Understanding the Hydrodynamics in Biomass Gasifiers

Ray Cocco

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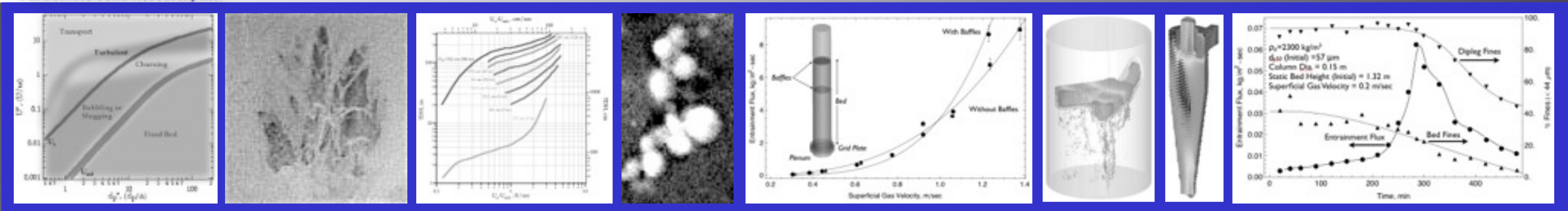
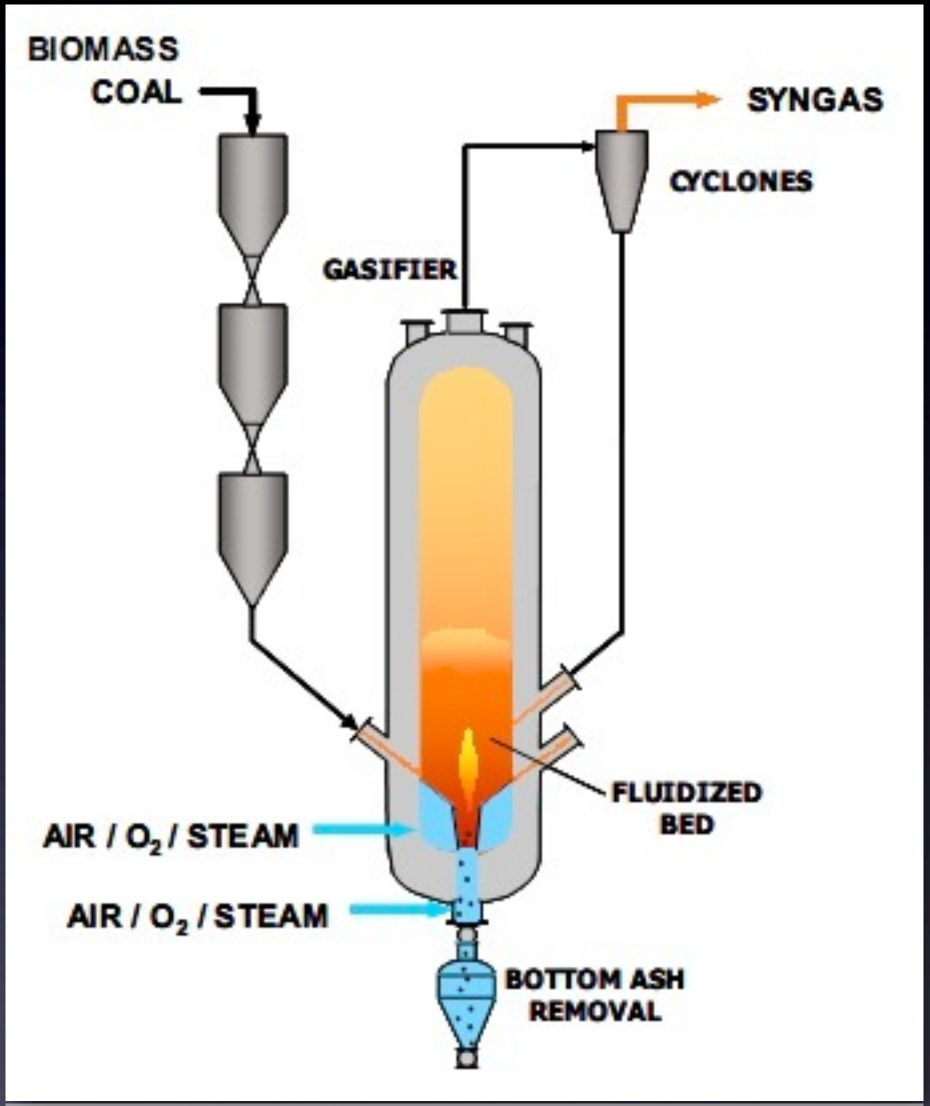
PSRI
Particulate Solid Research, Inc.

Applying the Fundamentals



Fluidized Bed Gasifier Concept

- Typical feeds
  - Coal
  - Black liquor
  - Wood
  - Everything else
- Bed mixtures
  - Biomass and sand or olivine
  - Biomass co-gasification with coal



GTI Concept

Outline

- Particle behavior and flow regimes
- Bed behavior
- Entrainment
- Bubble
- Multiphase jet
  - Gas jets
  - Gas-liquid jets
- Summary

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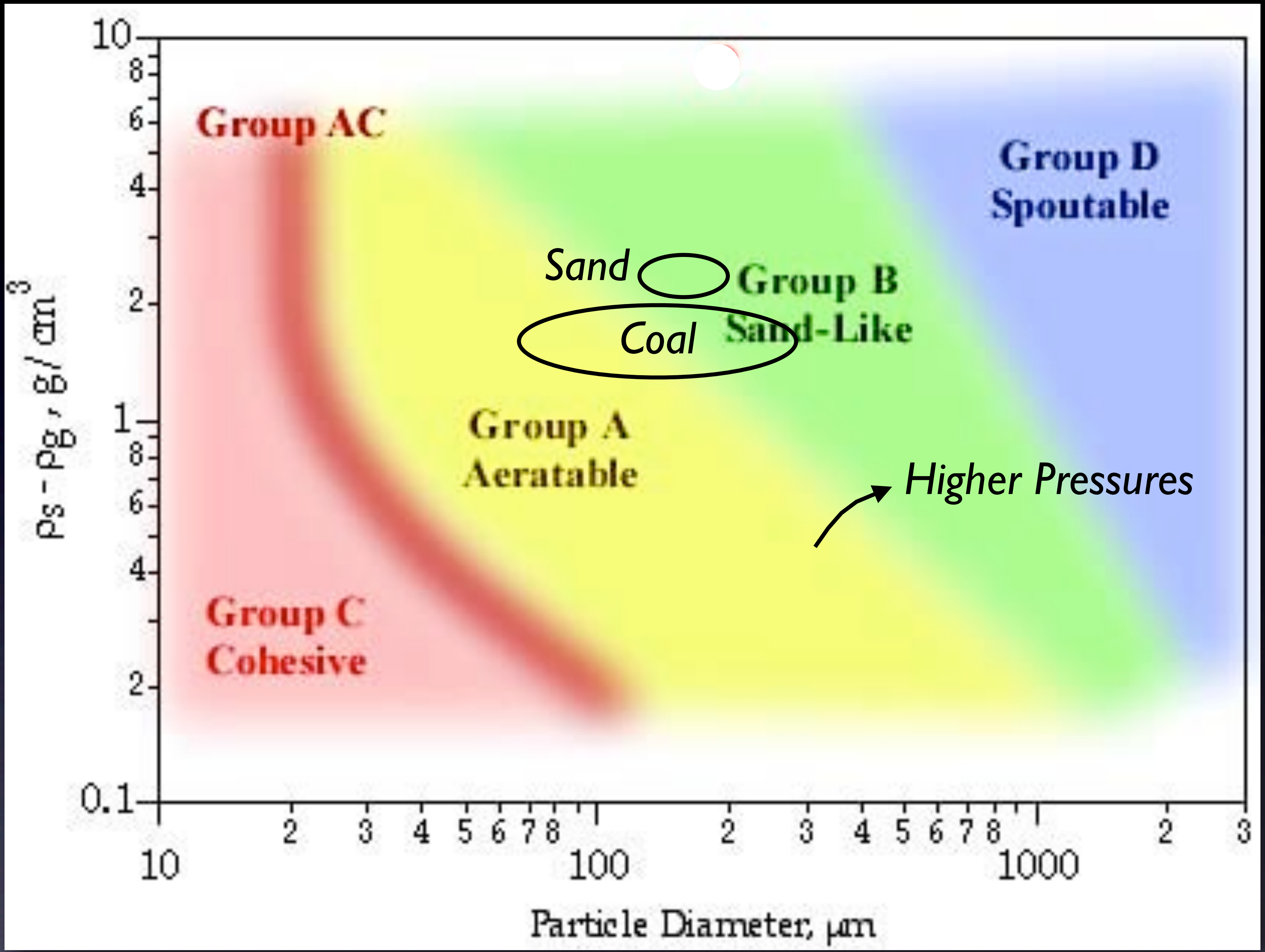
Particle Properties

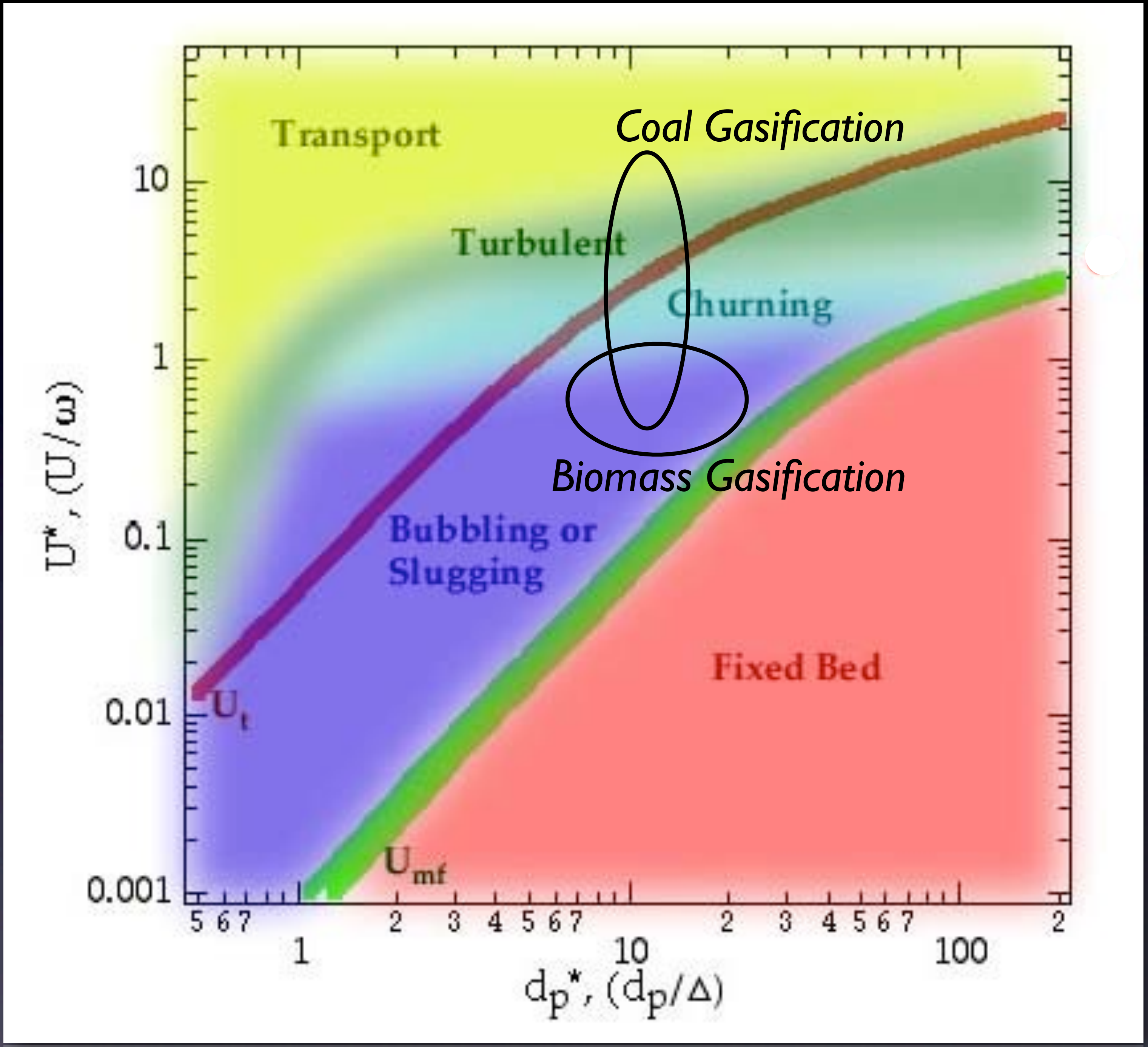


- Sand is "inert" and remains a Geldart Group B Particle
- Coal is typical fed in as Geldart Group B but bed properties can be more indicative of Geldart Group A

Differences Between Geldart Groups A and B

Properties	Geldart Group A	Geldart Group B
Bubbles	Small, 2 to 4 inches	Large! Prone to Slugging
Permeability	Low	High
Heat and Mass Transfer	High	Low
Bed Expansion	Significant!	Moderate
Entrainment	High	Low

Flow Regimes



- To date, most biomass gasifier concepts are bubbling and churning fluidized beds

Difference Between Flow Regimes

Properties	Bubbling	Turbulent
Bubbles	Regular Shaped, Stable	Elongated, Irregular, Unstable
Mass Transfer	High	Higher
Heat Transfer	Good	Best
Bed Profile	Relatively Uniform	Core-Annulus
Reactor Height	Short	Tall

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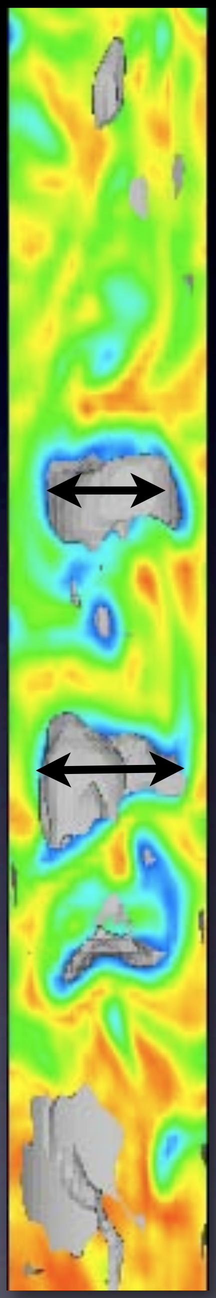
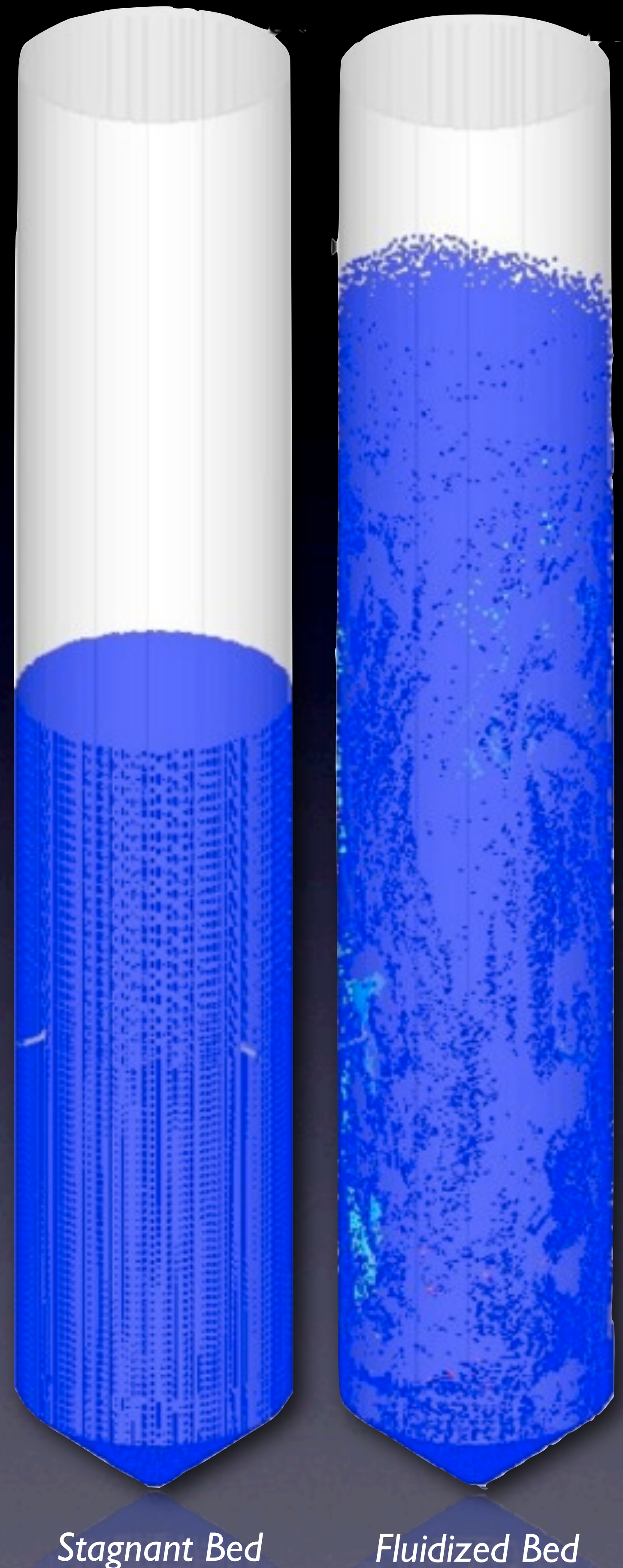
- Particle behavior and flow regimes
- Bed behavior
  - Slugging
  - Bed expansion
  - Jetsam/flotsam?
    - Biomass feeds
    - Agglomerates
  - Gas bypassing
- Entrainment
- Bubble
- Multiphase jet
  - Gas jets

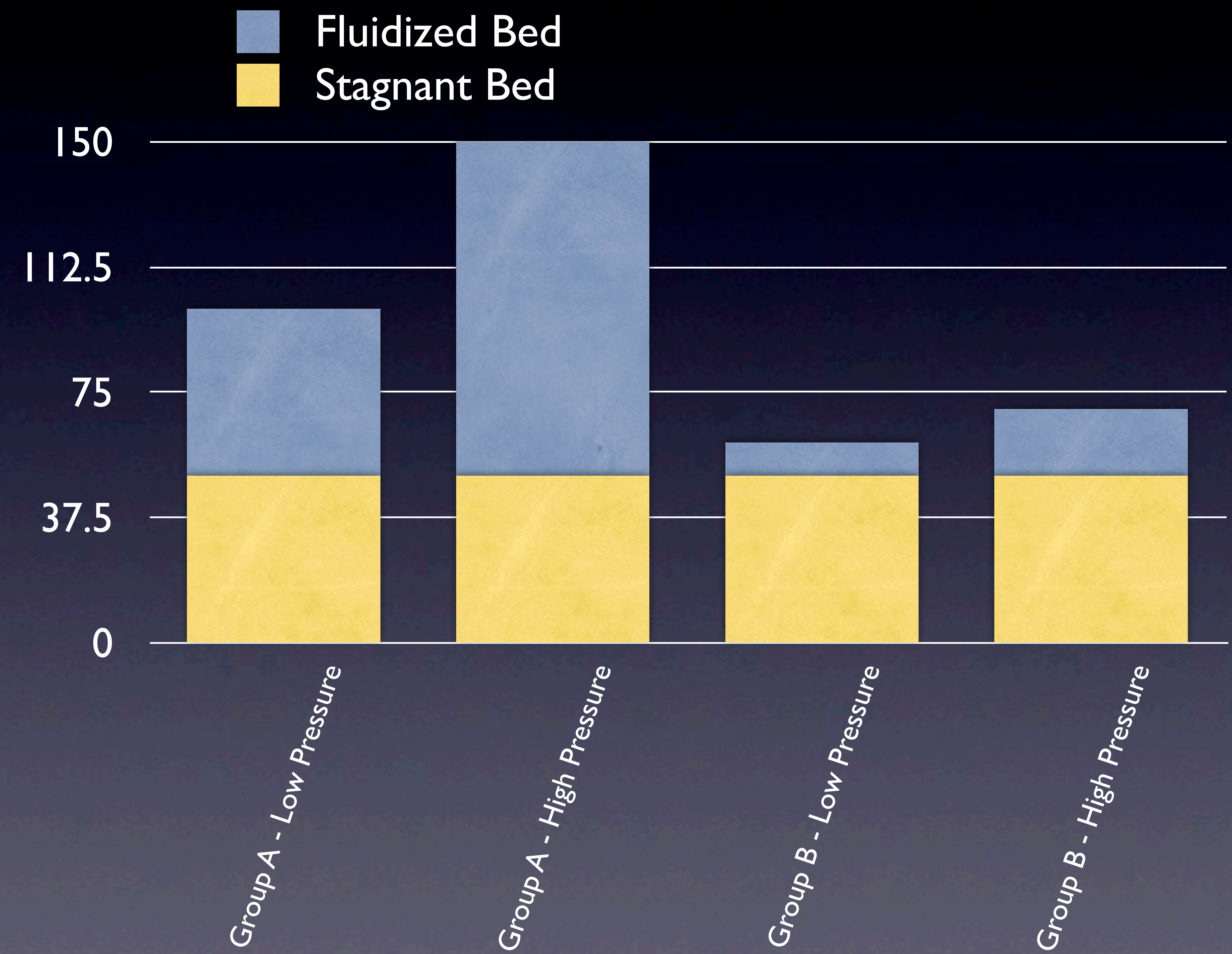
Slugging



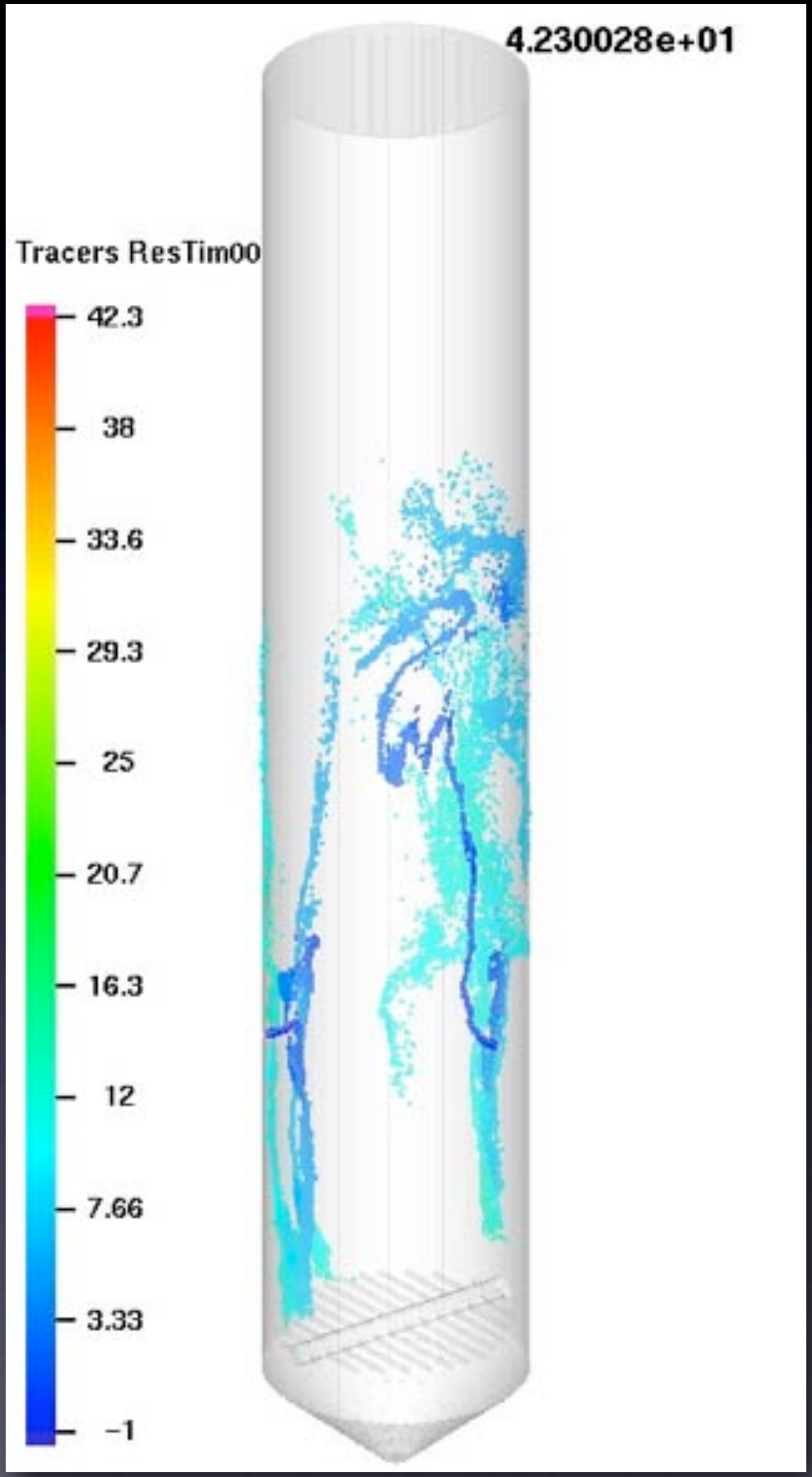
- Larger particles produce larger bubbles
- Larger bubbles rise faster than smaller bubbles
- Bubbles larger than 2/3 the diameter of the bed can cause the bed to slug
  - Issue with slugging
    - Unstable fluidization operation
    - May flood cyclones
    - Lower mass transfer
      - Residence time of gas in bubble
      - Surface to volume of exposure to emulsion

Bed Expansion



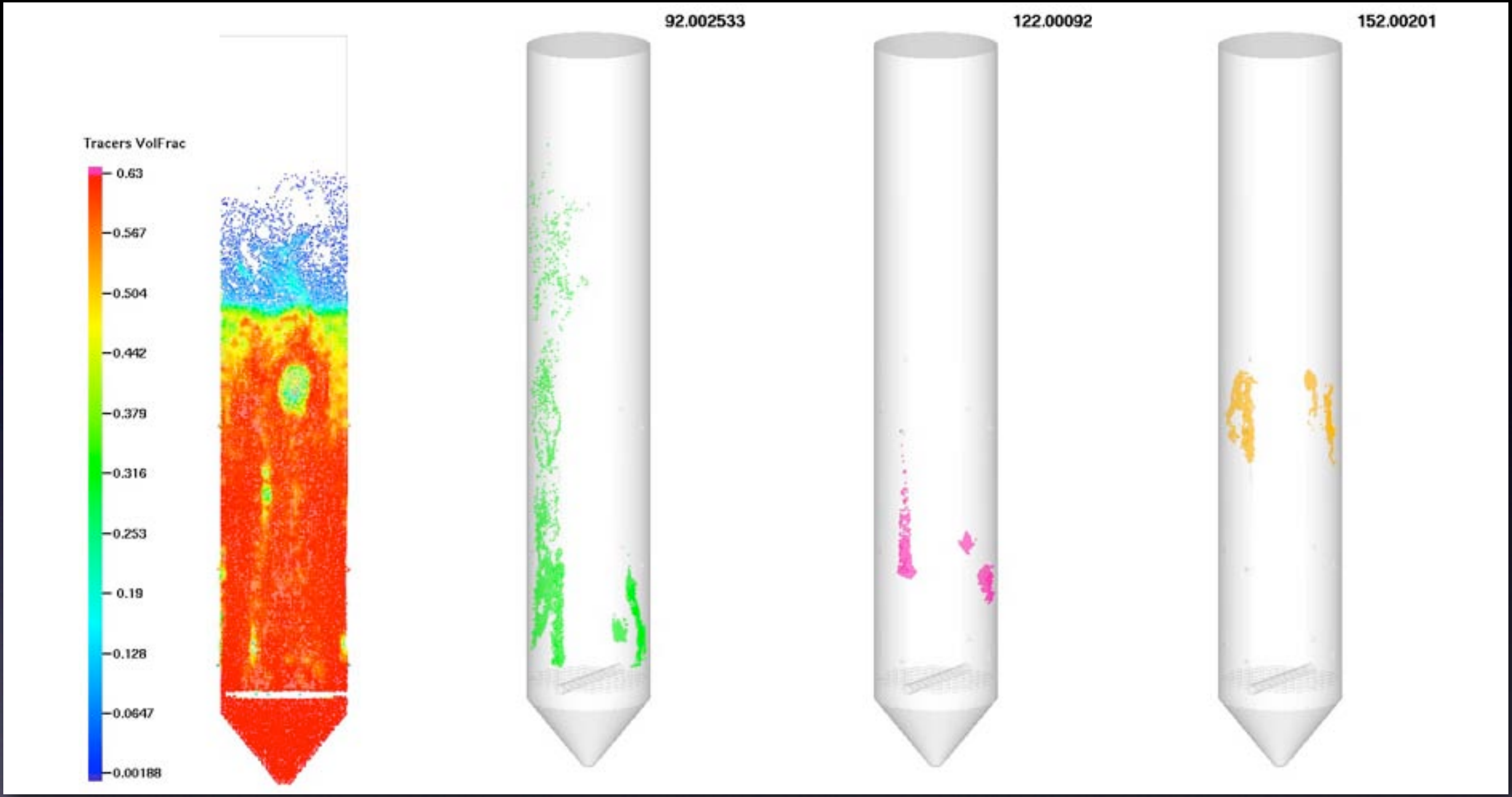


Jetsam & Flotsam - A Biomass Problem



- Coal injection into a 25-foot (7.6-m) diameter fluidized bed of coal
- Neutrally buoyant particles

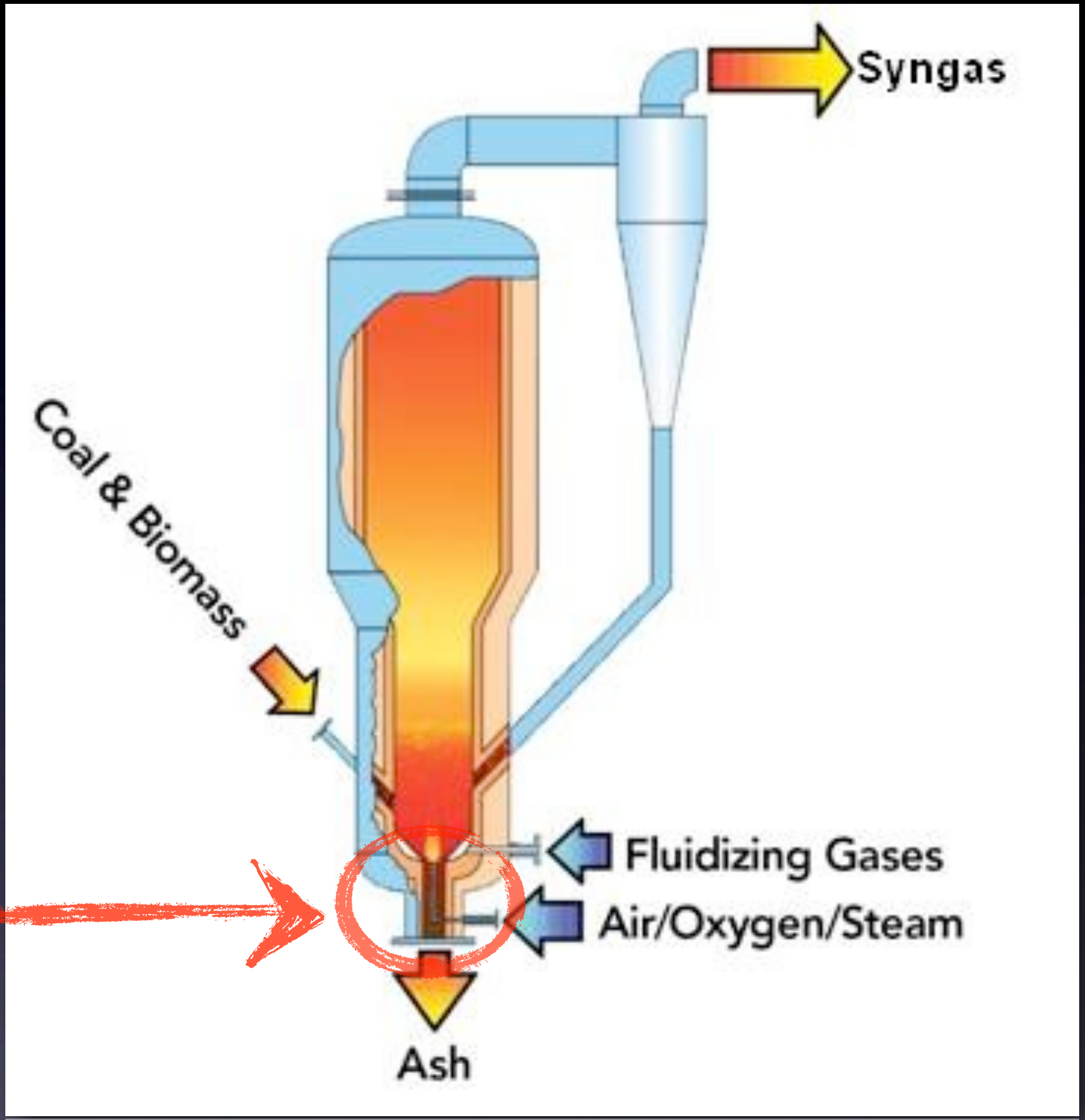
Jetsam & Flotsam - A Biomass Problem



- Little penetration in the bed
- Particle buoyancy seems to be important

Agglomerates

Built-in Classifier

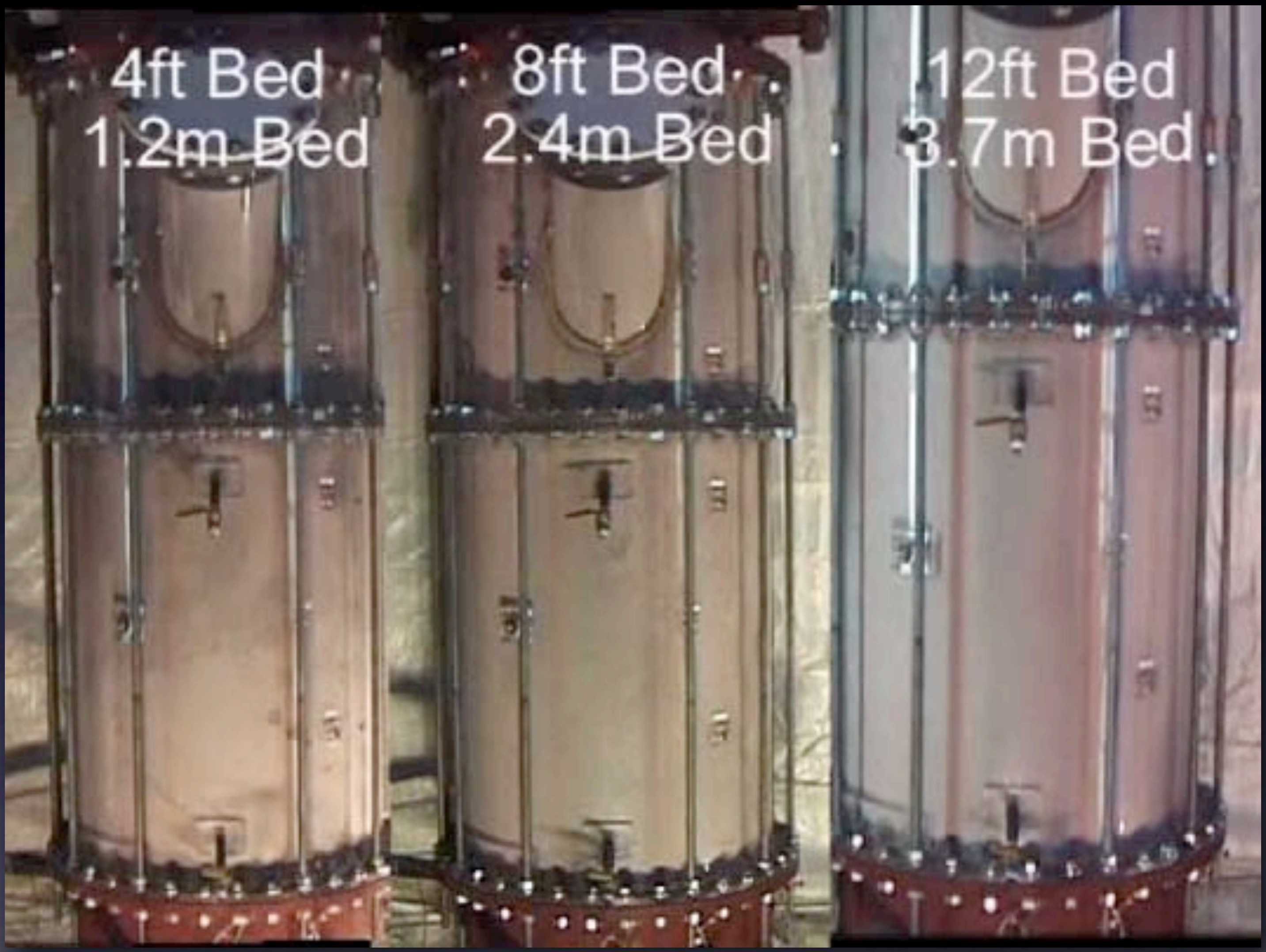


GTI U-Gas Process
SES

- Low quality coal
- Silica sand (bed and feed)

Gas Bypassing and Bed Heights

- Gas bypassing is a function of bed height or dense particles
    - Gas compression is the real issue
- What may be good in your pilot plant may not be sufficient in your commercial unit
- May be due to compression of the emulsion phase and bed permeability
- Mostly a Geldart Group A issue at low pressures



90 cm ID

0.9 m ID Fluidized Bed

Ug = 0.46 m/sec with FCC powder (3% fin

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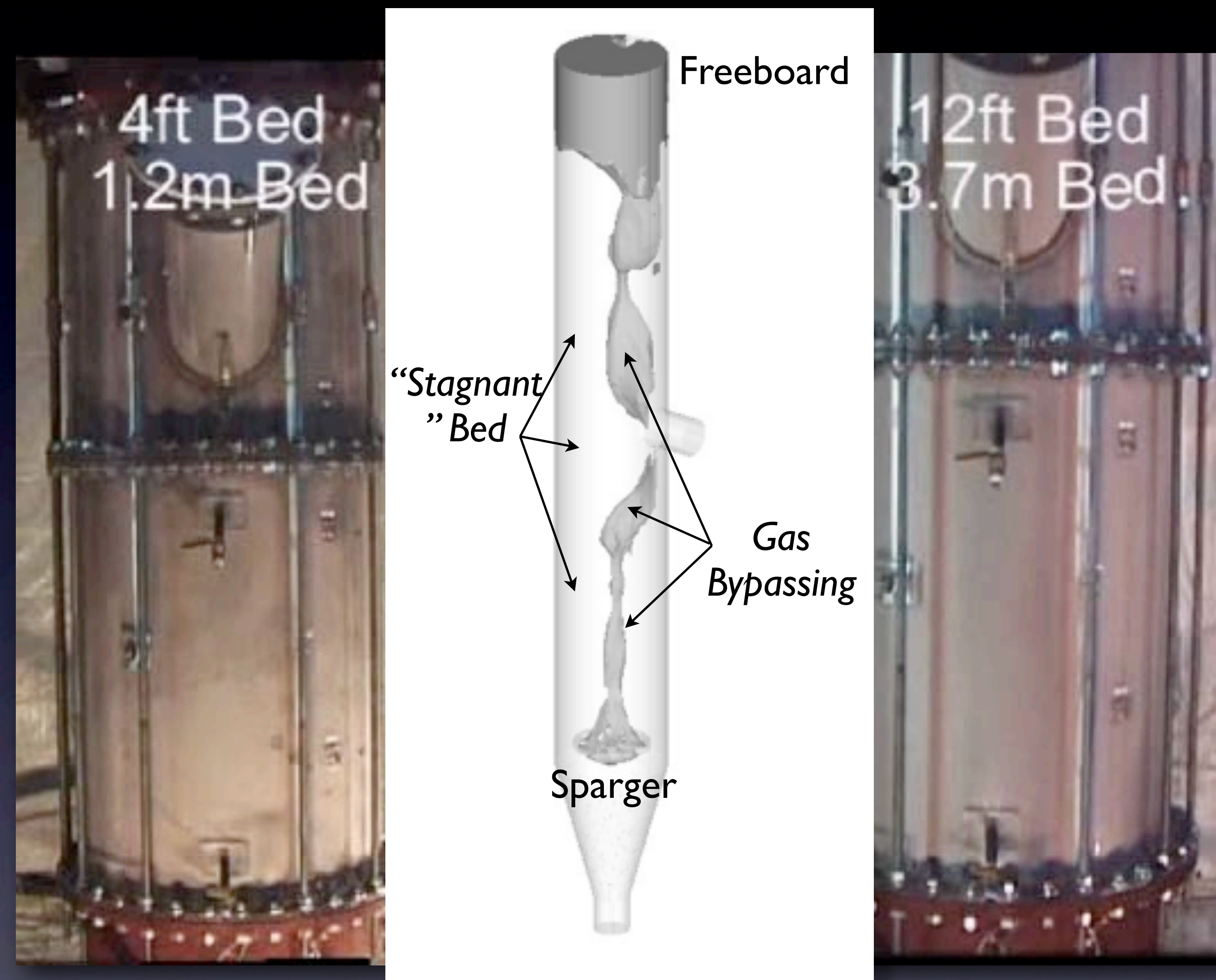

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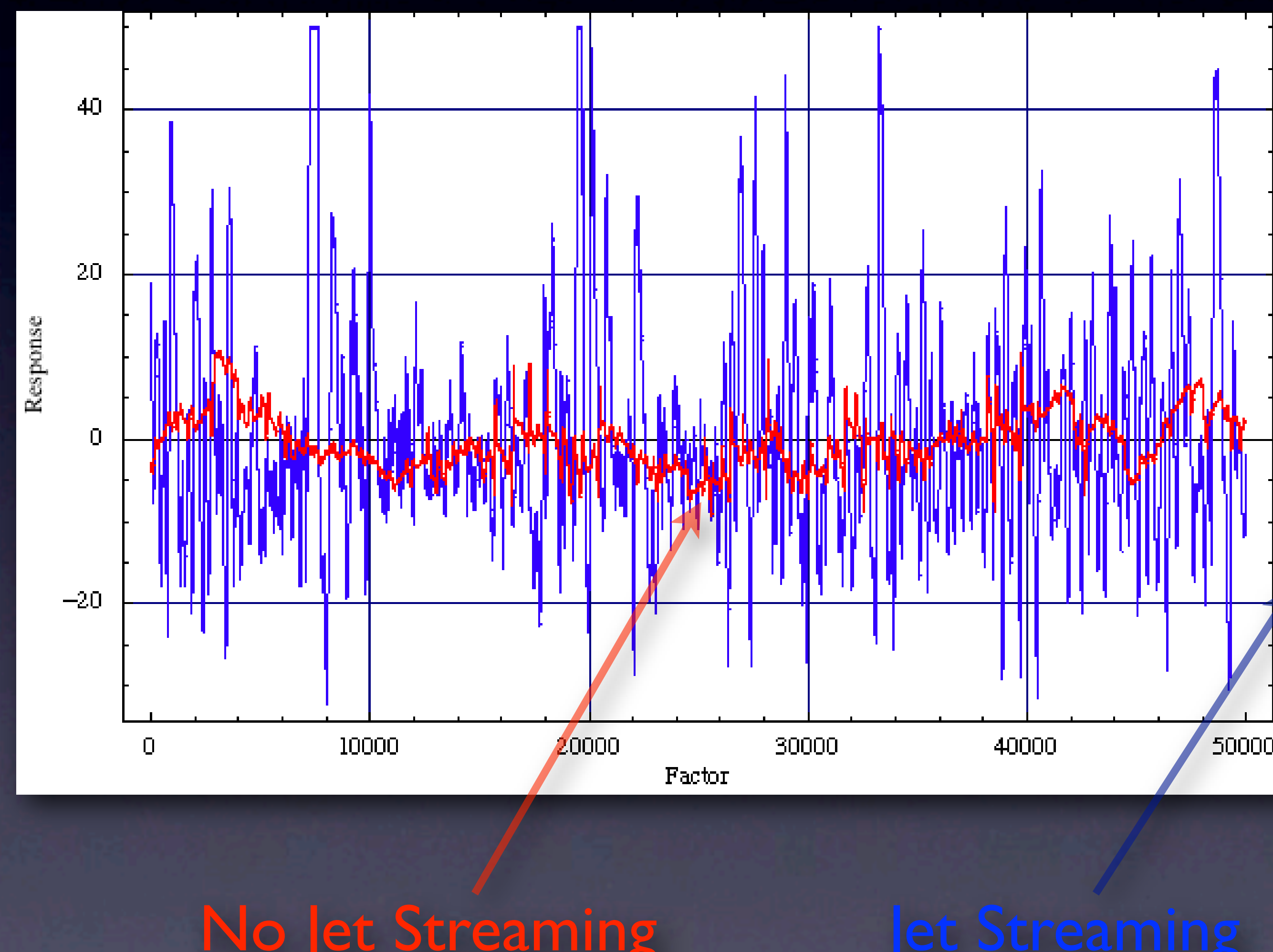
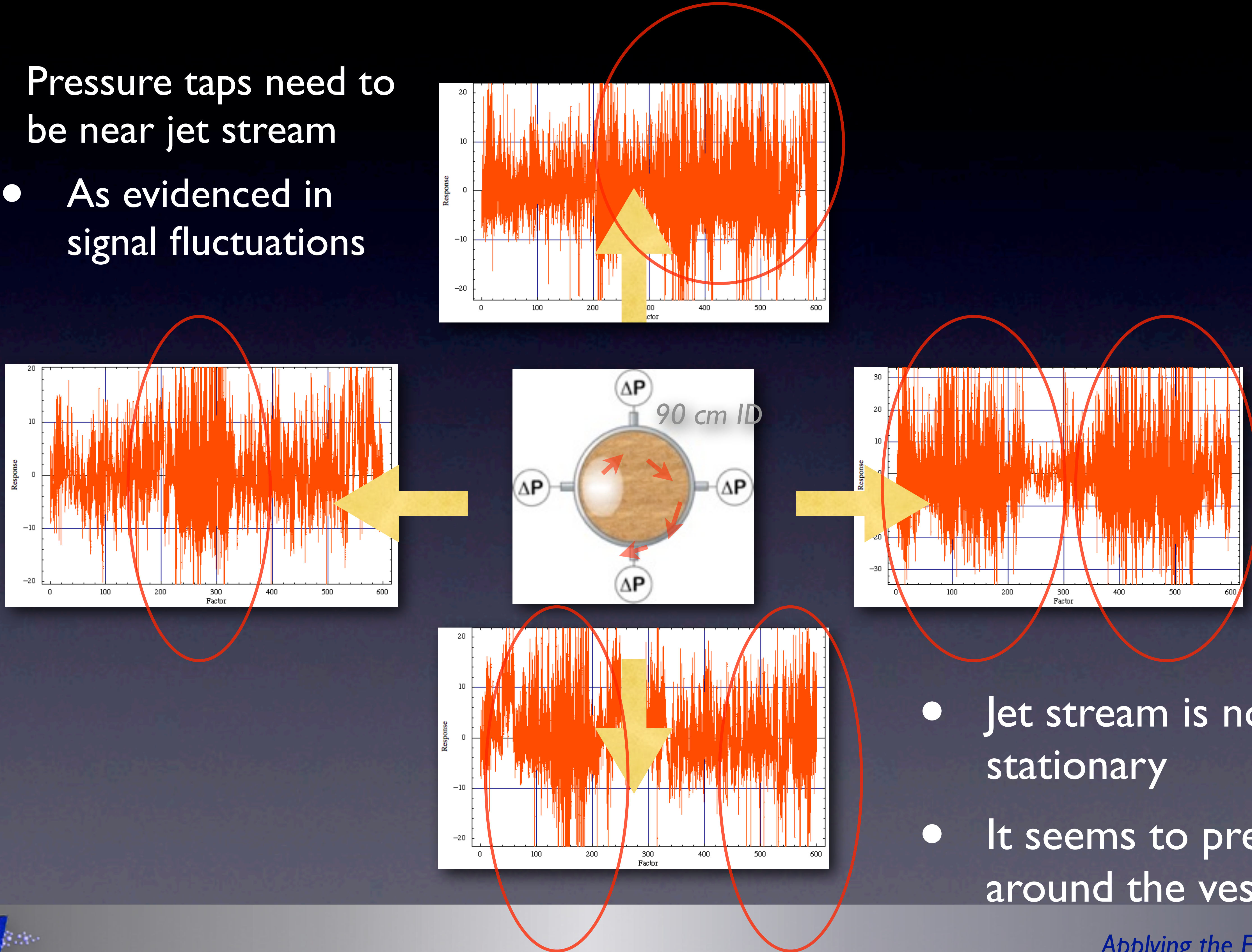
Pressure Fluctuations as an Indicator of Gas Bypassing



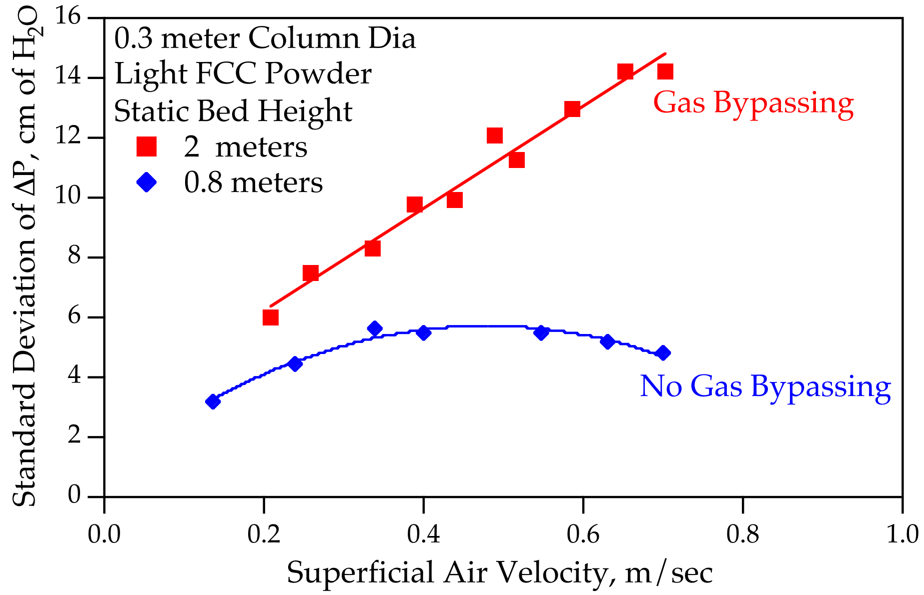
- Pressure fluctuations increased when jet streaming was present
  - But this was mostly a local detection

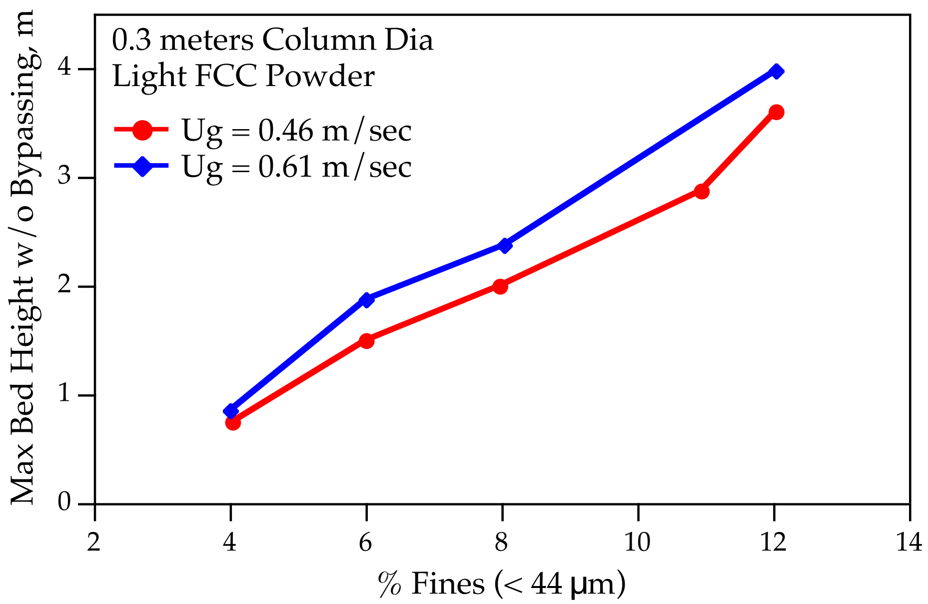
Precession of Gas Bypassing as Detected from Pressure Fluctuations

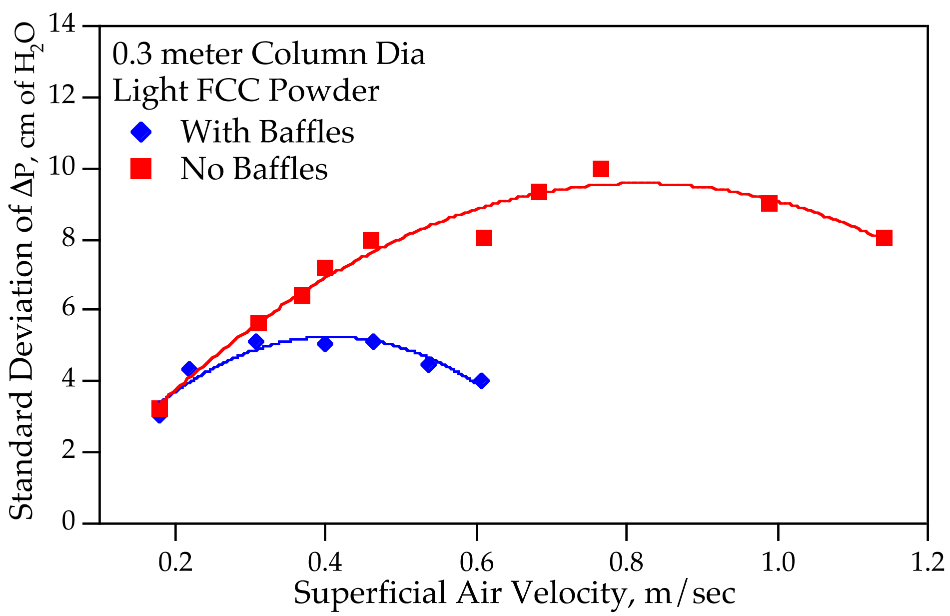
- Pressure taps need to be near jet stream
    - As evidenced in signal fluctuations



- Jet stream is not stationary
- It seems to precess around the vessel



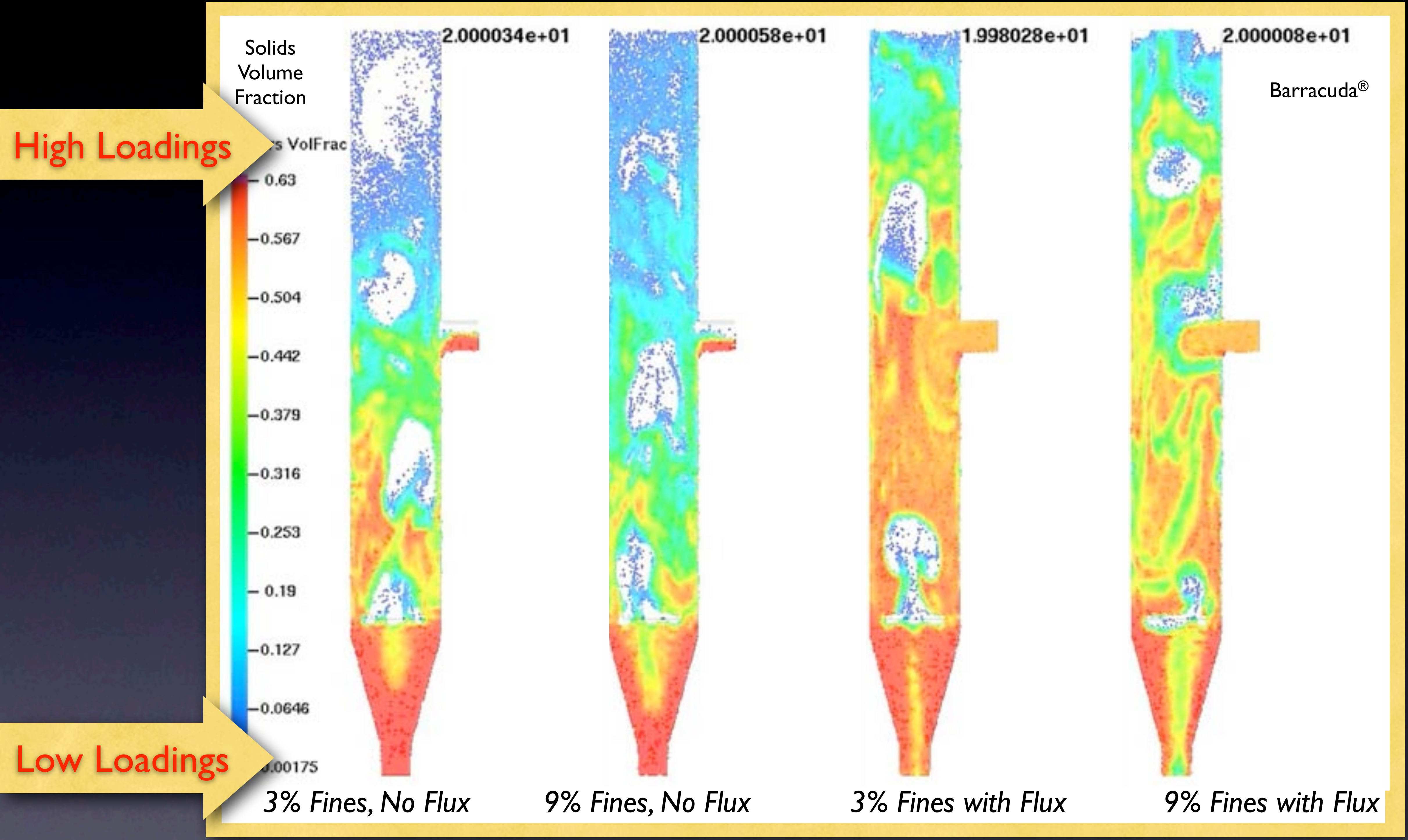




Managing Gas Bypassing

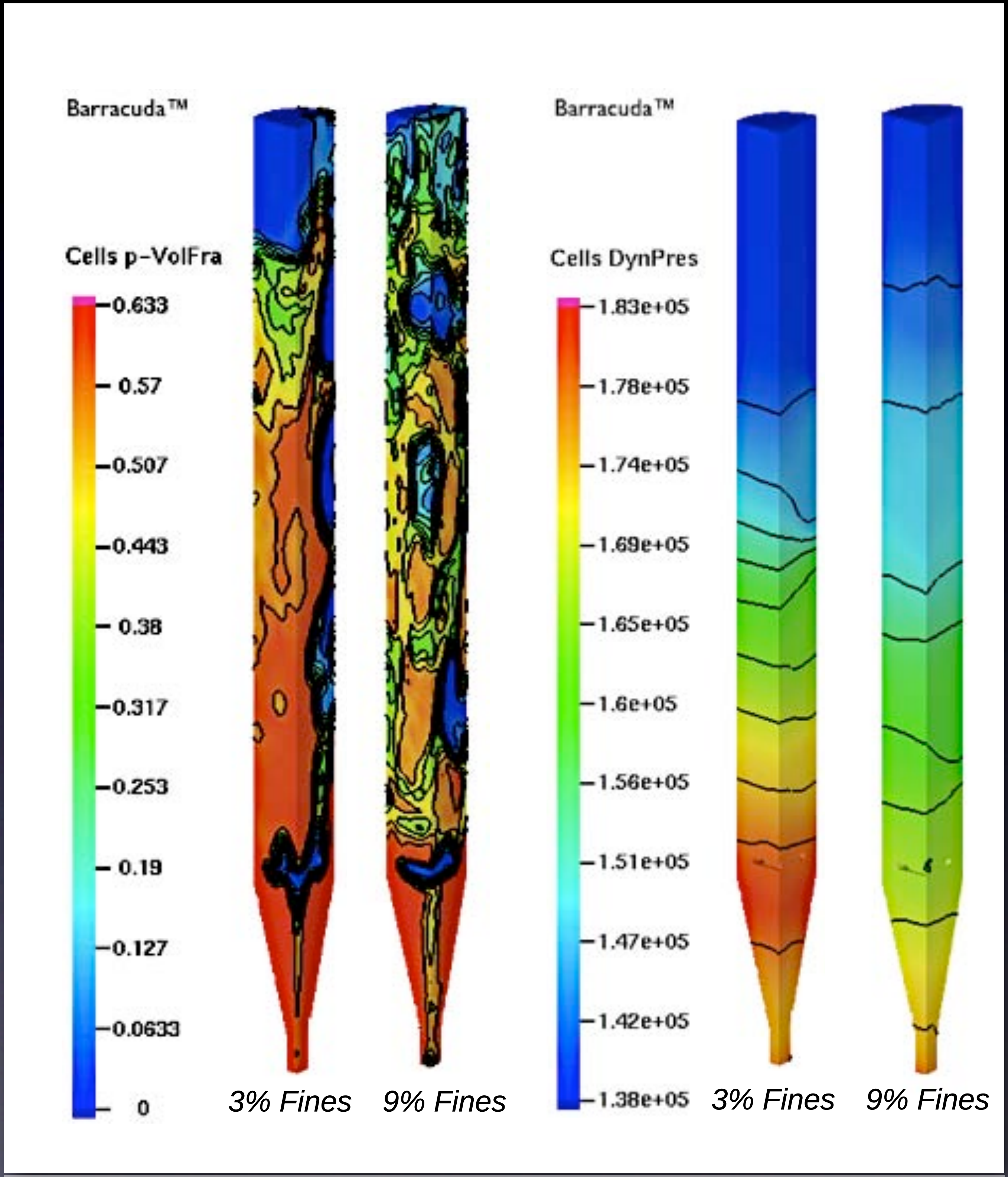
- Jet streaming is a function of gas permeability and bed weight
  - Most with Geldart Group A powders
- Jet streaming can be managed
  - Limiting the bed height
    - Not always possible
  - Adding particle fines
  - Increasing the pressure
    - More gas can get into the emulsion
  - Adding baffles

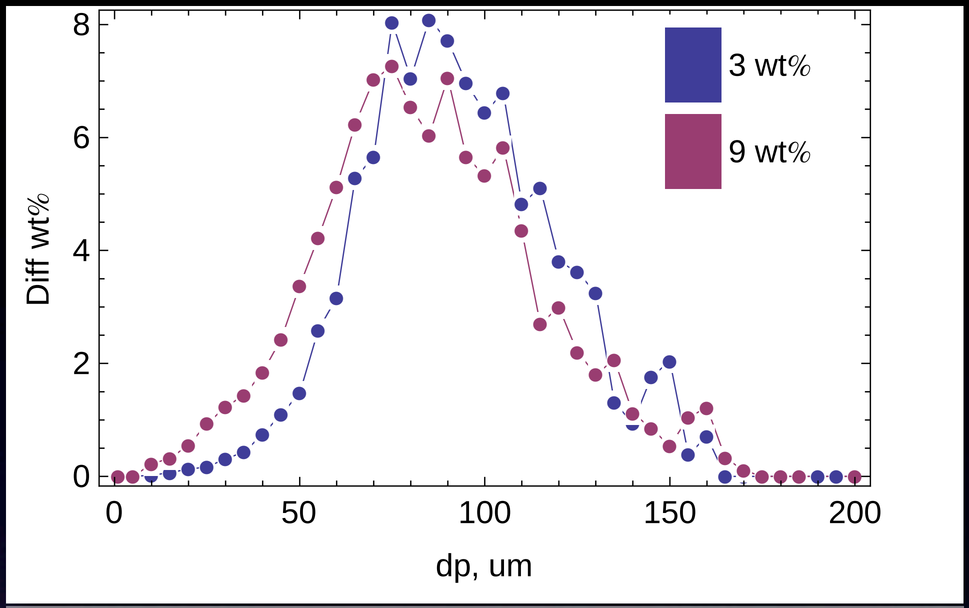
Effects of Imposed Solids Flux



2 ft/sec (0.6 m/sec) Superficial Gas Velocity

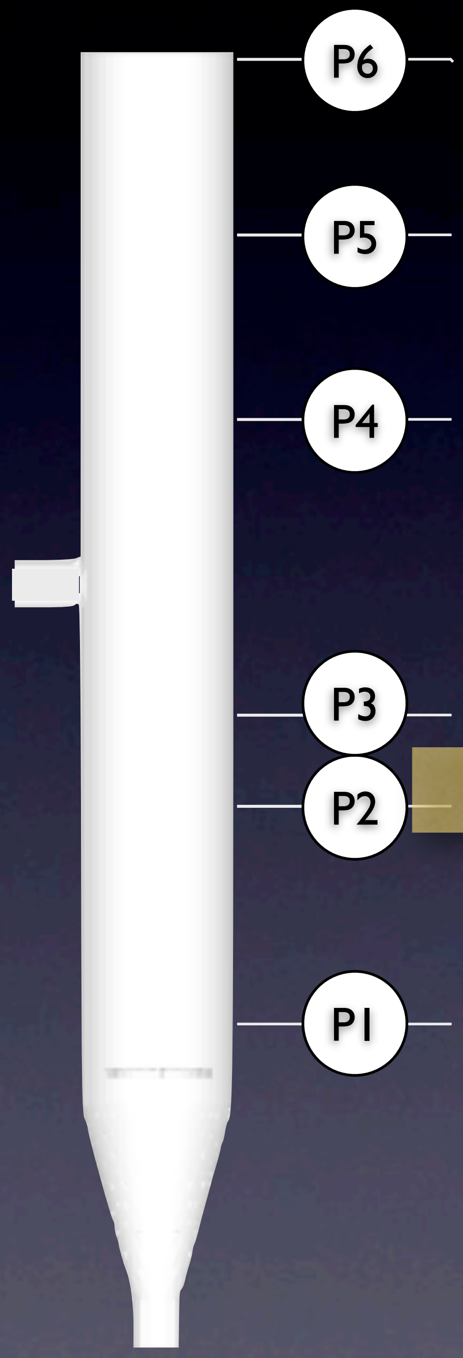
Modeling Gas Bypassing



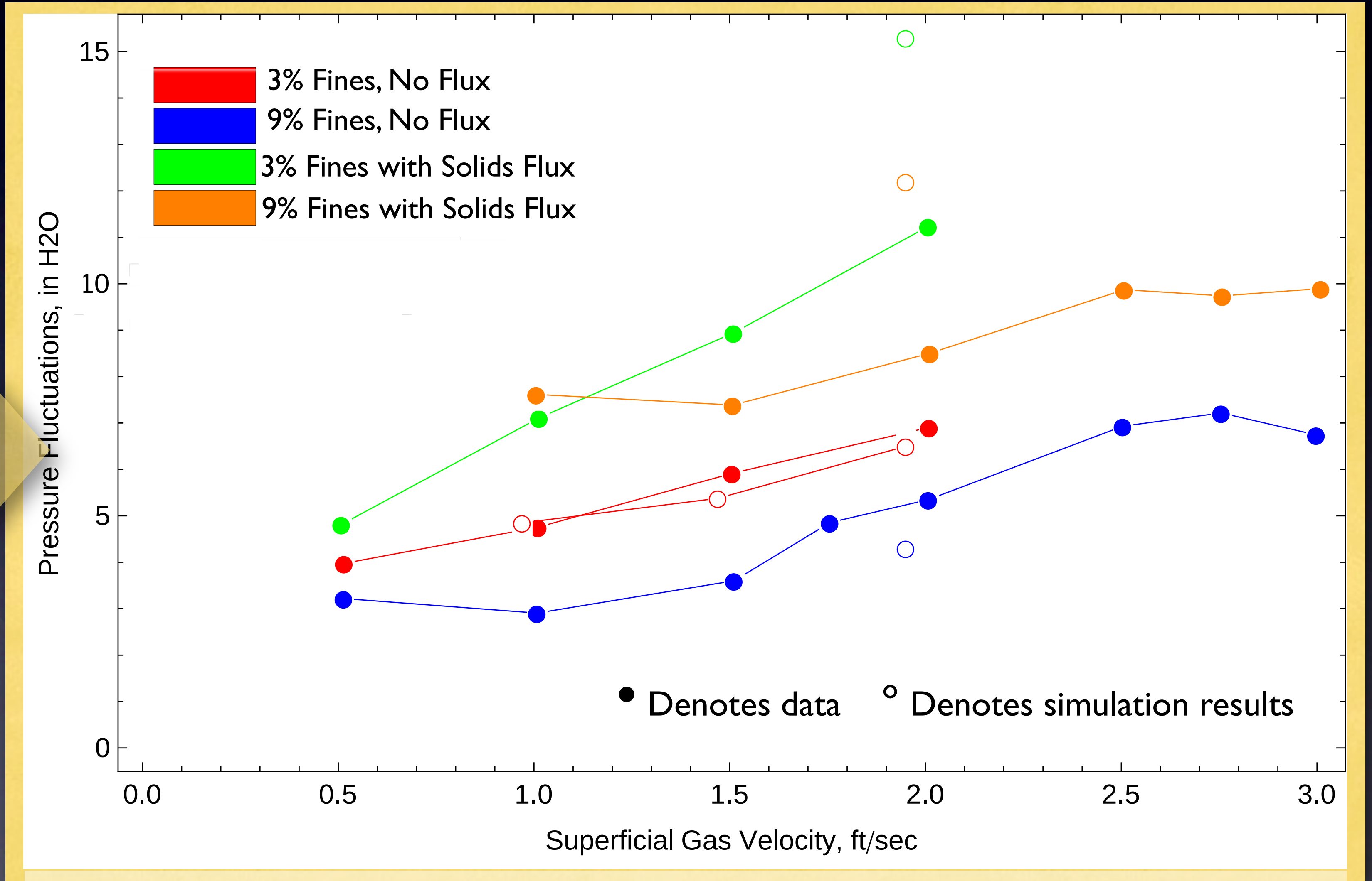


- Barracuda® was able to simulate the role of fines and jet streaming
  - In low fines case, regions of dense emulsions, 55% loading, were observed
  - In high fines case, maximum bed density did not exceed 40% loading.

Validation with Pressure Fluctuations



- Barracuda™ was able to capture the trends but over predicted pressure fluctuations for the imposed solids flux cases



Validation with Pressure Fluctuations

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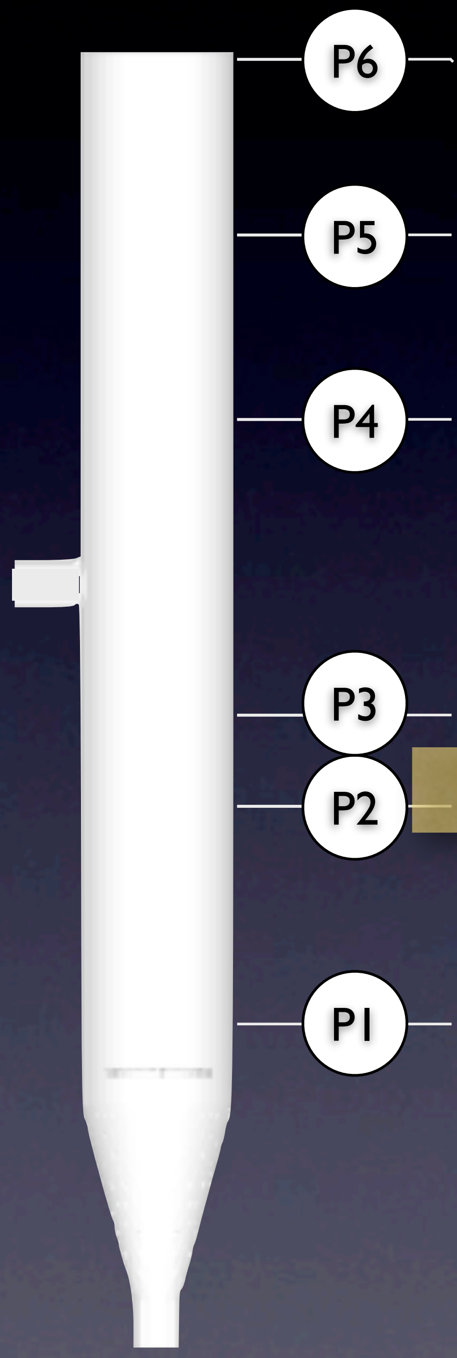
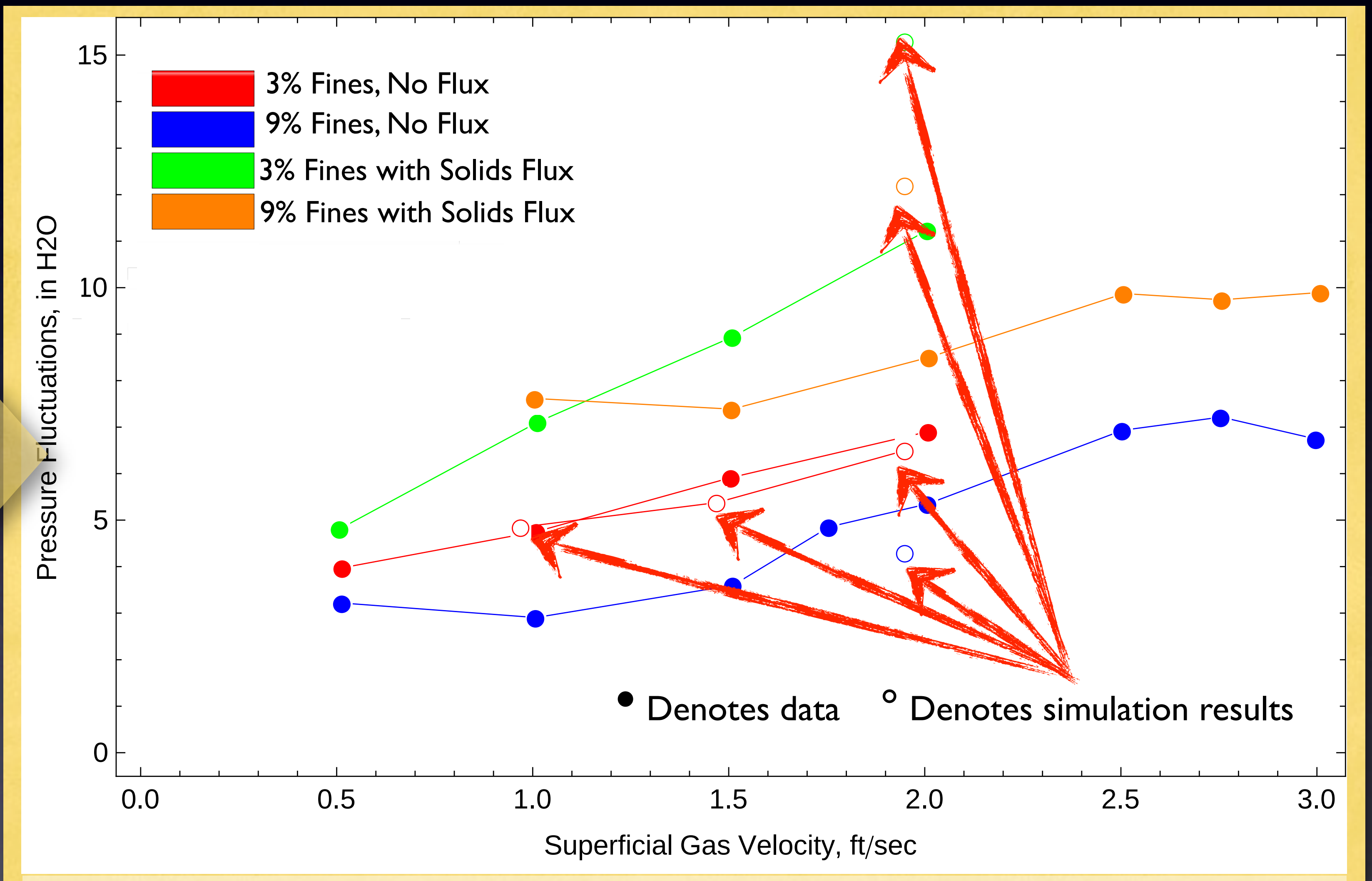
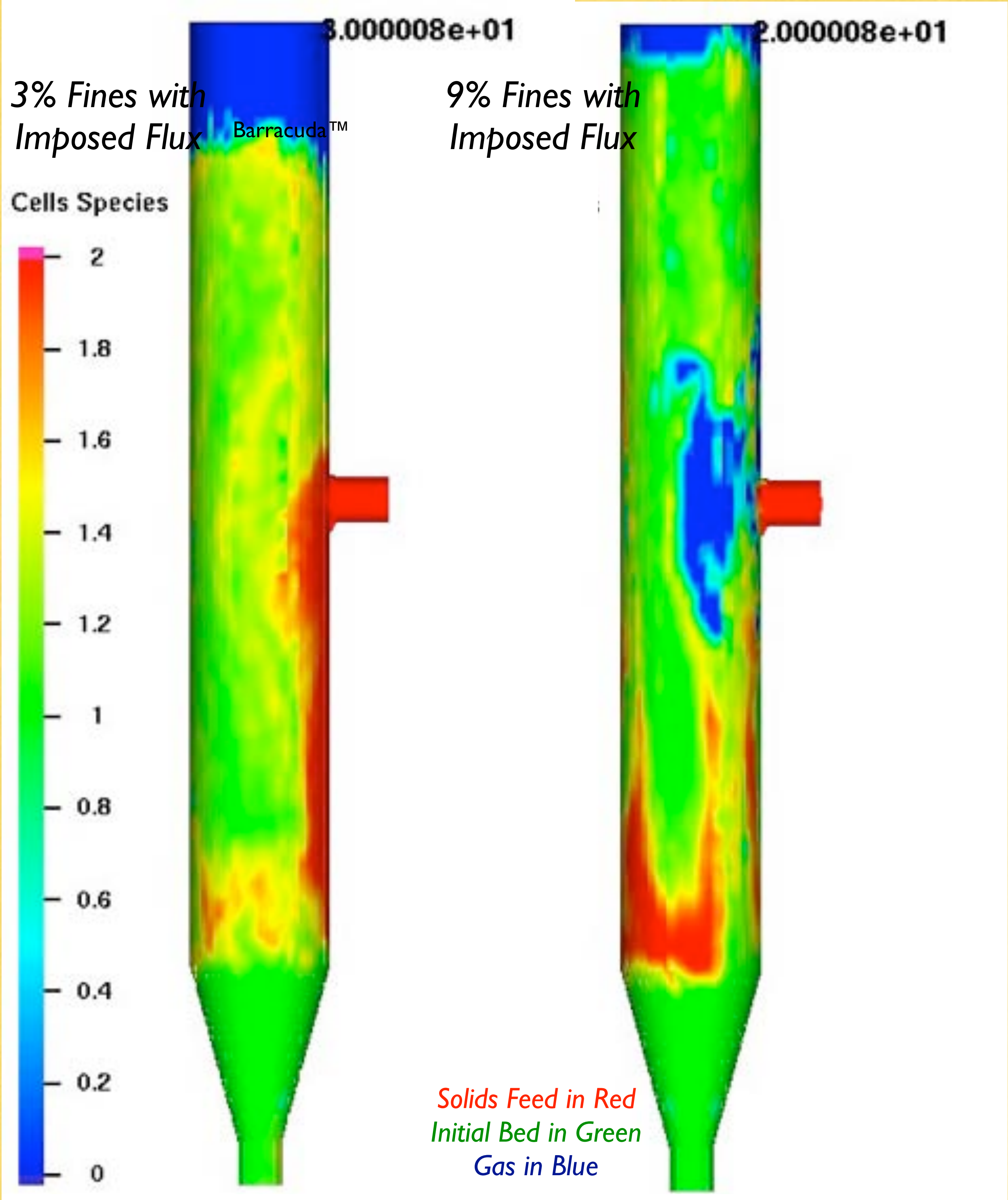
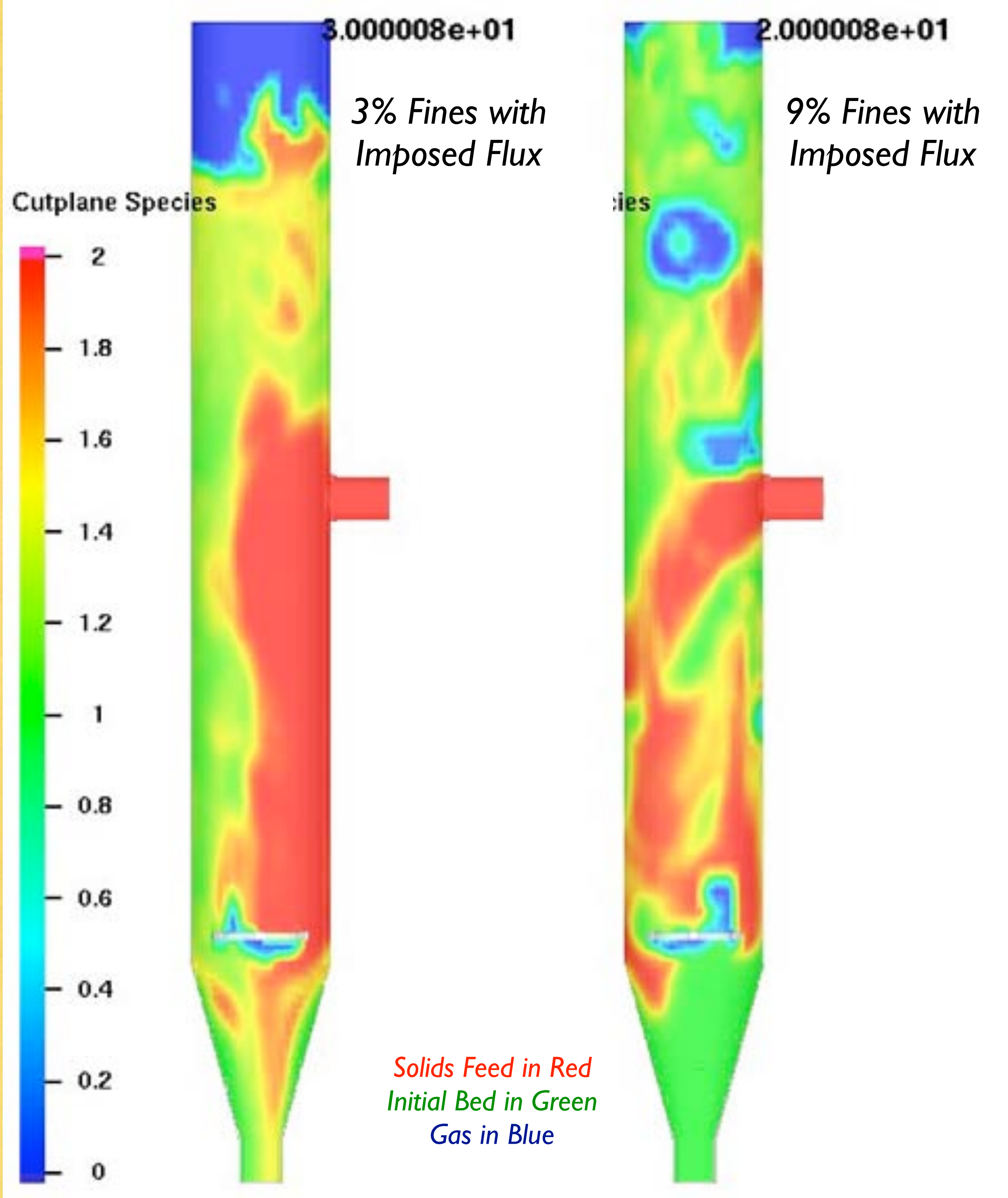




Mixing and Gas Bypassing



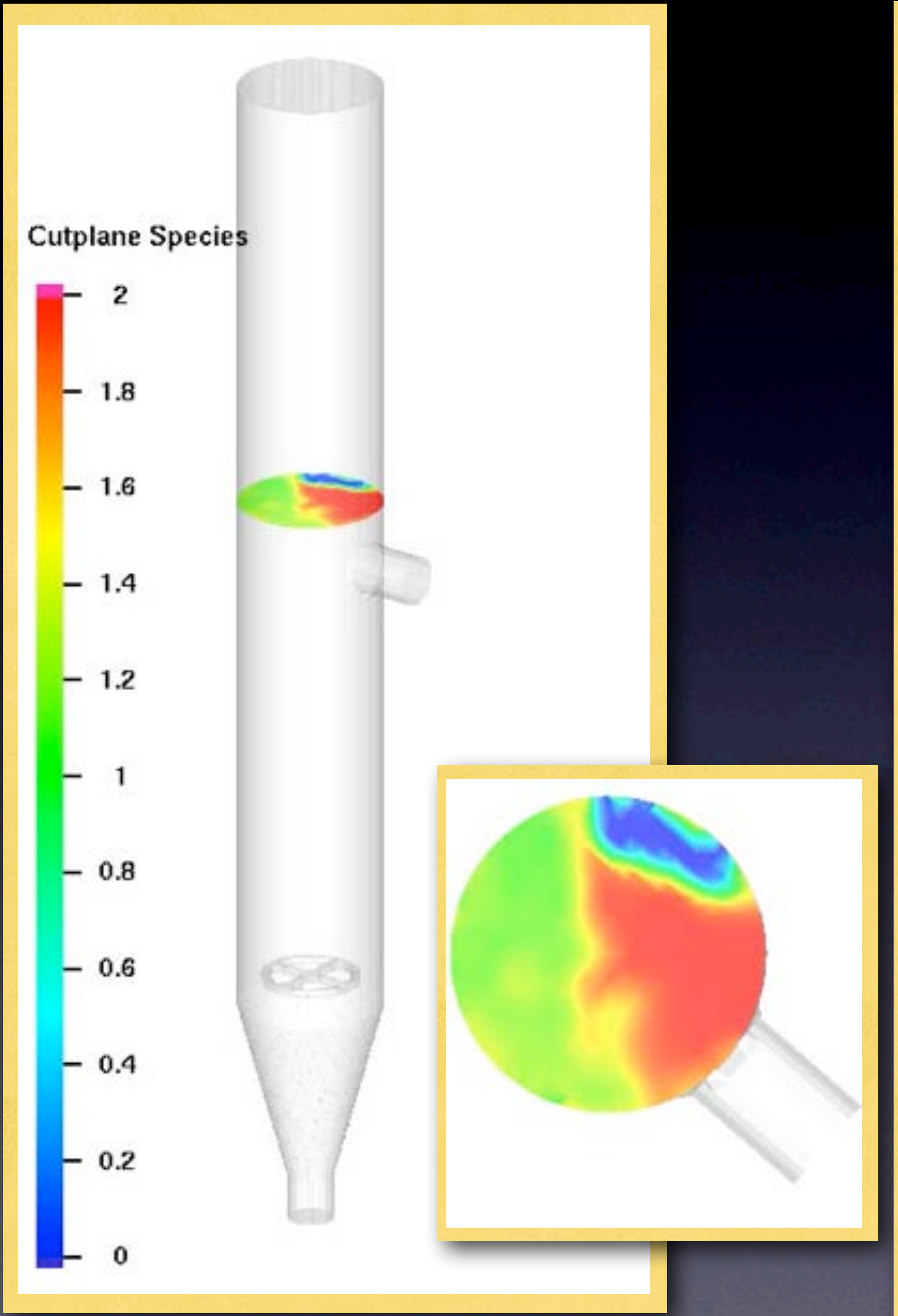
Exterior View - Wall



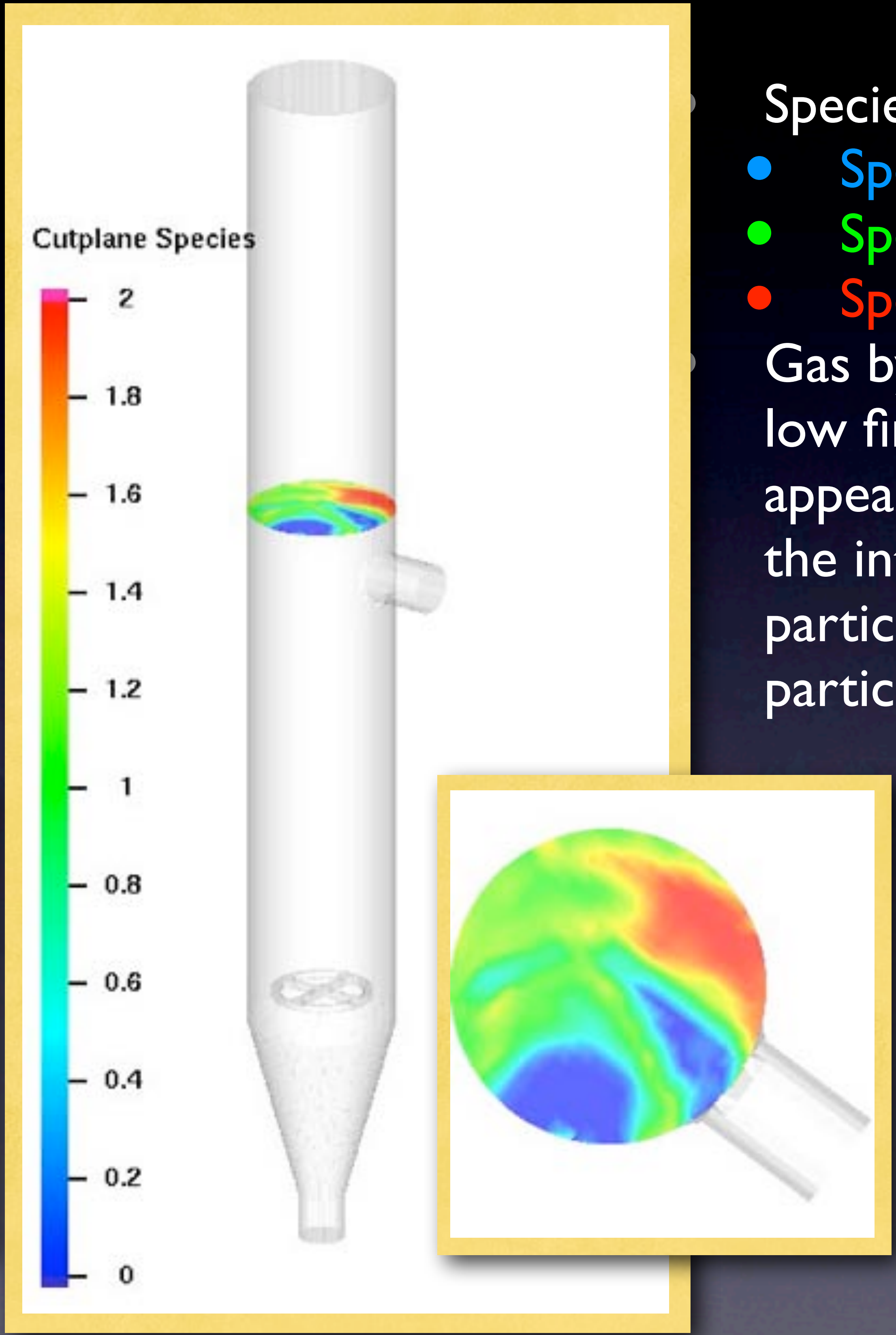
Sliced View

Gas Bypassing at the Interface

3% Fines with Imposed Flux



9% Fines with Imposed Flux



- Species legend
  - Species 0 - Gas
  - Species 1 - Bed
  - Species 2 - Dipleg
- Gas bypassing with low fines level appears to reside at the interface of bed particles and dipleg particles

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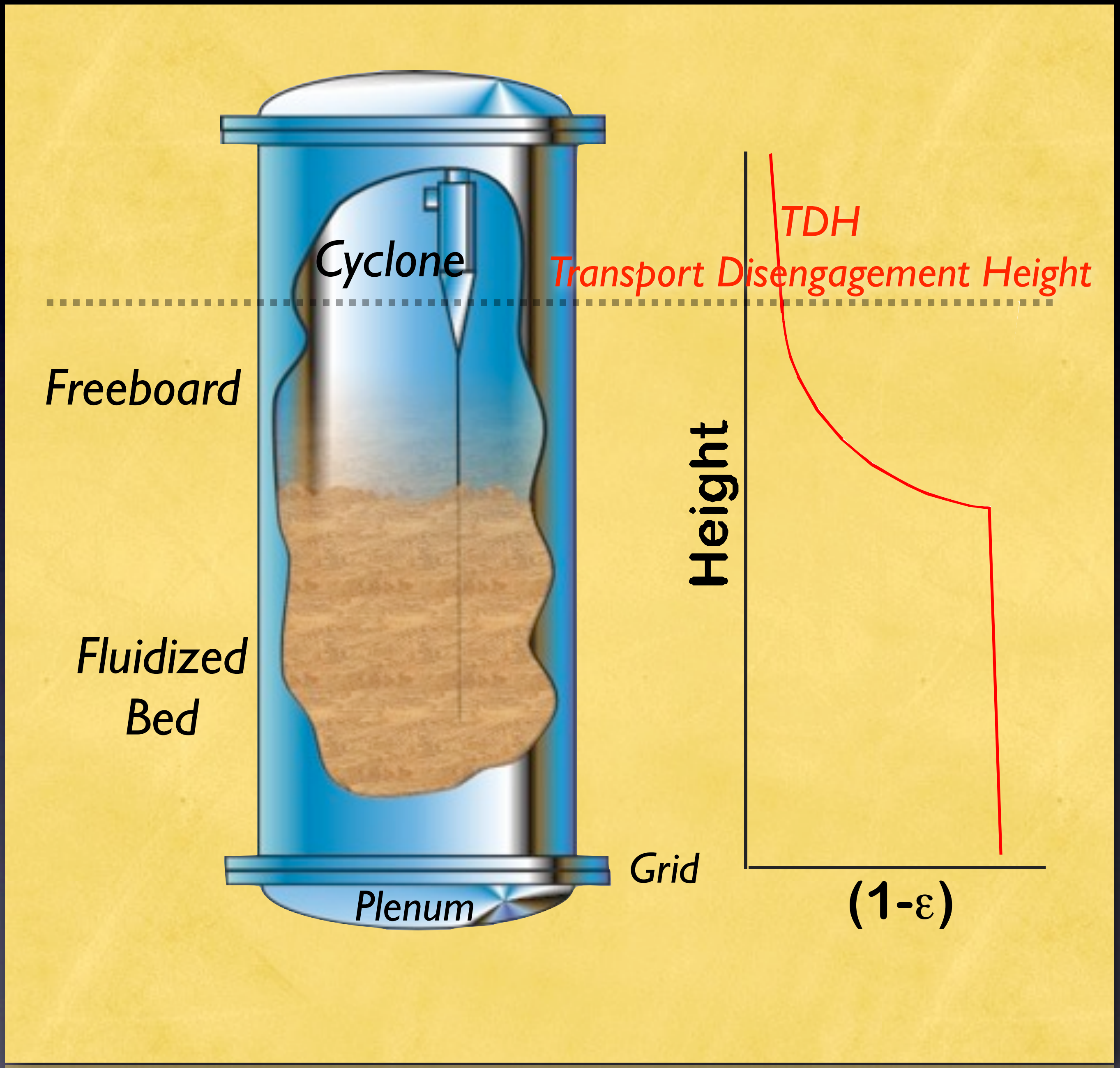
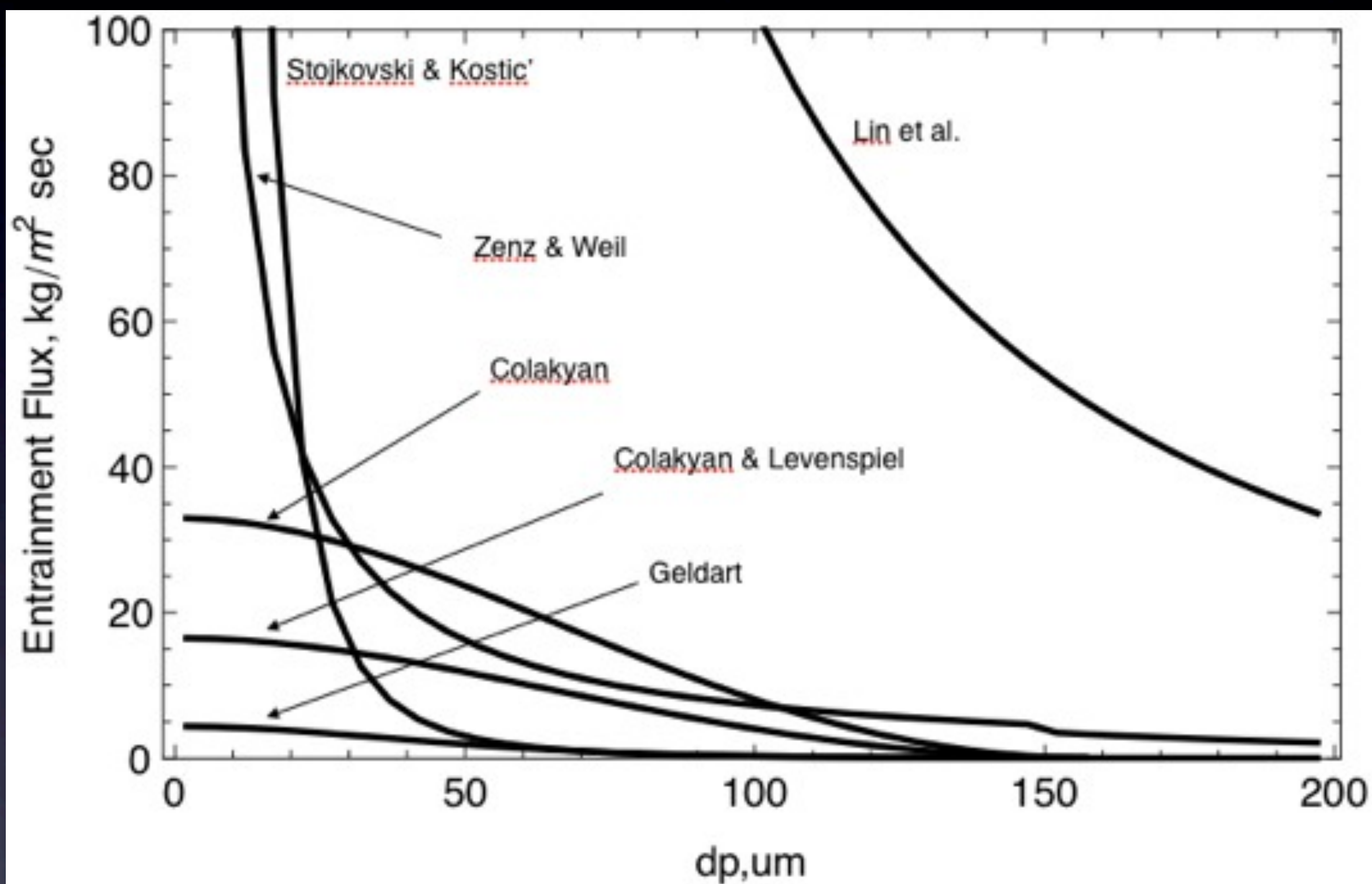
Entrainment



Bubble Burst

Bubble Burst with FCC Powder
6,600 frames per second
with University of Chicago

Calculated Entrainment Rates in a Fluidized Bed



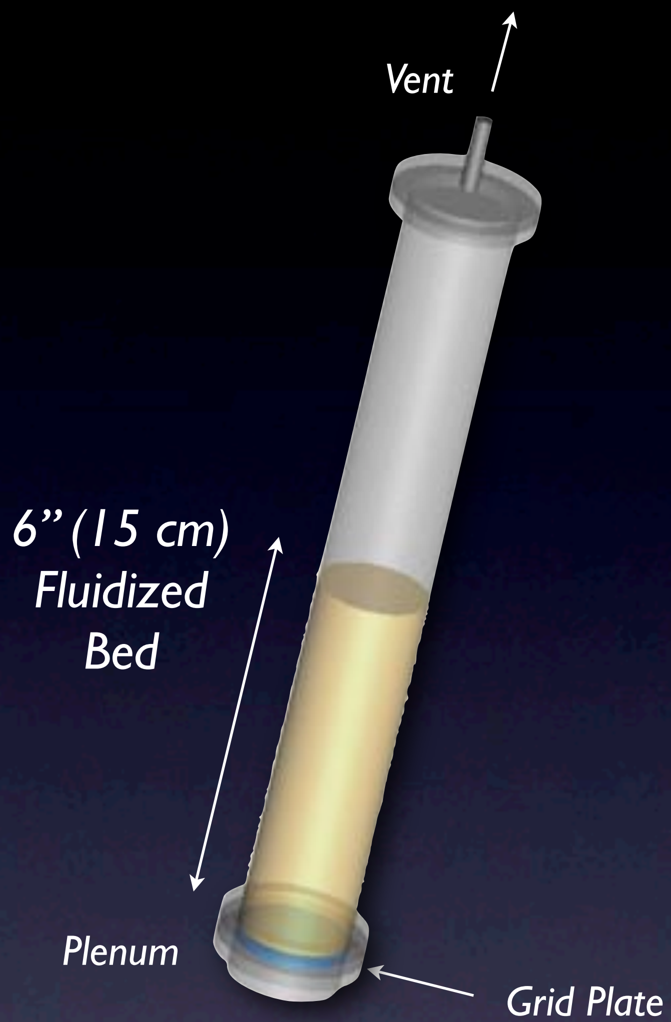
Entrainment rate calculations based on FCC catalyst powder with 9% fines in a 3-meters ID x 12-meters tall fluidized bed with a bed height of 6 meters and superficial gas velocity of 1 m/sec at room temperature

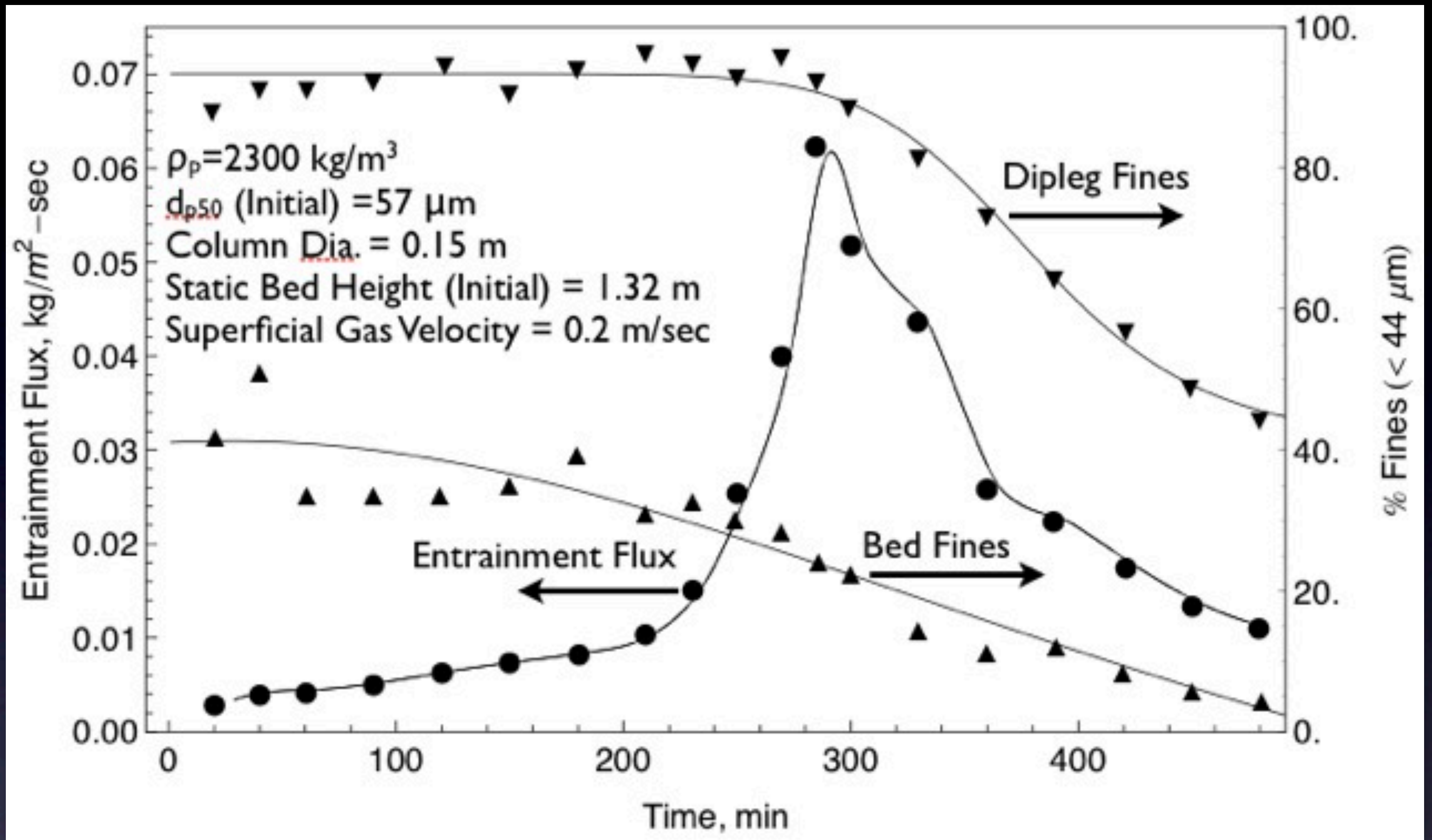
- Why do we see such a wide range of entrainment rates for small particles?
- Are some smaller particles behaving differently than others?

Stojkovski, V., Kostic', Z., Thermal Science, 7 (2003) 43-58.
Zenz, P.A., Weil, N.A., AIChE J., 4 (1958) 472-479.
Lin, L, Sears, J.T., Wen, C.Y., Powder Technology, 27 (1980) 105-115.

M. Colakyan, N. Catipovic, G. Jovanovic, T.J. Fitzgerald, AIChE Symp. Ser. 77 (1981) 66.
Colakyan, M., Levenspiel, O., Powder Technology, 38 (1984), pp. 223-232
Geldart, D., Cullinan, J., Georghiades, S., Gilvray, D., Pope, D.J., Trans. Inst. Chem. Eng., 57 (1979)

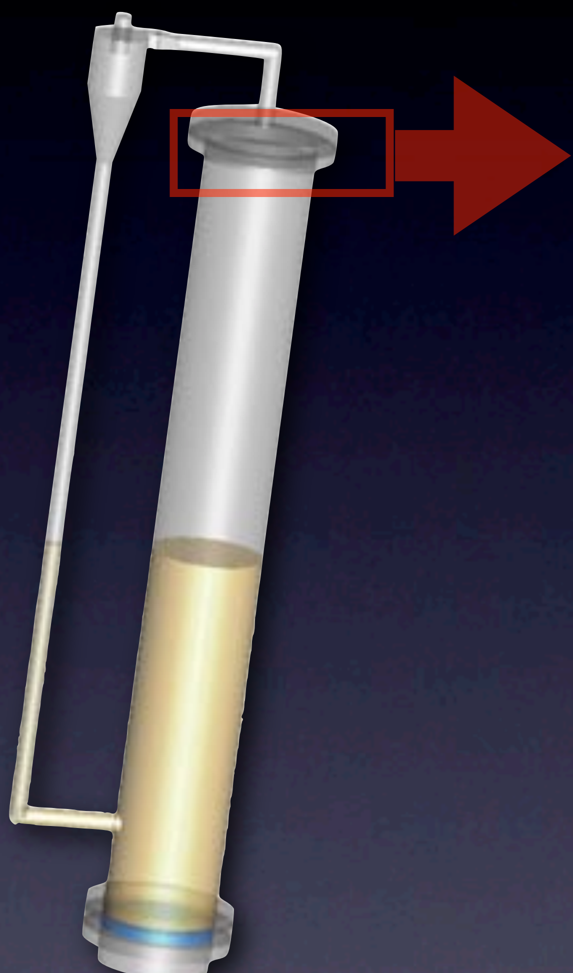
Batch Fluidization Test





- Replicated what was experienced in a commercial fluidized bed reactor
- The increase in entrainment rate corresponded to a decrease in the fines level in the bed and with the entrained solids

Particle Clusters in the Freeboard



Bayway FCC fines with d_{p50} of 27 microns in 6-in (15-cm) ID fluidized bed with superficial gas velocity of 2 ft/sec (0.6 m/sec)

Phantom V7.1 @ 6,500 fps (University of Chicago)

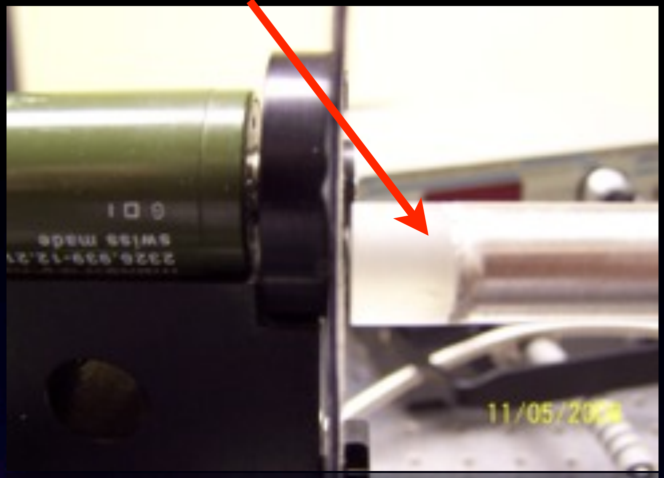
Hypothesis: Particle Clusters

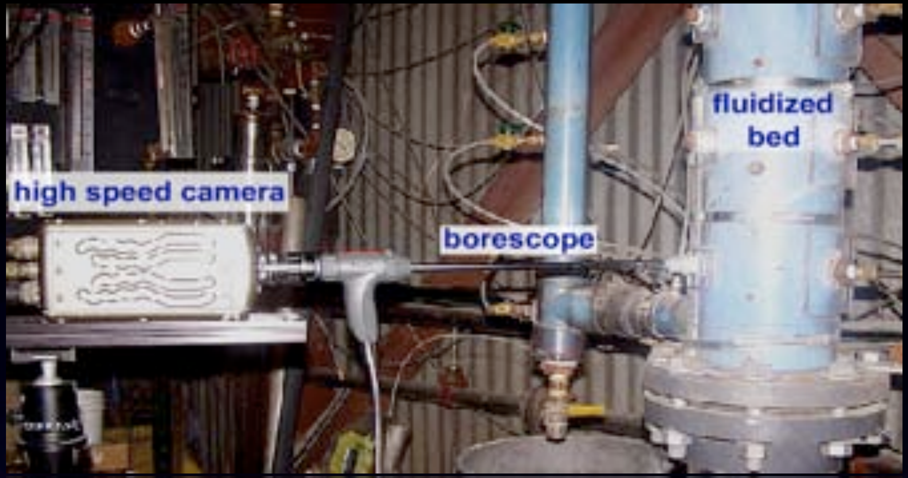
- Wilhelm and Kwauk postulated that particle clusters exist in 1948
- Kaye and Boardman suggested that particle clusters are possible when solids concentrations exceeded 0.05%
- Yerushalmi et. al. proposed that particle clustering explained the larger than expected slip velocity measured in a fast-fluidized bed
  - Geldart and Wong noted similar observations and conclusions
- Baeyens et. al. proposed that there is a critical particle size where clustering can occur
  - Karri et. al. noted similar findings

Wilhelm, R.H., Kwauk, M., Chemical Engineering Progress 44 (1948) 201.
Kaye, B.M., Boardman, R.P., Proc. Symp. on the Interaction between Fluids and Particles, Inst. Chem. Eng., London, 17, 1962.
Yerushalmi, J., Tuner, D.H., Squires, A.M., Industrial & Engineering Chemistry Process Design and Development 15 (1976)47–53.
Geldart, D., Wong, A.C.Y., AIChE Symp. Ser., 255 (1987), 1.
Baeyens et al. Powder technology. 71 (1992) 71-80
Karri, S.B.R., Knowlton, T.M., Internal Commnunication, 1990.

Looking Beyond the Walls

6 mm Optical Glass Spacer
(Guard Collar Removed)

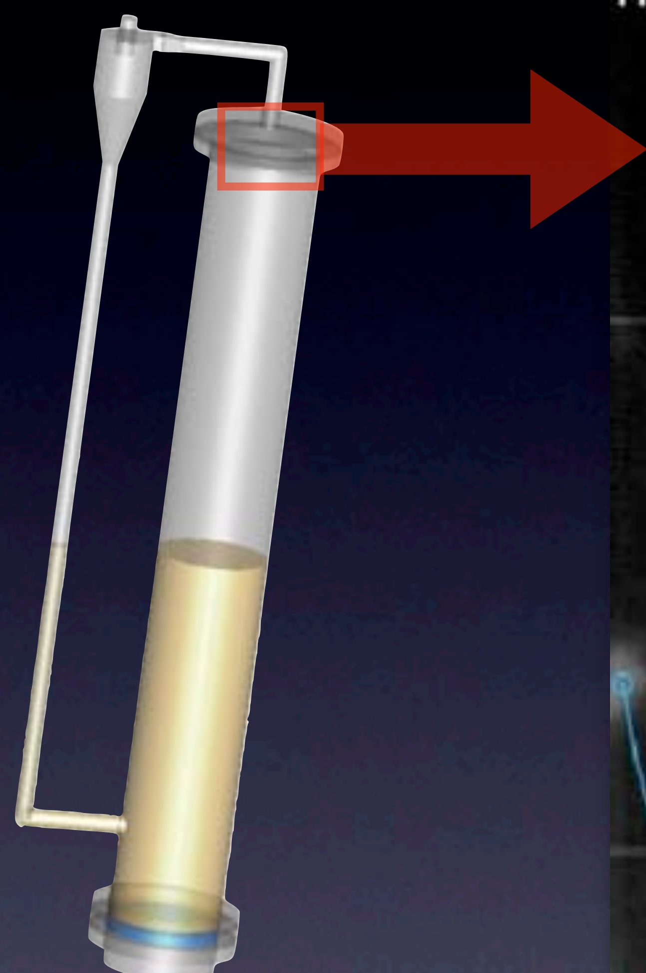


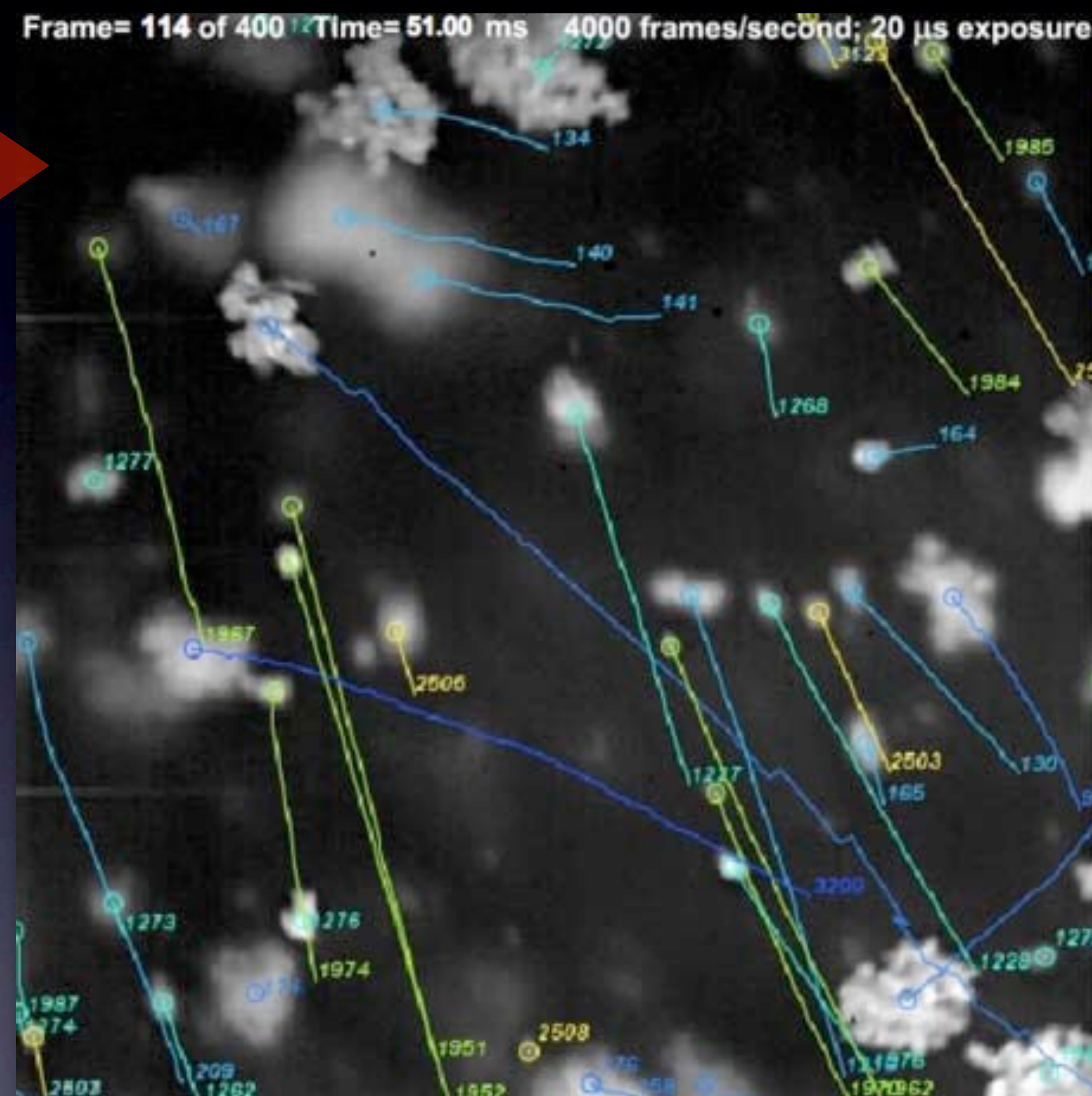


- Olympus R100-038-000-50 Industrial Rigid Borescope
  - 38 cm effective length
  - 50° field of view
  - 5 to ∞ mm depth of field
- 6 mm Optical Glass Spacer
  - With stainless steel Guard Collar (not shown)
- Liquid Filled Light Guide
- External lighting
- High speed camera ready

Polyethylene Clusters in Freeboard

Polyethylene with d_{p50} of 70 microns in 6-in (15-cm) ID fluidized bed with superficial gas velocity of 1 ft/sec (0.3 m/sec)



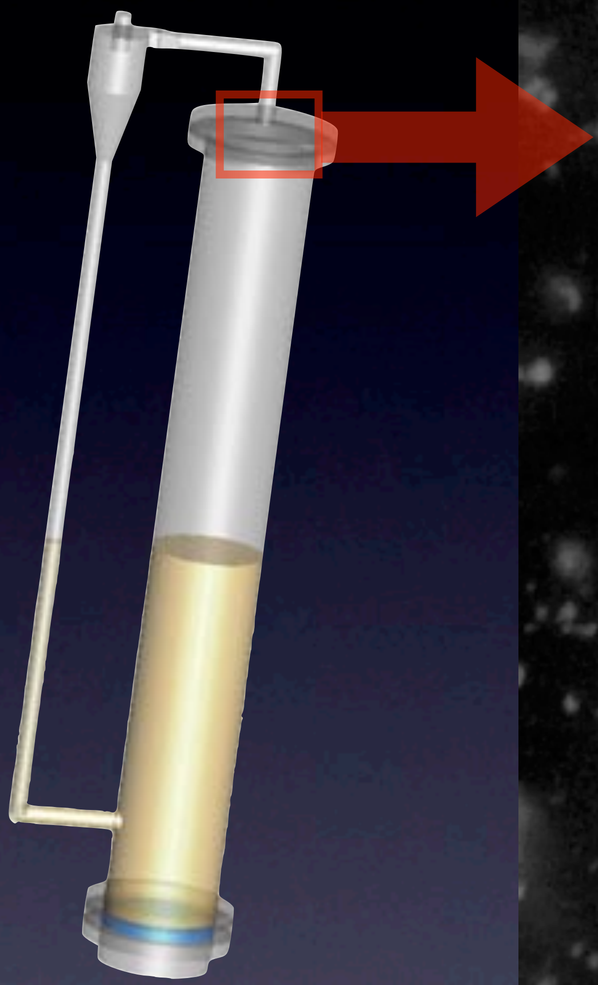


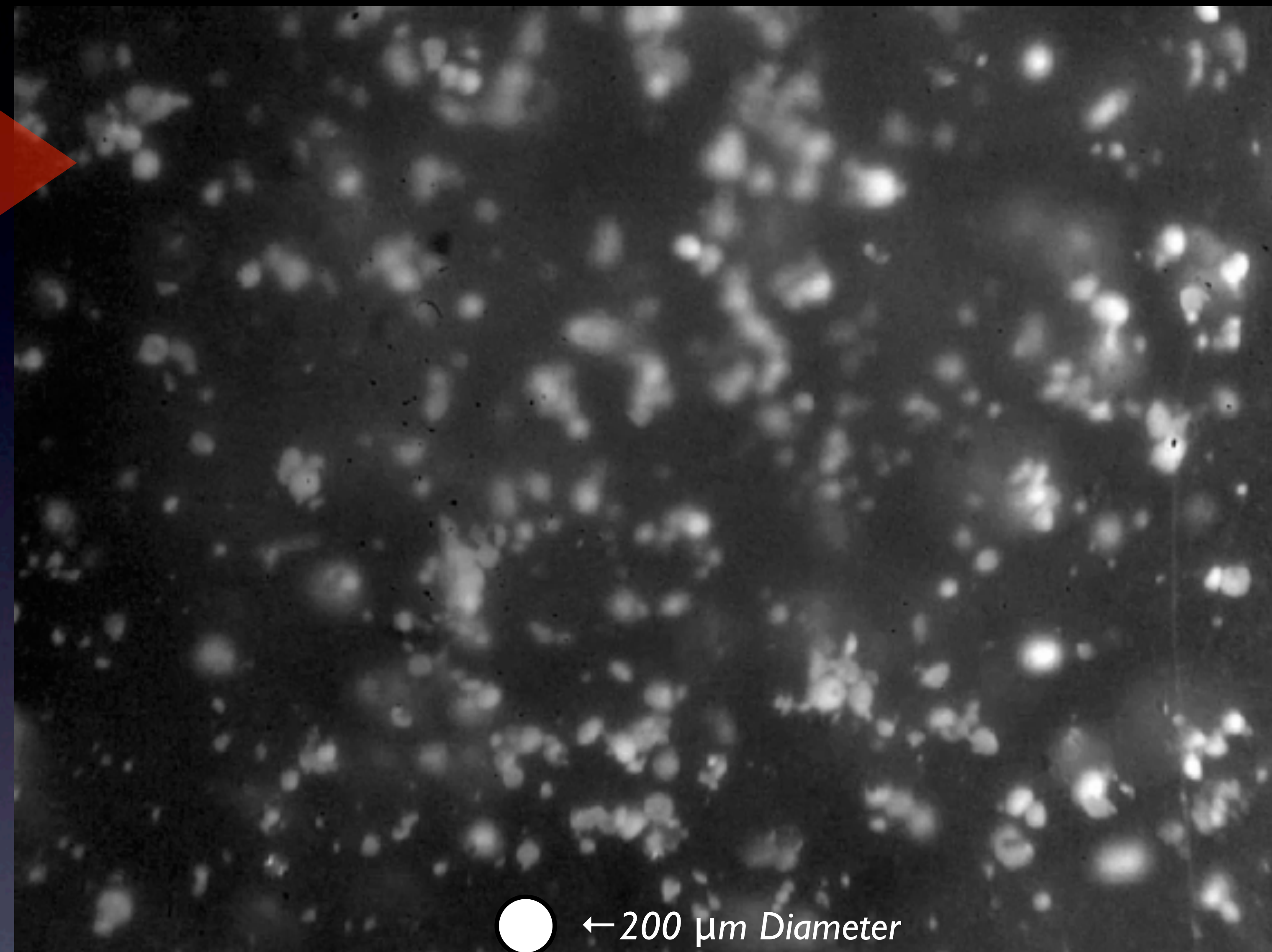
Phantom V7.1 @ 4000 fps, 20 µs exposure (NETL)

- Clusters can be traced and sized
- Average cluster size was 23 particles

FCC Catalyst Clusters in Freeboard

FCC powder with d_{p50} of 72 microns in 6-in (15-cm) ID fluidized bed with superficial gas velocity of 1 ft/sec (0.3 m/sec)



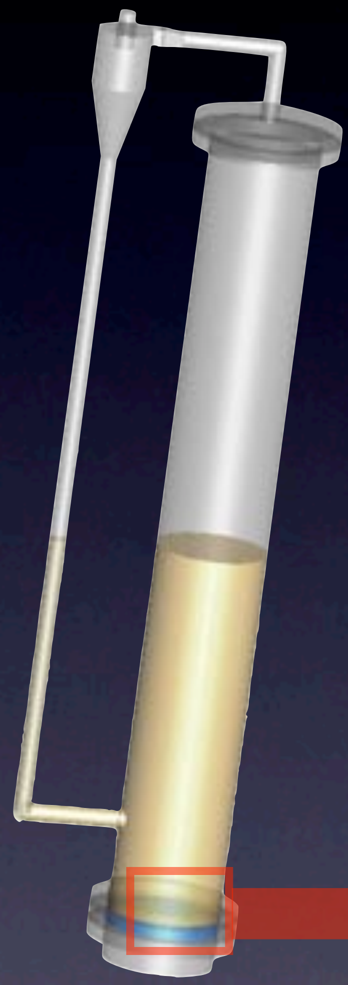


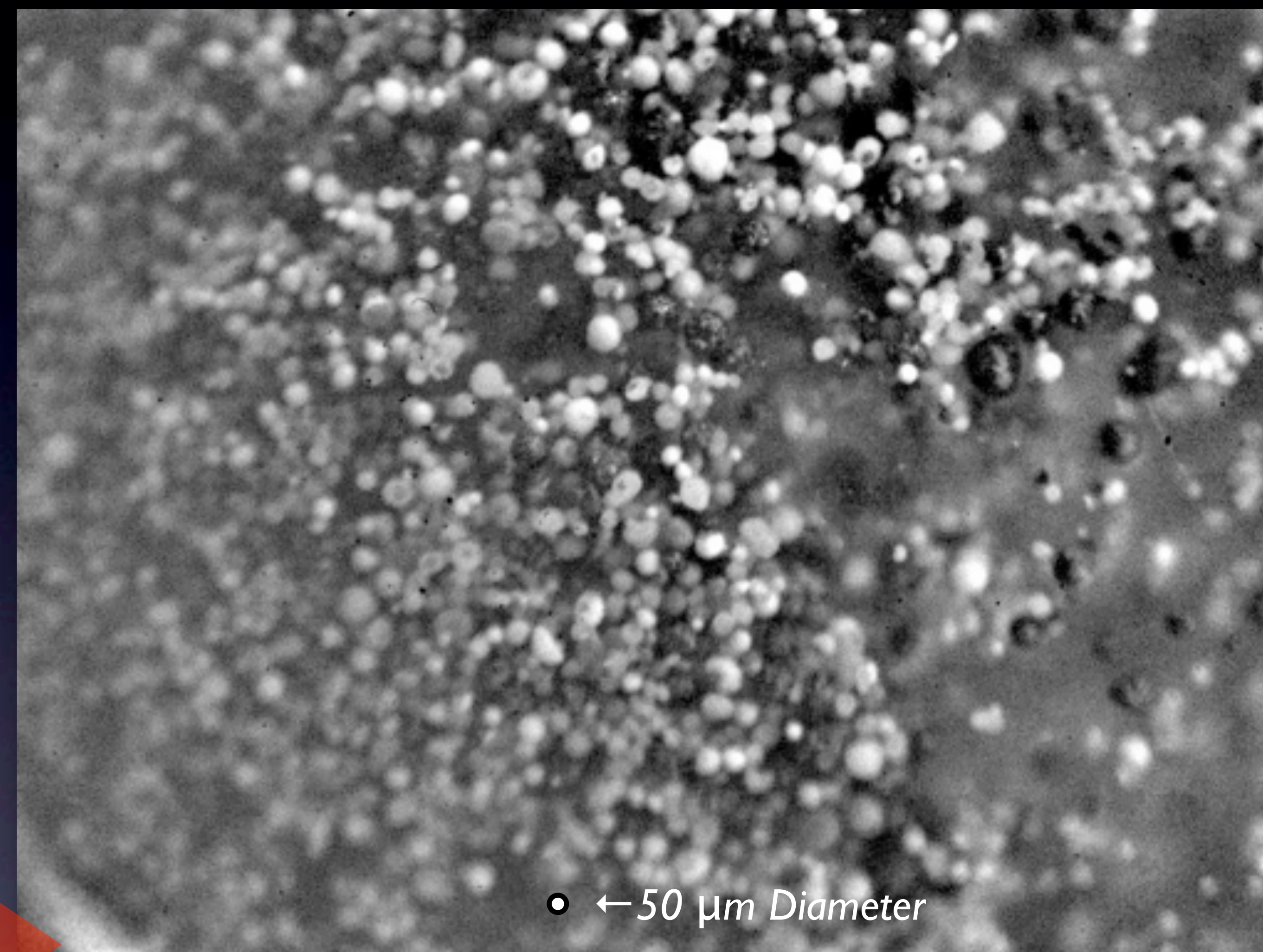
Phantom V7.1 @ 4000 fps, 20 µs exposure (NETL)

- 30% of the material in the freeboard was observed as clusters
- Average cluster size was 11 particles

FCC Catalyst Clusters in the Fluidized Bed

FCC powder with d_{p50} of 72 microns in 6-in (15-cm) ID fluidized bed with superficial gas velocity of 1 ft/sec (0.3 m/sec)



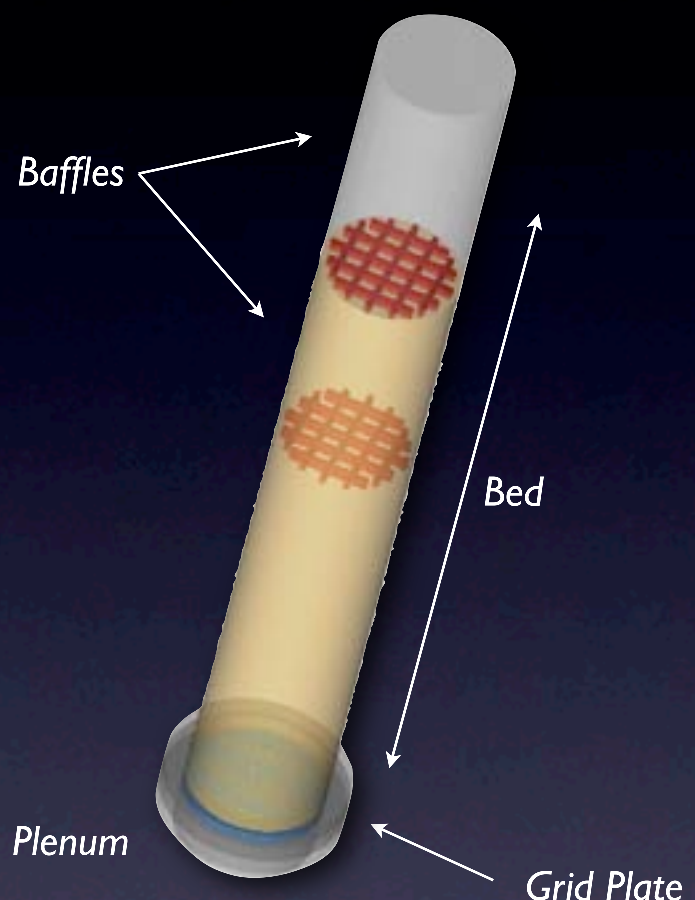


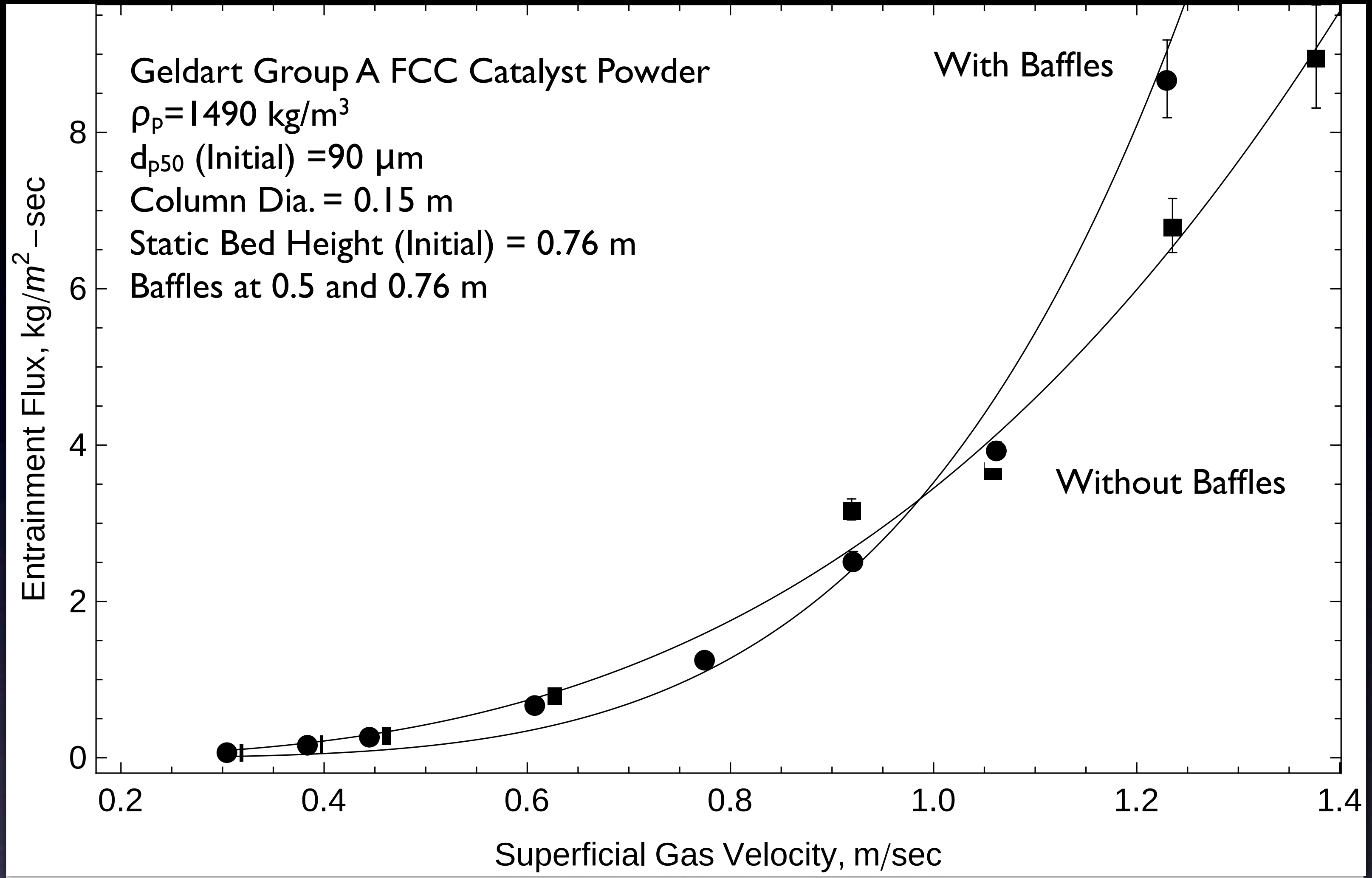
Phantom V7.1 @ 4000 fps, 20 µs exposure (NETL)

- Cluster observed near bubble region
- Can not distinguish if clusters are in the emulsion phase or not

Effects of Baffles

6-inch (15 cm) & 12-inch (30 cm) Fluidized Bed





- In a bed of FCC powder, the addition of baffles resulted in an increase in the entrainment rate at the higher velocities
- This was not observed for Geldart Group B particles
- Not a bed diameter effect

Effects of Baffles

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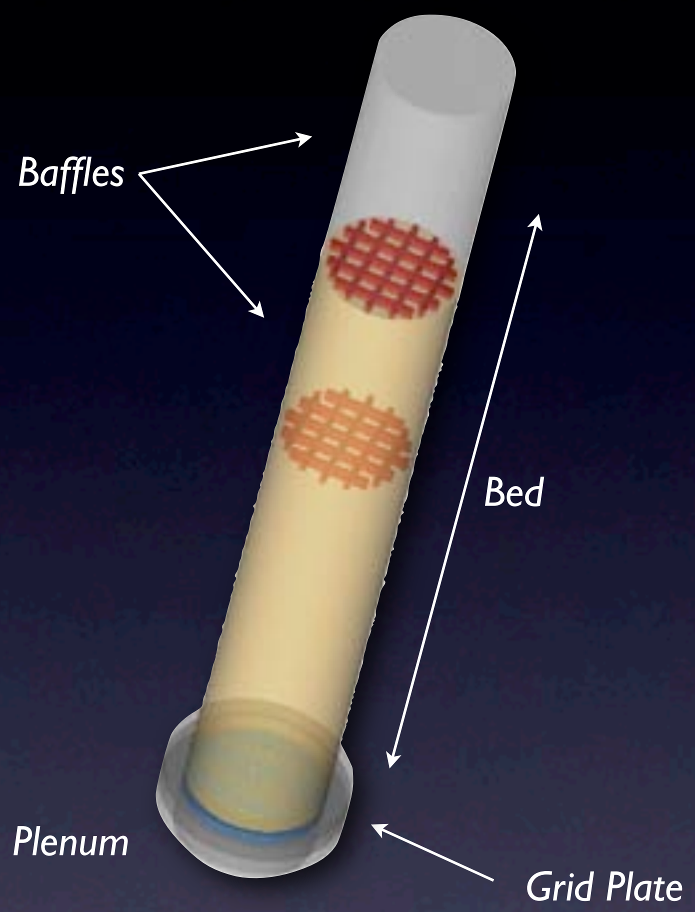

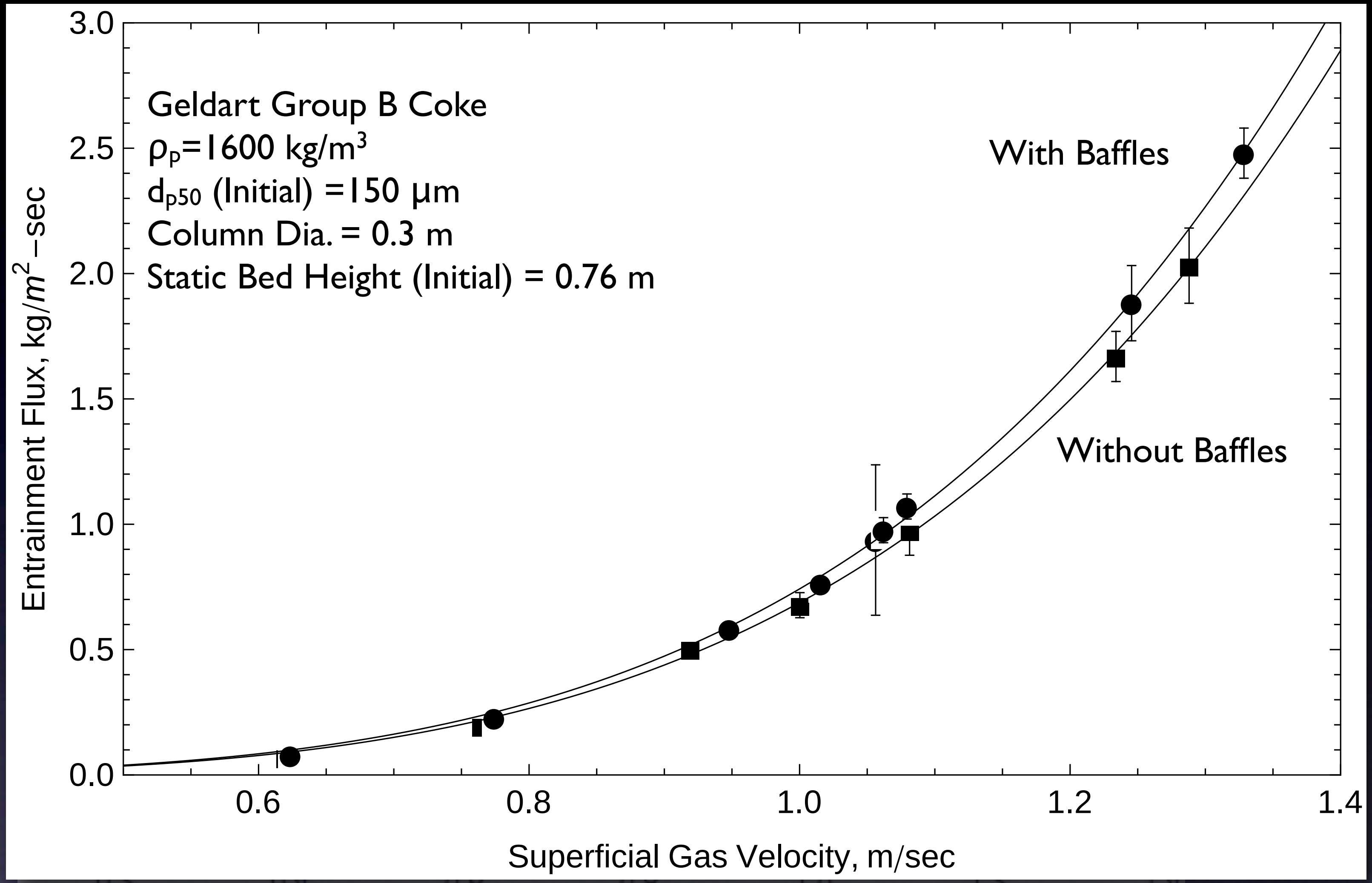

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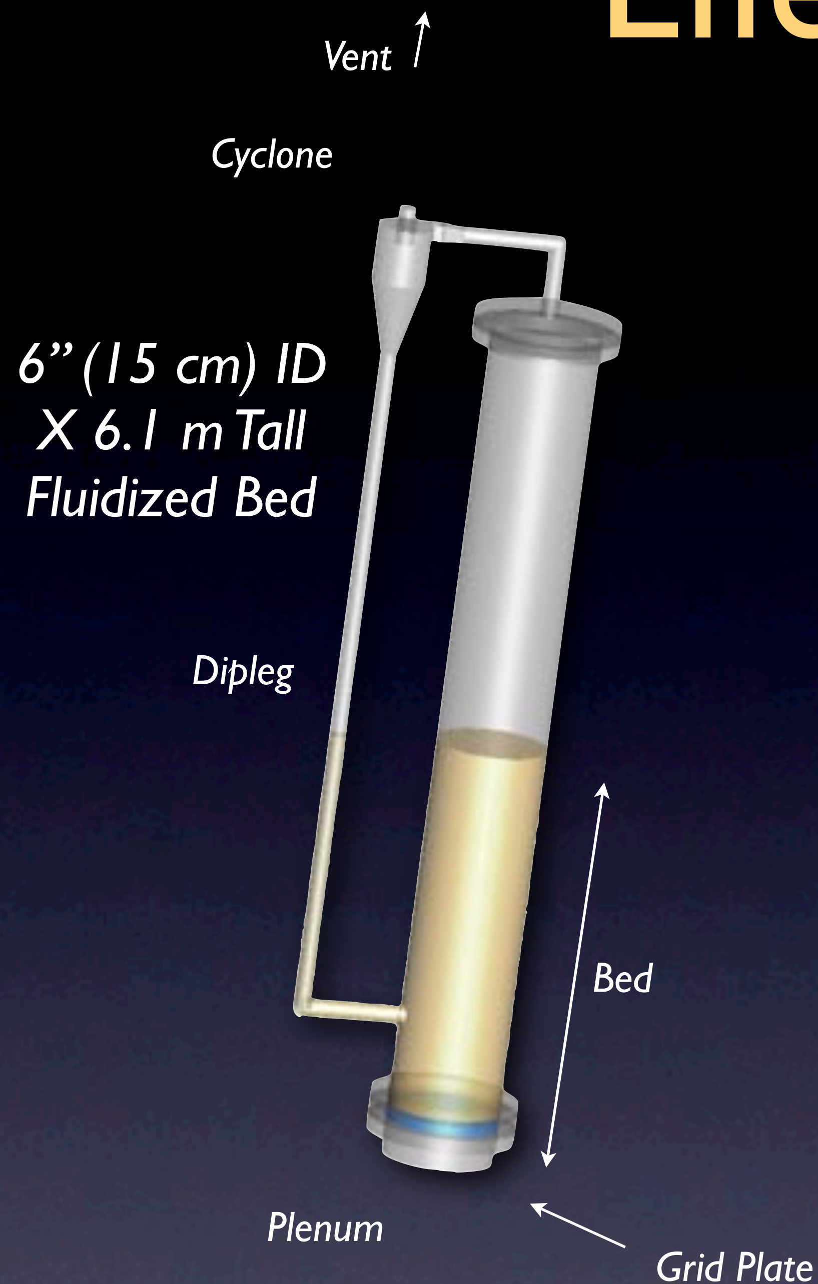
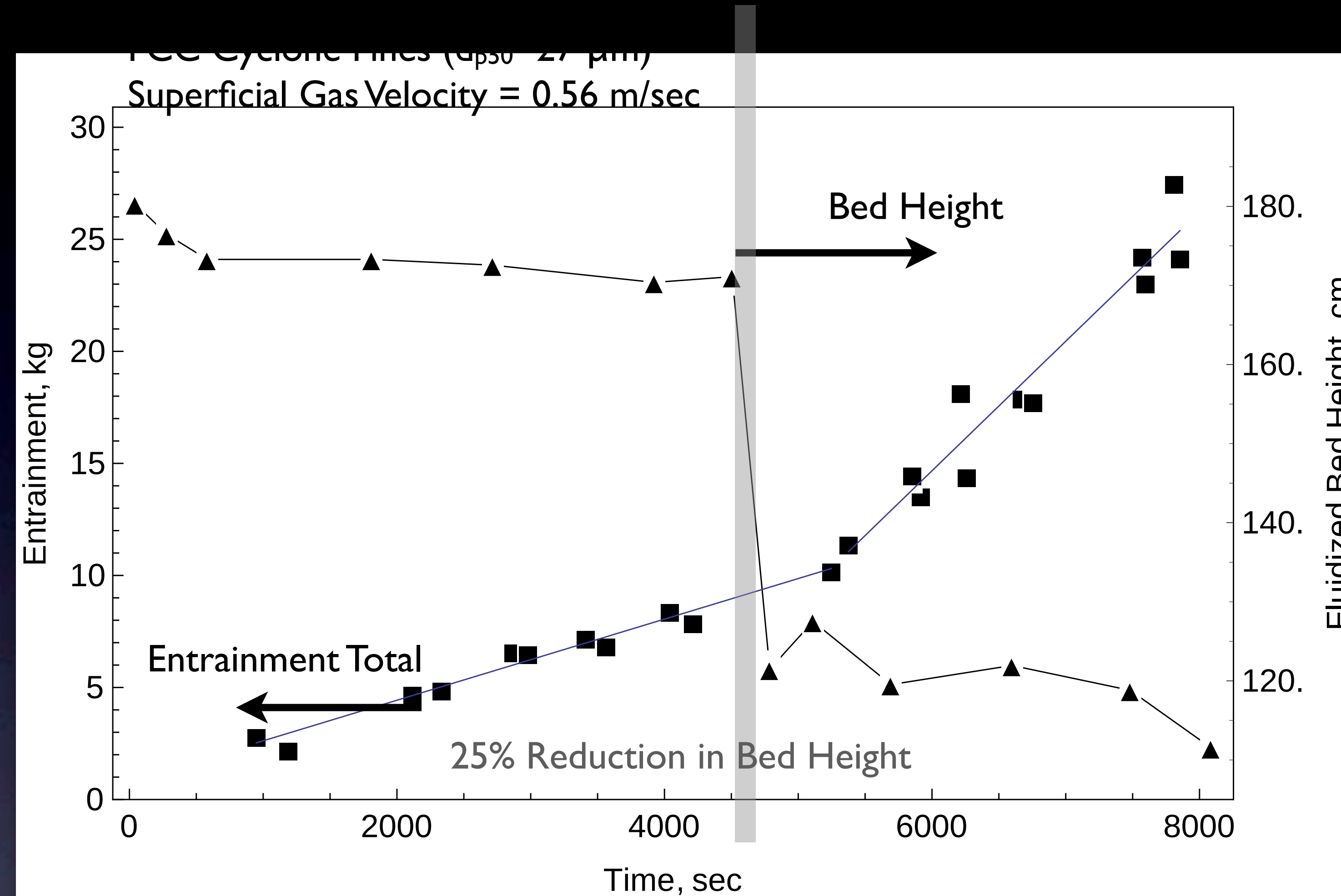
- Not a bed diameter effect

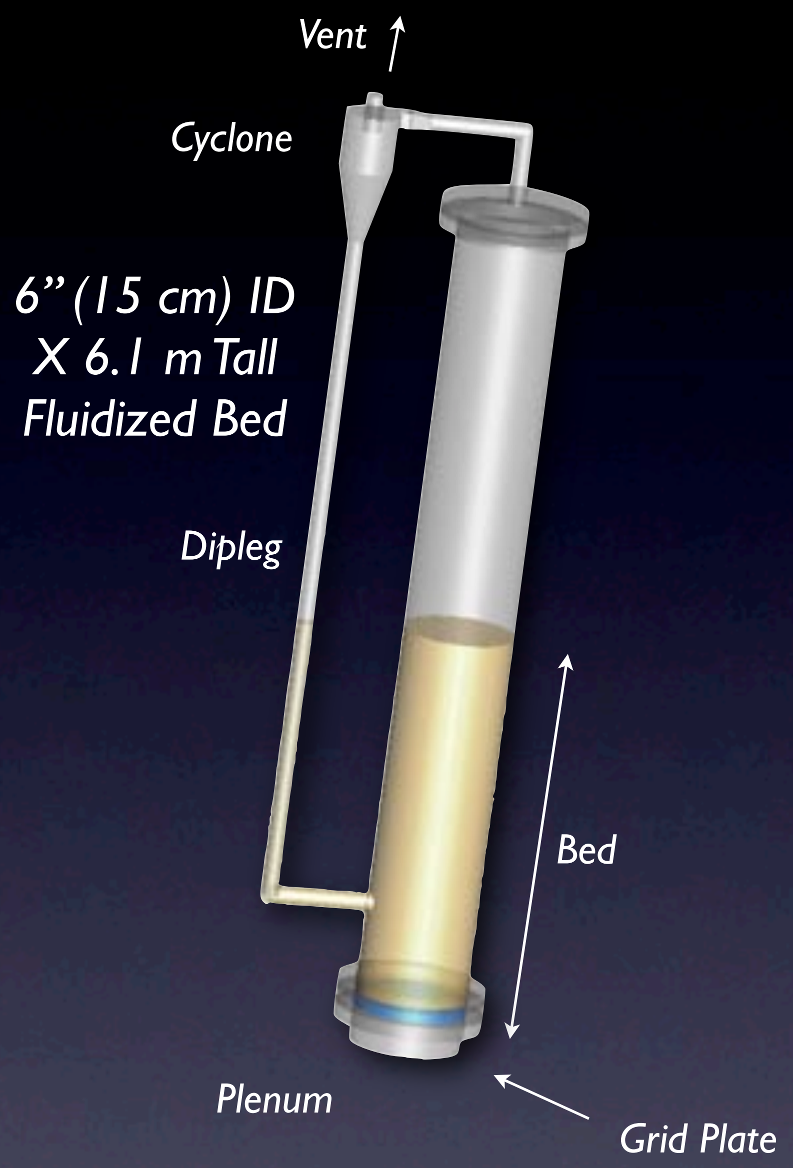
Effects of Bed Height

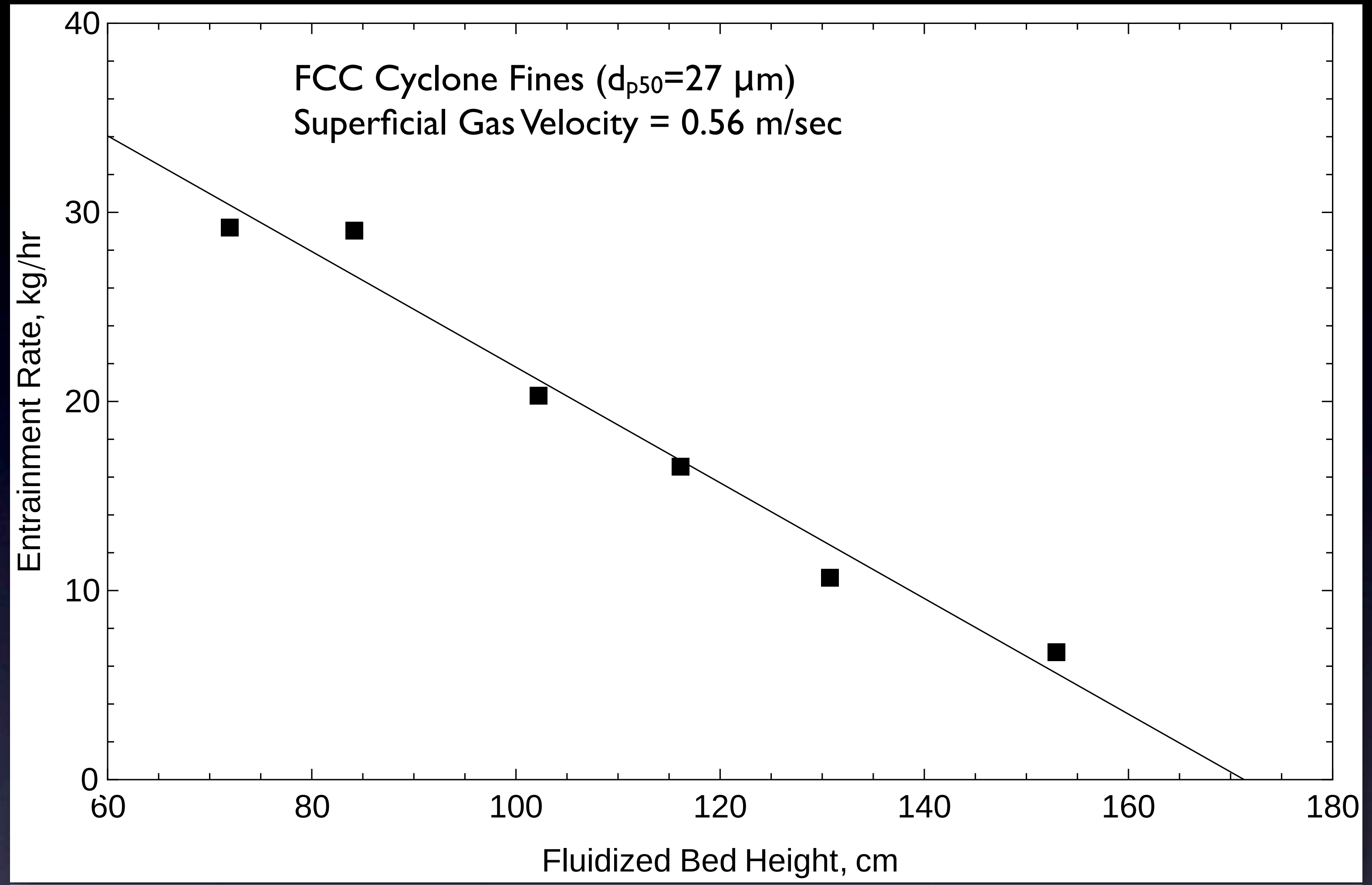




- Fines recycled back into the bed
- At 4500 seconds, the bed height was decreased by 25%
  - Entrainment rate increase corresponded with drop in bed height

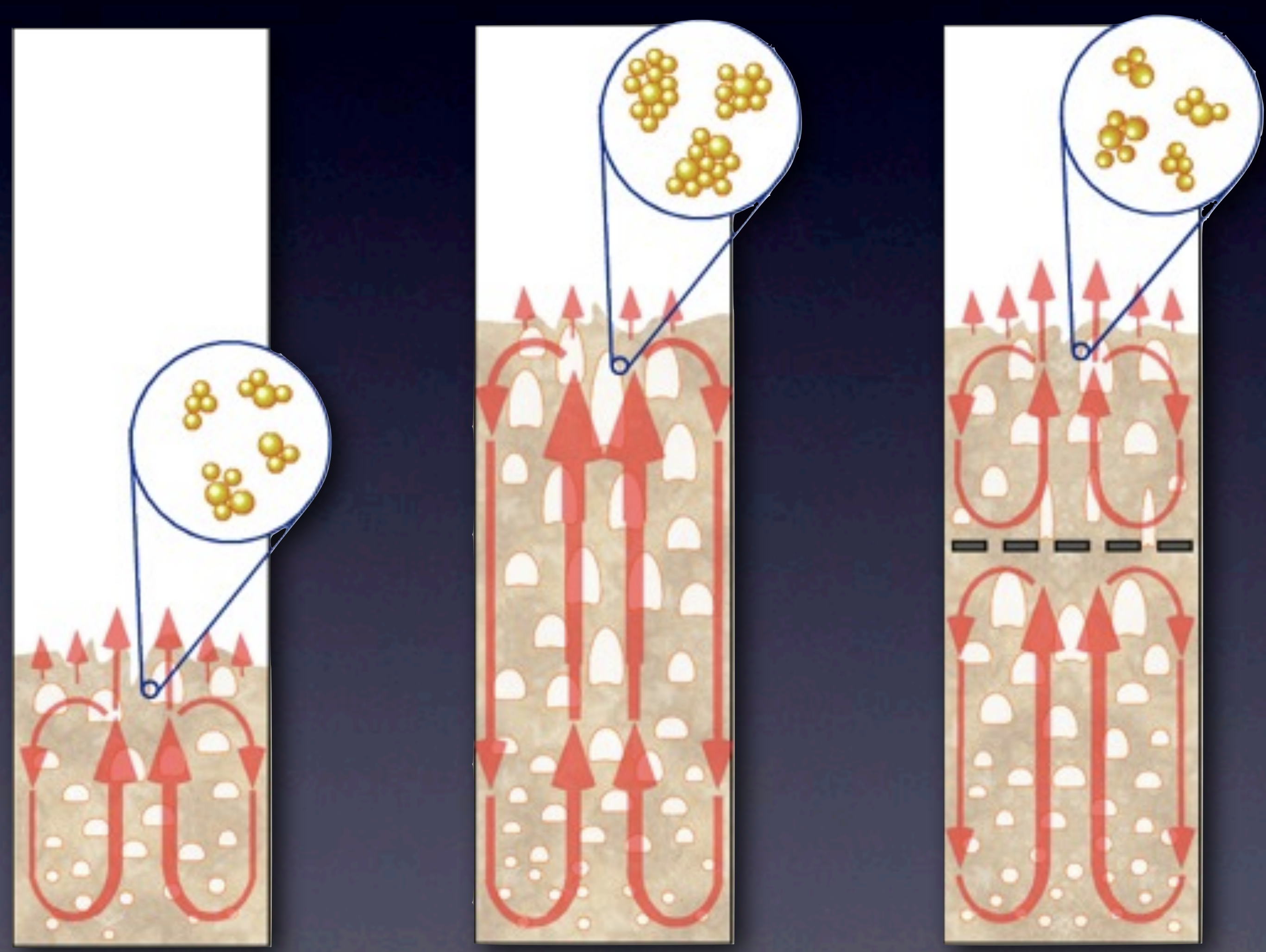
Effects of Bed Height





- Same material in the same unit
- Entrainment rate was measured at various bed heights
- Entrainment rate is inversely proportional to bed height

Particle Cluster Formation and Stability in Fluidized Beds



- Particle clusters may form near the bottom of the bed and continue to grow as they migrate to the top of the bed, possibly with the help of bubbles
- At the top of the bed, clusters are either entrained or circulate back down to the bottom of the bed.
- Several cycles of the circulation may be needed to build large clusters.
- As bed height is increased, the large circulation zone becomes more dominant and the possible residence time of a particle cluster in the bed becomes extended.
  - Baffles can inhibit cluster formation as these clusters appear to be weakly bound together

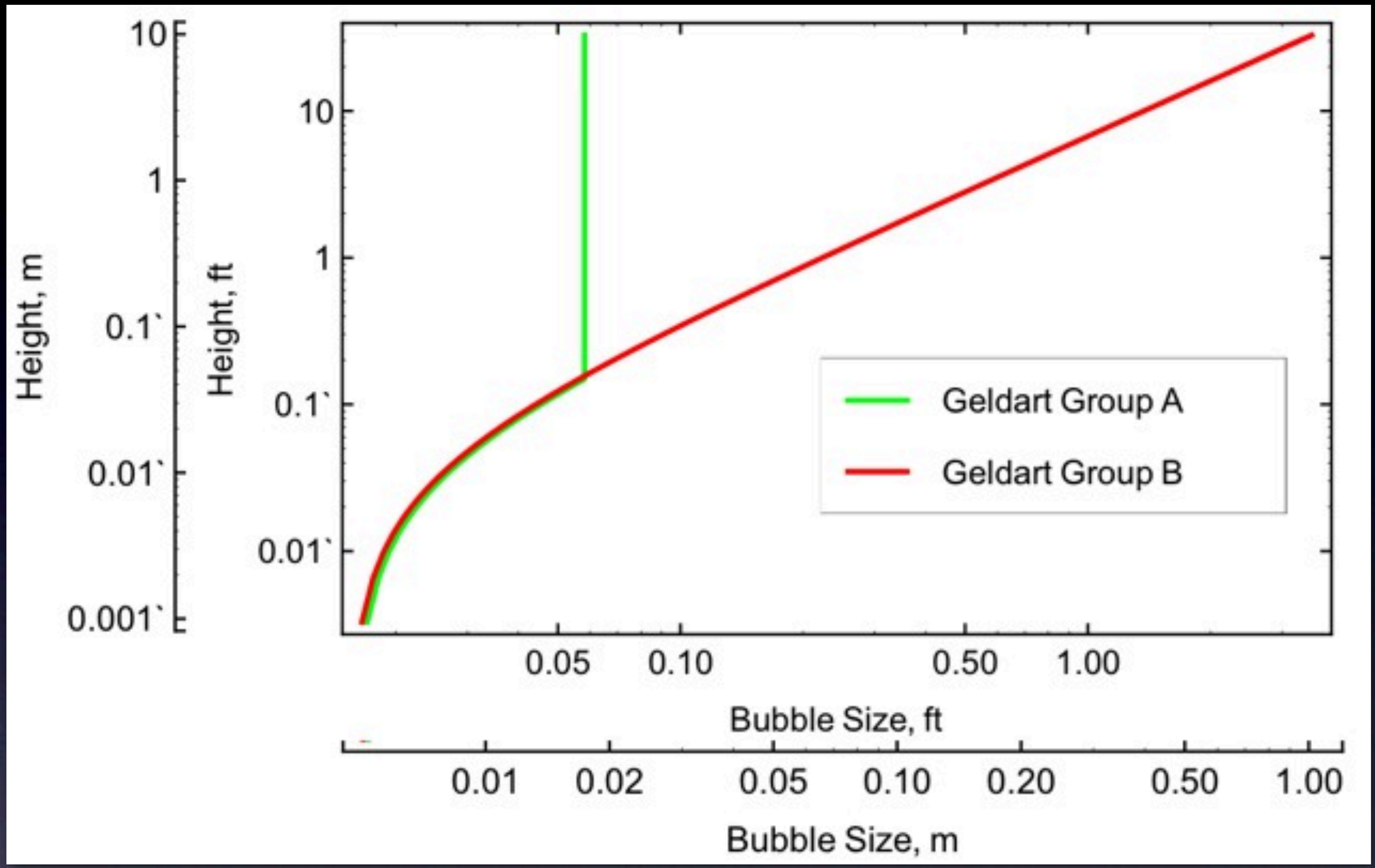
Implications

- Prediction of entrainment rate
  - Over prediction of entrainment rate can lead to over design of cyclone diplegs
    - Sizing a primary cyclone too large would result in too low of a flux in the dipleg
  - For some systems, many of the available entrainment rate correlations are not even close
  - There may be merit to a critical particle size for cluster formation
- Adding fines to your fluidized bed could actually lower your entrainment rate, significantly
  - Validated on a commercial unit
- CFD and other "fundamental" models can't predict this, yet.

Outline

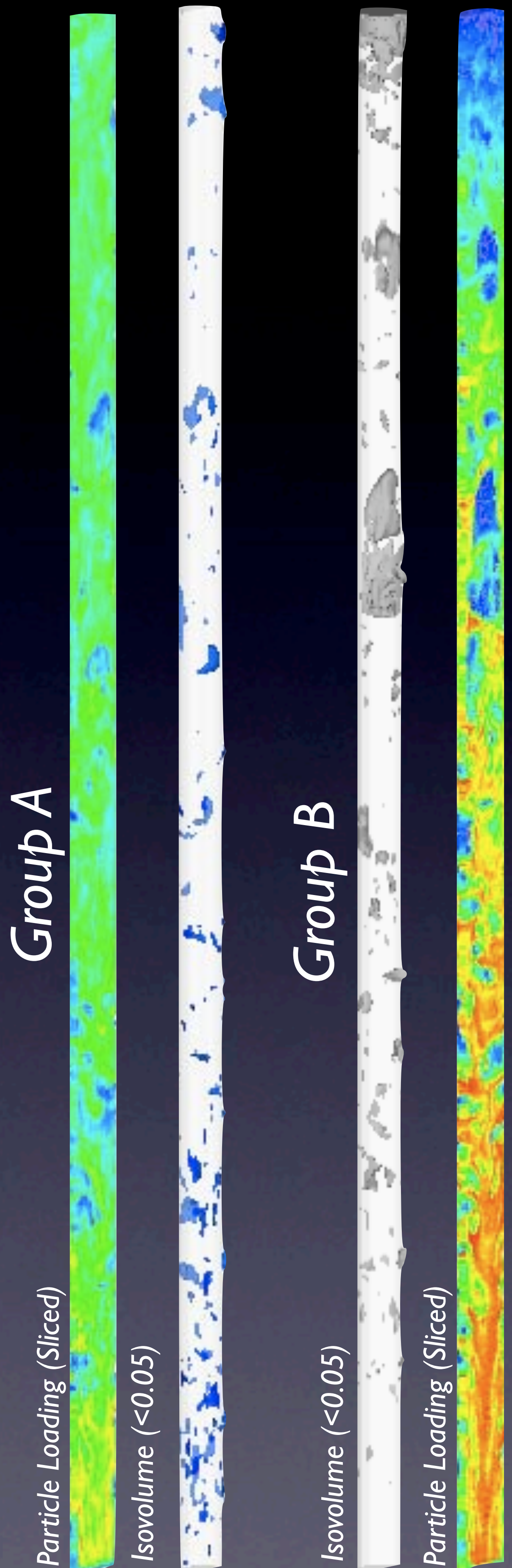
- Particle behavior and flow regimes
- Bed behavior
- Entrainment
- Bubble
- Multiphase jet
- Summary

Bubble Growth



- Bubbles in Group A particles are small and reach an equilibrium bubble size quickly
- Bubbles in Group B particles continue to grow and can get very large
    - Poor heat and mass transfer
    - Mechanical stresses

Bubbles with Group A and B Particles



- 1.2 ft/sec superficial gas velocity in 36" diameter bed
- Good fluidization for Geldart Group A particles
- Poor fluidization for Geldart Group B particles
  - Bubbles exceeded 2/3 the diameter of the bed
- Note bed expansion for Group A particles

Should They Be Called Bubbles

Outline

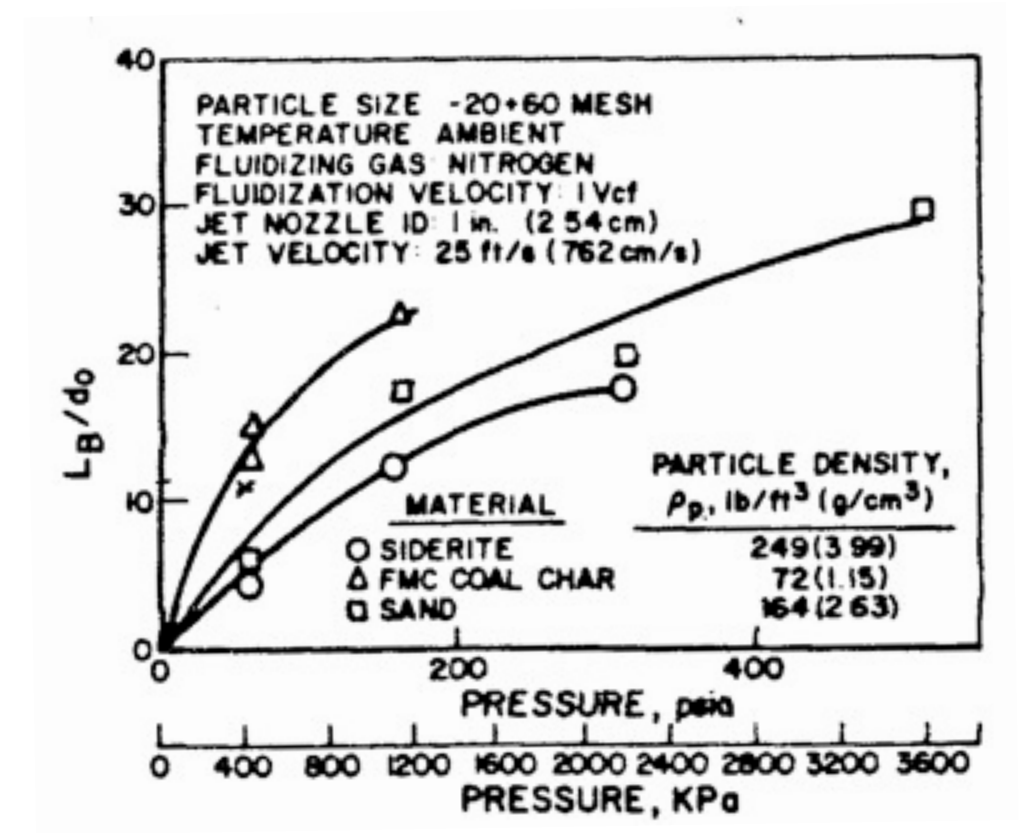
- Particle behavior and flow regimes
- Bed behavior
- Entrainment
- Bubble
- Multiphase jet
- Summary

Outline

- Particle behavior and flow regimes
- Bed behavior
  - Jetsam/floatsam?
- Entrainment
- Bubble
- Multiphase jet
  - Gas jets
  - Gas-solid jets
  - Gas-liquid jets
- Summary

Jet Penetration at High Pressures

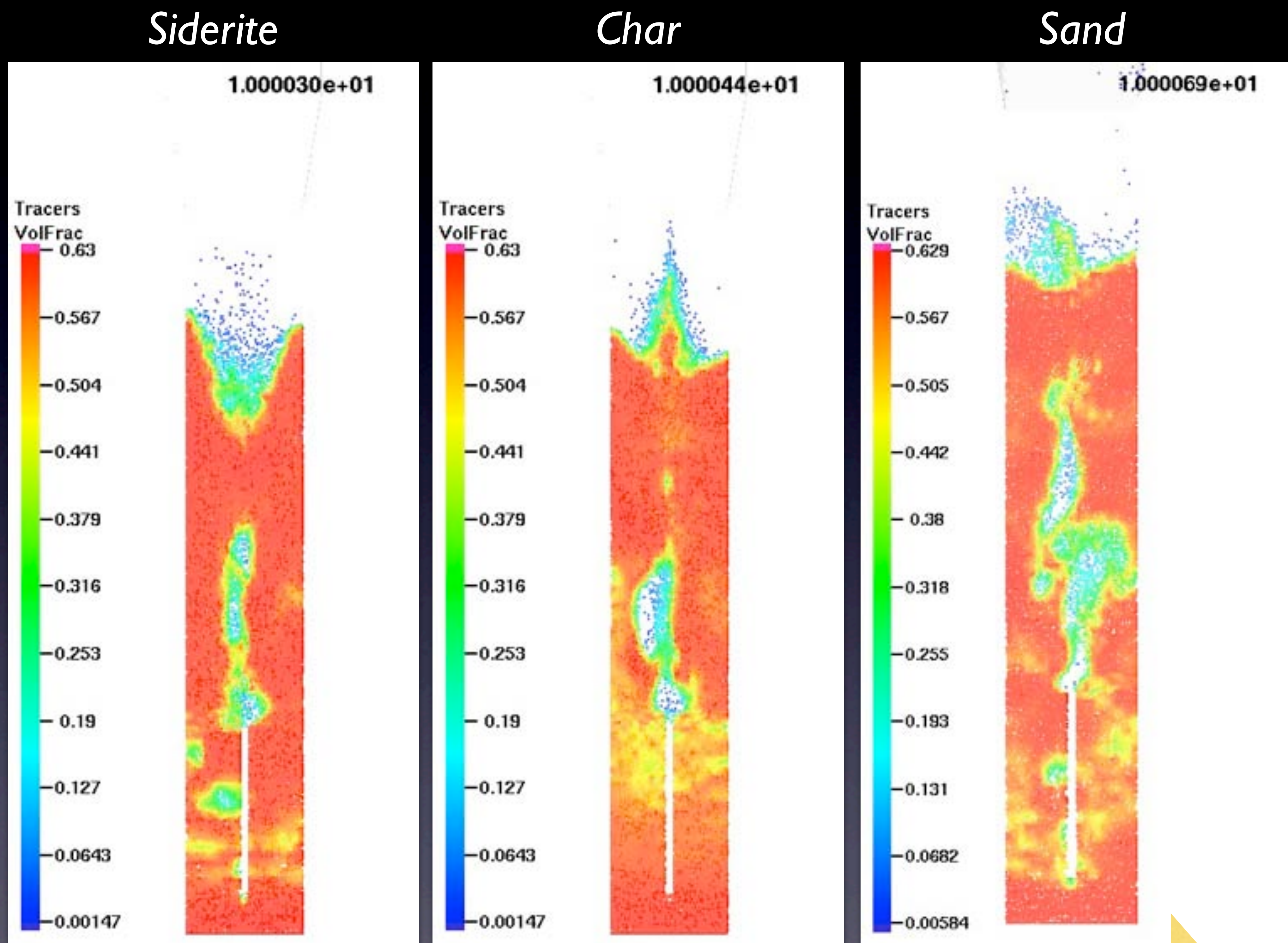
- From Knowlton, T.M. and Hirsan, I., "The Effect of Pressure on Jet Penetration in Semi-Cylindrical Gas Fluidized Beds", in "Fluidization", Grace and Matsen, Eds., p. 315, Plenum Press, New York. 1980.
- Three materials
    - Siderite
    - Coal char
    - Ottawa sand
- Jet velocity = 7.6 m/sec for all cases
- Superficial gas velocity = complete fluidization velocity
    - This changes with pressure



Material	Particle Density, kg/m^3
FMC Char	2629
Ottawa Sand	1158
Siderite	3988

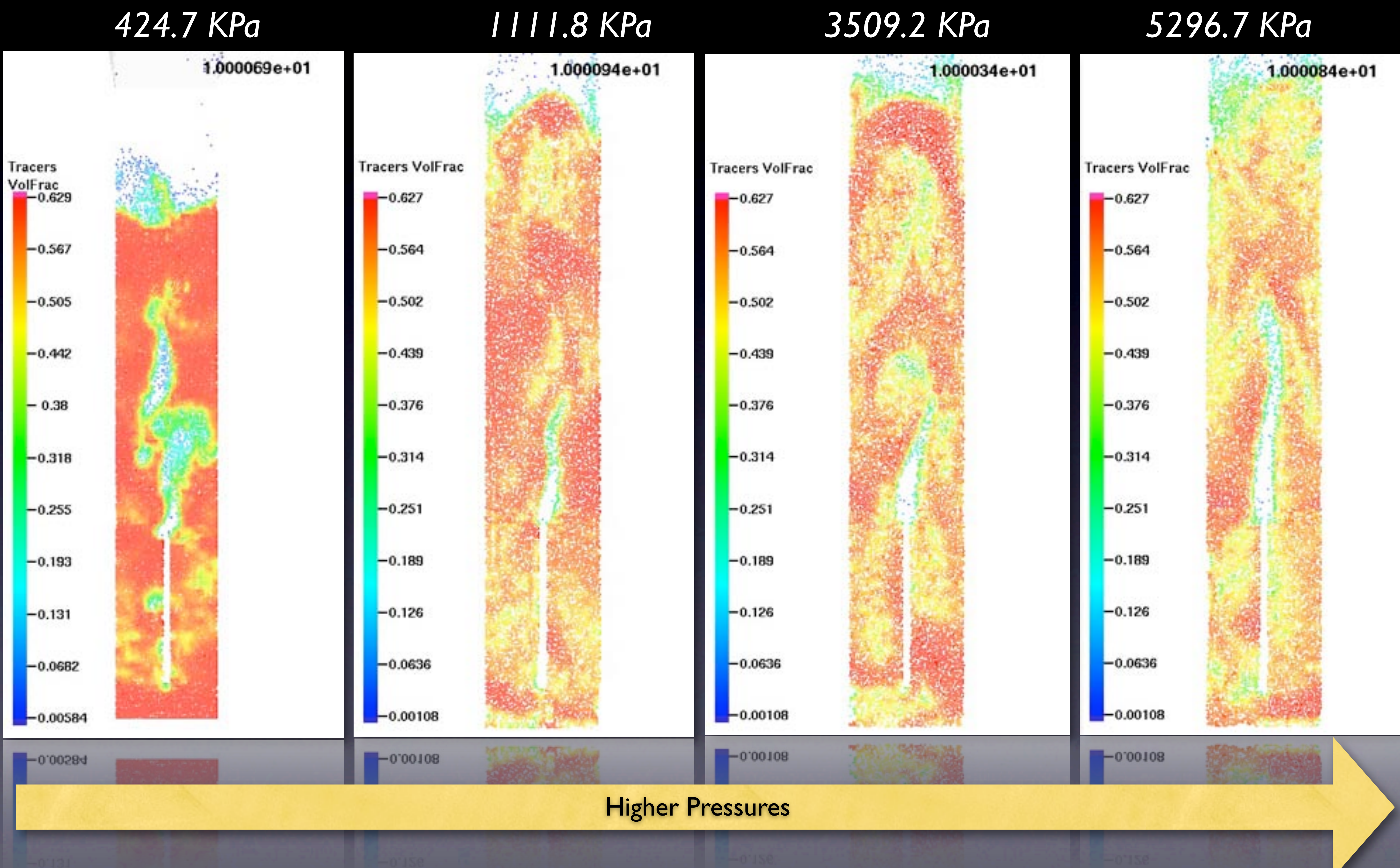
Simulations: Particle Density Effects

Material	Particle Density, kg/m^3
FMC Char	2629
Ottawa Sand	1158
Siderite	3988

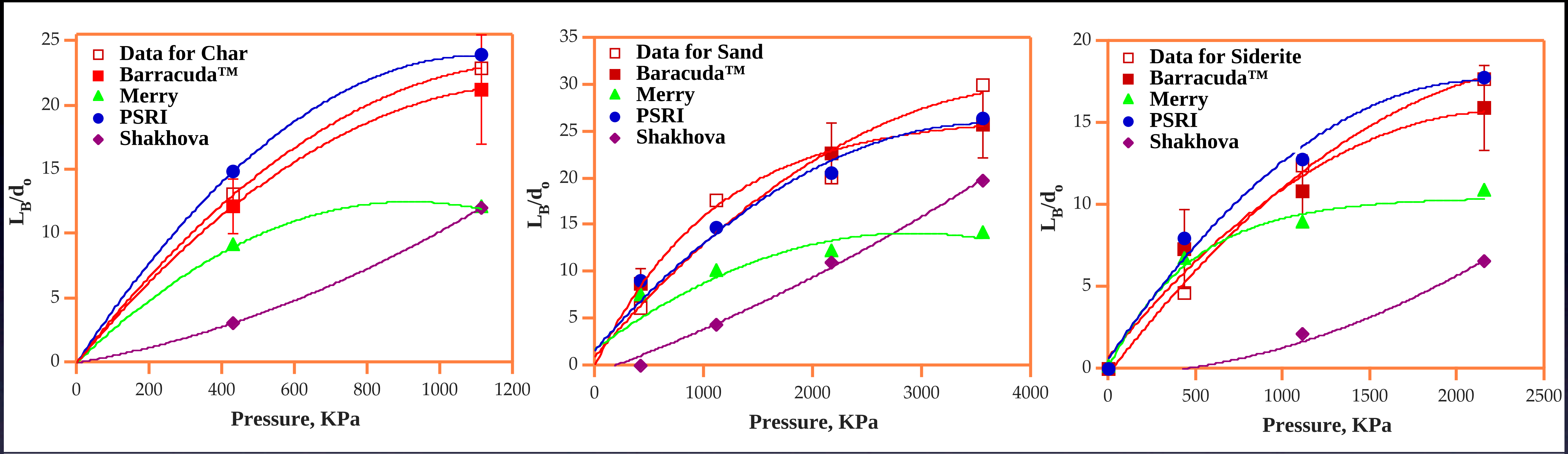


Lower Density

Simulations: Pressure Effects With Sand



Jet Penetration Correlations

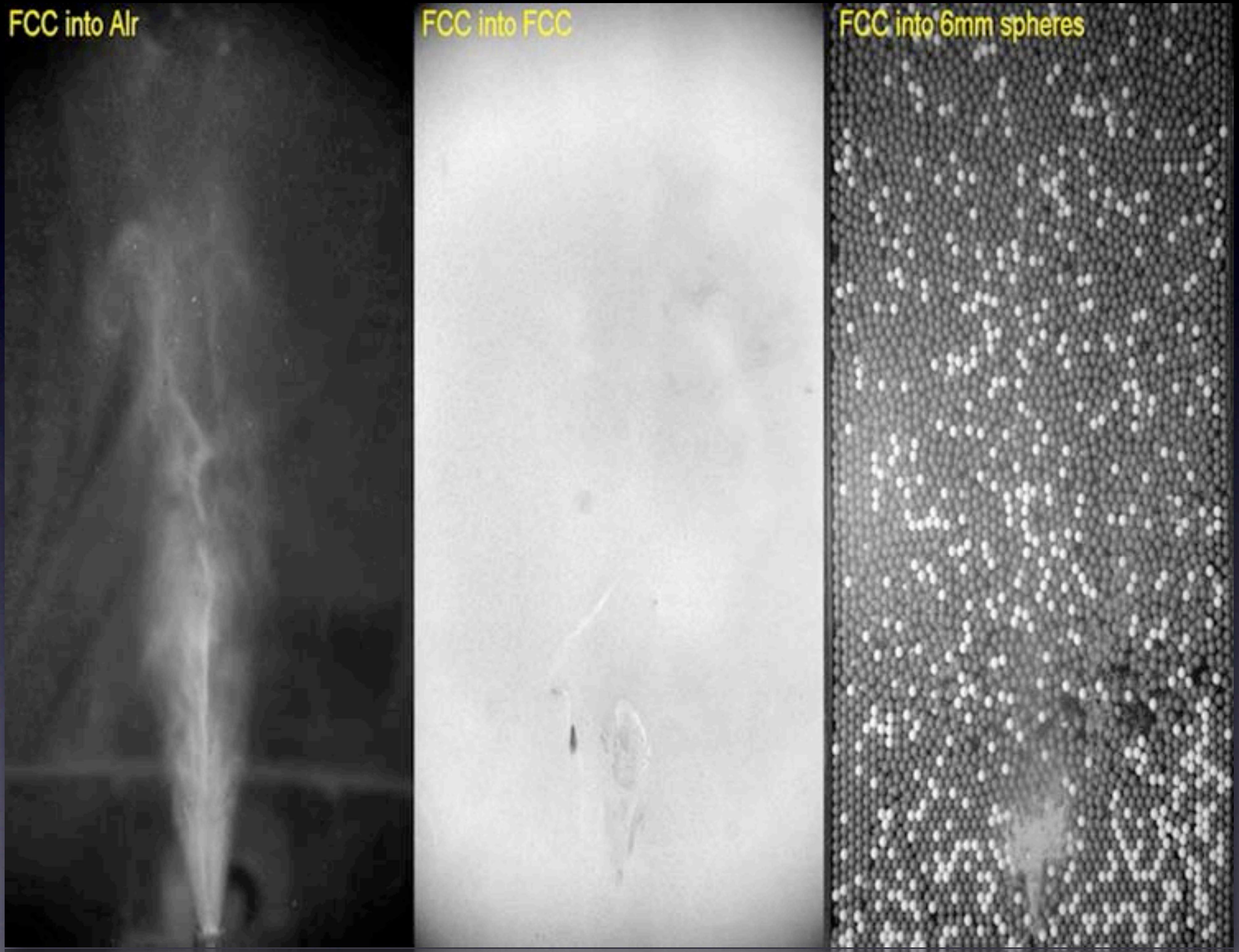


- Both Barracuda™ and PSRI correlations do well for all three materials at all pressures
- Merry and Shakhova did not fare well

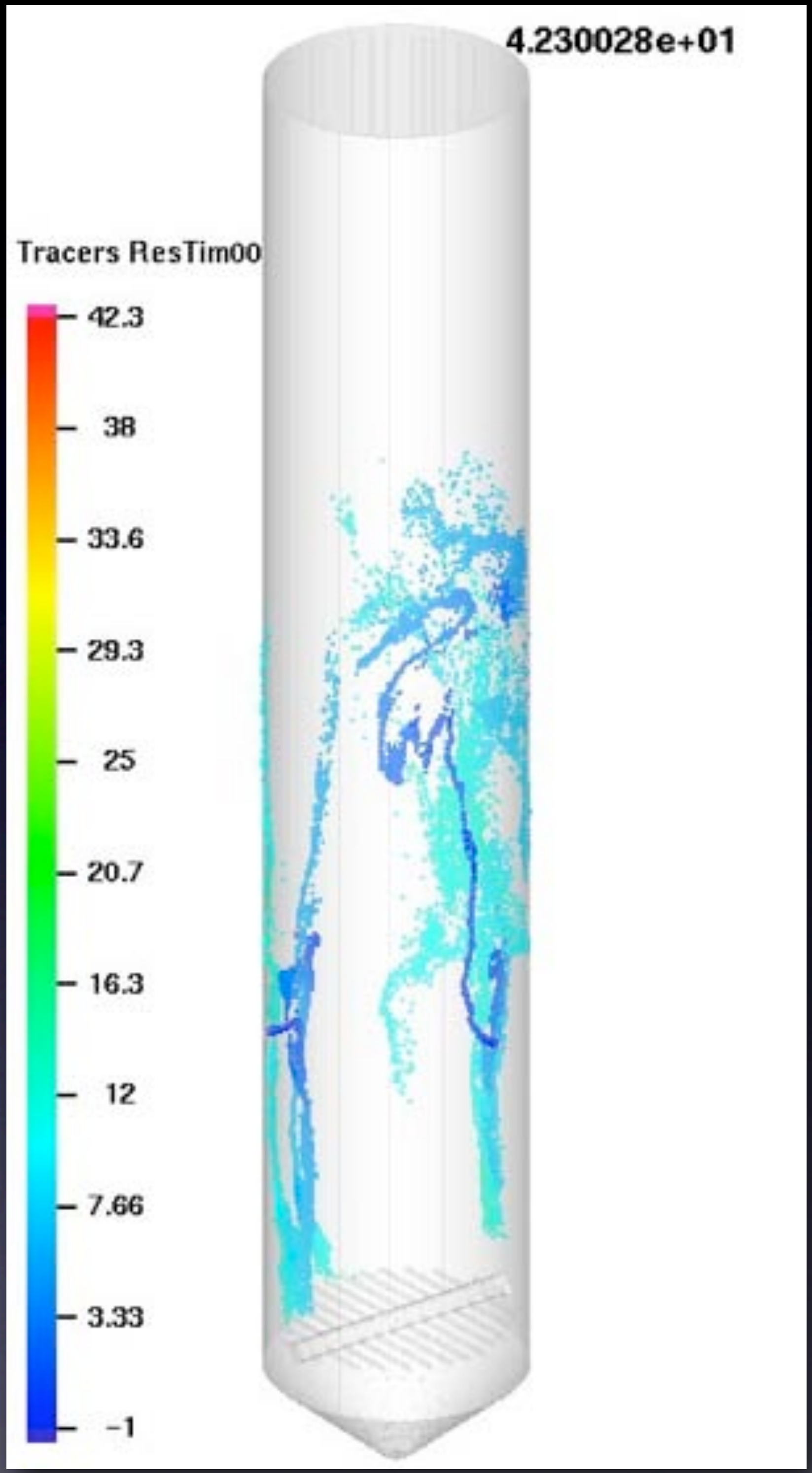
Merry, J.M.D., AIChE J., 21 (1975) 5

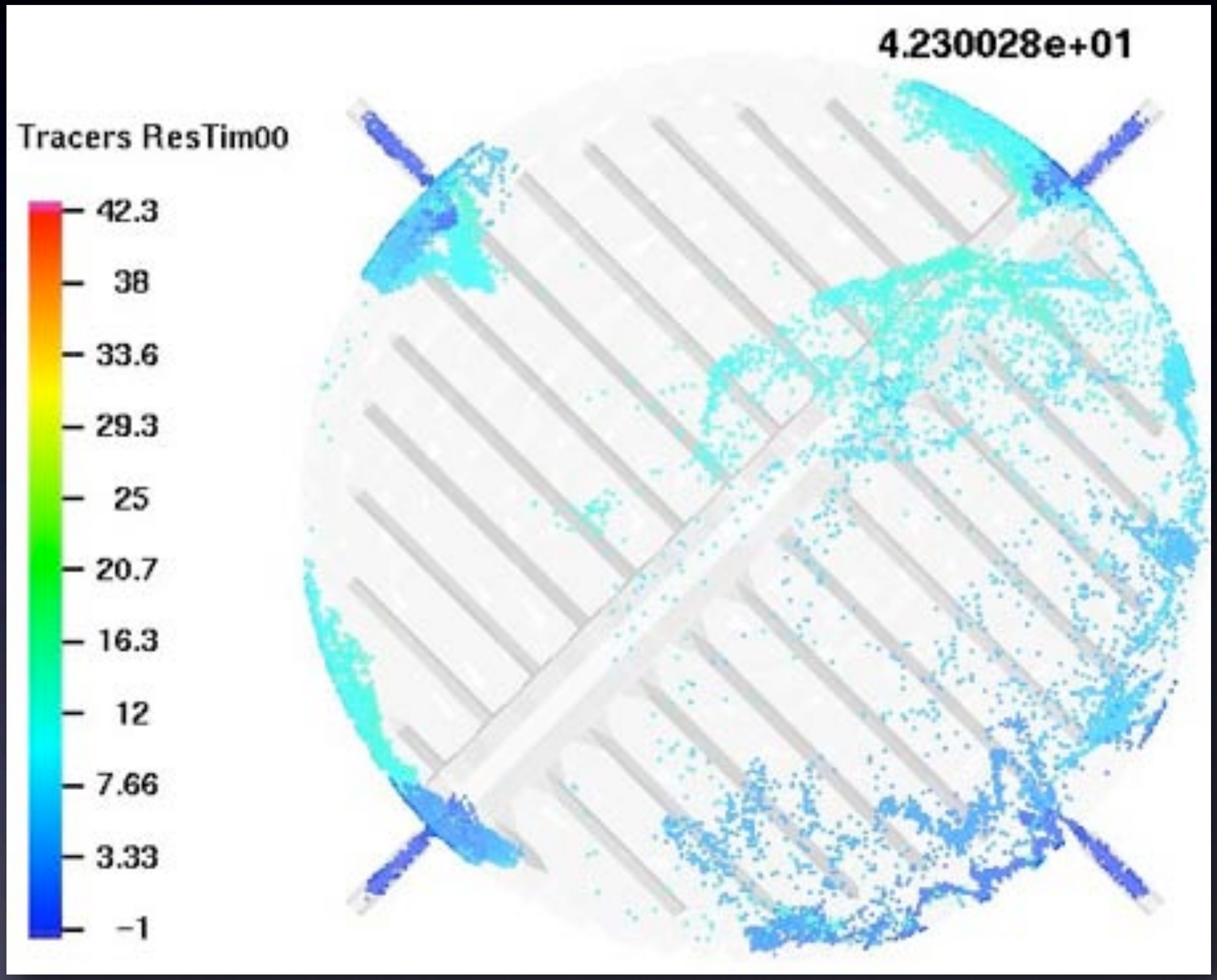
Shakhova, N.A. Inzh. Fiz. Zh., 14 (1968)

FCC/Fines Penetration in Jets



Simulating Where The Particles Go

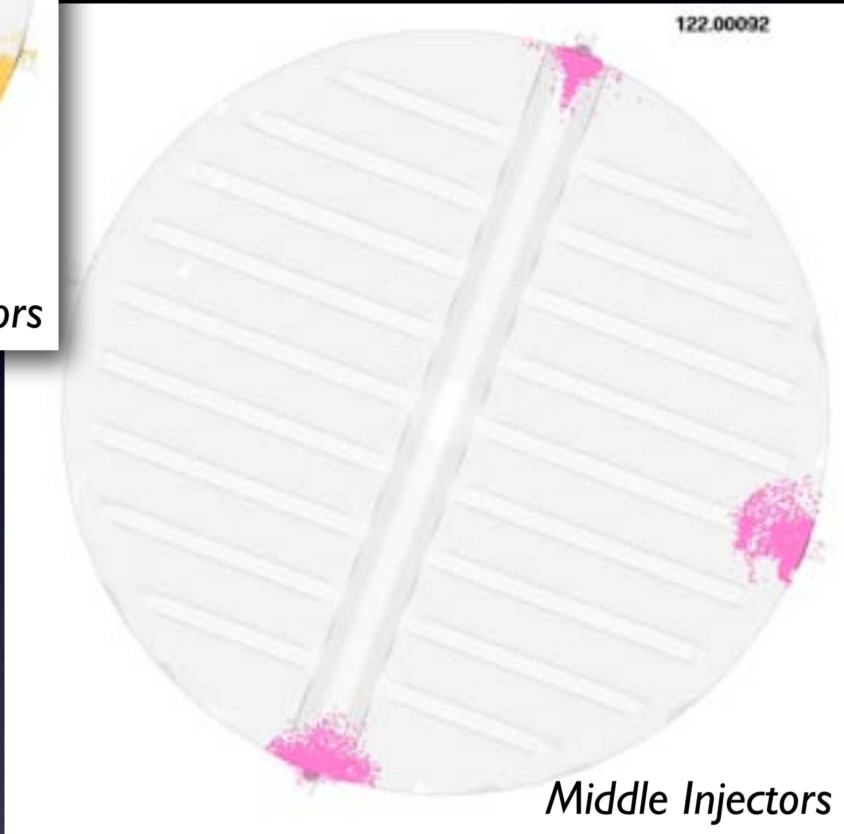




- Four nozzles start at 30 seconds

Biomass Injection

Top Injectors

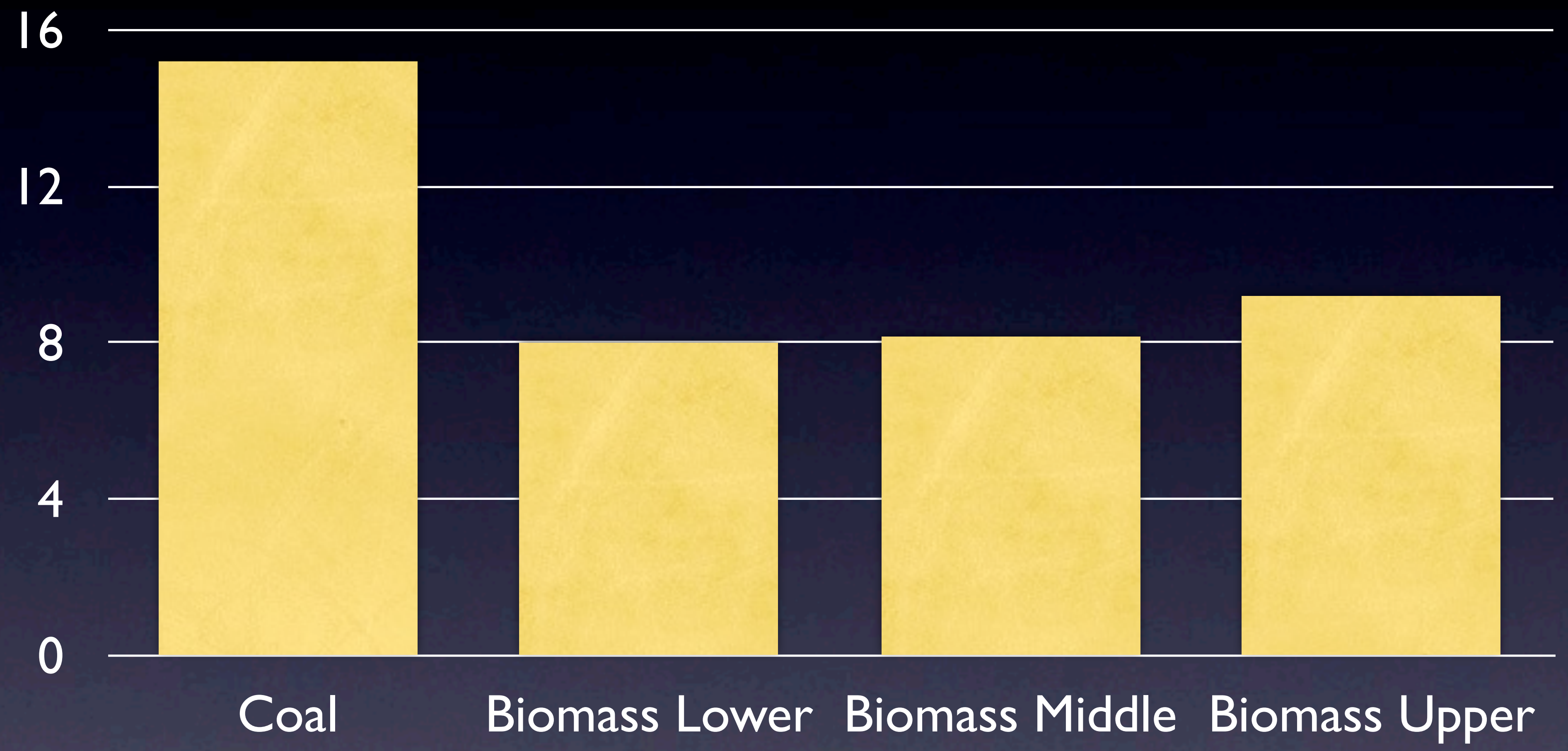


Middle Injectors

Bottom Injectors

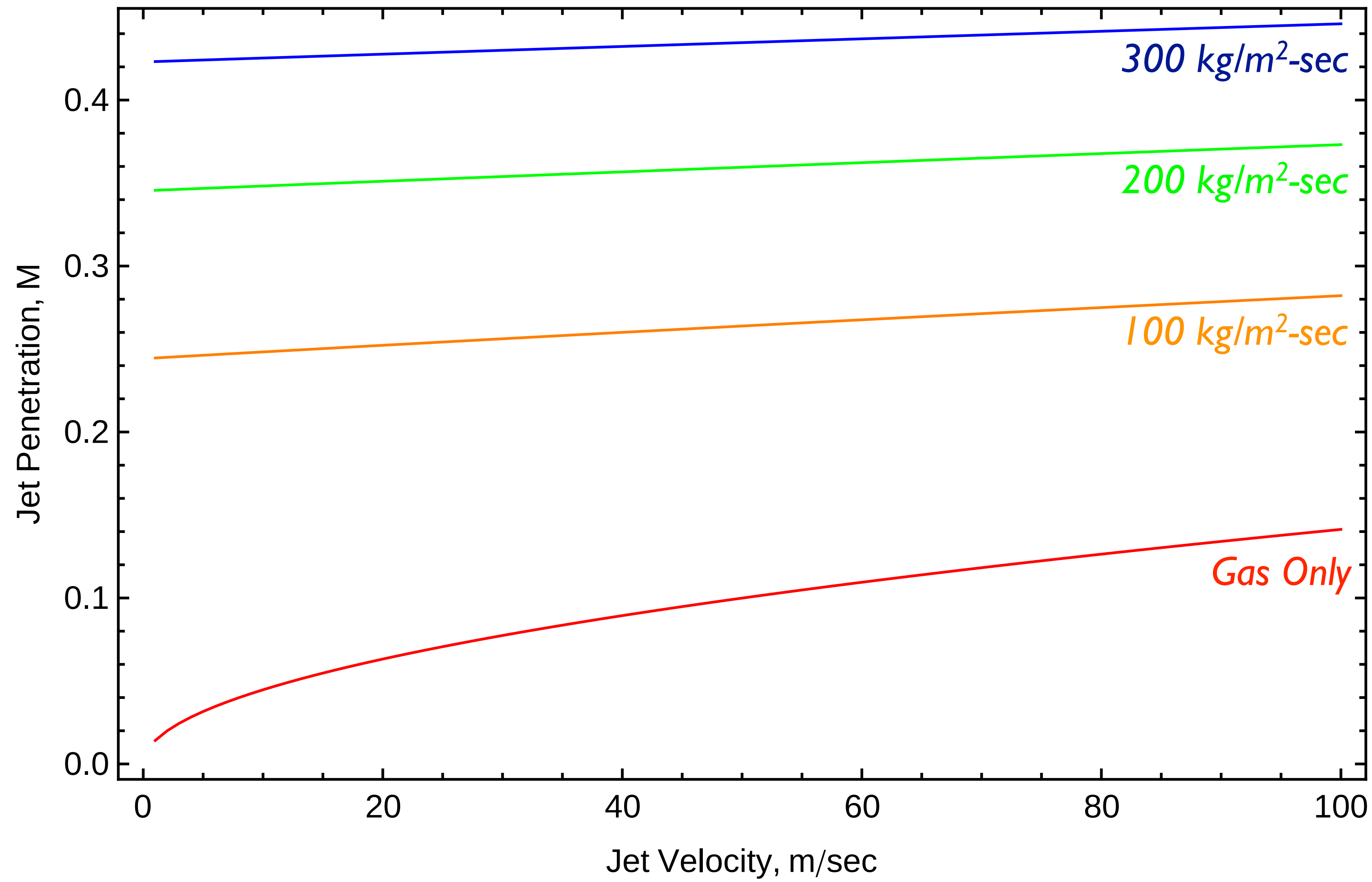
- Penetration does not go far from the wall

Biomass Jet Penetration



- Biomass never really gets past the wall and buoyancy keeps it there

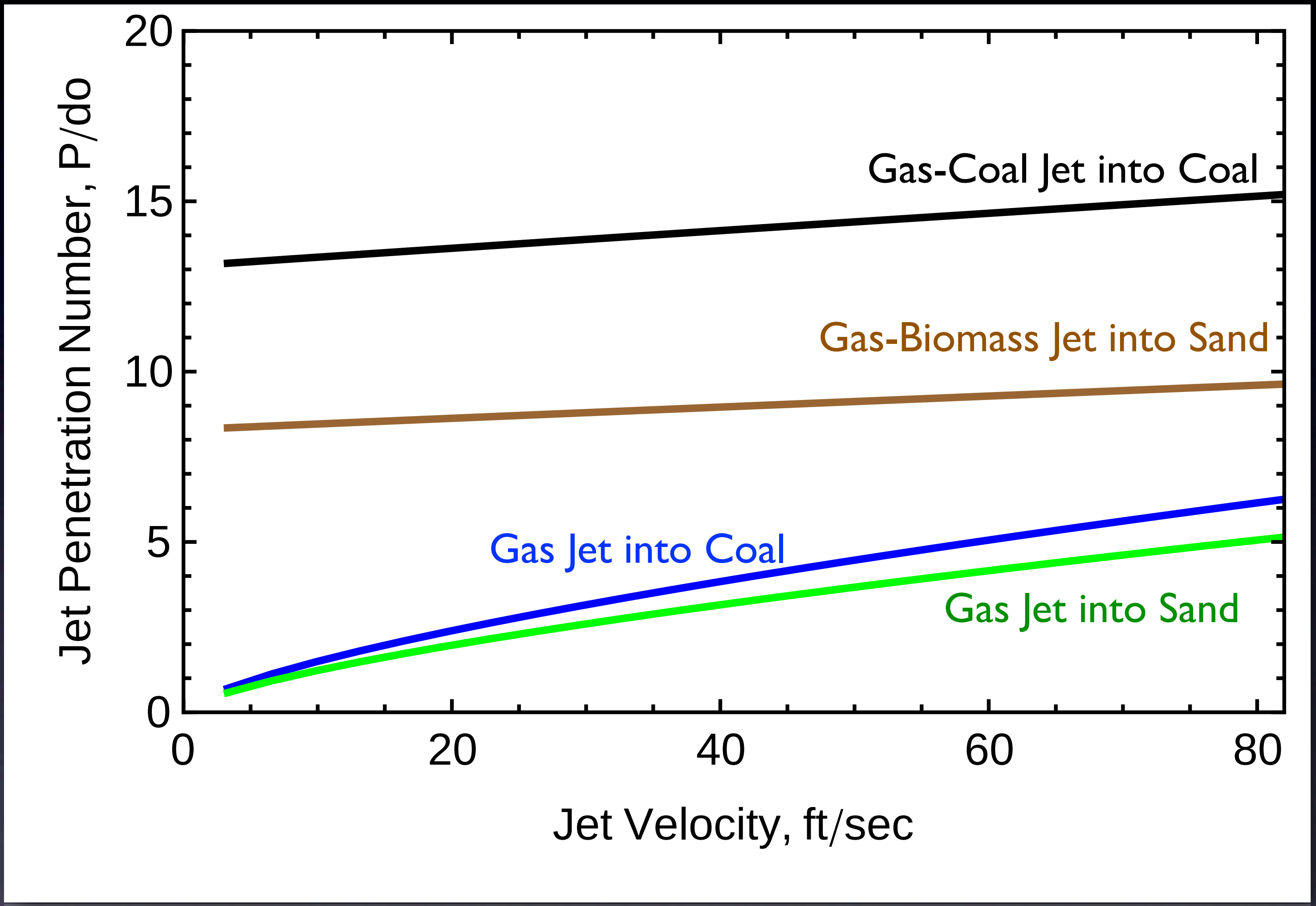
Particle Laden Jets via PSRI Jet Penetration Correlation



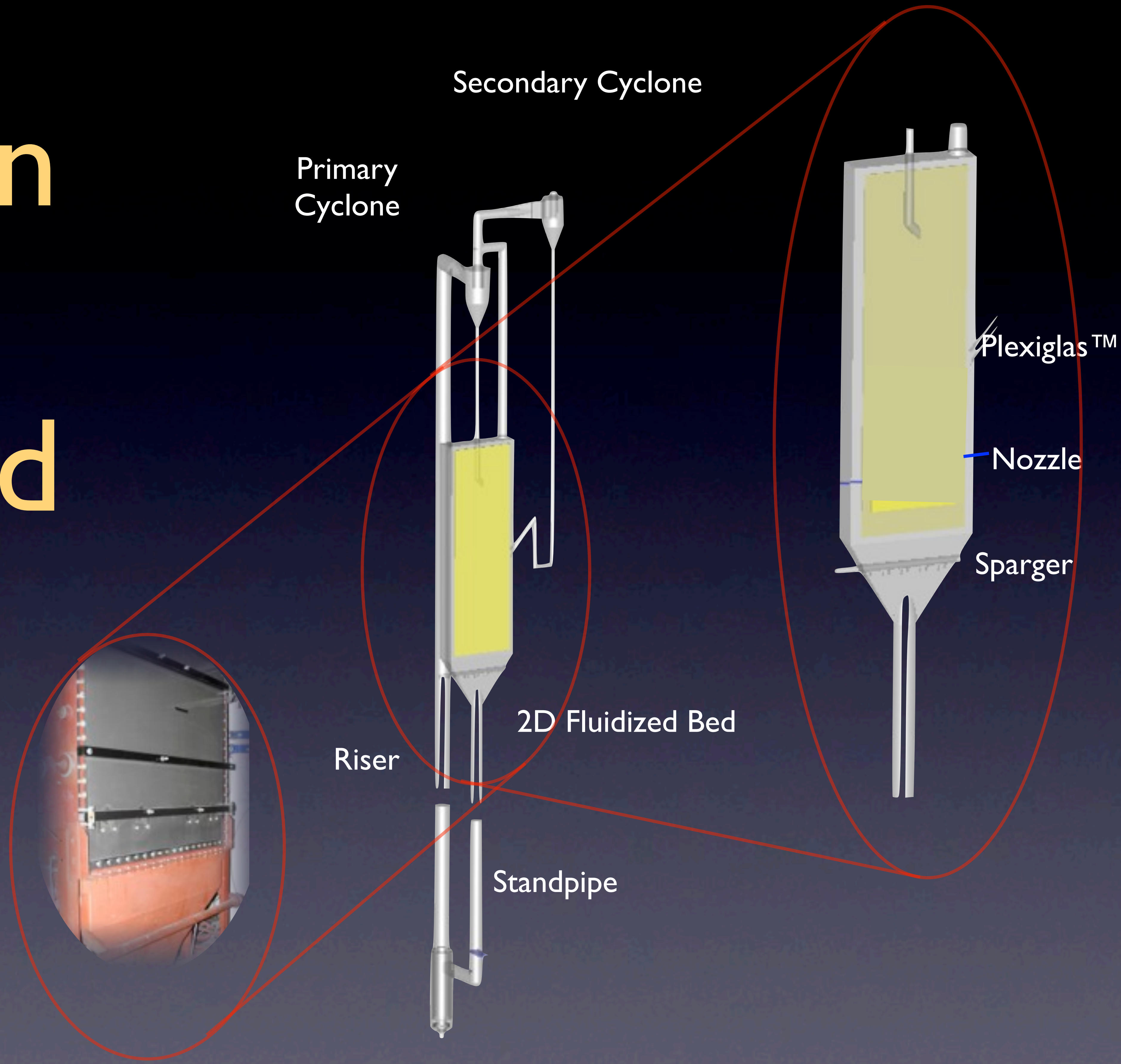
Air and Air-Sand Particles into a Fluidized Bed of Sand at 103 KPa and 800°C

- Particle momentum form a jet significantly increase the jet penetration length

Jet Penetration Length



Liquid Injection into a Fluidized Bed



Liquid Injection into a Fluidized Bed

~20 cm

- Phantom VII Color High-Speed Video Camera
  - 9900 fps at 20 microsecond shutter speed
  - Red dye in liquid to enhance contrast

Liquid Injection into a Fluidized Bed

1cm

8-inches (20 cm) from injector face

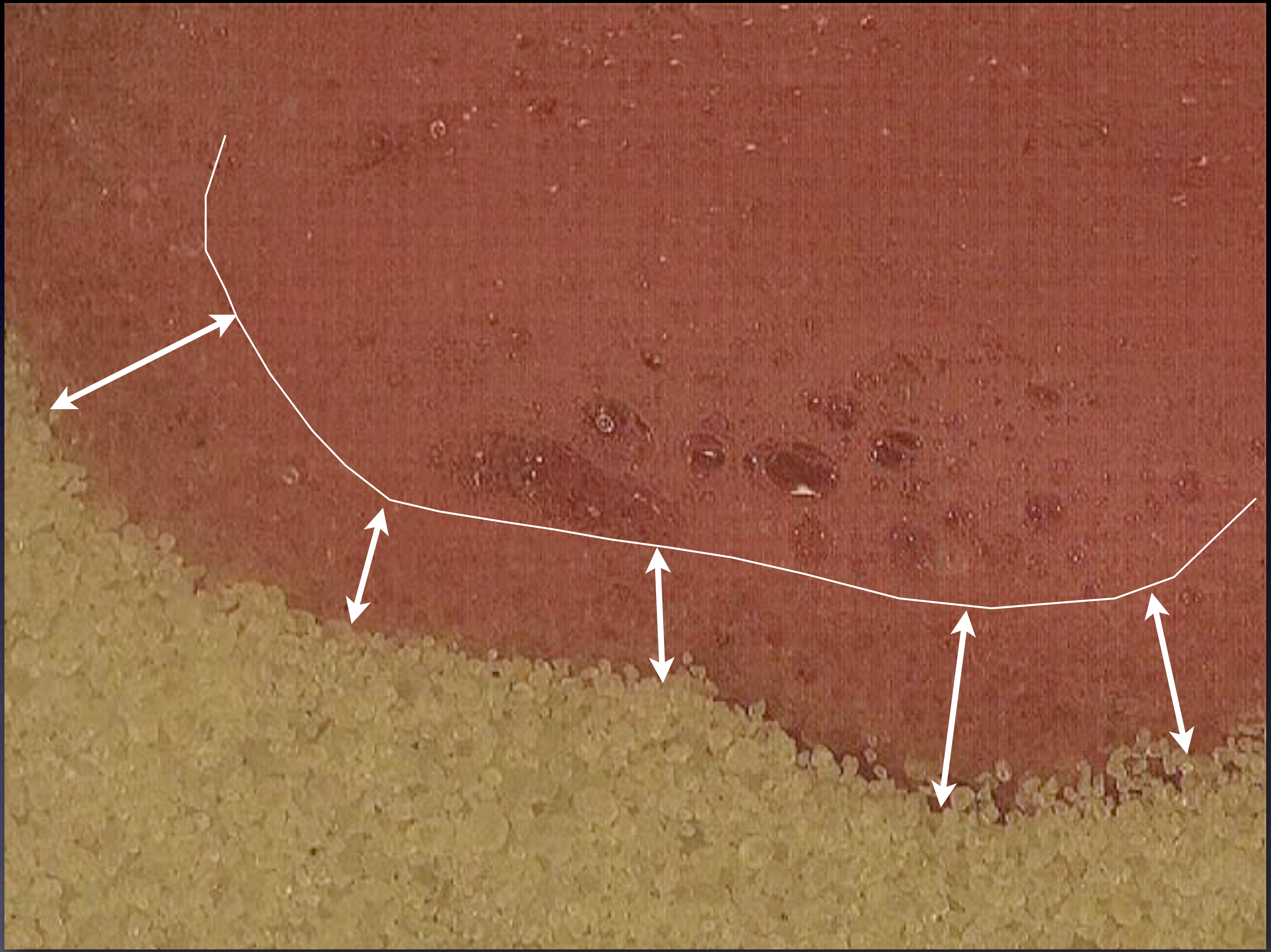
2-inches (5 cm) from injector face

- Phantom VII Color High-Speed Video Camera
  - 9900 fps at 20 microsecond shutter speed
  - With liquid dye for contrast

Jet - Fluidized Bed Boundary Layer

- Little liquid jet penetration after initial wetting of particles
- Little particle exchange between wetted particles and dry particles beyond boundary
- Boundary layer estimated at 0.18 ± 0.04 cm

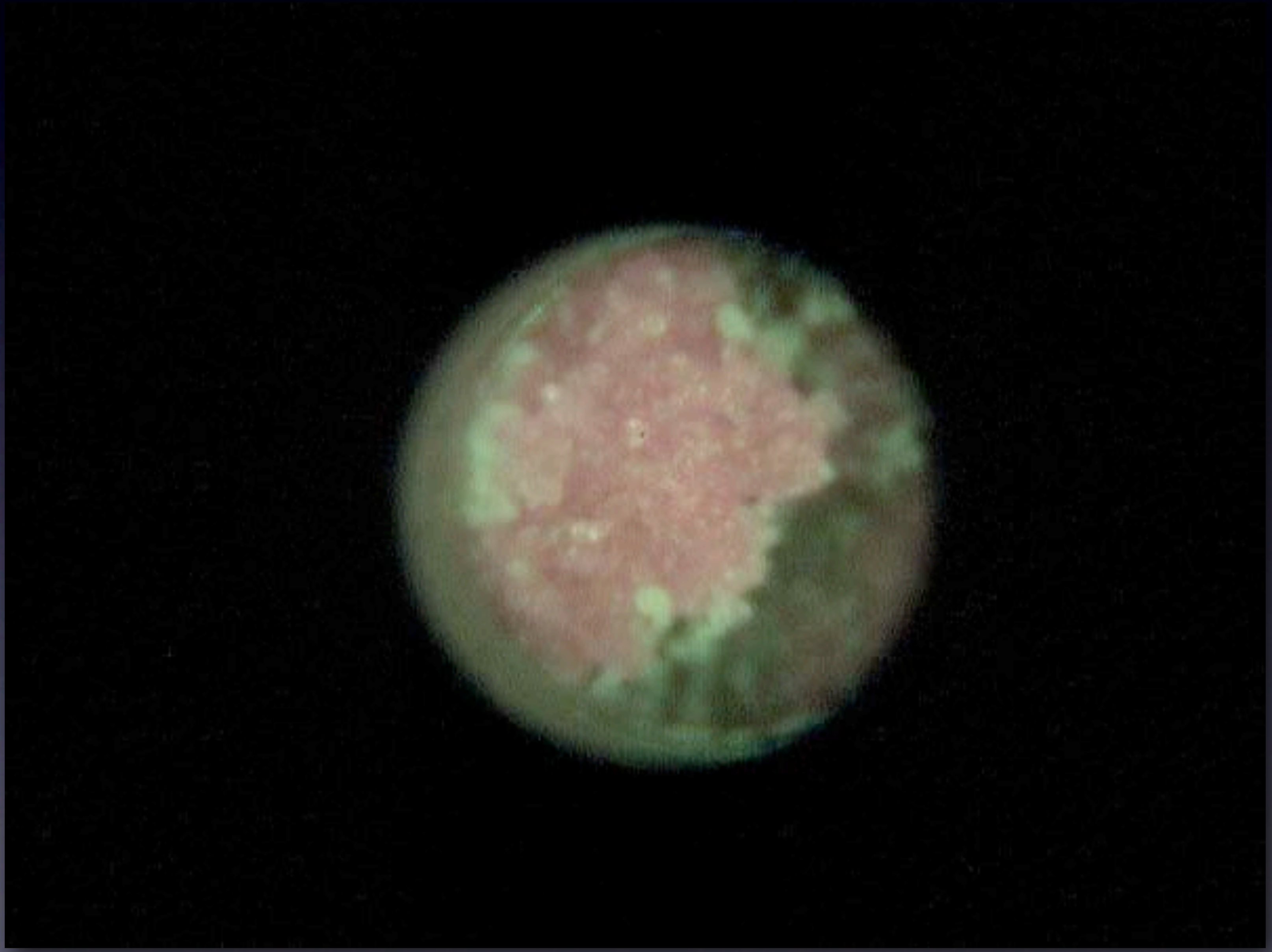
Jet - Fluidized Bed Boundary Layer



- Little liquid jet penetration after initial wetting of particles
- Little particle exchange between wetted particles and dry particles beyond boundary
- Boundary layer estimated at 0.18 ± 0.04 cm

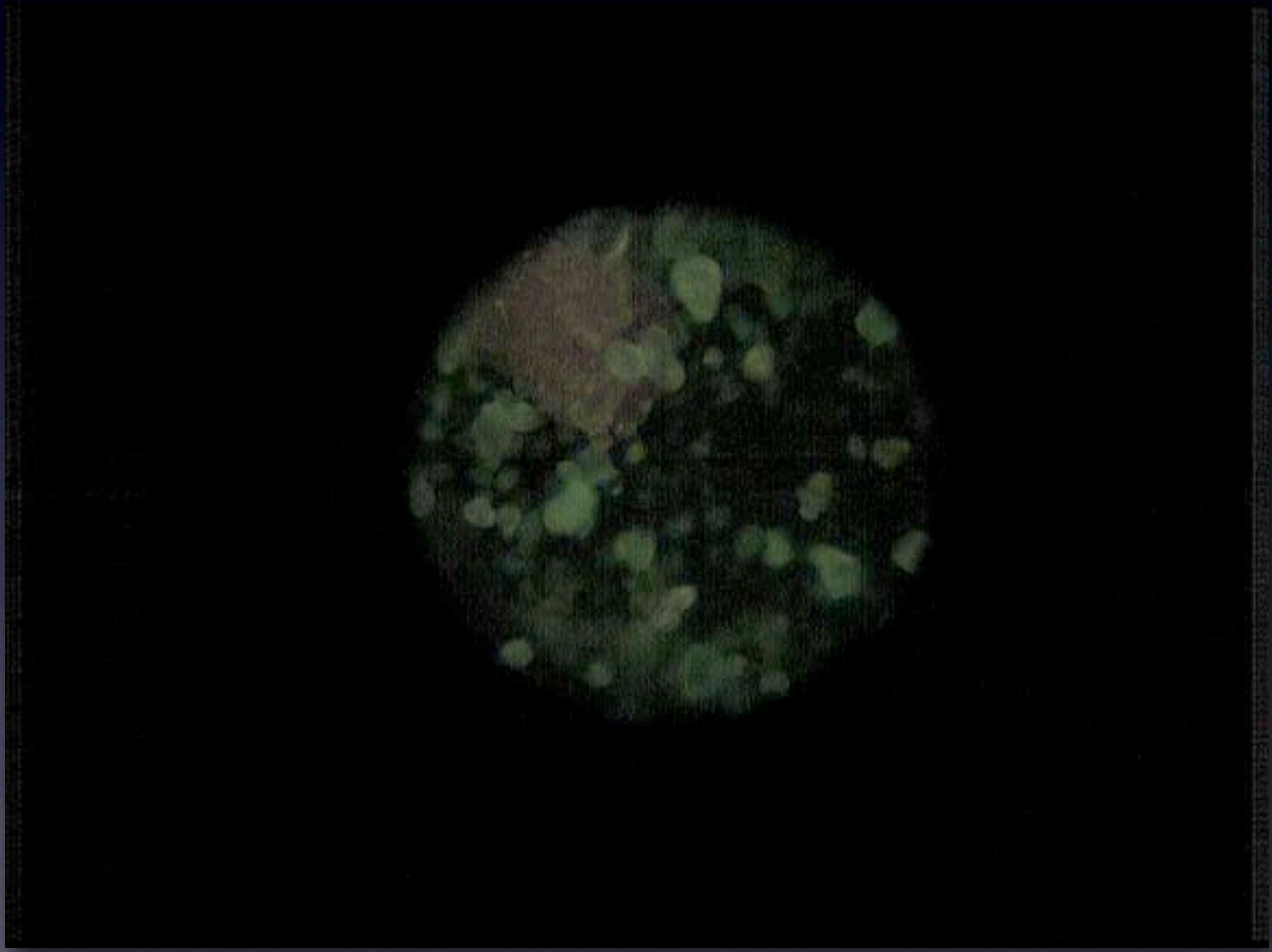
Liquid-Particle Interactions in a Fluidized Bed

- 1000 fps at 990 microsecond shutter speed
- 5-inches (12.7-cm) from nozzle face
- 1.5-inches (3.8-cm) from face plate (wall)
  - Estimated to be within the of jet
- 20 SCFH (0.6 SCMH) sweeping gas
- Liquid injection contains dye
- Small particles coating liquid droplets



Liquid-Particle Interactions in a Fluidized Bed

- 1000 fps at 990 microsecond shutter speed
- **9-inches (23-cm) from nozzle face**
- **1.0-inches (2.5-cm) from face plate (wall)**
  - Estimated to be at the boundary of the jet
- 5 SCFH (0.15 SCMH) sweeping gas
- Liquid injection contains dye
- Bigger particles coating droplets



Summary

- Particle properties under reaction conditions (including particle size) are a key design parameters
- Geldart Group A powders have small bubbles even in large units
  - Smoother fluidization
  - Significant bed expansion especially at higher pressures
  - Good heat and mass transfer
  - Gas bypassing could be an issue
  - Particle clustering could be an issue
- Geldart Group B powders have large bubbles in commercial units
  - Poorer heat and mass transfer
  - Unstable bed operations in some cases
  - Slugging could be an issue, even in commercial units
- Jet penetration is mostly driven by buoyancy!