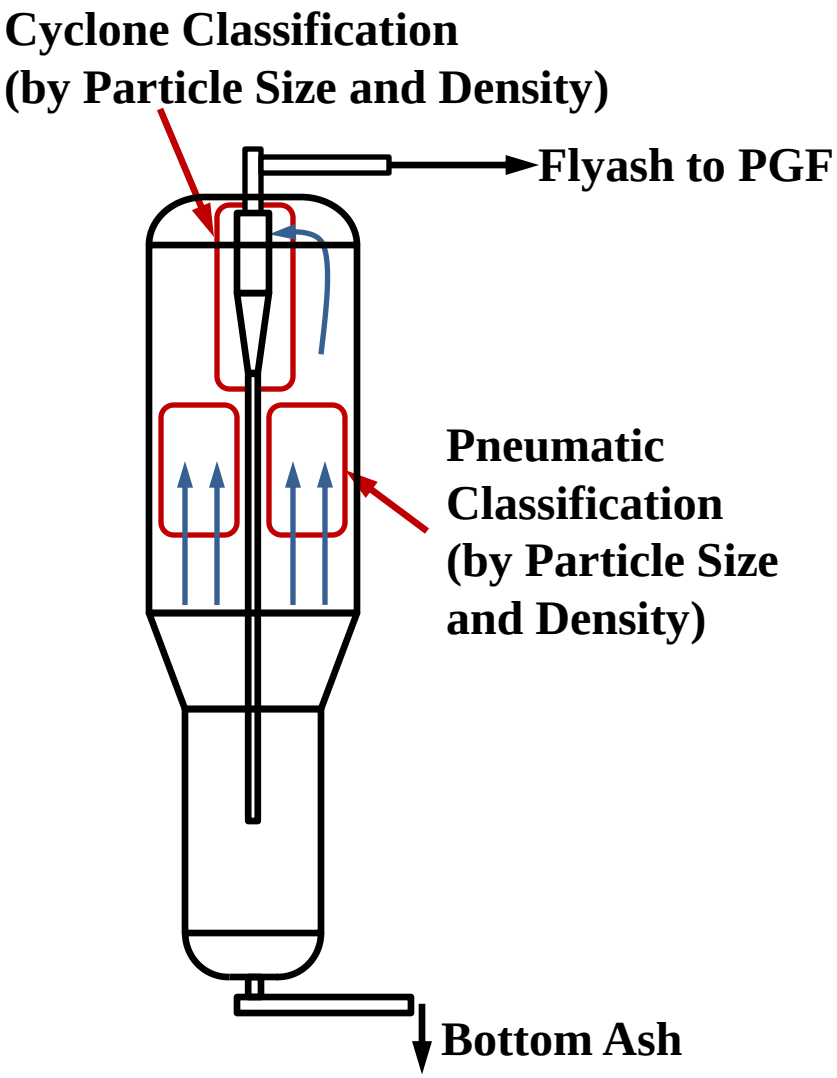
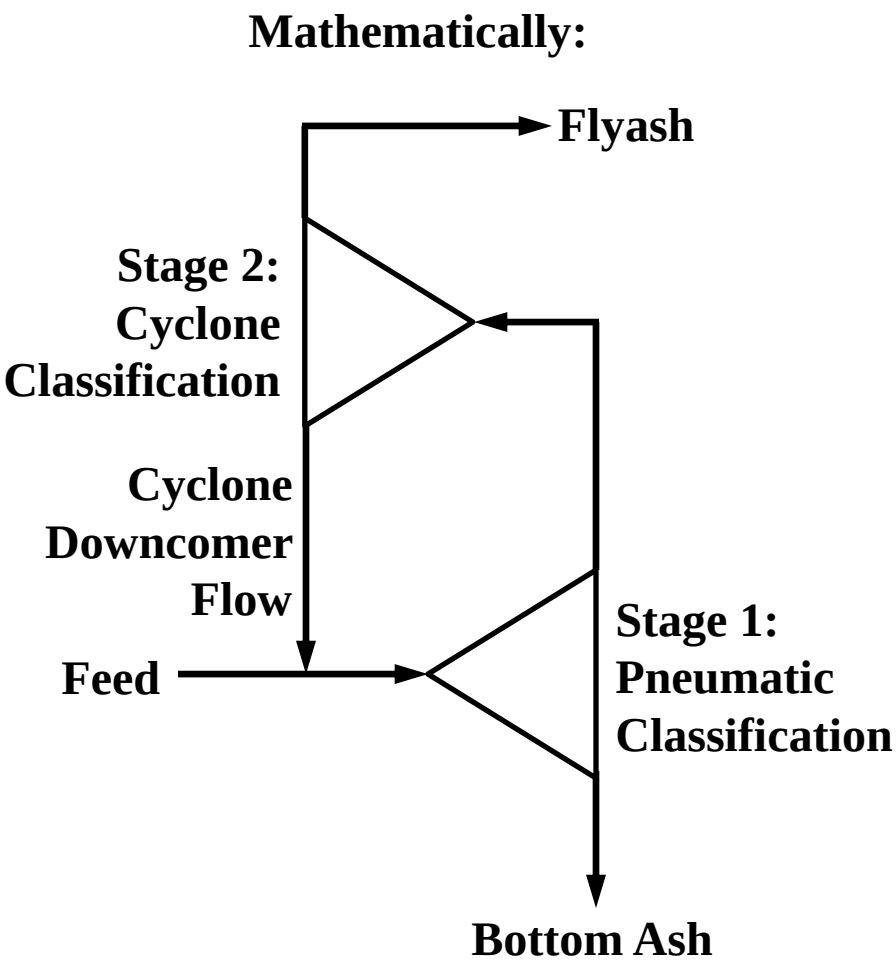
Fluidized Bed Solids Management:
How Knowledge of Fundamentals can Help Optimize Plant Operations

Example Coal-Fired Fluidized Bed Operations Issues

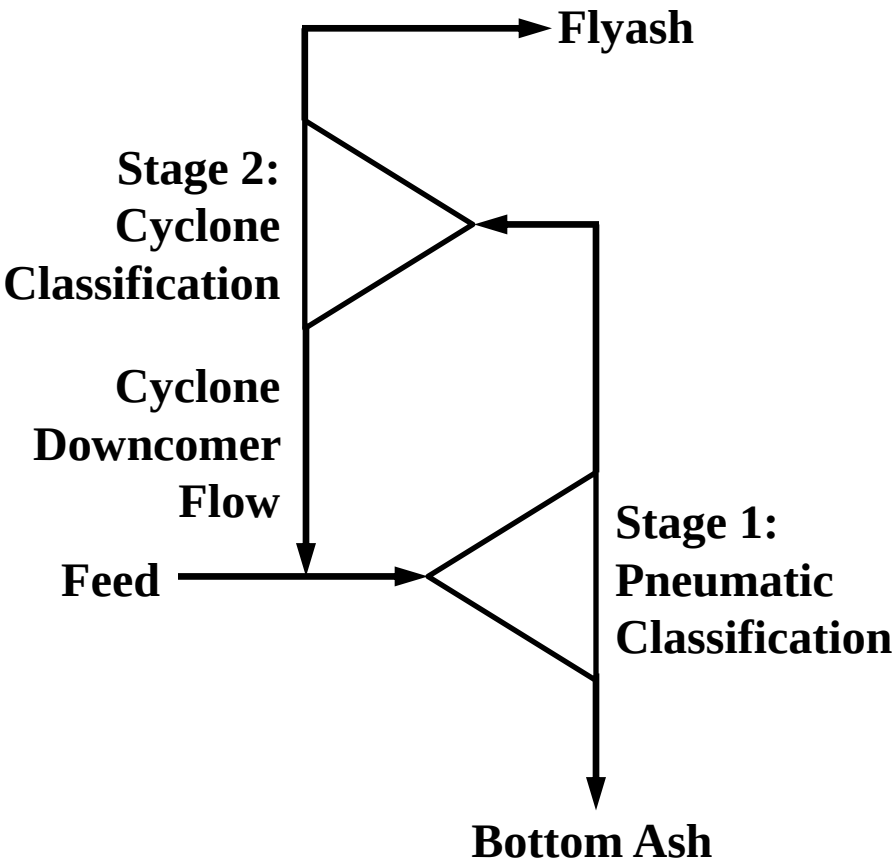
- **Higher than Design Bottom Ash Flow**
  - Plant Design Missed the Ash Split
  - Bottom Ash Equipment Runs Hot (may Aggravate Erosion)
- **Excessive Limestone Consumption Required to Maintain SO_2 Compliance**
- **Can these be Predicted Using Science?**
  - What are the Relevant Concepts to Consider?
  - How can these Concepts be Used to Construct Useful Mathematical Models?

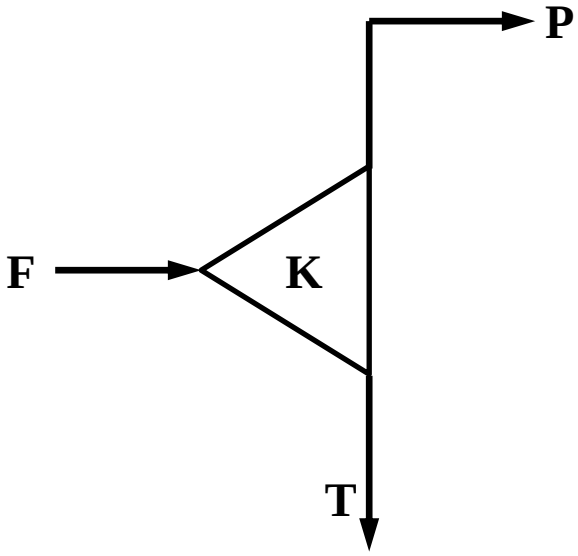
Concepts Relevant to Fluid Bed Solids Management: Classification



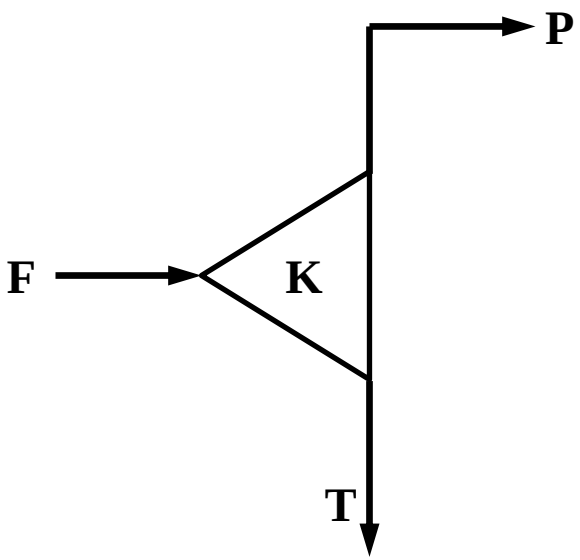


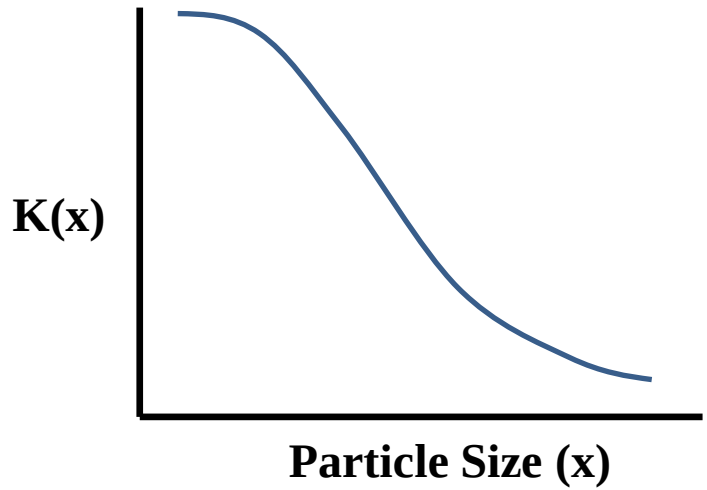
A Multistage Separation can be Described as a Single Separation





Mathematical Description of Classification





$$P = \sum_{x=1}^{x=n} K(x)F(x)$$

F(x): The Mass Fraction of Particles of Size x in Feed

K(x): The Mass Fraction of Particles of Size x in Feed that Report to the P Stream

Useful Relationships Relevant to Fluid Bed Solids Classification

U_{mf} = Minimum Fluidization Velocity

$$\frac{d_p u_{mf} \rho_g}{\mu_g} = \left[33.7^2 + 0.0408 \frac{d_p^{\,3} \rho_g (\rho_s - \rho_g) g}{\mu_g} \right]^2 - 33.7$$

U_t = Transport Velocity

$$u_t = \frac{g(\rho_s - \rho_g) d_p^{\,2}}{18 \mu_g}$$

$N_{RE} < 0.4$

$$u_t = \left[\frac{4}{225} \frac{(\rho_s - \rho_g)^2 g^2}{\rho_g \mu_g} \right]^{\frac{1}{3}} d_p$$

$0.4 < N_{RE} < 500$

$$u_t = \left[\frac{3.1 g (\rho_s - \rho_g) d_p}{\rho_g} \right]^{\frac{1}{2}}$$

$500 < N_{RE}$

Common to all of these:

d_p: <u>Particle Diameter</u>
ρ_s: <u>Particle Density</u>
ρ_g: Gas Density*
μ_g: Gas Viscosity*
g : Gravitational Acceleration Constant

***Function of Gas Temperature, Pressure, and Composition**

Concepts Relevant to Fluid Bed Solids Management: Particle Properties

- Particle Size
  - A Function of Preparation Method (Crushing and Grinding)
  - Topsize $u_{mf} < u_0$ in System
  - Fines with $u_t < u_0$ may have Short Residence Times
  - Attrition will Turn Big Pieces into Small Ones
  - **<u>Reacting Particles can Change in Size</u>**
  - **Particle Size is a Distributive Property (i.e. all Particles do not have the Same Property as the Composite Analysis)**

Concepts Relevant to Fluid Bed Solids Management: Particle Properties

- Particle Density
  - Depends on Mineral Composition
    - ✓Coal: 1.3 to 2+
    - ✓Coal Char: See Above
    - ✓Shale: ~2.8
    - ✓Ash: ~2.5
  - **<u>Reacting Particles can Change in Density</u>**
    - ✓**<u>Particles that Lose Mass at Constant Size can Weaken</u>**
  - **Particle Size is a Distributive Property (i.e. all Particles do not have the Same Property as the Composite Analysis)**

Concepts Relevant to Fluid Bed Solids Management: Particle Properties

- Examples of Reacting Particles in Fluid Bed Systems- Fuel
  - **Devolatilization: Particle can Swell and Lose Mass**
  - **Combustion: Particle Loses Mass**
    - ✓ $\boldsymbol{C + O_2 \rightarrow CO_2}$
  - **Gasification: Particle Loses Mass**
    - ✓ $\boldsymbol{C + H_2O \rightarrow CO + H_2}$
    - ✓ $\boldsymbol{C + CO_2 \rightarrow 2CO}$

Higher Carbon Content Particles can Lose More Mass and Become Weaker

Concepts Relevant to Fluid Bed Solids Management: Particle Properties

- Examples of Reacting Particles in Fluid Bed Systems- Limestone
  - **Calcination: Particle Loses Mass**
    - ✓ $\boldsymbol{CaCO_3 \rightarrow CaO + CO_2}$
  - **Sulfation: Particle Gains Mass**
    - ✓ $\boldsymbol{CaO + \frac{1}{2}O_2 + SO_2 \rightarrow CaSO_4}$

Calcination Weakens Particles

Bed Solids Reaction with Acid Gas Species: Analogous to Carbonation Reaction in the DMR

Concepts Relevant to Fluid Bed Solids Management: Attrition

- Attrition Turns Bigger Pieces into Smaller Pieces
- Function of:
  - Particle Strength
  - Kinetic Energy Associated with Particle Collisions
- **<u>Particle Strength</u>**
  - May not Change in Non-Reacting Particles
  - **<u>May Change in Reacting Particles</u>**

Concepts Relevant to Fluid Bed Solids Management: Attrition

Attrition Conventions (Non-Reacting Particles)

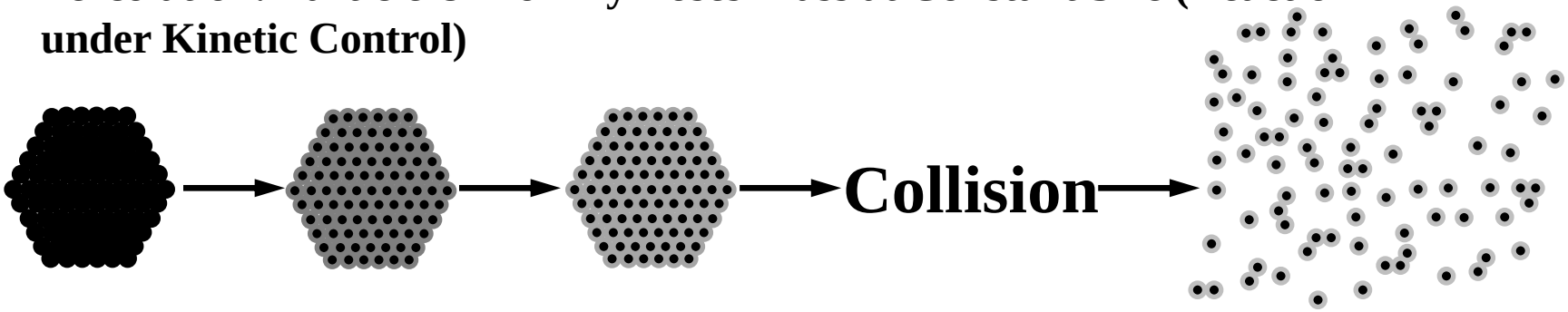
Abrasion: Very Fine Particles are Removed from "Mother Particle"

Fragmentation: Breakage Products Closer in Size to Original Particle

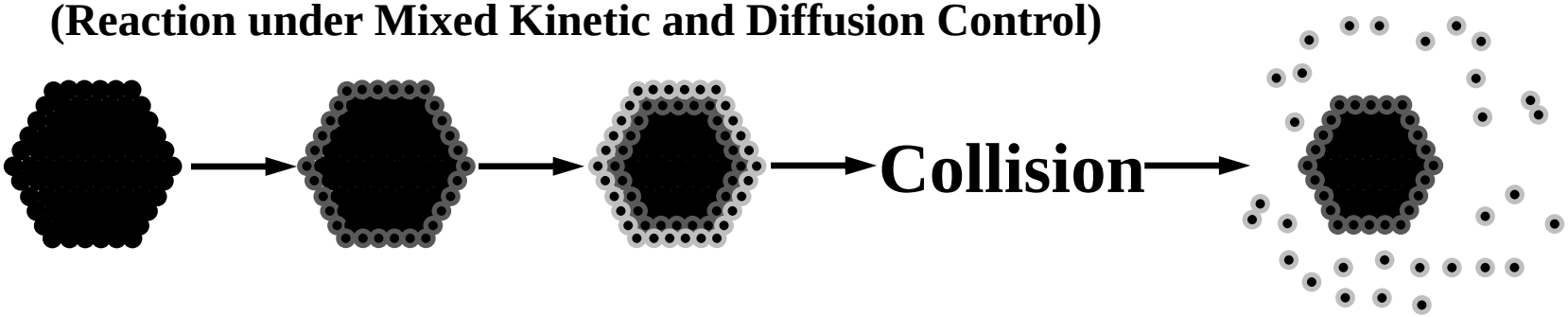
Concepts Relevant to Fluid Bed Solids Management: Attrition

Attrition Conventions (Reacting Particles)

Percolation: Particle Uniformly Loses Mass at Constant Size (Reaction under Kinetic Control)



Peripheral Percolation: Particle Loses Mass with a Shrinking Core (Reaction under Mixed Kinetic and Diffusion Control)



Concepts Relevant to Fluid Bed Solids Management: Recap So Far

- **A Fluid Bed System can Classify Particles into Output Streams**
- **Particle Properties Relevant to Classification:**
  - **Size**
  - **Density**
- **Particle Size Changes Due to Attrition**
- **Reacting Particles Can Behave Differently from Non-Reacting Particles**

Concepts Relevant to Fluid Bed Solids Management: Particle Classes and Distributive Properties

- **All Bed Particle do Not Have Identical Properties**
- **Classes of Bed Particles in the DMR**
  - **Derived from Startup Bed (Bauxite or Alumina)**
  - **Derived from DMR Fuel (Char)**
  - **Derived from DMR Fuel (Ash)**
  - **Varying Levels of Alkali Deposition and Carbonation**
- **Classes of Bed Particles in the CRR**
  - **Derived from Startup Bed (Bauxite or Alumina)**
  - **Makeup Bed (Bauxite or Alumina)**
  - **Derived from CRR Fuel (Char)**
  - **Derived from CRR Fuel (Ash)**

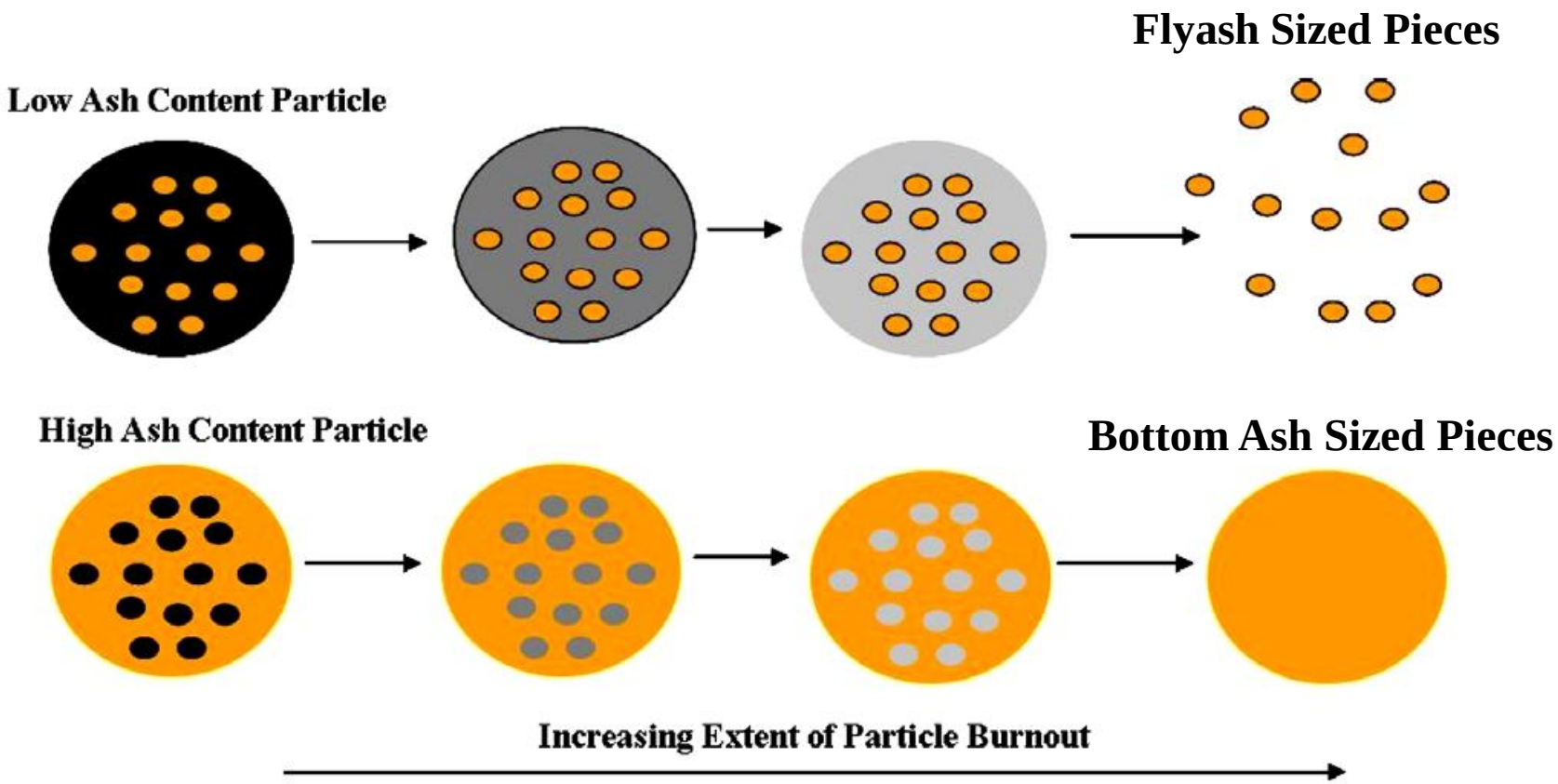
All Particles are Not the Same as the Composite Analysis- Even within a Particle Class

This is What 8% Ash Coal Looks Like to a Fluidized Bed

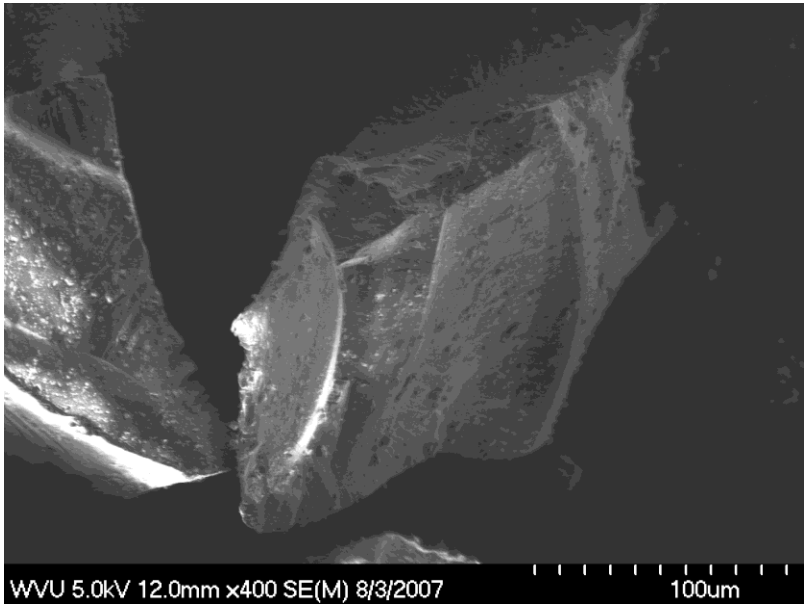
		Density Fractions							
Microns		1.30 Float		1.30 x 1.60		1.60 x 2.60		2.60 Sink	
Passing	Retained	Wt%	% Ash	Wt%	% Ash	Wt%	% Ash	Wt%	% Ash
	600	2.54%	3.52%	1.86%	13.80%	0.56%	52.00%	0.10%	66.66%
600	425	5.19%	3.18%	4.53%	12.75%	0.40%	50.08%	0.07%	65.39%
425	212	14.90%	2.80%	10.31%	11.99%	0.81%	49.56%	0.20%	64.51%
212	150	6.39%	2.34%	4.35%	12.35%	0.37%	50.19%	0.09%	64.38%
150	106	5.54%	2.43%	3.51%	12.03%	0.32%	53.04%	0.10%	63.06%
106	75	5.16%	2.11%	3.32%	11.59%	0.30%	55.02%	0.15%	65.00%
75	0	8.12%	2.54%	19.69%	9.08%	0.71%	58.11%	0.42%	67.45%

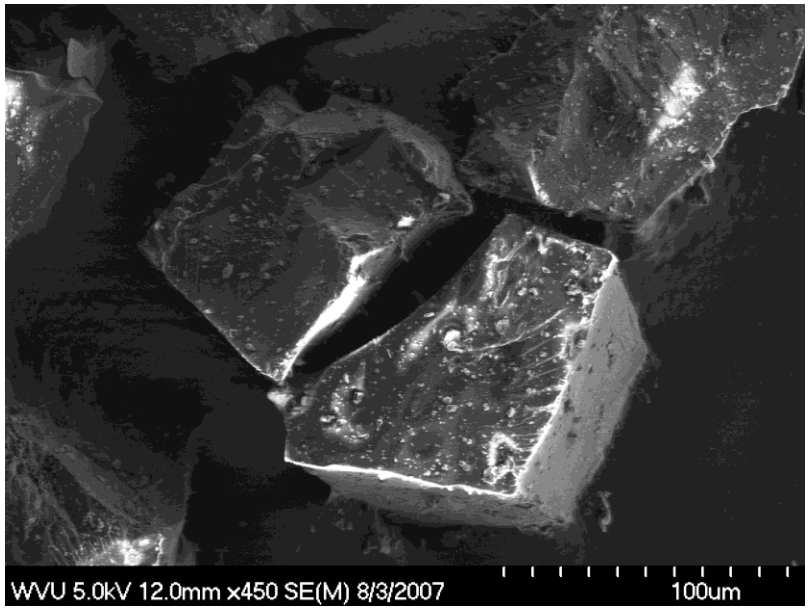
Size Fractions

How the Density Distribution of Fuel Affects Attrition Behavior



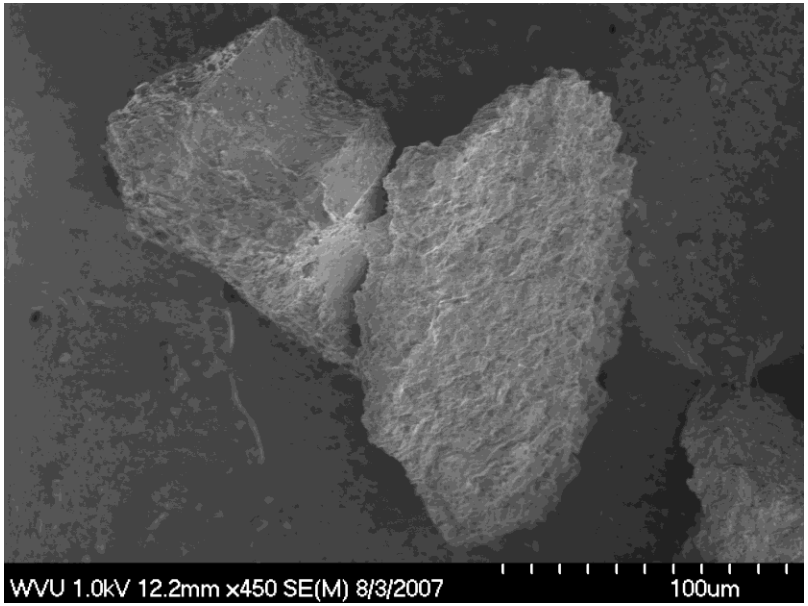
Ground Pittsburgh Bed Coal
1.3 Float Fraction

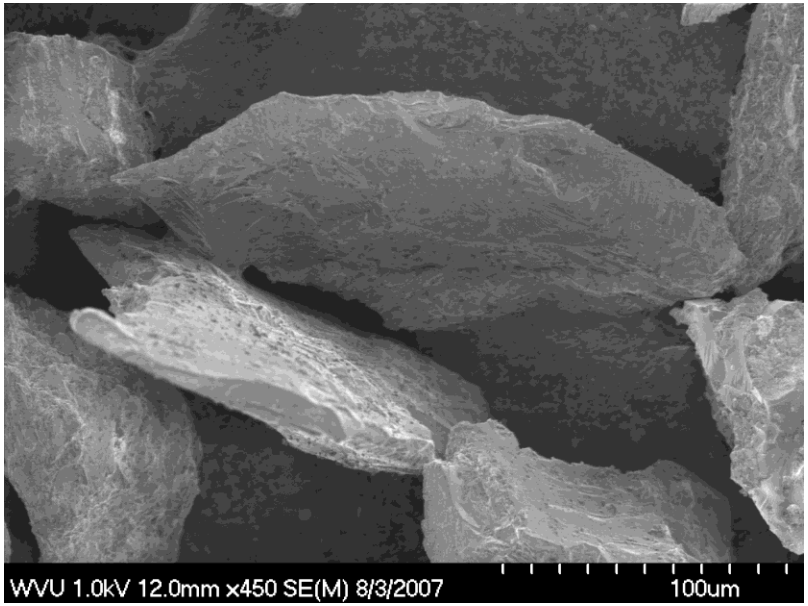




47.8 % of the Fuel	**Ash Analysis:**	
	48.94%	**SiO_2**
2.6 wt% Ash	**26.76%**	**Al_2O_3**
	10.71%	**Fe_2O_3**
14.1 wt% of Ash in Composite Fuel	**3.56%**	**CaO**
	0.95%	**MgO**
51.2% of Combustibles in Fuel	**0.44%**	**Na_2O**
	1.49%	**K_2O**

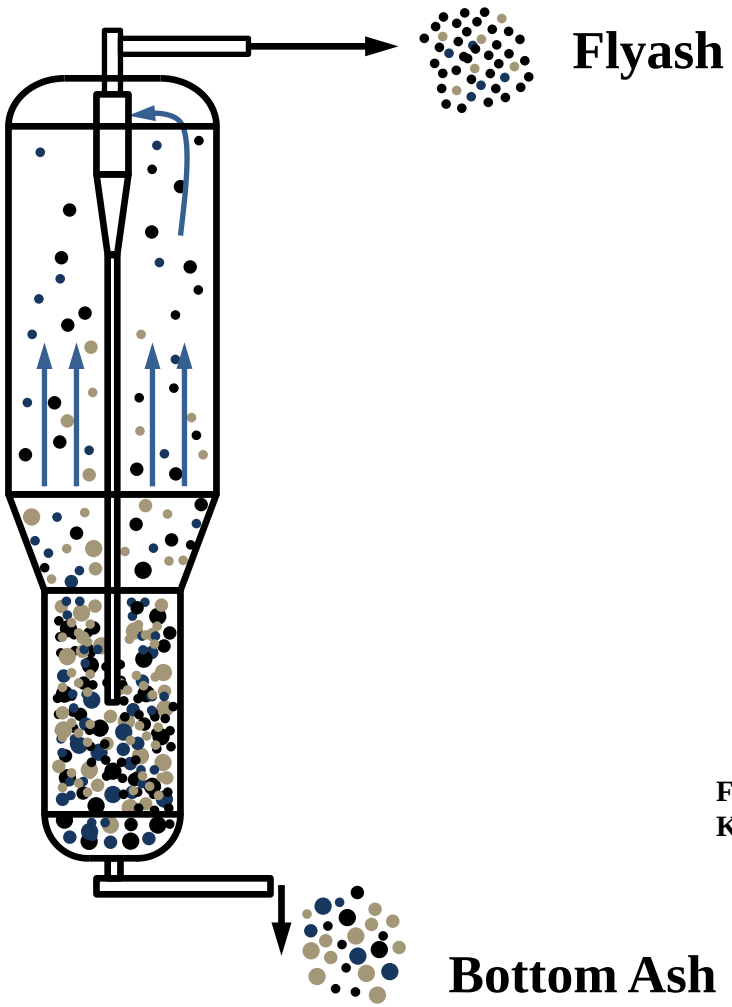
Ground Pittsburgh Bed Coal
1.6 by 2.6 Fraction

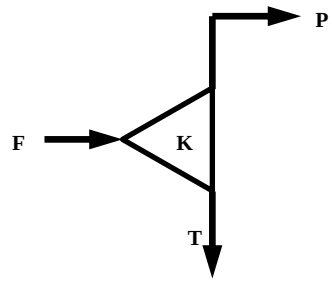


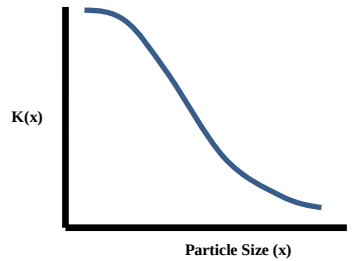


3.5 % of the Fuel	**Ash Analysis:**	
	54.65%	**SiO_2**
52.6 wt% Ash	**21.10%**	**Al_2O_3**
	15.36%	**Fe_2O_3**
20.1 wt% of Ash in Composite Fuel	**2.82%**	**CaO**
	0.72%	**MgO**
1.8% of Combustibles in Fuel	**0.34%**	**Na_2O**
	1.71%	**K_2O**

Grouping Particles By Class and Tracking Behavior Separately: The Particle Population Model







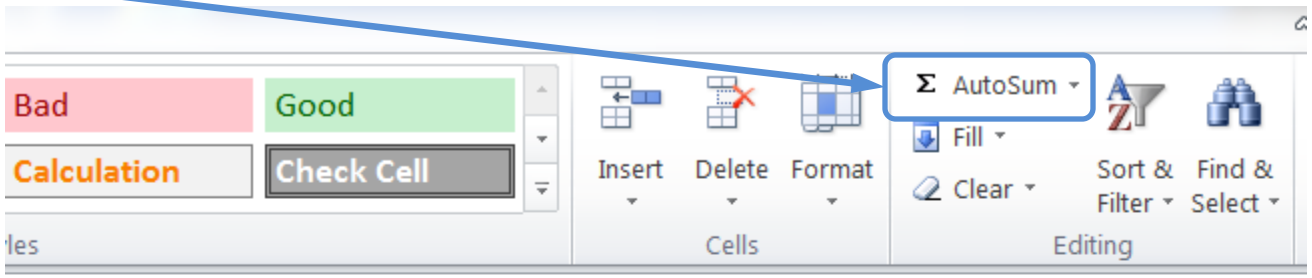
$$P = \sum_{x=1}^{x=n} K(x)F(x)$$

F(x): The Mass Fraction of Particles of Size x in Feed
K(x): The Mass Fraction of Particles of Size x in Feed that Report to the P Stream

Grouping Particles By Class and Tracking Behavior Separately: The Particle Population Model

Q: This has sum notation, which is almost as bad as integrals. <u>It must be complicated. We don't have time to learn this.</u>

A: Here is the sum button in Excel



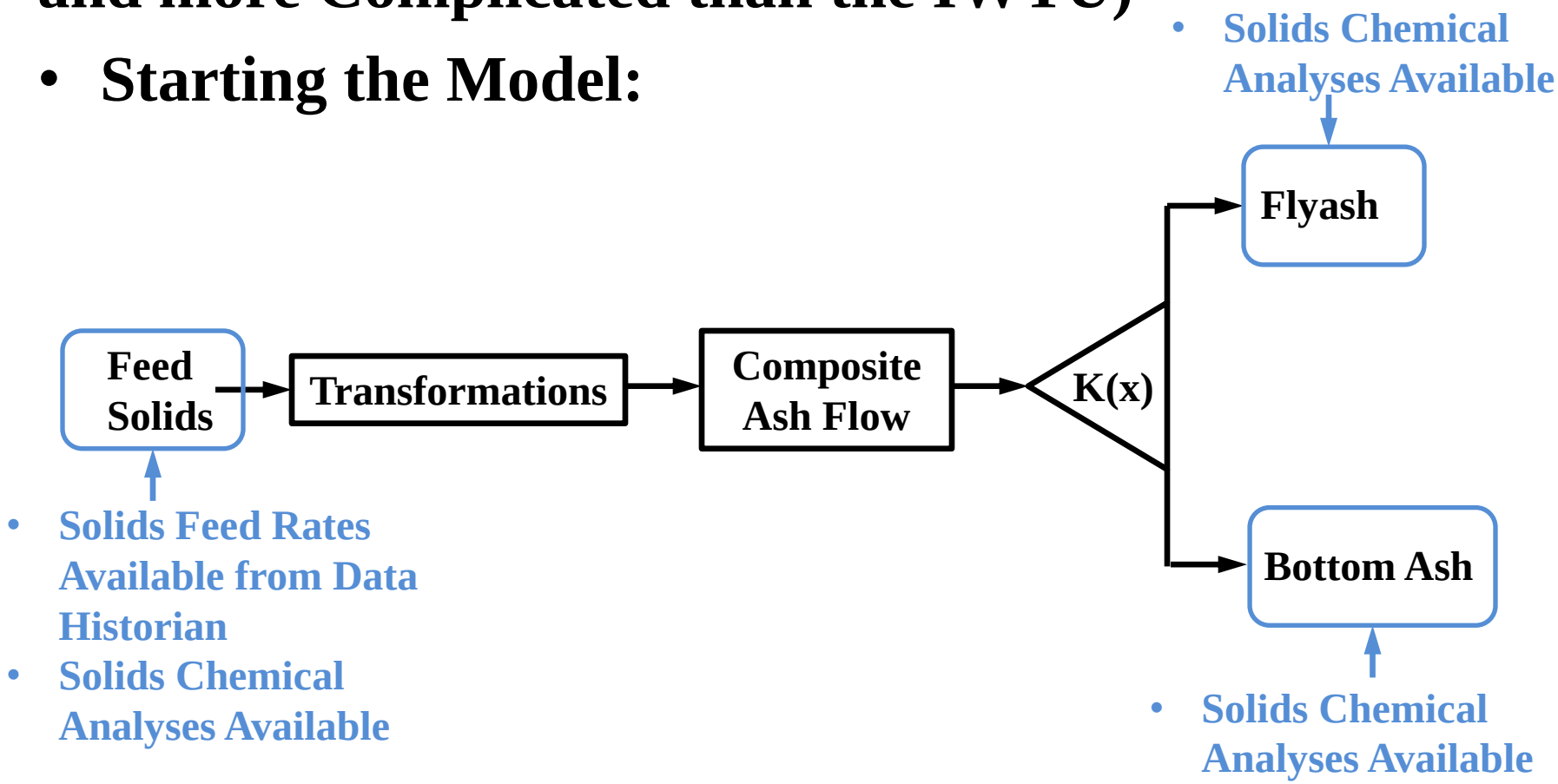
O	P	Q	R	S	T	U
		Particle Size, μm				
		1,000	10%			
		800	20%			
		600	30%			
		400	20%			
		200	10%			
		100	10%			
			100%			

$$P = \sum_{x=1}^{x=n} K(x)F(x)$$

The Particle Population Model: Development and Use

Examples from Commercial CFB Boilers (Larger and more Complicated than the IWTU)

- **Starting the Model:**



The Particle Population Model: Development and Use

Calculating the Ash Split from Simultaneous Material Balances:

$$F_1A_1+F_2A_2=F_{FA}A_{FA}+F_{BA}A_{BA}$$

$$F_1B_1+F_2B_2=F_{FA}B_{FA}+F_{BA}B_{BA}$$

Known:

F_1: Feed Rate of Solids 1 from DCS
F_2: Feed Rate of Solids 2 from DCS
A_1: A Content of Solids 1 (Chemical Analysis)
A_2: A Content of Solids 2 (Chemical Analysis)
A_{FA}: A Content of Flyash (Chemical Analysis)
A_{BA}: A Content of Bottom Ash (Chemical Analysis)
B_1: B Content of Solids 1 (Chemical Analysis)
B_2: B Content of Solids 2 (Chemical Analysis)
B_{FA}: B Content of Flyash (Chemical Analysis)
B_{BA}: B Content of Bottom Ash (Chemical Analysis)

For Best Results, A and B should Analyze as Oxides and Remain in the Solid Phase Throughout the Process (SiO_2, etc.)

Unknown:

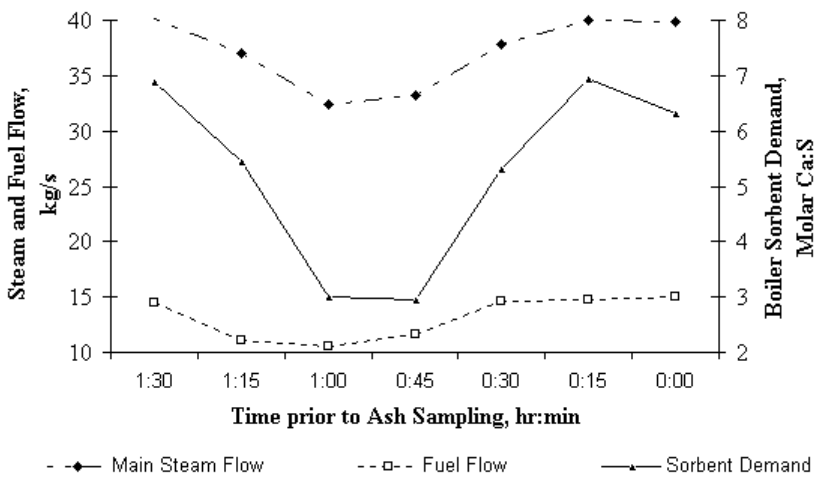
F_{FA}: Flyash Flow Rate
F_{BA}: Bottom Ash Flow Rate

Two Equations
Two Unknowns

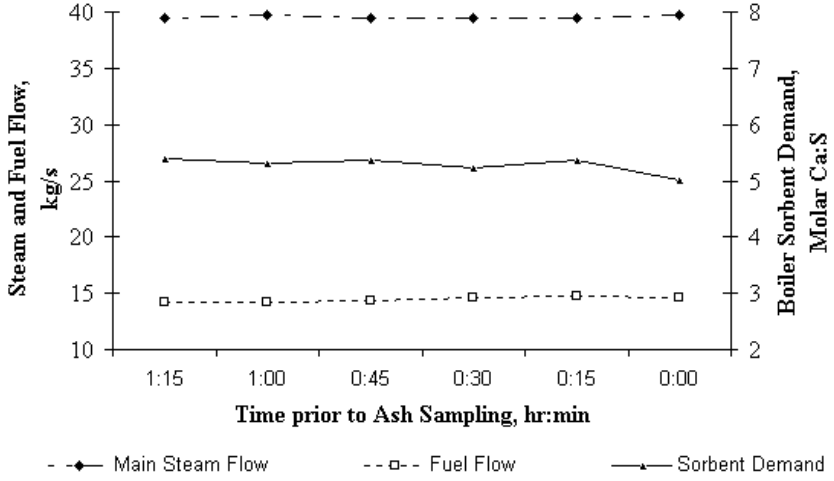
The Particle Population Model: Development and Use

Calculating the Ash Split from Simultaneous Material Balances: Plant Operations Must be Relatively Constant Prior to Ash Sampling

Bad Trend in CFB Power Plant



Good Trend in CFB Power Plant



The Particle Population Model: Development and Use

Calculating the Ash Split from Simultaneous Material Balances:

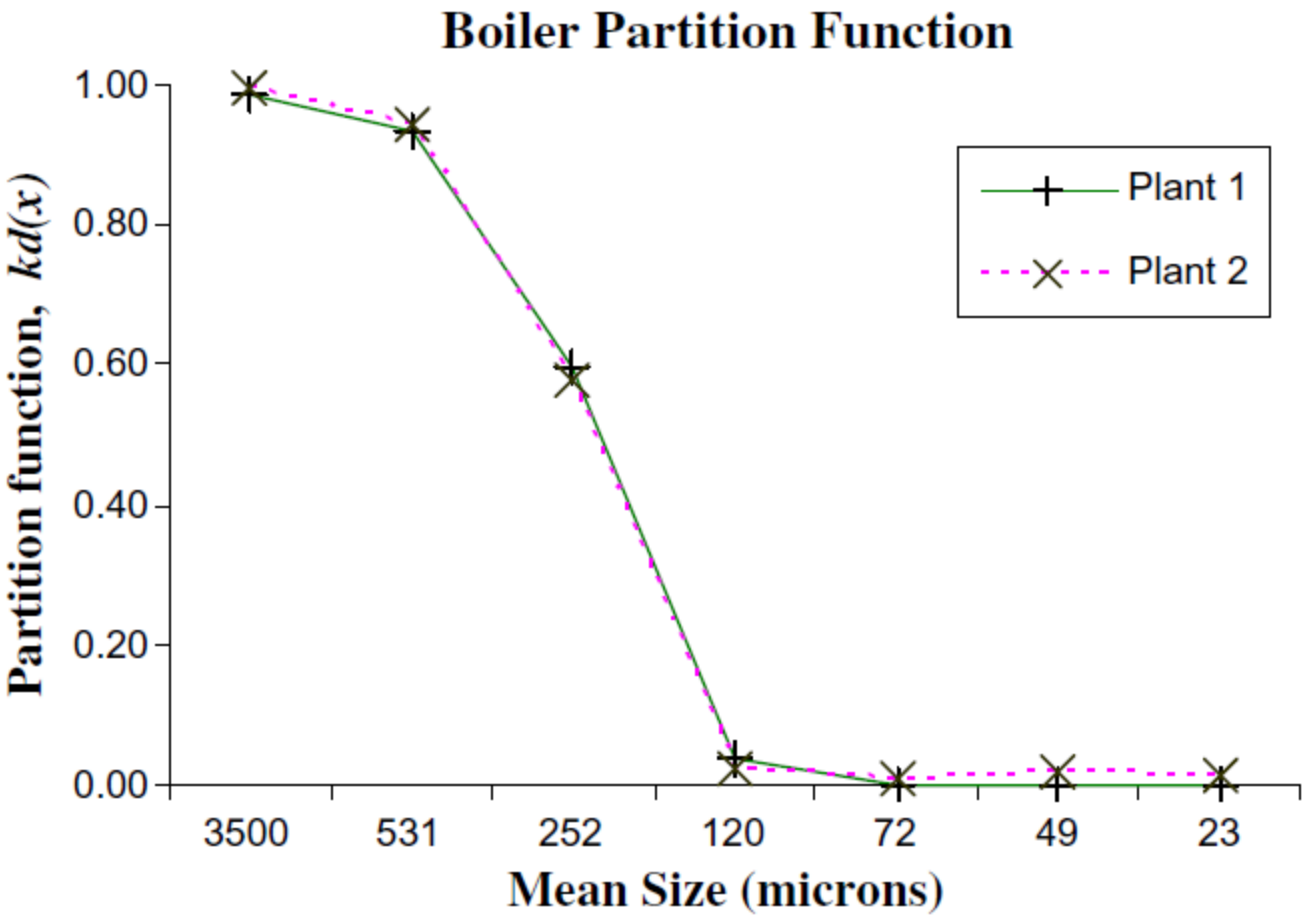
30 MW Plant Test Results

Plant Test	2	4	11	16	20
Fuel Flow Rate, PPH	106,920	114,048	123,552	126,720	112,464
Sorbent Flow Rate, PPH	3,722	6,732	5,623	6,970	4,594
Flyash Flow Rate, PPH	32,472	31,680	36,432	31,680	34,056
Bottom Ash Flow Rate, PPH	38,808	45,936	46,728	54,648	42,768
Ash Split, % Bottom Ash	54%	59%	56%	63%	56%

From Ash Stream Flow Rates and Particle Size Analyses We can Calculate the Partition Function

Particle Size, µm		Flyash		Bottom Ash		Wt% Partitioned to Bottom Ash, i.e. K(x)
Passing	Retained	Wt%	PPH Flow Rate	Wt%	PPH Flow Rate	
	707	0	0	80.1	30,888	100
707	354	0	0	12.8	4,990	100
354	149	2.9	871	3.9	1,505	63
149	90	4.9	1,584	3.2	1,267	44
90	53	6.3	1,980	0	0	0
53	38	21.7	7,049	0	0	0
38	0	64.1	20,592	0	0	0
Total		99.9	32,472	100	38,808	0

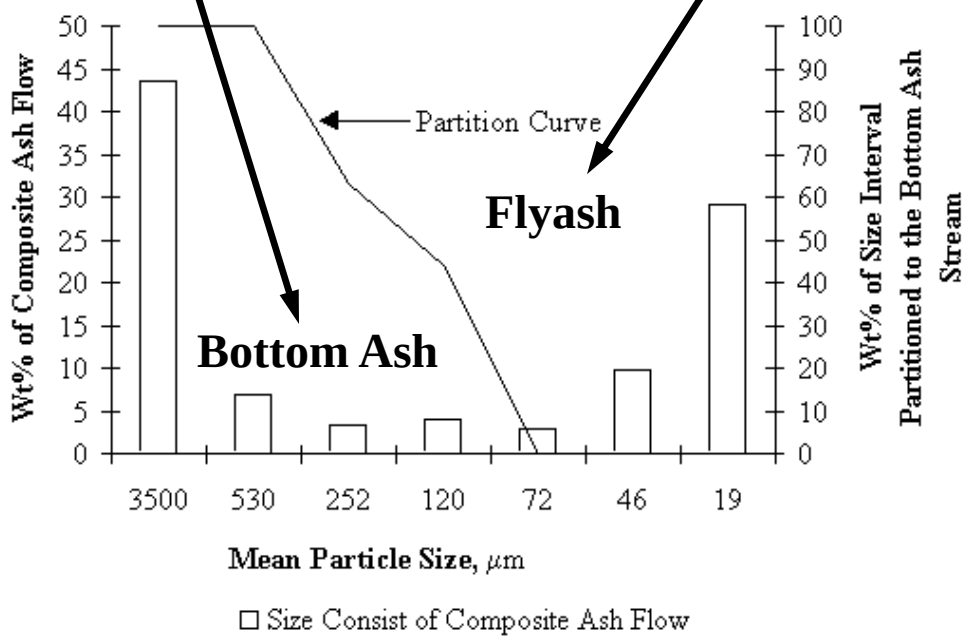
The Particle Population Model: Development and Use for Two Commercial CFB Power Plants



Recap: What Makes Flyash and Bottom Ash?

Coarse Particles in the Feed that are Still Coarse after Exposure to the Bed

Fines in the Feed + Attrition Products



Plant Data

Ash Split Model

$$F_{ba,f} = F_f \sum_x \sum_y k_d(x)\left[1 - K_{f,a}(y)\right] M_{f,x,y} A(x,y)$$

$$F_{ba,s} = F_s (1 - L_s)(1 + S) \sum_x k_d(x) M_{s,x} (1 - K_{s,a})$$

$$F'_{ba} = F_{ba,f} + F_{ba,s}$$

Predicted Bottom Ash Flow

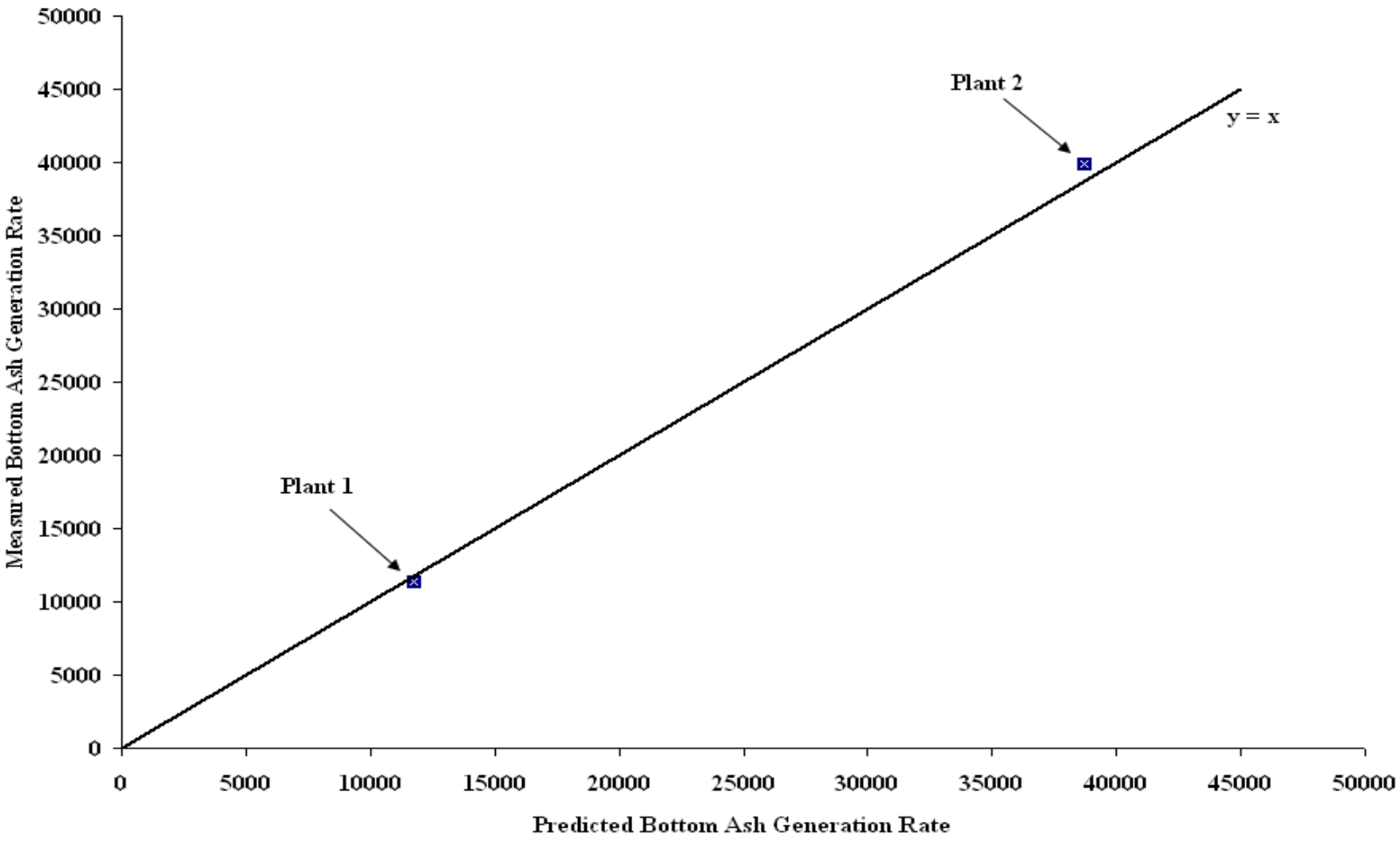
Tested at Two CFB Power Plants in Pennsylvania

Plant 1- 40% Ash High Sulfur Fuel

Plant 2- 60% Ash Low Sulfur Fuel

Same Attrition Coefficient Assumed for both Fuels

Comparison of Ash Split Model Predictions with Operating Results from Two Power Plants



Limestone Demand Model

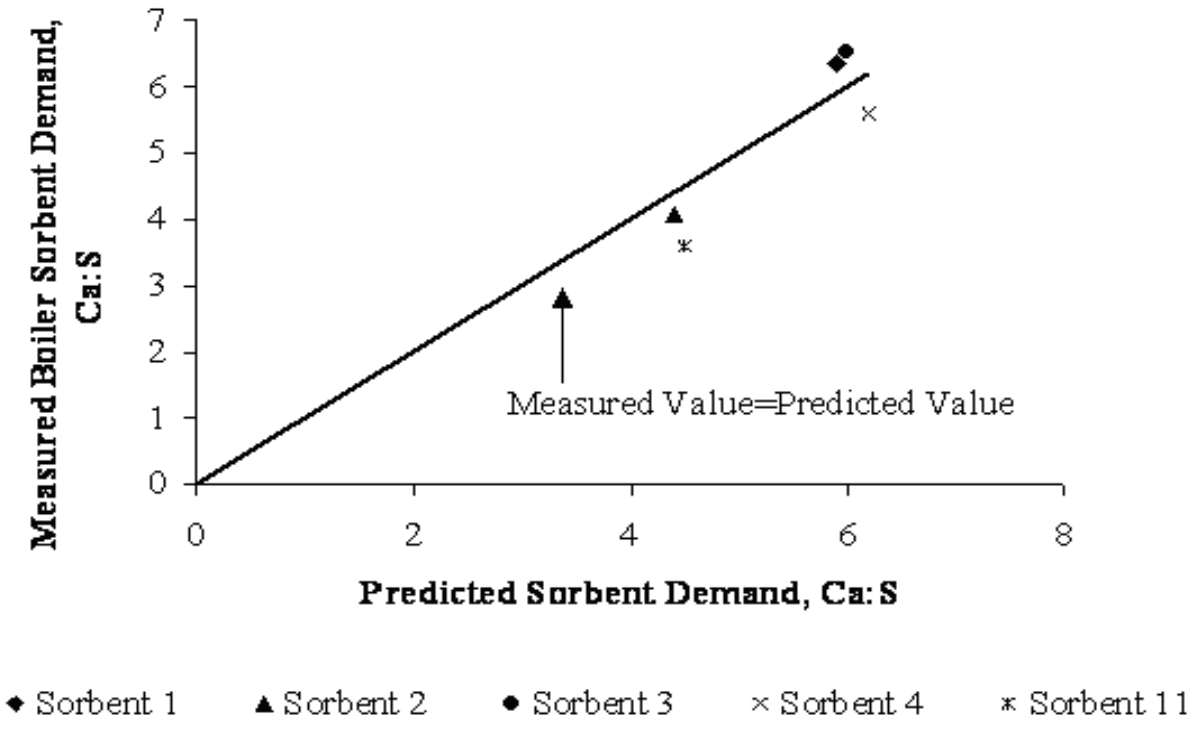
$$\phi_{ba} = \left(1 - I_{s,a}\right)\sum_{x=1}^{nx} k_d(x) M_{s,x}$$

$$\phi_{fa} = 1 - \phi_{ba} = 1 - \left(1 - I_{s,a}\right)\sum_{x=1}^{nx} k_d(x) M_{s,x}$$

$$F_s' = \frac{F_f S_f}{\sigma\left(\frac{\phi_{ba}}{R_{ba}} + \frac{\phi_{fa}}{R_{fa}}\right)} \frac{MW_{CaO}}{MW_s} \frac{1}{Ca_s}$$

Predicted Boiler Limestone Demand

Tested at a CFB Power Plant for a Range of Limestones

- **75-99 wt% $CaCO_3$, 32-62 wt% Passing 200 Mesh**
- **Two Petrographic Classes (Micritic and Sparry)**
- **All Ground in the Same Limestone Plant, Fired at Full Load in the Boiler**

Comparison of Limestone Demand Model Predictions with Operating Results for a Range of Limestones