PARTICLE SIZE ANALYSIS
CHARACTERIZATION OF SOLID PARTICLES

- SIZE
- SHAPE
- DENSITY

<table>
<thead>
<tr>
<th>Term</th>
<th>Shape</th>
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<tbody>
<tr>
<td>Cylindrical</td>
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<tr>
<td>Discoidal</td>
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<tr>
<td>Spherical</td>
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<td>Tabular</td>
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<td>Ellipsoidal</td>
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<td>Equant</td>
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<td>Irregular</td>
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SPHERICITY, $\varphi_s$

Equivalent diameter, Nominal diameter

- $\varphi_s = \frac{\text{Surface of a sphere of same volume as particle}}{\text{Surface area of the particle}}$
- Let
- $v_p = \text{volume of particle}, s_p = \text{surface area of the particle},$
- $D_p = \text{Equivalent diameter} = \frac{\pi}{6} D_p^3$
- Surface area of the sphere of diameter $D_p, S_p = \pi D_p^2 = \frac{6v_p}{D_p}$
- $\varphi_s = \frac{S_p}{s_p} = \frac{6v_p}{s_p D_p}$

It is often difficult to calculate volume of particle, to calculate equivalent diameter, $D_p$ is taken as nominal diameter based on screen analysis or microscopic analysis
Sphericity of particles having different shapes

<table>
<thead>
<tr>
<th>Particle</th>
<th>Sphericity</th>
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<tr>
<td>Sphere</td>
<td>1.0</td>
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<tr>
<td>cube</td>
<td>0.81</td>
</tr>
<tr>
<td>Cylinder, length = diameter</td>
<td>0.87</td>
</tr>
<tr>
<td>hemisphere</td>
<td>0.84</td>
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<tr>
<td>sand</td>
<td>0.9</td>
</tr>
<tr>
<td>Crushed particles</td>
<td>0.6 to 0.8</td>
</tr>
<tr>
<td>Flakes</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Sphericity, Table 7.1, McCabe Smith

- Sphericity of sphere, cube, short cylinders \((L=D_p) = 1\)
VOLUME SHAPE FACTOR

\[ v_p \propto D_p^3 \]

\[ v_p = a D_p^3 \]

Where, \( a = \text{volume shape factor} \)

For sphere, \( v_p = \frac{\pi}{6} D_p^3 \) or \( a = \frac{\pi}{6} \)
Commonly used measurements of particle size

- Feret's diameter
- Martin's diameter
- Projected area diameter
- Maximum horizontal intercept

[Diagram showing measurements of particle size with annotations for length, width, and various diameters]
Particle size/ units

• Equivalent diameter : Diameter of a sphere of equal volume

• Nominal size : Based on;
  ✓ Screen analysis and
  ✓ Microscopic analysis

• For Non equidimensional particles Diameter is taken as second longest major dimension.

• Units:
  ✓ Coarse particles – mm
  ✓ Fine particles in micrometer, nanometers
  ✓ Ultrafine - surface area per unit mass, sq m/gm
Particle size determination

- Screening > 50 $\mu m$
- Sedimentation and elutriation - > 1 $\mu m$
- Permeability method - > 1 $\mu m$
- Instrumental Particle size analyzers: Electronic particle counter – Coulter Counter, Laser diffraction analysers, Xray or photo sedimentometers, dynamic light scattering techniques
Screening

• Mesh Number = Number of opening per linear inch

• Clear opening = \( \frac{1}{\text{mesh number}} - \text{Wire thickness} \)
Standard Screen Sizes

BSS = British Standard Screen
IMM = Institute of Mining & Metallurgy
U.S. Tyler mesh
US. ASTM = American Institute for testing Materials

- Ratio of aperture of two consecutive sieves = \( 2, \sqrt{2}, \frac{4}{\sqrt{2}} \) [2, 1.41, 1.18]

<table>
<thead>
<tr>
<th>British fine mesh (B.S.S. 410) (^{(3)})</th>
<th>I.M.M. (^{(4)})</th>
<th>U.S. Tyler (^{(5)})</th>
<th>U.S. A.S.T.M. (^{(5)})</th>
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<tr>
<td>Sieve no.</td>
<td>Nominal aperture in.</td>
<td>μm</td>
<td>Sieve no.</td>
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<td>300</td>
<td>0.0021</td>
<td>53</td>
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<td>240</td>
<td>0.0026</td>
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<td>90</td>
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</table>
MIXED PARTICLE SIZE ANALYSIS:
Differential and Cumulative Screen Analysis

• Average particle size, \( \overline{D_{p_i}} \)

• Mass fraction, \( x_i \)

• Cumulative mass fraction, \( \phi \)
  - Cumulative mass fraction bigger than a particle size
  - Cumulative mass fraction smaller than a particle size

• Differential screen analysis curve
  - Plot Mass fraction vs Average particle size

• Cumulative screen analysis curve
  - Plot Cumulative mass fraction vs Average particle size
<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Mesh No.</th>
<th>Screen Opening $D_{pi}$ (cm)</th>
<th>Mass retained on a screen $m_i$ (gm)</th>
<th>Mass Fraction $x_i = m_i/M$</th>
<th>Average particle diameter $\overline{D_{pi}}$</th>
<th>Cumulative fraction $\Phi$, Larger than $\overline{D_{pi}}$</th>
<th>Cumulative Fraction Smaller than $\overline{D_{pi}}$</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.00</td>
<td>0.00</td>
<td>$\sum m_i = M$</td>
<td>$\sum x_i = 1$</td>
<td>1.00</td>
<td>0.00</td>
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<td>2</td>
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</tbody>
</table>
Differential and Cumulative Screen Analysis Curves
MIXED PARTICLE SIZES : Surface area, Specific Surface area, Volume surface mean diameter

- \( v_p = \text{volume of particle}, \)
- \( s_p = \text{surface area of particle}, \)
- \( D_p = \text{Diameter of particle} \)
- \( \rho_p = \text{density of material} \)
- Number of particles in a mass of “m”

- \( N = \frac{\text{Total volume}}{\text{volume of one particle}} = \frac{m/\rho_p}{v_p} \)
- Total surface area:
- \( A = Ns_p = \frac{m}{v_p \rho_p} \frac{6v_p}{D_p \varphi_s} = \frac{6m}{\varphi_s \rho_p D_p} \)  

\[ [\varphi_s = \frac{6v_p}{D_p s_p}] \]
Specific surface area, $A_w$ area/mass

- $A = NS_p = \frac{m}{v_p \rho_p} \frac{6v_p}{D_p \varphi_s} = \frac{6m}{\varphi_s \rho_p D_p}$
  \[\varphi_s = \frac{6v_p}{D_p s_p}\]

- $A_{total} = \frac{6m_1}{\varphi_s \rho_p D_{p1}} + \frac{6m_2}{\varphi_s \rho_p D_{p2}} + \cdots + \frac{6m_n}{\varphi_s \rho_p D_{pn}}$

- $A_w = \frac{A_{total}}{M} = \frac{6m_1/M}{\varphi_s \rho_p D_{p1}} + \frac{6m_2/M}{\varphi_s \rho_p D_{p2}} + \cdots + \frac{6m_n/M}{\varphi_s \rho_p D_{pn}}$

- $A_w = \frac{6x_1}{\varphi_s \rho_p D_{p1}} + \frac{6x_2}{\varphi_s \rho_p D_{p2}} + \cdots + \frac{6x_n}{\varphi_s \rho_p D_{pn}}$

- $A_w = \frac{6}{\varphi_s \rho_p} \sum_{i=1}^{n} \frac{x_i}{D_{pi}}$

**Volume surface mean diameter**
[also known as Sauter Diameter]

- $\overline{D_s} = \frac{6}{\varphi_s \rho_p A_w} = \frac{6}{\varphi_s \rho_p} \frac{6}{\varphi_s \rho_p} \sum_{i=1}^{n} \frac{x_i}{D_{pi}} = \frac{1}{\sum_{i=1}^{n} \frac{x_i}{D_{pi}}}$
AVERAGE PARTICLE SIZE

• Volume surface mean diameter:

\[
\overline{D_s} = \frac{6}{\varphi_s \rho_p A_w} = \frac{1}{\sum_{i=1}^{n} \frac{x_i}{D_{pi}}}
\]

• Arithmetic Mean Diameter:

\[
\overline{D_N} = \frac{\sum_{i=1}^{n} (N_i \overline{D_{pi}})}{\sum_{i=1}^{n} N_i} = \frac{\sum_{i=1}^{n} (N_i \overline{D_{pi}})}{N_T}
\]

• Mass Mean diameter

\[
\overline{D_w} = \sum_{i=1}^{n} x_i \overline{D_{pi}}
\]

• Number of particles:

\[
N_i = \frac{m_i / \rho_p}{a \overline{D_{pi}}^3} \quad \text{and} \quad N_T = \sum_{i=1}^{n} N_i = \frac{1}{a \rho_p} \sum_{i=1}^{n} \frac{m_i}{\overline{D_{pi}}^3}
\]
VOLUME MEAN DIAMETER

- Volume mean diameter: Diameter of a particle with average volume:

- **Average particle vol**

\[
\text{Average particle vol} = \frac{\text{Total volume}}{N_T} = aD_v^3
\]

\[
N_i = \frac{m_i/\rho_p}{aD_{pi}^3} \quad \text{and} \quad N_T = \sum_{i=1}^{n} N_i = \frac{1}{a\rho_p} \sum_{i=1}^{n} \frac{m_i}{D_{pi}^3}
\]

\[
aD_v^3 = \frac{\text{Total volume}}{\text{Total number}} = \frac{M/\rho_p}{\frac{1}{a\rho_p} \sum_{i=1}^{n} \frac{m_i}{D_{pi}^3}} = \frac{1/\rho_p}{\frac{1}{a\rho_p} \sum_{i=1}^{n} \frac{x_i}{D_{pi}^3}}
\]

\[
D_v = \left[ \frac{1}{\sum_{i=1}^{n} \frac{x_i}{D_{pi}^3}} \right]^{1/3}
\]
Number of particles
Shape Factor $a$

- $v_p = a D_p^3$
- $N_T = \sum_{i=1}^{n} \frac{m_i}{a \rho_p D_{pi}^3}$
- Number of particles per unit mass

$$N_w = \frac{N_T}{M} = \frac{1}{M} \sum_{i=1}^{n} \frac{m_i}{a \rho_p D_{pi}^3} = \frac{1}{a \rho_p} \sum_{i=1}^{n} \frac{x_i}{D_{pi}^3}$$

$$N_w = \frac{1}{a \rho_p D_v^3}$$
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<th>Φ, Cumulative fraction Larger than $\overline{D_{pi}}$</th>
<th>Cumulative Fraction Smaller than, $\overline{D_{pi}}$</th>
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PROPERTIES OF MASSES OF PARTICLES

- Bulk density or **apparent density**, \( \rho_b \), is defined as the weigh per unit volume of material including voids inherent in the material as tested. It is a measure of the fluffiness of the material.

\[
\rho_b = \frac{m}{V_T} = \frac{m}{V_p + V_v} \quad \text{and} \quad \rho_t = \frac{m}{V_p}
\]

- **Porosity**. It is the ratio of the void volume and bulk volume.

\[
\varepsilon = \frac{V_v}{V_T}
\]

\[
\varepsilon = \frac{V_T - V_p}{V_T} = 1 - \frac{V_p}{m} \frac{m}{V_T} = 1 - \frac{\rho_b}{\rho_t}
\]

**Pourability** is defined as a measure of the time required for a standard quality of material to flow through a funnel of specified dimension. It characterizes the handling properties of fine particles.
• **Angle of repose**, $\alpha_r$, is defined as the angle formed between sloping side of a cone shaped pile of material and the horizontal if the mass is truly homogeneous, $\alpha_r$ would be equal to $\alpha_m$, the **angle of internal friction**. In practice, the angle of repose is smaller than the angle of internal friction, of those inside the mass and are often drier and sticker.

• **Coefficient of internal friction** is the measure of resistance present when one layer of solids over another layer of same particles. It is defined as:

$$\text{Coeff. Of internal friction} = \tan \alpha_m$$

• For free flowing material $\alpha_m$ is between 15$^0$ to 30$^0$
• In solid masses the pressure is not the same in all directions. If pressure is applied in one direction it creates some pressure in other directions, but it is always smaller than the applied pressure. It is minimum in the direction at right angles to the applied pressure. The ratio of the normal pressure to the applied pressure in a mass of solid, is a material constant, generally denoted by $K'$

$$K' = \frac{\text{normal pressure}}{\text{applied pressure}} = \frac{1 - \sin \alpha_m}{1 + \sin \alpha_m}$$

$K'$ approaches zero for cohesive solids and free flowing material, its value is between 0.36 to 0.6

• **Coefficient of external friction** is the measure of the resistance at an interface between particles and the wall of different material of construction.

  Coefficient of External friction = $\tan \beta_s$

  – Where $\beta_s$ is the **angle of external friction of solid and material**.
SOLIDS CONVEYING
• Screw conveyors
• Belt conveyors
• Bucket elevators
  • Spaced-Bucket Centrifugal-Discharge Elevators
  • Spaced-Bucket Positive-Discharge Elevators
  • Continuous-Bucket Elevators
  • Super-capacity Continuous-Bucket Elevators
  • V-Bucket Elevator-Conveyors
  • Skip Hoists
• Vibrating or oscillating conveyors
• Continuous flow conveyors
  • Apron Conveyors
• Pneumatic conveyors
• Hydraulic Conveyors
SELECTION OF CONVEYORS

• Capacity requirement: Belt for larger capacity and screw cannot handle large capacity
• Length of travel: belt conveyors; miles, Pneumatic convey 300m, vibrating convey or even less
• Lift or lift and horizontal shift: single or mixed
• Material characteristics – chemical and physical, size, friability, flowability, abrasiveness, moisture or oxidation effect
• Processing requirement; dewatering, heating cooling
Screw conveyor

• Helicoid (helix rolled from flat steel bar) or sectional flight mounted on a pipe or shaft rotating in a U shaped trough
  – Horizontal of slight incline upto 20 of finely divided solids, sticky material, semisolid materials, boiler ash. Etc.
  – Continuous spiral for dry granular free flowing material
  – Discontinuous spirals for wet, muddy and thick materials.
  – Short distance upto about 40m
  – Types of flow:
    • Archemedian flow or
    • Plug flow
  – Unit operation – mixing, heating & cooling with hollow shaft
BELT CONVEYORS

- Continuous **belt** passing around two large pulleys at two ends, **one drive pulley** other **tail** pulley.
  - Universal application
  - Very long distances several km
  - Speed up to 300m/min 5000tons/hr
  - Slope upto 30°
  - Material – neoprene, Teflon, natural rubber, vinyls, cotton, asbestos fibre, etc.
  - Various designs of idlers
  - May require cleaning by revolving brush, metal or rubber scraper, taut wire
Idlers and Plate support arrangements:
(a) Flat belt on idler  (b) flat belt on continuous plate  
(c) troughed belt on 20 deg idler  (d) troughed belt on 45 deg idler 
(e) Same as d but with rolls of equal lengths  
(f) troughed plate on continuous plate
Plan View

Unloading station

Belt conveyor 1

Load

Belt conveyor 2

Belt conveyor 3

Tension pulleys

Max. Inclination 18°-20°

Driving pulleys

Load

Belt conveyor 4

Max. belt speed 10-15 mph

Reloading station

Change of direction requires additional reloading stations
Feeders to Belt conveyors - Vibratory and Star Feeder
BELT CONVEYOR DISCHARGE ARRANGEMENTS:
(a) over end pulley (b) over end pulley by reversible shuttle conveyor (c) through travelling tripper (d) through fixed trippers
FOOD PROCESSING BELT FABRICATION : CUSTOM BAKERY BELTING & BELT CONVEYORS
With a perfect belt for every application, discover what Great Lakes Belting can do for your bakery!

LIGHTWEIGHT BELTING

Automation of the manufacturing processes has led to small pulleys and process conditions that lend themselves to the flexibility and versatility of lightweight belting. The thermoplastic, heat welded splices provide superior reliability, flexibility and sanitary properties.

Other key belt properties for this market segment are low stretch/shrink, cut and abrasion resistance, oil/fat resistance, good product release/grip properties, easily cleanable/hygienic constructions, lateral flexibility/stability and conformance with FDA/3A/USDA standards.

Click Here to Learn More about the Basics of Lightweight Belting

MODULAR BELTING

Many food manufacturers embrace the use of plastic modular belts for their sanitary benefits (e.g., non-porous thermoplastics, contoured easy to clean surfaces, partially exposed hinge rods, etc.), low maintenance and ease of repair. Industrial manufacturers also see the value that plastic modular belts add to the bottom line.

These inherent benefits include higher strength, lower weight, lower product-to-belt friction levels, as well as high resistance to abrasives and corrosives.

Click Here to Learn More about Plastic Modular Belting

RESOURCES

Basic Elements of Equipment Cleaning and Sanitizing in Food Processing and Handling Operations: A useful guide to cleaning and sanitizing procedures.

Volta Belting: Flat Belts for the Food Industry: These smooth base belts have cut and abrasion resistant surfaces, eliminating any crevices where bacteria may harbor. Their non-absorbent nature also makes cleaning simple and environmentally friendly, with a drastic reduction in water usage and cleaning time.

Volta Belting - Conveying Solutions: Simply Safe and Hygienic: Governments and consumers expect unblemished safety processes from farm to fork.

CONTACT US

Bakery, confectionery, snack foods, meat and poultry, dairy, fruits and vegetables, and seafood - Great Lakes Belting can help you design a custom conveyor system that will save you time and money.

Name
Telephone Number
E-Mail Address
Message

Contact Us Today!
• Bucket elevator consists of a number of buckets attached to a continuous double strand chain which passes over two pulleys
• Solids fed directly to bucket and also scooped up from the bottom.
• Emptied from the top by turning of the bucket.
• Line speed 1-2m/s
BUCKET ELEVATORS
(a) Spaced-Bucket Centrifugal-Discharge Elevators
(b) Spaced-Bucket Positive-Discharge Elevators
(c) Continuous-Bucket Elevators
(d) Supercapacity Continuous-Bucket Elevators
• Spaced bucket; Centrifugal discharge – free flowing, fine or small lump material like grain, coal, sand or dry chemicals

• Spaced bucket positive discharge - buckets are for sticky materials which tend to lump, inverted for positive discharge, knockers can also be used

• Continuous – finely pulverized or fluffy materials, the back of the preceding bucket serves as a discharge chute for the bucket. Gentle movement Preventing degradation

• Super capacity continuous bucket: Very high tonnage, big particles, Generally inclined
SKIPHOIST: Batch bucket elevator

- Uncounter weighted: only winding machine power requirement is high
- Counter weight: reduces power consumption
- Balanced use two buckets and hence works twice as fast
CONTINUOUS FLOW CONVEYOR

• **Principle:** When a surface is pulled transversely through a mass of granular powder or small lump material it will pull a cross section of material along with it which is greater than the area of the surface itself.

• **Generally a chain with blades is operated in a powder to cause the powder to flow in the same direction.**
FLIGHTS FOR CONTINUOUS FLOW CONVEYORS

- L - highly adhesive powder
- B - moderate adhesive powder
- KL highly adhesive powder containing granular material
- KB1 – Moderately adhesive powder containing some granular material
CONTINUOUS FLOW CONVEYORS:
(a) Horizontal (b) Z type (c) Loop feed elevator for dewatering
APRON COVEYORS

• A type of continuous flow conveyor where series of overlapping pans are mounted between two strands of roller chains
PRESSURE, VACUUM, PRESSURE-VACUUM PNEUMATIC TRANSPORTATION
FLUIDIZATION
• Gas flow between 15 to 30m/s in pipes ranging from 50 to 400 mm diameter.
• Particle size range from fine powder to 6.5mm, Bulk density from 16 to 3200kg/m3
• Pressure System
  – 1-5 atm gauge
  – Free flowing material for any particle size – 5-6 mm
  – Flow rates more than 9000kg/hr
  – Pressure loss in the system 0.5 atm
  – Rotary Air lock valve required
• Vacuum System
  – Lower flow rates 7000kg/hr and 300m
  – Fine powders
  – No Rotary air lock valve required.
• Pressure Vacuum system
HYDRAULIC CONVEYING / SLURRY TRANSPORTATION

• Generally particles less than 50 micron
• Main application in Mining industry
• Fluid used is water
• Velocity more than settling velocity of particles,
• Critical velocity, below which particles will settle out range between 1-5m/s,
• Pressure drop calculated using same equation with allowance for increase in density and viscosity.
STORAGE OF SOLIDS

• BULK STORAGE
Coarse large quantity solids like gravel and coal outside in large piles.
Protection from
• BIN STORAGE -
✓ Silos – tall and small diameter
✓ Bins – fairly wide and Not tall
✓ Hoppers – Small vessel with sloping bottom, generally temporary storage before feeding solids to a process.
Types of Bins

Wedge/Plane Flow

Chisel

L > 3B

Conical

Pyramidal

Watch for inflowing valleys in these bins!
Types of Bins

Conical

Pyramidal

Watch for inflowing valleys in these bins!
PRESSURE IN BINS AND SILOS

Janssen Equation: Pressure at any height \( h \), from the base

\[
P = \frac{\rho_b g D}{4 f_w} k \left[ 1 - \exp \left( \frac{4 f_w K (h - H)}{D} \right) \right]
\]

If value of \( H \) is sufficiently large which is the case at the base of the base of the cylindrical portion of the hopper:

\[
P_0 = \frac{\rho_b g D}{4 f_w} K
\]

\( \rho_b \)=Bulk density
\( H \)= level of solid bed,
\( g \)= acceleration due to gravity
\( D \)= Diameter of hopper
\( f_w \)= Coefficient of friction between solids and wall

\[
K' = \frac{\text{normal pressure}}{\text{applied pressure}} = \frac{1 - \sin \alpha_m}{1 + \sin \alpha_m}
\]

\( \alpha_m \)= effective angle of internal friction.
Pressure at the base of a vertical bin filled with particulate solids

\[ P = \frac{\rho_b g D}{4 f_w} \left[ k \left( 1 - \exp \frac{4 f_w K (h - H)}{D} \right) \right] \]
FLOW OUT OF BINS

• Mass Flow - all the material in the hopper is in motion, but not necessarily at the same velocity [Cone angle from vertical axis=0-40°]

• Funnel Flow - centrally moving core, dead or non-moving annular region

• Expanded Flow - mass flow cone with funnel flow above it
Figure 10-1. In mass flow (A) all material moves in the bin including near the walls. In funnel flow (B) the material moves in a central core with stagnant material near the walls. Expanded flow (C) is a combination of mass flow in the hopper exit and funnel flow in the bin above the hopper (normally used in retrofit situations).
COMMON DESIGNS FOR MASS FLOW HOPPERS

(A) CONICAL HOPPER  (B) SQUARE OPENING  (C) CHISEL

(E) WEDGE  (F) PYRAMID
Design for Funnel Flow
HOPPER DESIGN PROBLEMS

(A) RATHOLING OR PIPING
(B) BRIDGING/DOMING
(C) FLUSHING
HOPPER DESIGN PROBLEMS

• **RATHOLING/PIPING.** Ratholing or piping occurs when the core of the hopper discharges (as in funnel flow) but the stagnant sides are stable enough to remain in place without flowing, leaving a hole down through the center of the solids stored in the bin.

• **FLOW IS TOO SLOW.** The material does not exit from the hopper fast enough to feed follow on processes.

• **NO FLOW DUE TO ARCHING OR DOMING.** The material is cohesive enough that the particles form arch bridges or domes that hold overburden material in place and stop the flow completely.

• **FLUSHING.** Flushing occurs when the material is not cohesive enough to form a stable dome, but strong enough that the material discharge rate slows down while air tries to penetrate into the packed material to loosen up some of the material. The resulting effect is a sluggish flow of solids as the air penetrates in a short distance freeing a layer of material and the process starts over with the air penetrating into the freshly exposed surface of material.
HOPPER DESIGN PROBLEMS

- **INCOMPLETE EMPTYING.** Dead spaces in the bin can prevent a bin from complete discharge of the material.

- **SEGREGATION.** Different size and density particles tend to segregate due to vibrations and a percolation action of the smaller particles moving through the void space between the larger particles.

- **TIME CONSOLIDATION.** For many materials, if allowed to sit in a hopper over a long period of time the particles tend to rearrange themselves so that they become more tightly packed together. The consolidated materials are more difficult to flow and tend to bridge or rat hole.

- **CAKING.** Caking refers to the physiochemical bonding between particles what occurs due to changes in humidity. Moisture in the air can react with or dissolve some solid materials such as cement and salt. When the air humidity changes the dissolved solids re-solidify and can cause particles to grow together.