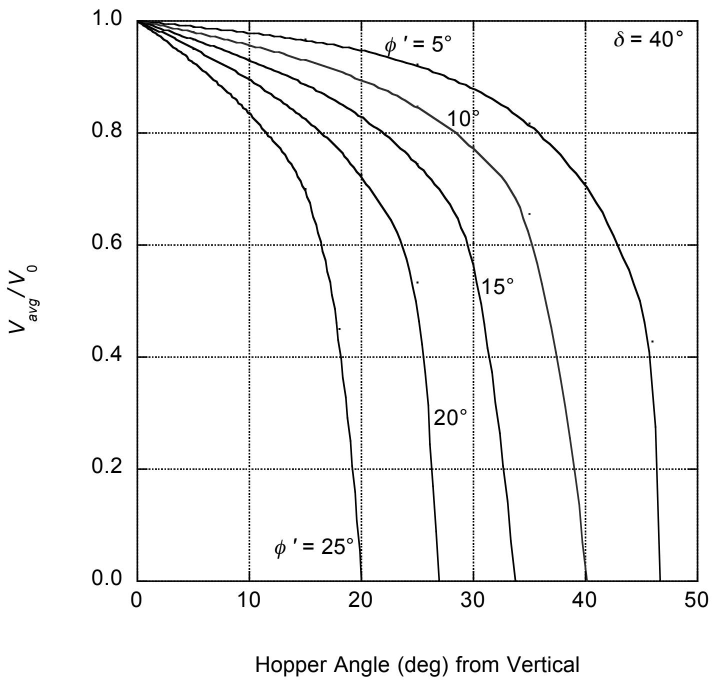
Hopper Angle (deg) from Vertical

V_{avg}/V_0



δ = 40°
ϕ ' = 5°
10°
15°
20°
ϕ ' = 25°
V_{avg}/V_0
1.0
0.8
0.6
0.4
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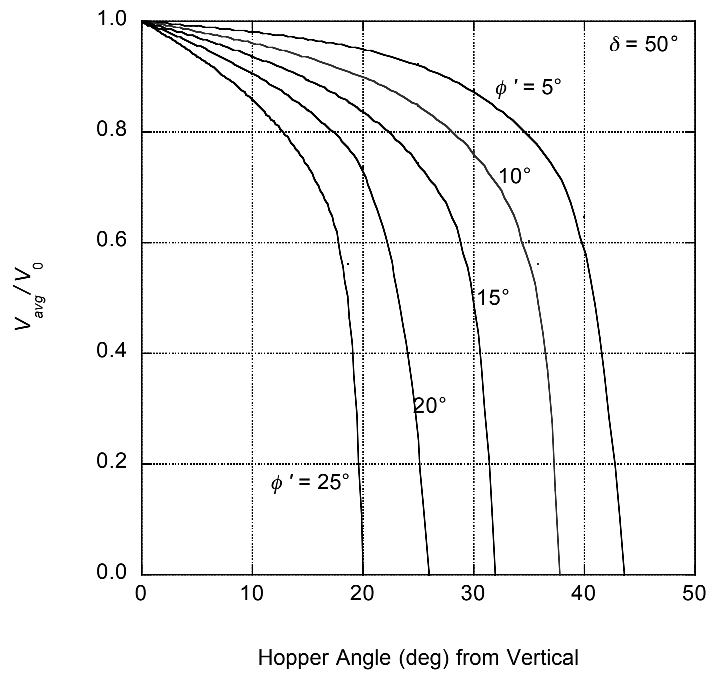
Hopper Angle (deg) from Vertical



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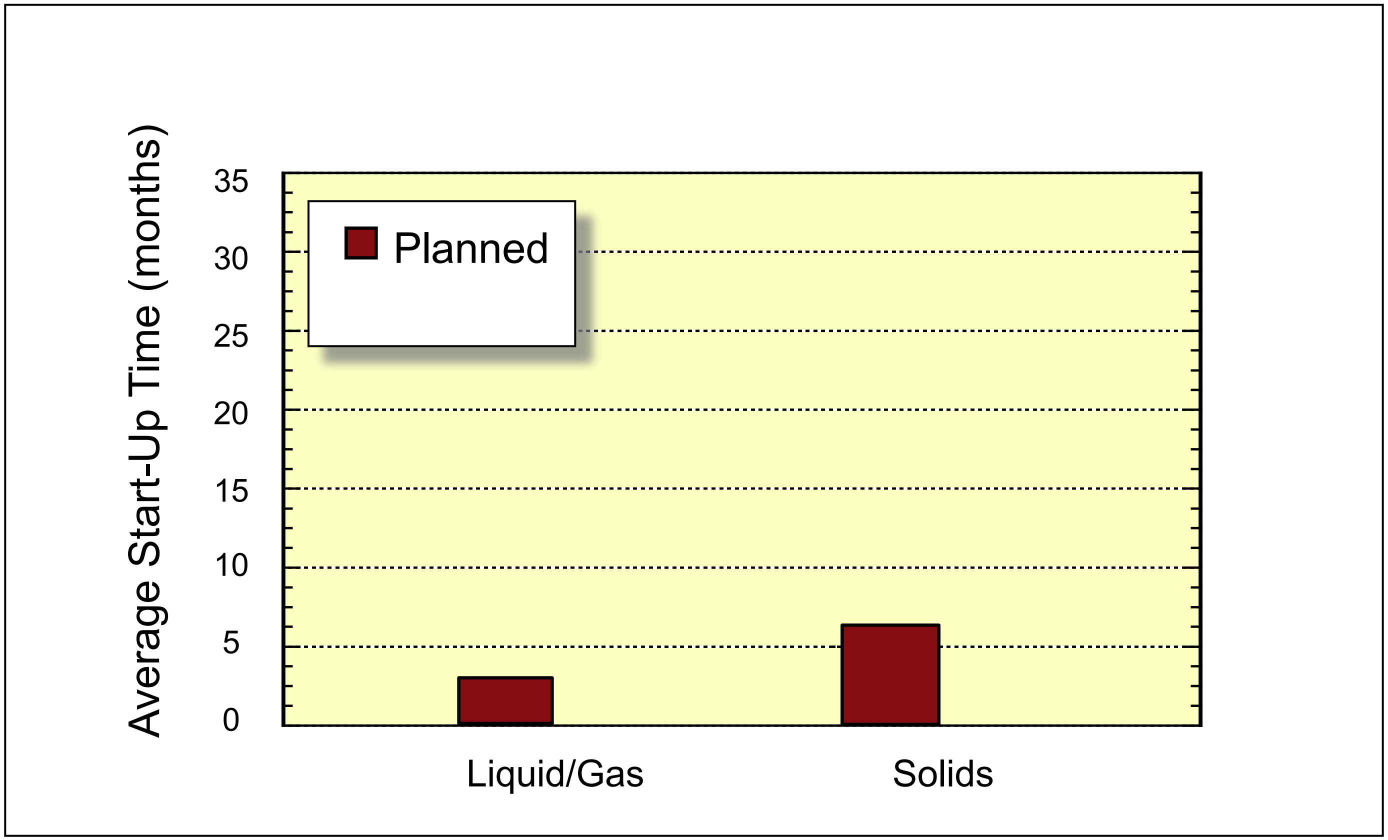
Hopper Angle (deg) from Vertical

Letdown chutes

Rand Corporation Study

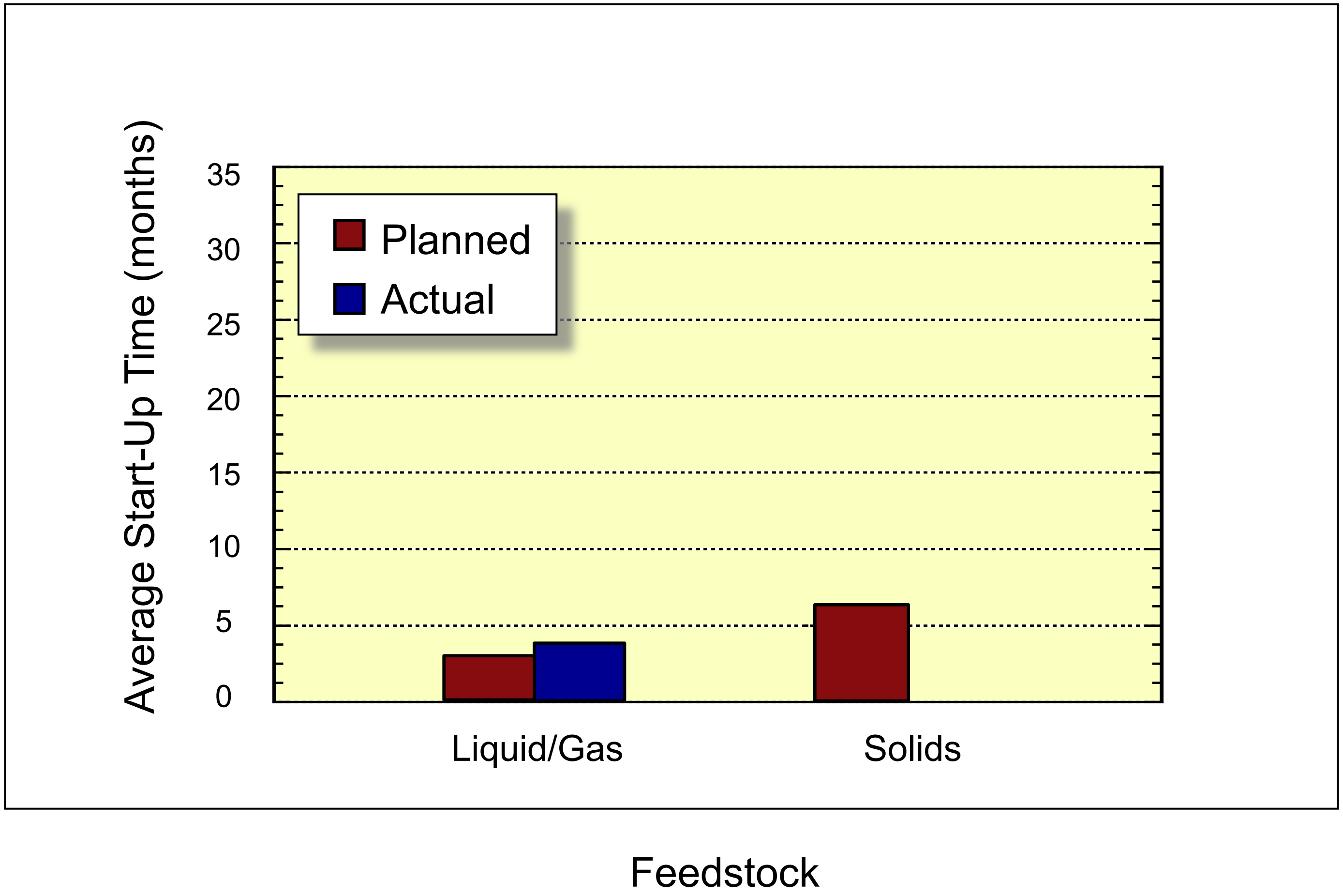
- Study by independent organization
- 40 solids processing plants in U.S. and Canada
- Six-year duration

Planned vs. actual start-up

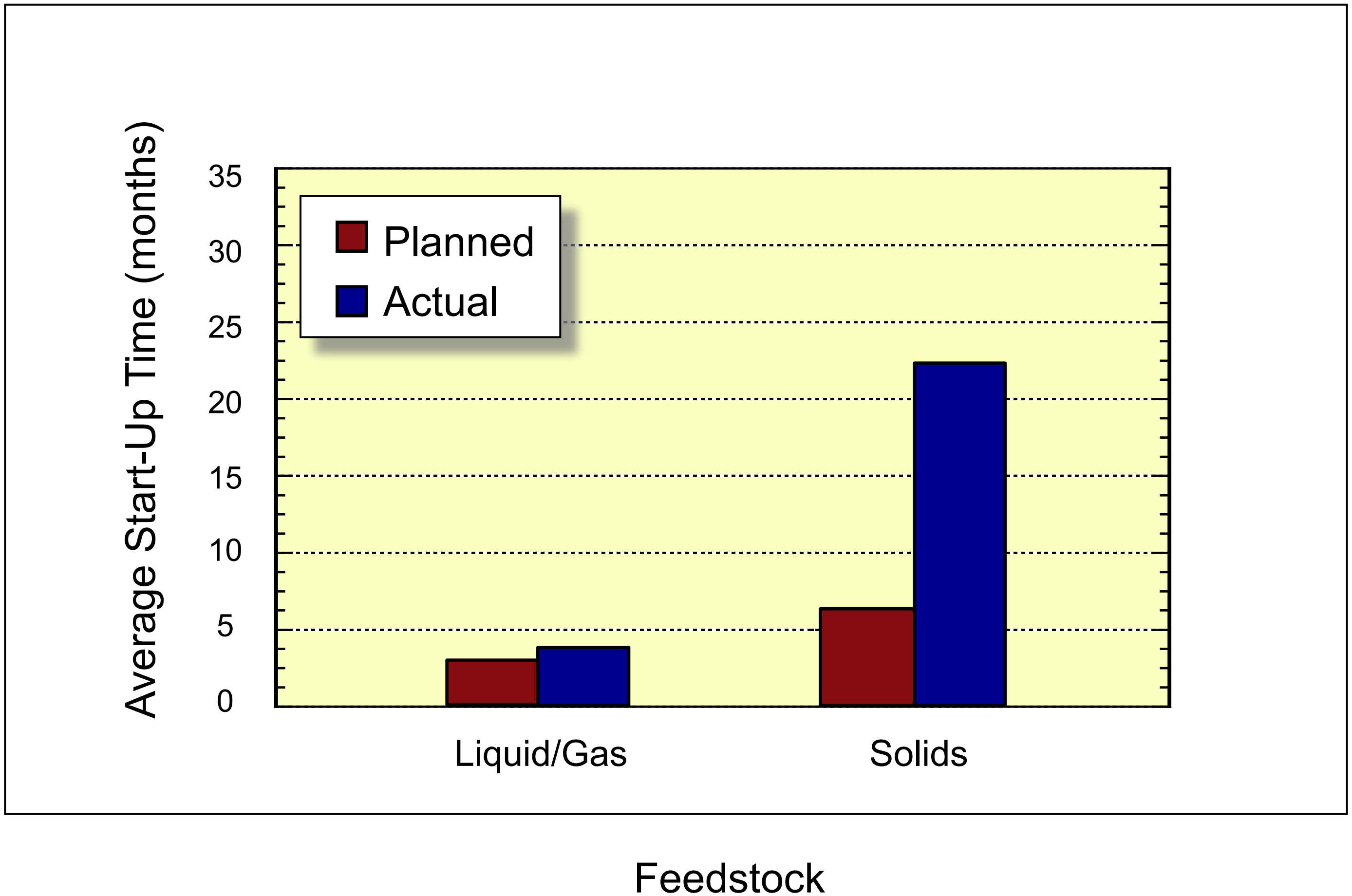


Feedstock

Planned vs. actual start-up



Planned vs. actual start-up



Rand conclusions

- 80% experienced solids handling problems
- Average startup time *ca.* 20 months (*vs.* 4 mo. for fluids)
- Typical performance 40 to 50% of design

Flow and Storage of Powders

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