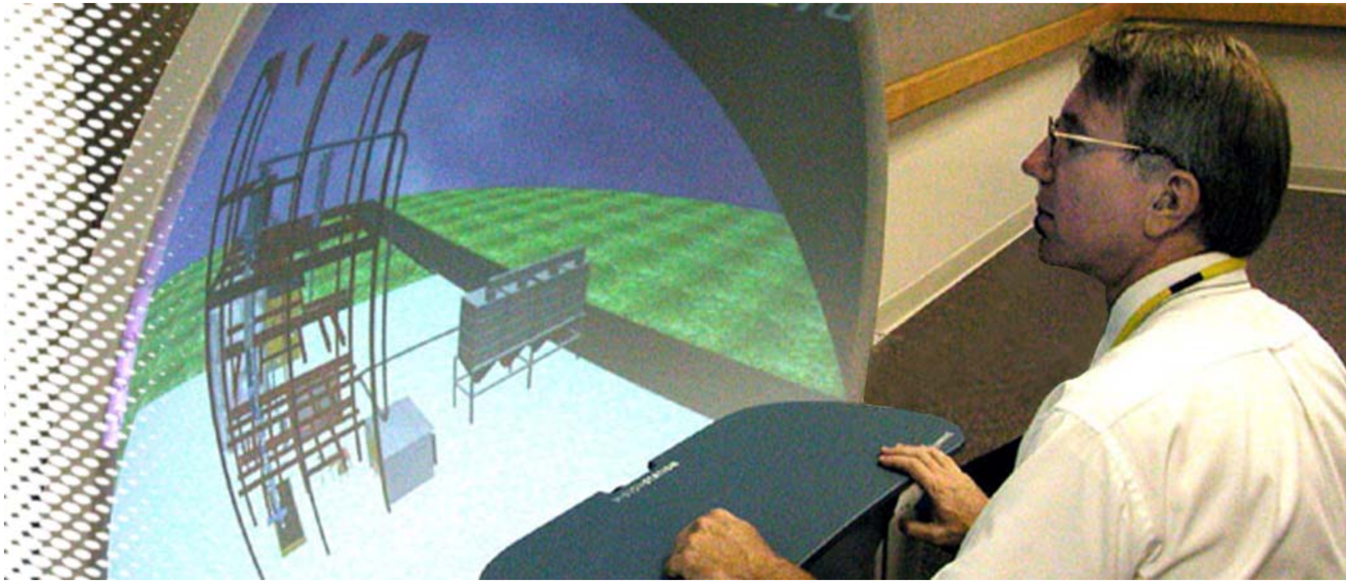

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# Model Validation Challenge Problem: Riser Testing at NETL

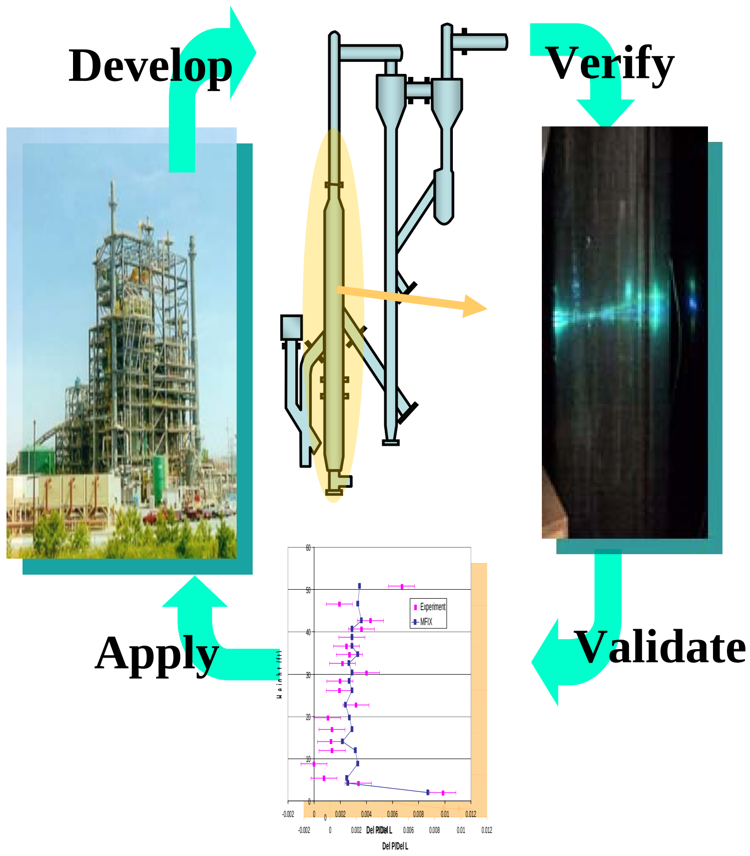
Presenter: Larry Shadle

Poly-Dispersity Work Shop
*April 24-25, 2009*
*Morgantown, WV*

U.S. DEPARTMENT OF ENERGY

# Content

- **Challenge problem: history, motivation, proposed goals and test matrix.**
- **NETL Facilities and Diagnostics**
- **Jet penetration test matrix and results**
- **Test Results Data Base**



# Challenge Problem

- **Two set of experiments to benchmark the ability of CFD codes to simulate each**
  - bubbling fluidized bed: PSRI bypassing or channeling in deep fluid beds
  - transport risers: NETL progress in similar problem 5 yrs ago *(Knowlton  et al., CFB8)* with dense flow conditions an abrupt Tee at the exit
- **Supply raw data as well as reduced data.**
- **Schedule:**
  - Test systems/conditions released by summer
  - Simulations due by end of winter 2010
  - Test results posted by end of winter 2010
  - Target CFB10 to report on compiled results

# Response Parameters – Fluid Bed Cases

- **Fixed parameters**
  - Fluid bed geometry and configuration
  - Ambient conditions and Relative humidity
- **Independent Parameters:**
  - Particle Size and/or Size Distribution
  - Flow rates and velocities
  - Solids inventories or bed heights
- **Dependent Parameters:**
  - Pressures and pressure drops
  - P fluctuations at various locations
  - Fiber optic measurements to produce - Bubble rise size, velocity and Concentration at 1 height and higher beds at up to 3
  - High speed video images
- **Optional cases: varying the amount of fines & internal baffles**

# Response Parameters – CFB Riser Cases

- **Fixed parameters:**
  - CFB geometry and configuration
  - Ambient conditions & Relative humidity
- **Independent Variables:**
  - Group A and Group B
  - Gas Velocity and flux
  - Mass flow measurements and Fluxes
- **Dependent variables:**
  - Pressures and Pressure profiles
  - Fiber optic radial velocity and concentrations at 3 locations
  - HS video PIV at fixed locations.
    - Clusters: Videos showing velocity of individual particles, and clusters for PEB over time
    - Concentration and trajectories
- **Optional cases: varying the amount of fines & internal baffles**

# Validation Criteria

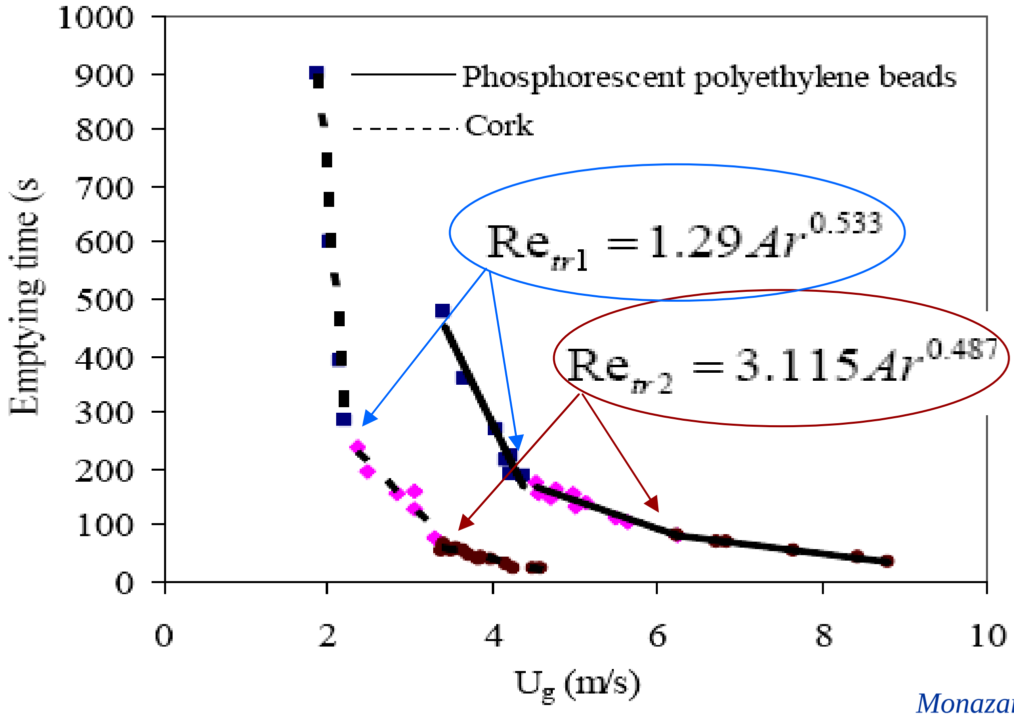
- **Level 1 Macro-scale**
  - Axial pressure profile
  - Riser bed-density as f($z$, $U_g$ and $M_s$)
  - Dynamic transfer functions
- **Level 2 Meso-scale**
  - Radial distribution of solids $v_s$, $\varepsilon_s$, *and* $G_s$.
  - Riser radial distribution as f($z$, $U_g$ and $G_s$).
  - Streamer size frequency and v.
  - Pressure fluctuations power spectrum
- **Level 3 Micro-scale**
  - Dispersed particle $\varepsilon_s$, TKE, and Granular temperature
  - Cluster size, frequency, $v$, $\varepsilon_s$, TKE, and Granular temperature.
  - Particle Collisions

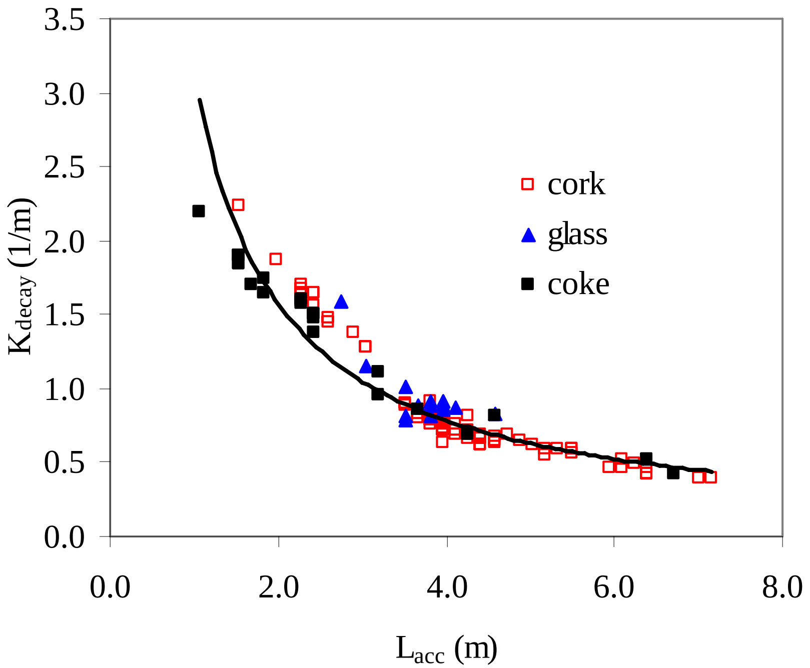
# Macro-Scale Validation

- **Length of Influence at of riser entrance and abrupt exit**
- **Influence of fines on CFB loop - $M_s$**
- **Influence of riser velocity and $M_{inv}$ on $M_s$**
- **Regime Transitions from transients**

$$\frac{\varepsilon_{app} - \varepsilon_{FD}}{\varepsilon_b - \varepsilon_{FD}} = e^{-K_{decay} z}$$

$$K_{decay} = \pi / L_{acc}$$




*Monazam and Shadle (2008) Ind. Eng. Chem. Research, **47**, p. 8423-8429.*

# Macro-Scale Validation

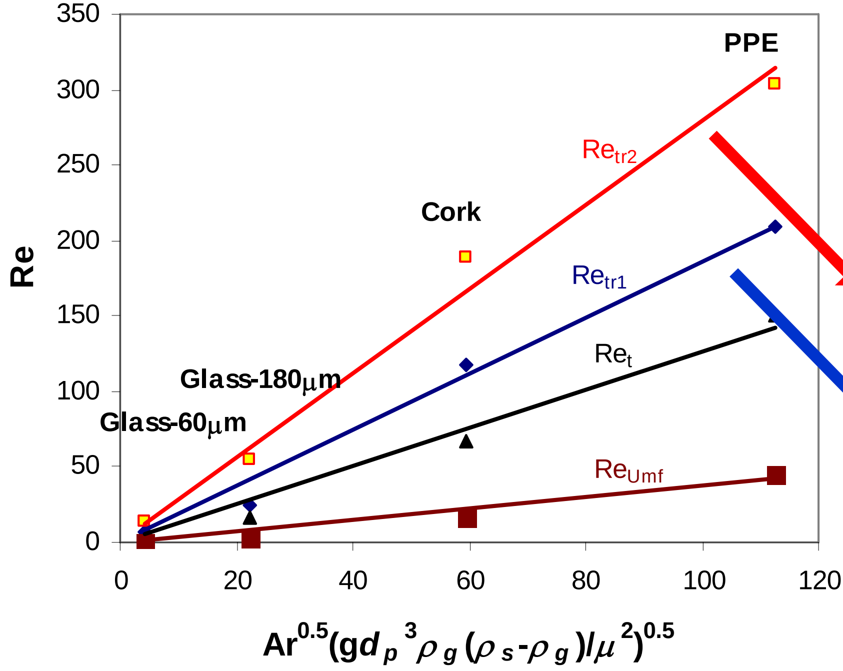
- **Pressure profiles**
- **Effective drag at critical transitions in transport regimes**

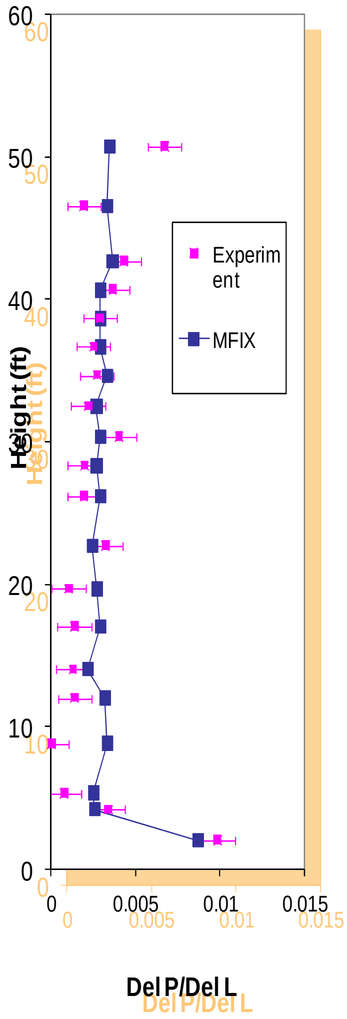
$$\frac{\pi}{4} d_p^2 C_d \rho_g \frac{U^2}{2} = \frac{\pi d_p^3}{6} (\rho_p - \rho_g) g$$

$$Re = \sqrt{\frac{4}{3C_d}} \cdot Ar^{0.5}$$

$$Re_{tr2} = 3.115 Ar^{0.487}$$

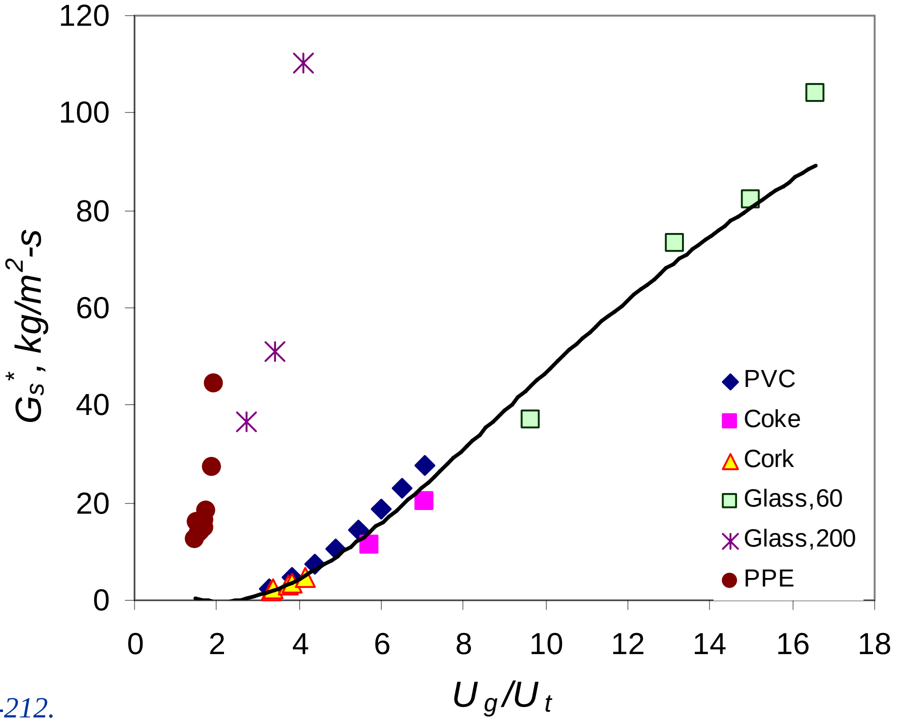
$$Re_{tr1} = 1.29 Ar^{0.533}$$



# Meso-Scale Validation

- **Streamers and back-mixing zones**
- **Regime Transitions**
- **Recirculation zones**
- **Dispersion**
- **Jet Penetration**



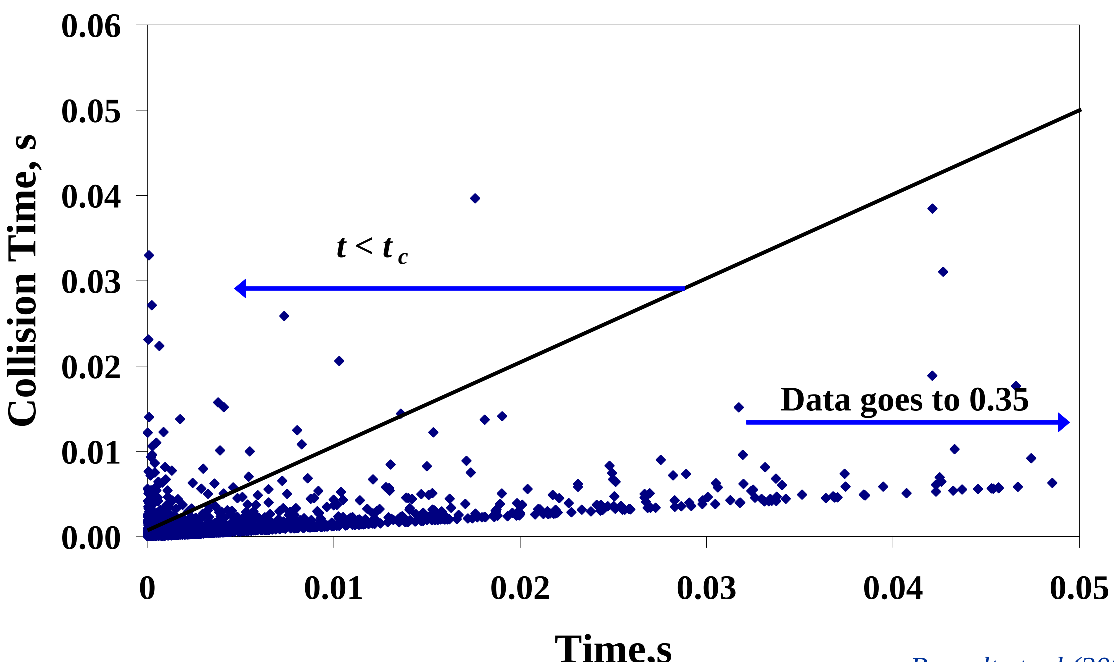

*Monazam et al.(2001) Beds, Powder Technology, **121**, p.205-212.*

| Material | SCC Expression | Eq | $R^2$ |
|---|---|---|---|
| PPE only | $\ln G_s^* =(35.11-102.55/(U_g/U_t)+80.85/(U_g/U_t)^2$ | 1 | 0.957 |
| original SCC paper | $\ln G_s^* =(5.485-16.48/(U_g/U_t)+0.9989/(U_g/U_t)^2$ | 2 | 0.985 |
| PVC, cork, coke, glass60 | $\ln G_s^* =(5.933-23.76/(U_g/U_t)+27.245/(U_g/U_t)^2$ | 3 | 0.989 |

# Micro-Scale Validation

- **Granular temperature measurements**
- **Clusters and dispersed phases**
- **Particle collisions**

$$\tau_c = E(t) \approx \frac{V}{N\pi d_p^2 \sqrt{(v_i - v_m)^2}}$$

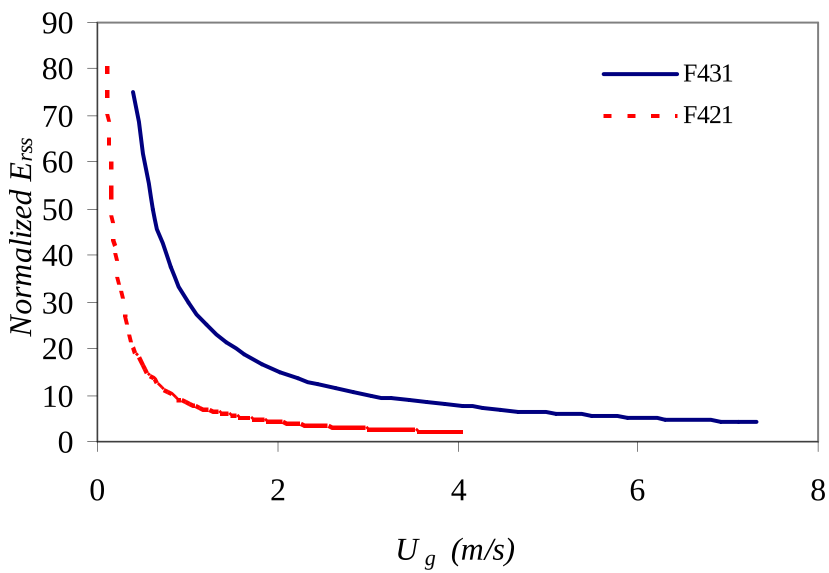


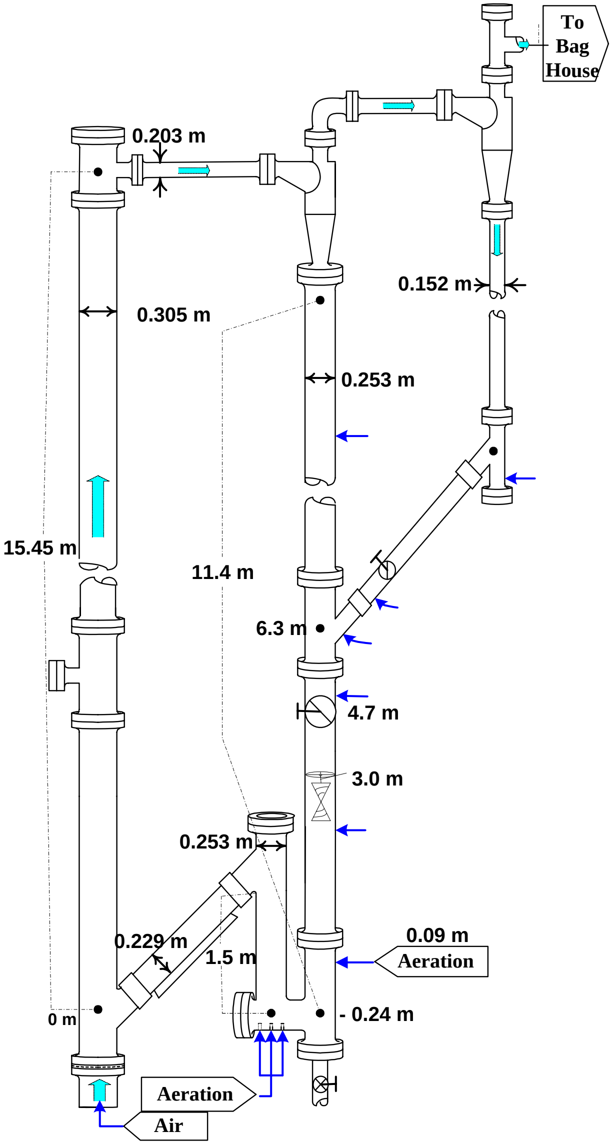

*Breault et a l.(2008Powder Technology, **182**, p. 137-145.*

# Test Systems and Operating Conditions

- **Configuration and detailed dimensions**
- **Operating conditions and sampling locations**

$$E_{rss} = \sqrt{\left(\Delta u_1 \frac{\partial f}{\partial u_1}\right)^2 + \left(\Delta u_2 \frac{\partial f}{\partial u_2}\right)^2 + \cdots + \left(\Delta u_n \frac{\partial f}{\partial u_n}\right)^2}$$








*Shadle et al.(2004) Ind. Eng. Chem. Research, **43**(15), p. 4166-4173.*

# CFB Riser Test Data Base

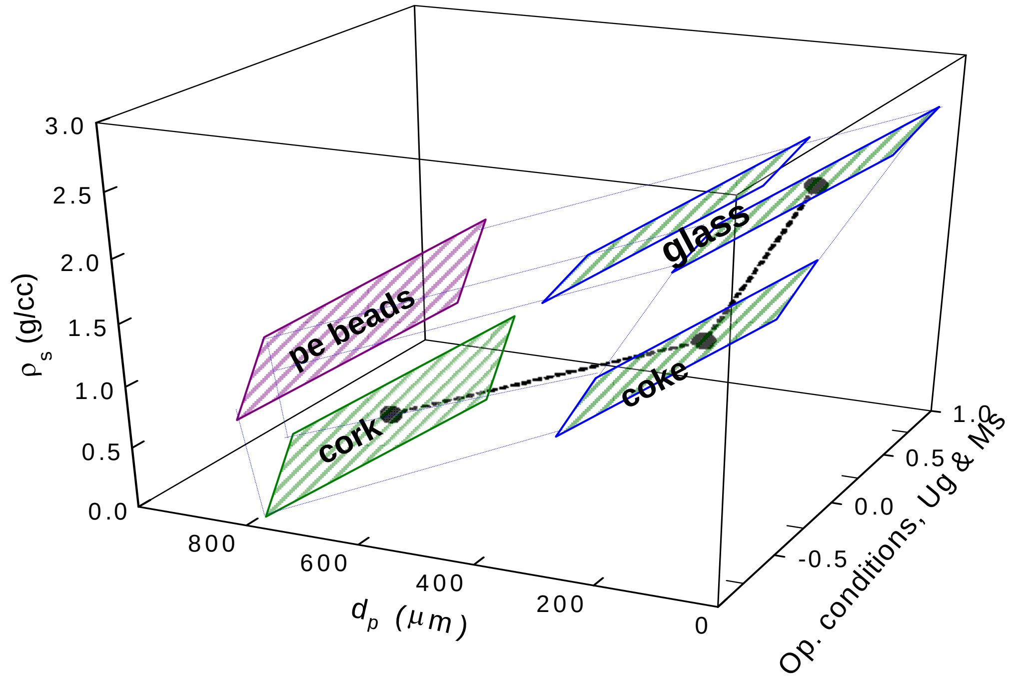
## Test Results Data Base

- **Raw data filed by date**
  - Advanced instrumentation
  - Process Data
    - Steady state (5 min-avg -$M_{inv}$, $\Delta$P's, $U_g$'s, $M_s$ )
    - Temporal data (1s - $\Delta$P's, $U_g$'s, $M_s$)
- **Reduced data filed by bed material *and* by system configuration**
  - Summarized by test matrix
  - Proc. data x-ref by $U_g$ and $M_s$
  - Adv. Inst. indexed by sampling location

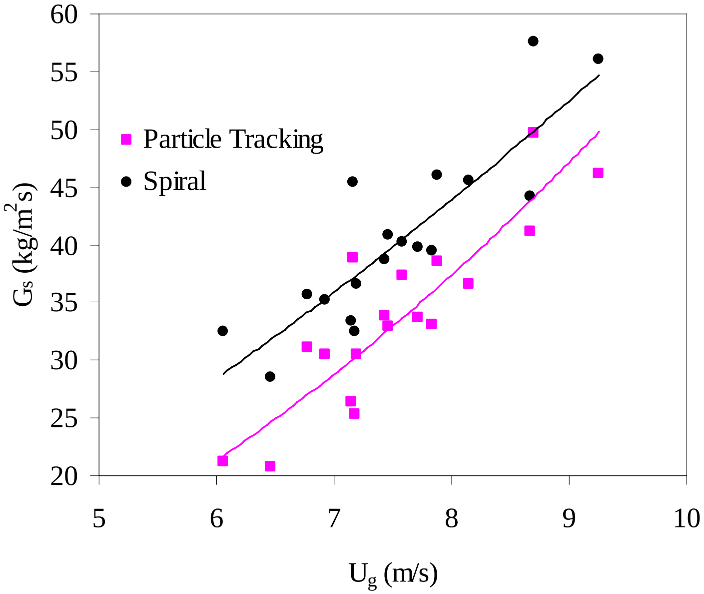
## Advanced Instrumentation

- **Raw data**
  - Unprocessed signals (software)
- **Reduced data**
  - Fiber Optic ($v_p$, $\varepsilon_s$ stats)
  - High Speed Video (clips, $v_p$, $\varepsilon_s$)
  - LDV ($v_p$ stats)
  - High Speed $\Delta$P's (power spectrum)
  - Spiral ($M_s$)
  - Piezo-Electric (local $G_s$ up, down stats)

# Granular materials tested



# Solids Circulations Rate Uncertainty



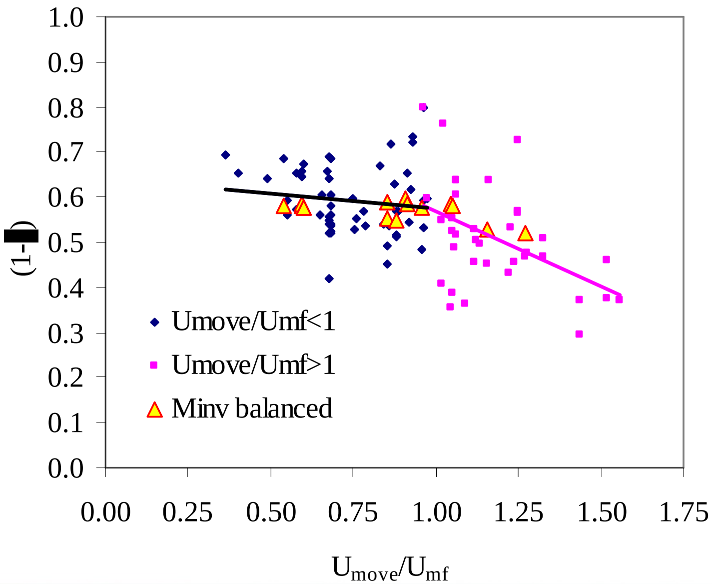

- **Tested methods for $M_s$**
- **Spiral allows real-time control**

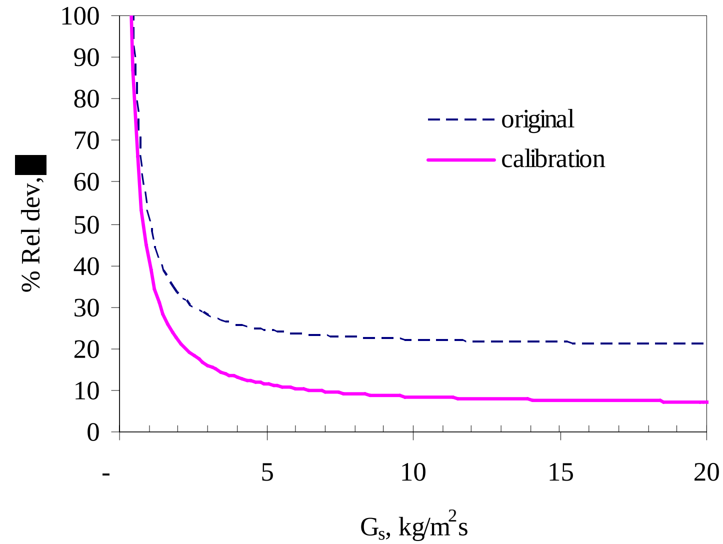
$$\dot{Q}_s = \frac{\pi}{4} D_{sp}^2 \frac{\Delta H}{\Delta t}$$

$$\dot{m}_s = -\frac{\pi}{4g} D_{Riser}^2 \frac{d\Delta P_{Riser}}{dt}$$

$$\dot{m}_s = \rho_s (1-\varepsilon_b) \frac{\pi}{4} D_{Sp}^2 V_{Spiral}$$

$$E_{rss} = \sqrt{\left(\Delta\rho_s \frac{\partial \dot{m}_s}{\partial \rho_s}\right)^2 + \left(\Delta\varepsilon_b \frac{\partial \dot{m}_s}{\partial \varepsilon_b}\right)^2 + \left(\Delta D_{Sp} \frac{\partial \dot{m}_s}{\partial D_{Sp}}\right)^2 + \left(\Delta V_s \frac{\partial \dot{m}_s}{\partial V_s}\right)^2}$$



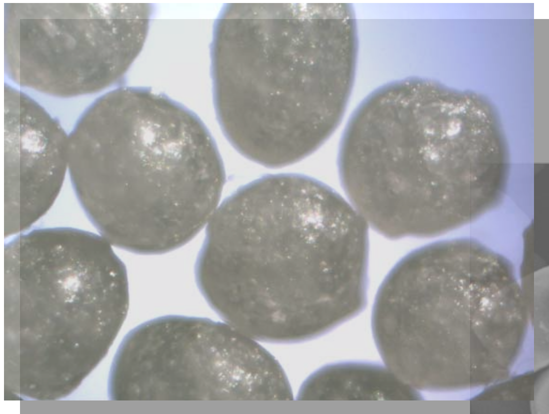



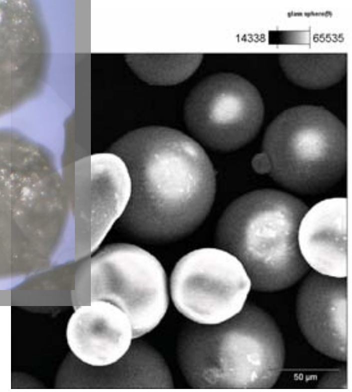


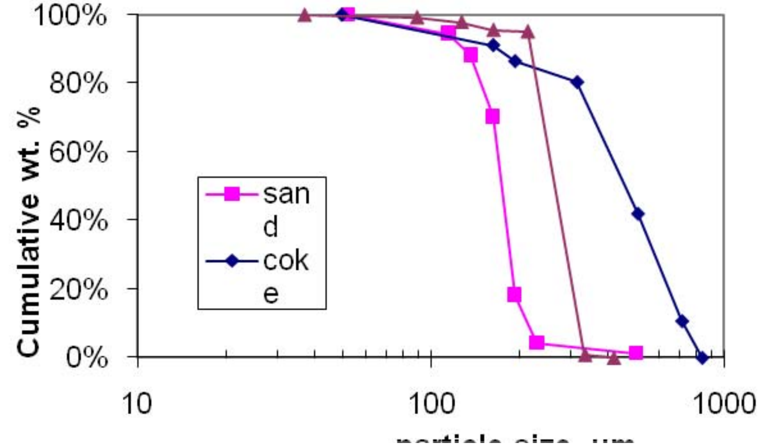


*Ludlow et al.(2008), Powder Technology, **182**, p. 379-387.*

# Granular Materials

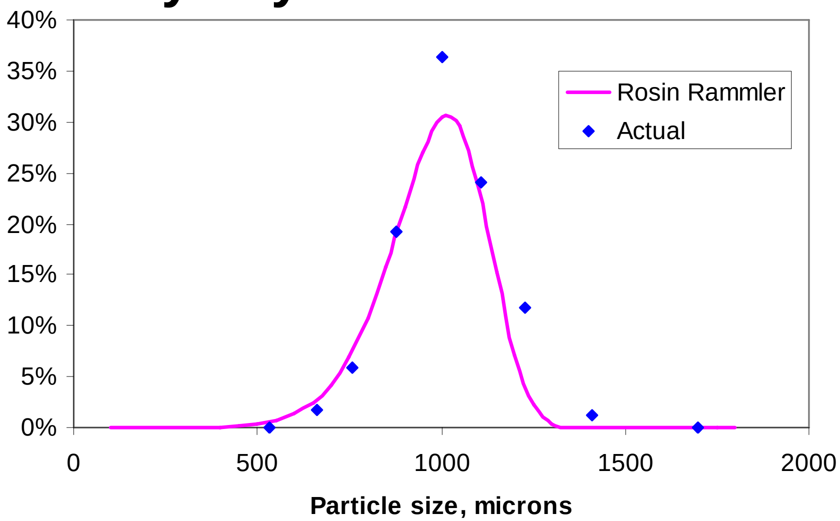


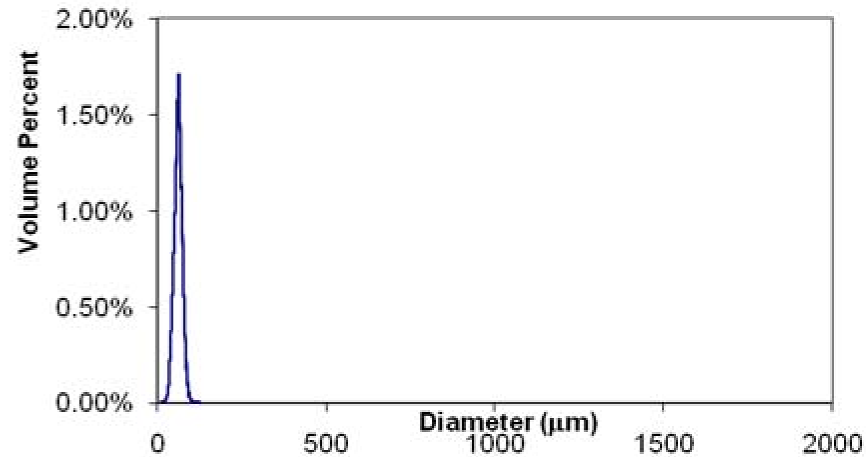


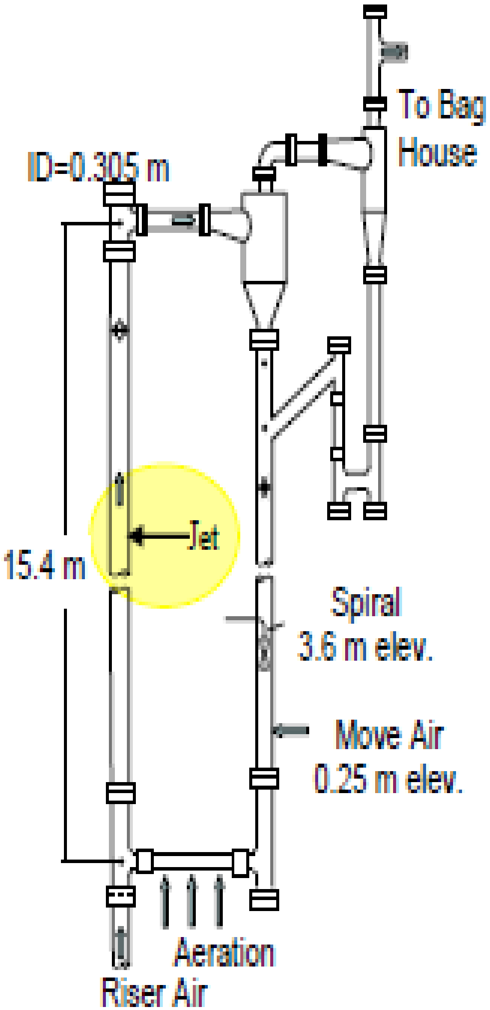

**750-1000 micron Polyethylene Beads**

**60 micron Glass Beads**



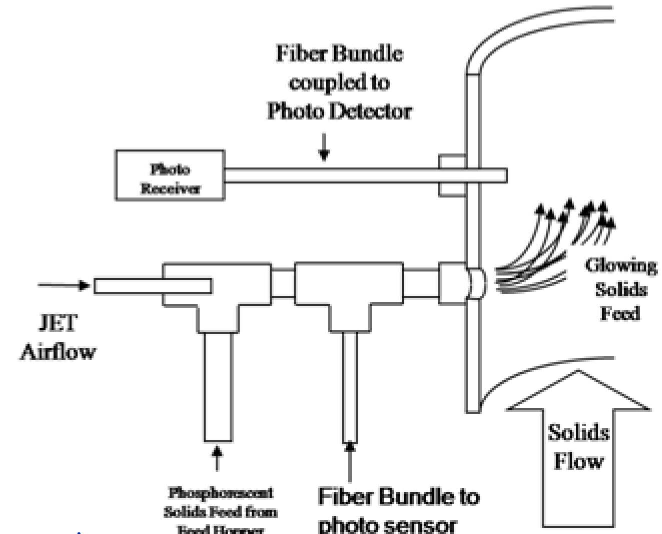



# Jet Penetration Tests




- **Purpose: Evaluate distribution of coal fed into Transport Gasifier**
- **Approach: Solids tracer and impact probe**

| | Jet conditions | | Riser conditions | |
|---|---|---|---|---|
| Std No. | Void fraction | $U_{jet}$ m/s | Riser Air m/s | Circ rate kg/s |
| 0 | 0.97 | 16.64 | 7.62 | 11.34 |
| 1 | 0.97 | 8.53 | 7.62 | 11.34 |
| 2 | 0.97 | 37.18 | 7.62 | 11.34 |
| 3 | 0.95 | 16.64 | 7.62 | 11.34 |
| 4 | 0.99 | 16.64 | 7.62 | 11.34 |
| 5 | 0.99 | 36.83 | 7.62 | 11.34 |
| 6 | 0.97 | 16.64 | 7.62 | 2.83 |
| 7 | 0.97 | 16.64 | 5.49 | 1.42 |



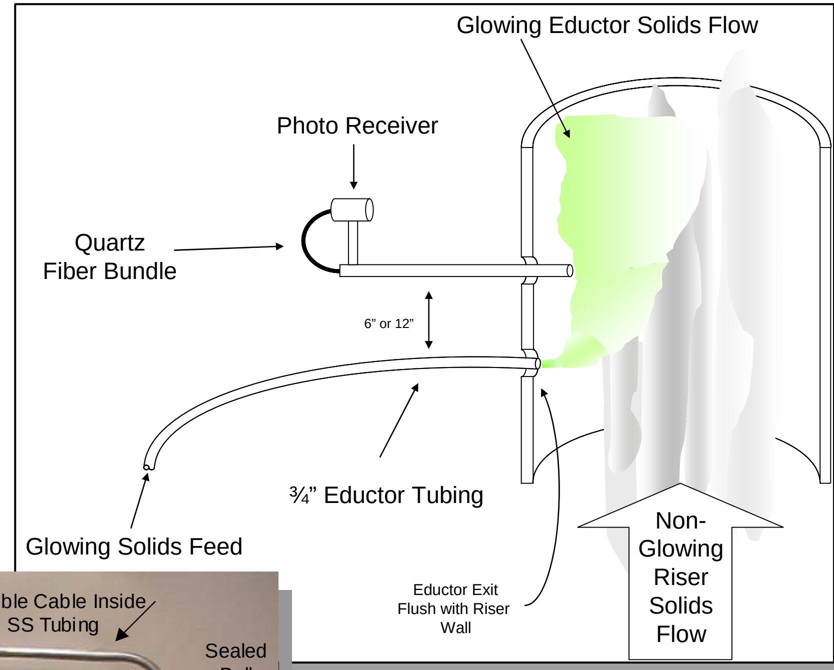

*Shadle, et al.(2008),"Circulating Fluidized Bed Technology IX, TuTech Innovation GmbH, Hamburg, Germany, p. 307-312.*

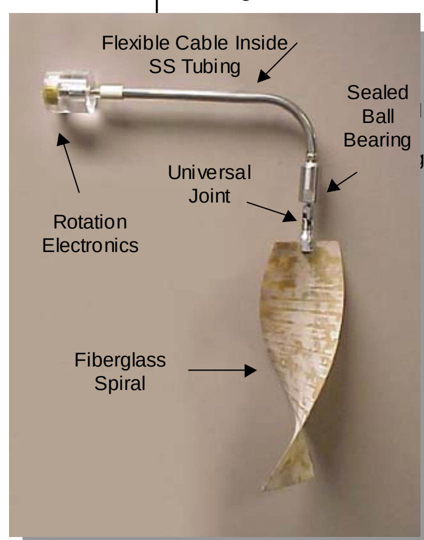
# Operating Methods

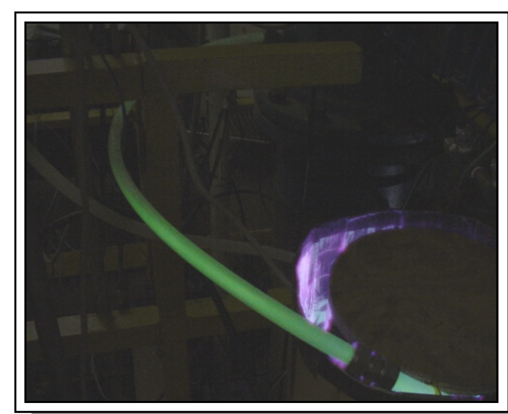
## Solids jet injection and tracer

- **Riser test conditions established controlling polyethylene beads and air flow rates**
- **Phosphorescent polyethylene beads injected into the riser through 2 cm port in the wall**
- **Solids transported in transparent plastic tubing coiled around a UV lights prior to injection into riser**
- **Phosphorescing particles detected by sensitive photosensors downstream.**
- **Solids Flow to jet metered using 10 cm Spiral flow feedback to control move aeration and feed hopper pressure**

*Shadle, et al.(2008),"Circulating Fluidized Bed Technology IX, TuTech Innovation GmbH, Hamburg, Germany, p. 307-312.*



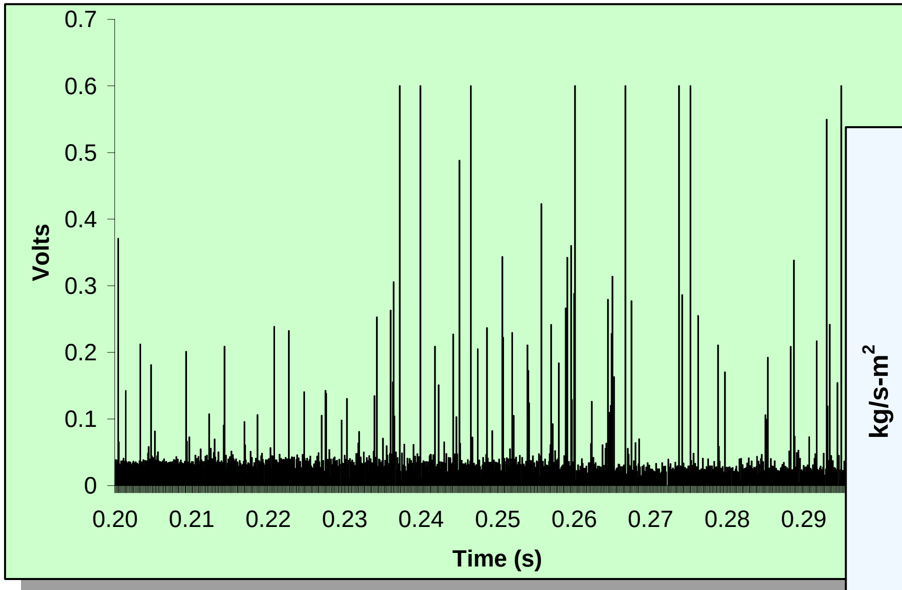



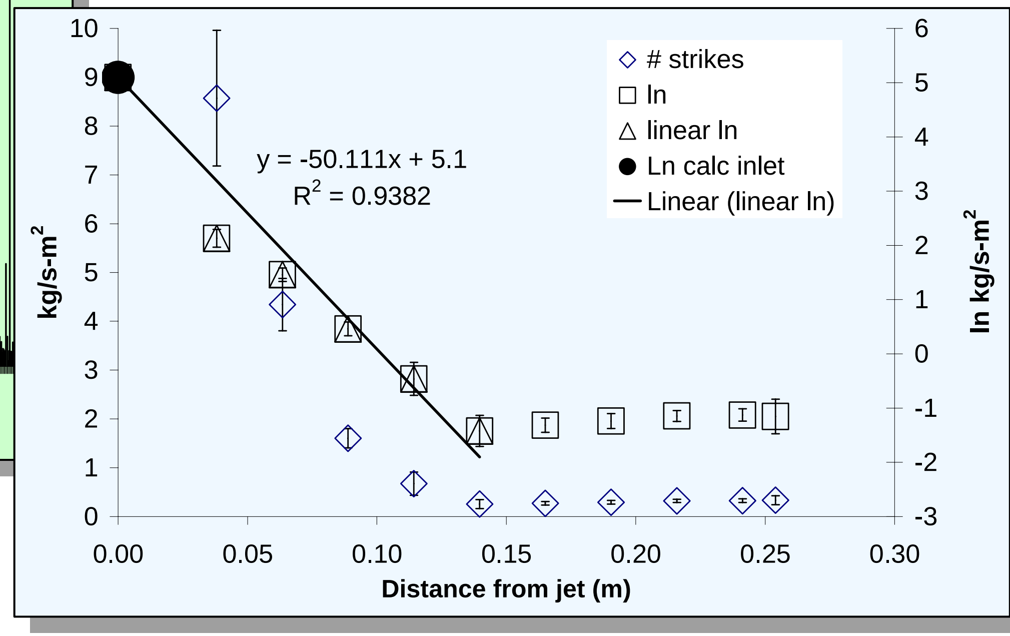
# Solids impact in line with jet inlet

*Shadle, et al.(2008),"Circulating Fluidized Bed Technology IX, TuTech Innovation GmbH, Hamburg, Germany, p. 307-312.*

A)




B)




## Typical Piezoelectric Transducer Responses:

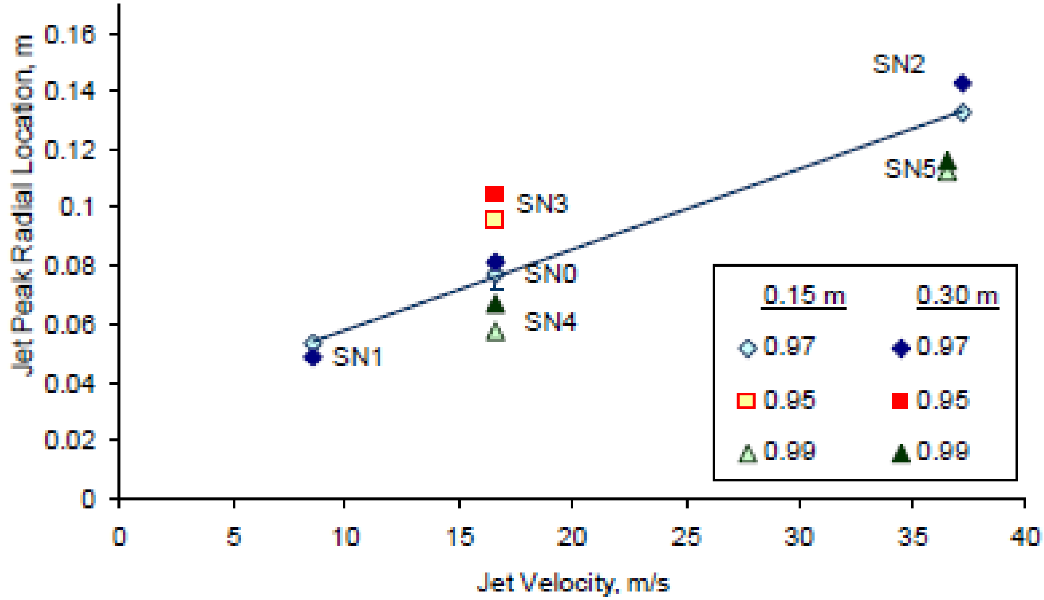
A) Intensity with time and

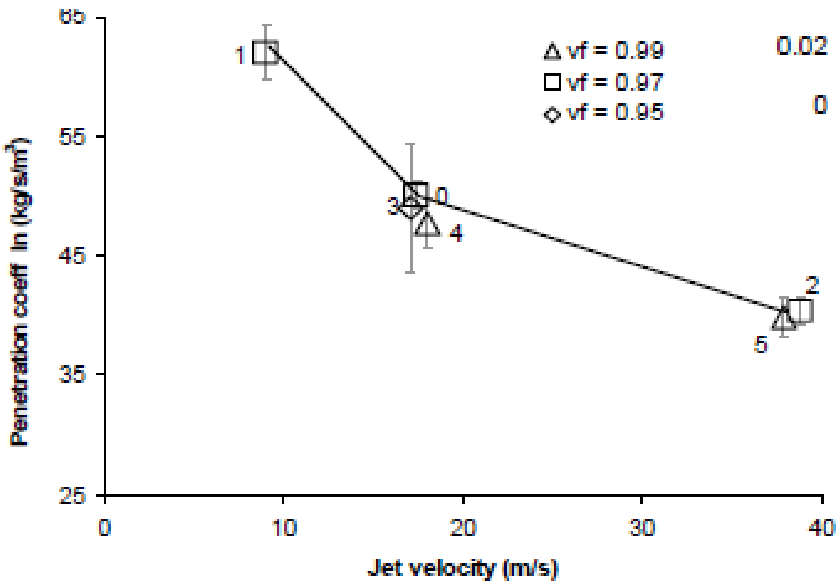
B) Jet decay with distance from jet

# Jet Penetration

*Jet location and decay rate measured as a f($U_j$ and $\varepsilon_s$)*

- **Jet location and decay rate measured as a f($U_j$ and $\varepsilon_s$)**

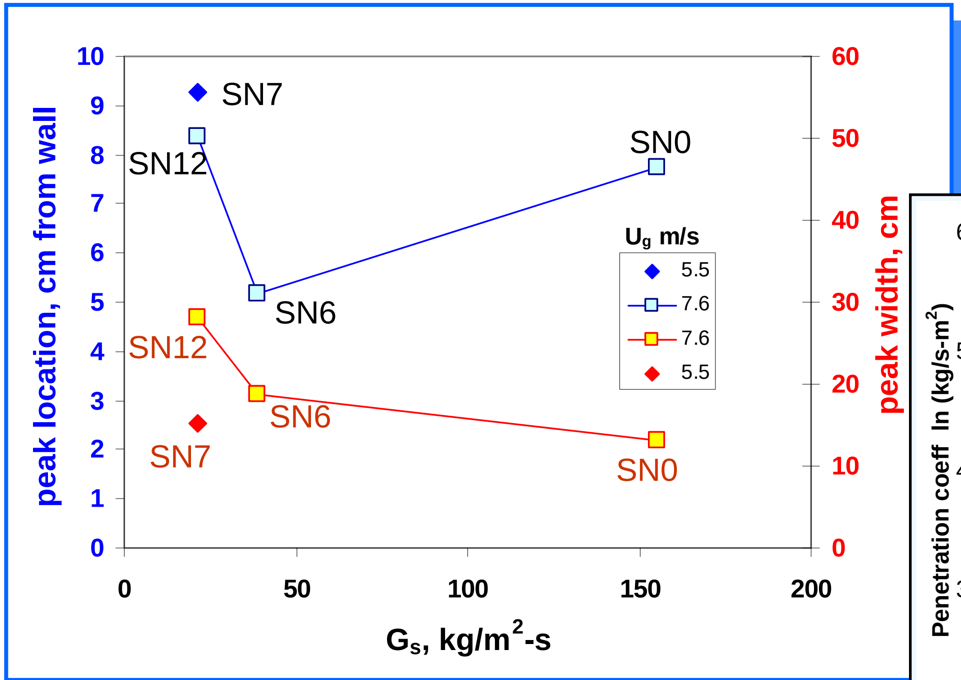



*Shadle, et al.(2008),"Circulating Fluidized Bed Technology IX, TuTech Innovation GmbH, Hamburg, Germany, p. 307-312.*

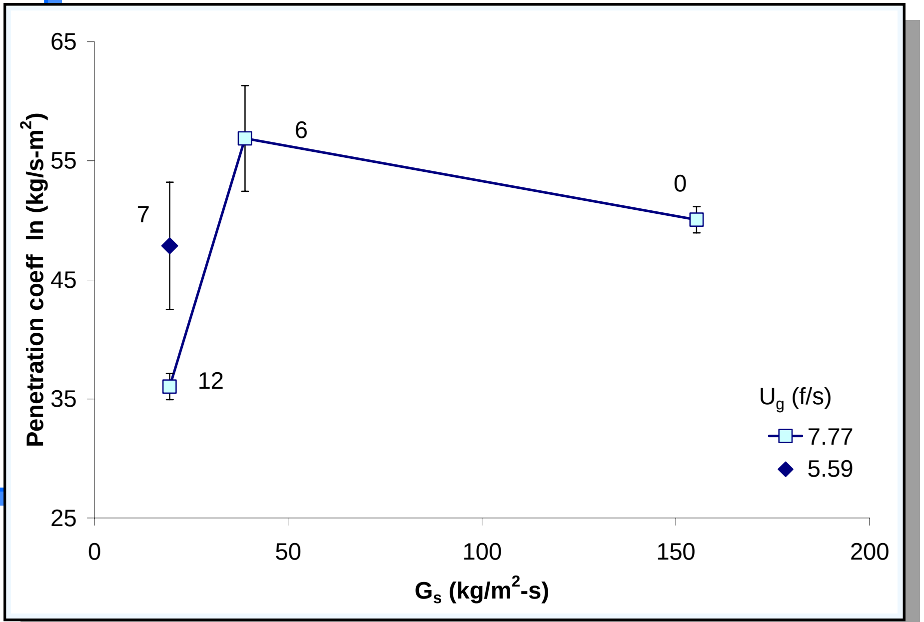
# Jet Particle Tracking

## The dependence of riser conditions




Jet peak location and width for various riser conditions (SN labels)

Penetration coefficients for various riser conditions (SN labels)




- Counter-intuitive result: Gas phase turbulent dissipation rather solids loading determines penetration
- Our hypothesis proposed is that dissipation is effected by particle size and number of particles and their abilities to develop turbulence in wakes



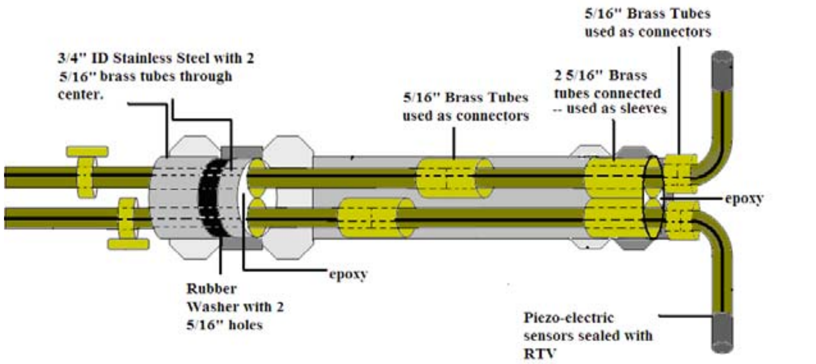


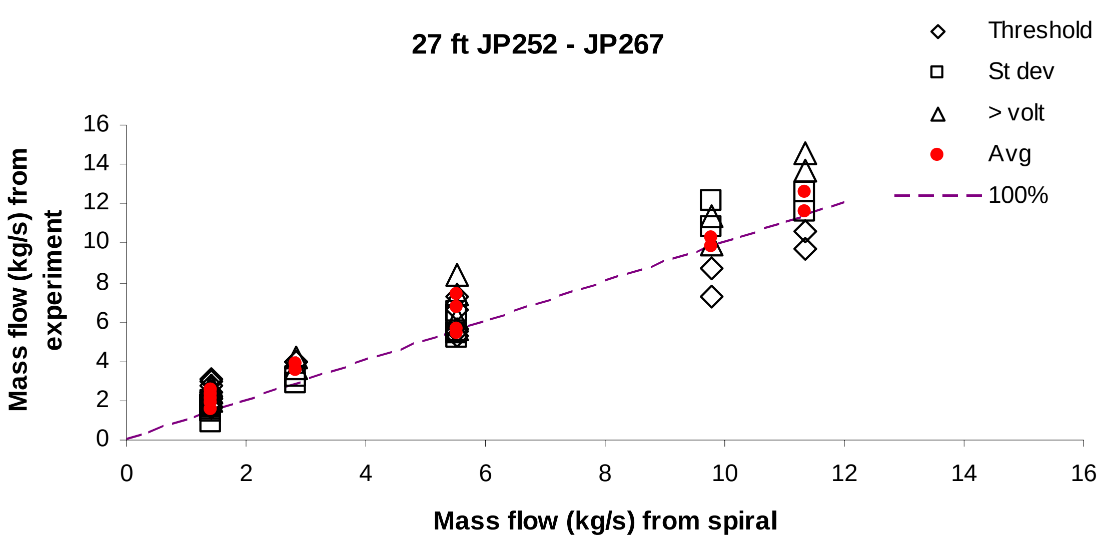
*Shadle, et al.(2008),"Circulating Fluidized Bed Technology IX, TuTech Innovation GmbH, Hamburg, Germany, p. 307-312.*

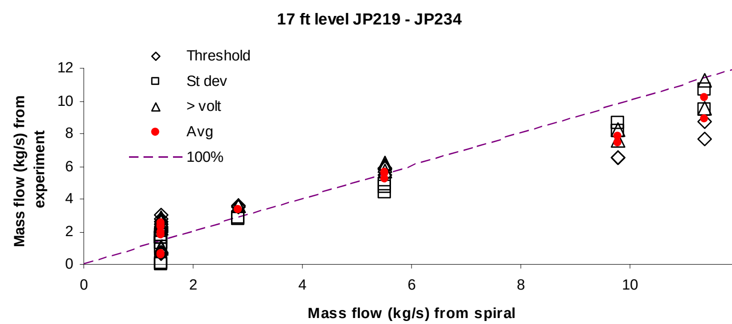
# Local Solids Flux Measurement

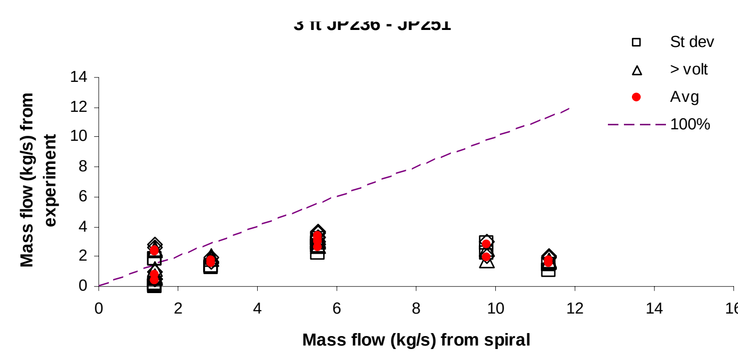
- **Solids sampling is time consuming and unreliable as bed material changes.**
- **Impact probe (piezo-electric) worked well estimating the no. of particles hitting it when estimating jet penetration.**
- **Evaluated it for use as local flux measure**
- **Used several data reduction methods – no clear best.**

Internal View



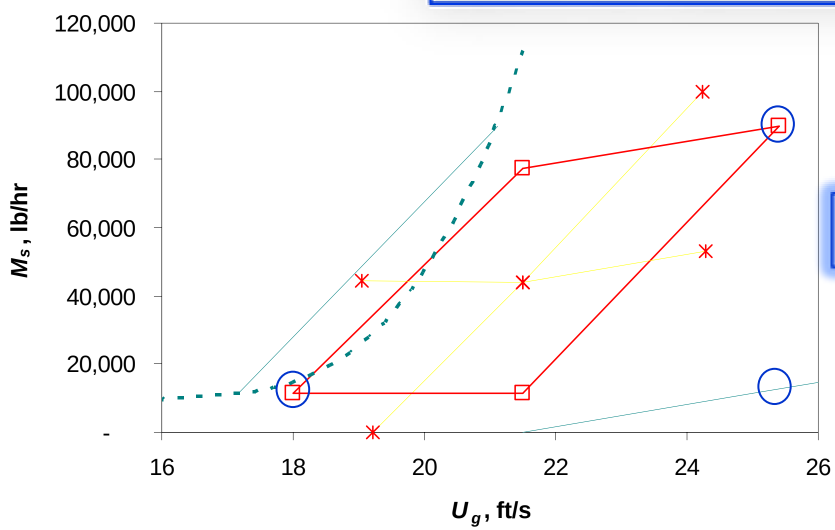
# Jet Penetration Test Matrix

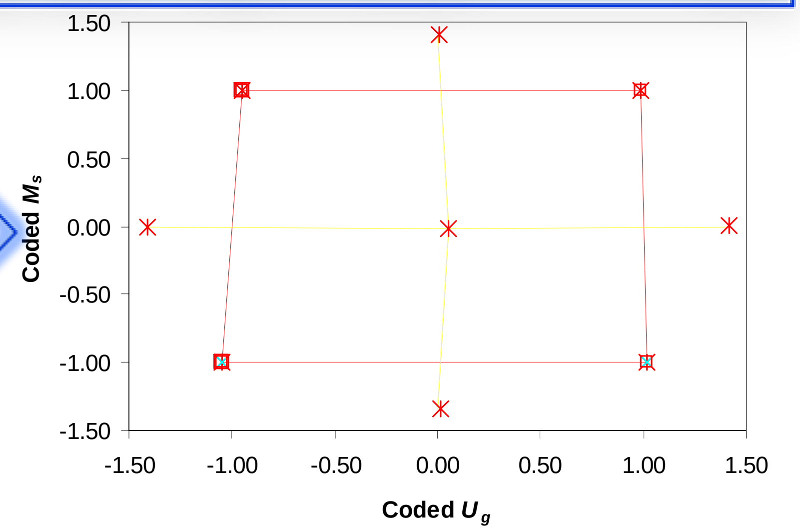
- **Test conducted above fast fluidization**
- **Transformed to allow to extend and allow ANOVA**
- **Factorial points and center point completed**
- **Star points proposed for challenge problem**

| Planned Coded | | baseline values | | Target Setpoints | |
|---|---|---|---|---|---|
| dUg | Ms | Ug* | dM' | $U_g$, ft/s | $M_s$, lb/hr |
| -1 | -1 | 17.2 | 0 | 18.1 | 11,250 |
| 1 | -1 | 17.2 | 0 | 21.5 | 11,250 |
| -1 | 1 | 20.5 | 0 | 21.4 | 77,435 |
| 1 | 1 | 21.1 | 12624 | 25.4 | 90,058 |
| 0 | 0 | 18.8 | 0 | 21.4 | 44,342 |
| 1.414 | 0 | 19.3 | 8957 | 24.3 | 53,299 |
| -1.414 | 0 | 18.8 | 0 | 19.0 | 44,342 |
| 0 | 1.414 | 21.6 | 8785 | 24.2 | 99,927 |
| 0 | -1.414 | 16.6 | 0 | 19.2 | - |

$U_g = \alpha + \beta * dU_g$ coded+ $U_g^*$ **(1)** $dM_s' = \alpha + \beta U_g$ **(3)**

$M_s = \alpha + \beta * M_s$ coded+$dM_s'$ **(2)** $U_g^* = \alpha + \beta M_s$ **(4)**



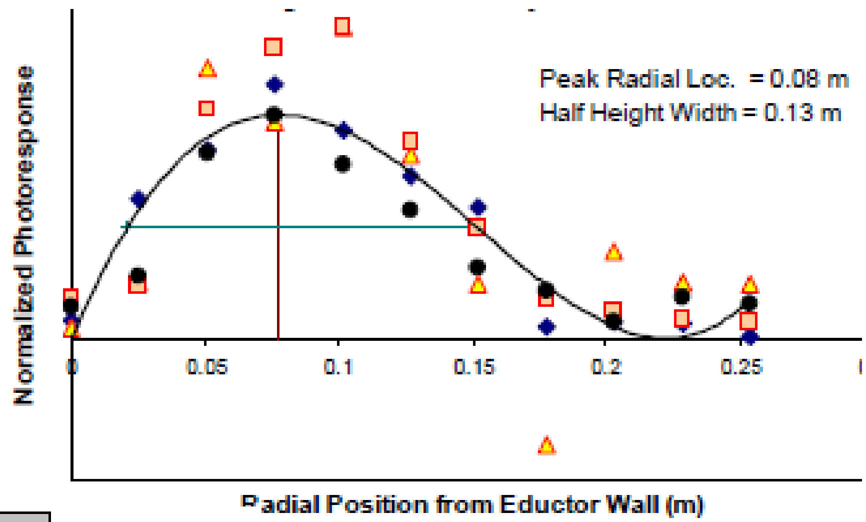



# Actions Items Challenge Problem

- **Finalize schedule**
- **NETL Riser Tests & PSRI FB tests**
  - Describe test conditions, materials and system configuration
  - Define validation criteria
    - Report on guidelines and examples on experimental uncertainty (NETL)
  - Conduct tests
  - Prepare facility
    - Remove aspherical particles (NETL)
    - Install diversion valve & Replace impulse lines into plastic sections
  - Prepare test data base descriptions, indices, etc
- **Other**

# Solids Tracer

- **Tracer particles measured at 15 and 30 cm above the jet**
- **Radial distribution mapped**
- **Characterized response by peak location and half-width**




| | 0.15 m Above Jet | | 0.30 m Above Jet | | |
|---|---|---|---|---|---|
| | Radial Peak Location (m) | Half-Height Width (m) | Radial Peak Location (m) | Half-Height Width (m) | Riser Pressure Drop (kPa) |
| SN0 | 0.08 | 0.13 | 0.08 | 0.15 | 16.527 |
| SN1 | 0.05 | 0.10 | 0.05 | 0.11 | 16.941 |
| SN2 | 0.13 | 0.18 | 0.14 | 0.17 | 16.393 |
| SN3 | 0.10 | 0.12 | 0.10 | 0.15 | 16.647 |
| SN4 | 0.06 | 0.11 | 0.07 | 0.14 | 16.564 |
| SN5 | 0.11 | 0.15 | 0.12 | 0.17 | 17.247 |
| SN6 | 0.05 | 0.19 | 0.08 | 0.16 | 6.364 |
| SN7 | 0.09 | 0.15 | 0.13 | 0.20 | 8.973 |

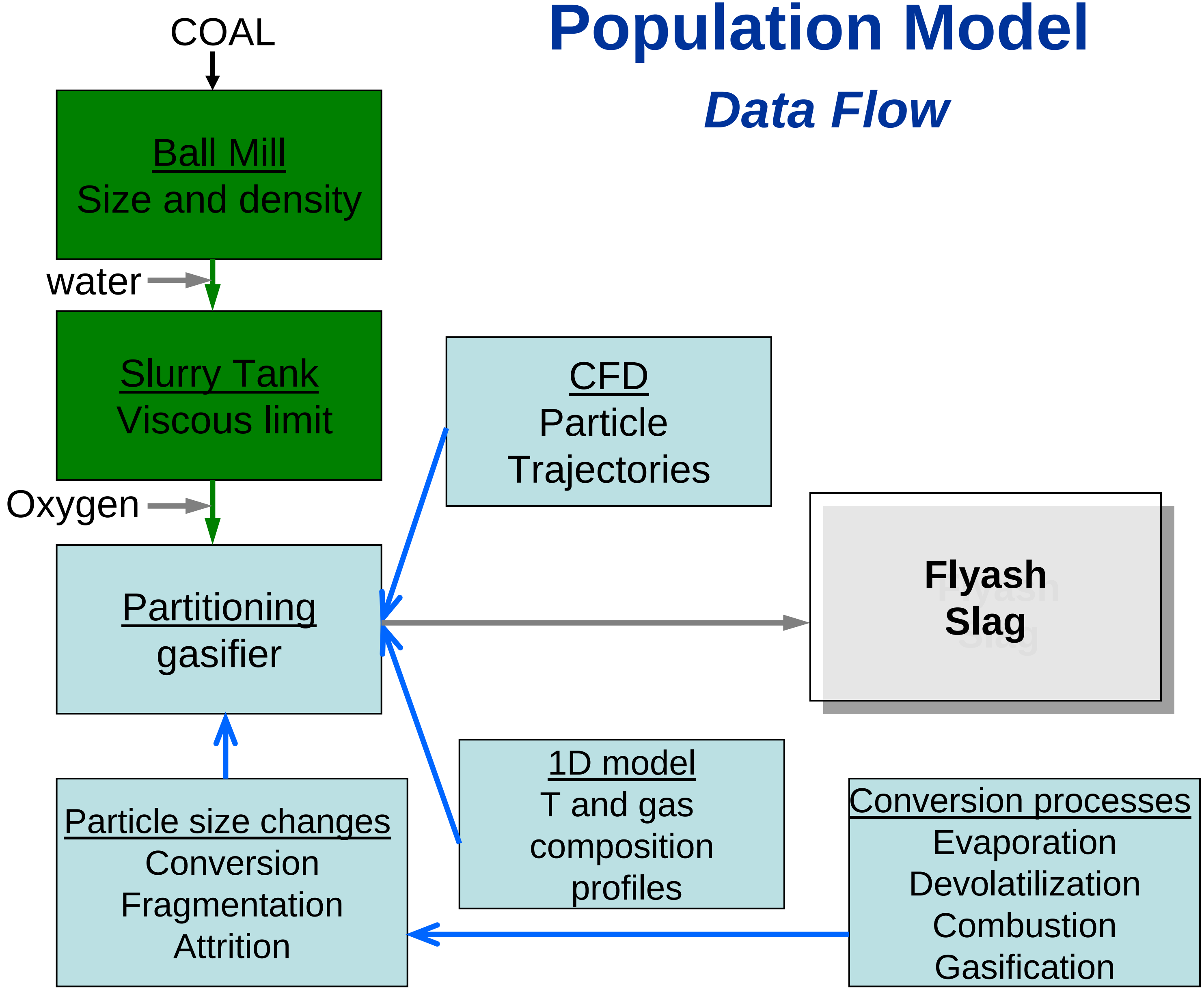
# The NETL Spiral

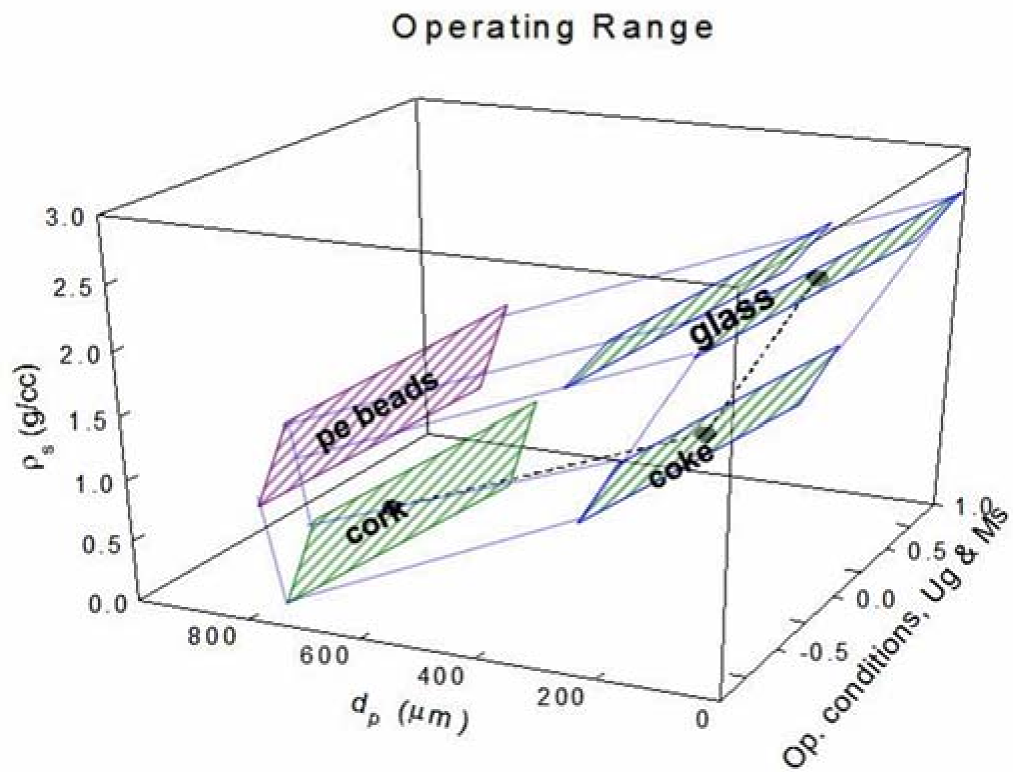
- **Data acquisition software averages encoder counts over 2 seconds**
- ***Assuming* 1 foot of bed travel = 180 degrees of Spiral rotation = 64 counts (Ideally)**
  – Counts/Second gives Bed Velocity

- ***Assuming* plug flow for bed flow**
- ***Assuming* cross sectional area of bed = Area of Flow**
- **Bed Velocity x Area of Flow = Bed Volumetric Flow**
- ***Assuming* the Bulk Density of the bed is known**
  – Bed Volumetric Flow x Bulk Density = Bed Mass Flow

# Population Model

## *Data Flow*




Operating Range
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ρs (g/cc)
pe beads
glass
cork
coke
800
600
400
200
0
dp (μm)
1.0
0.5
0.0
-0.5
Op. conditions, Ug & Ms