PIPELINE PLUG PREVENTION: Enlightenment Yielded From Initiative M-1 Testing Results

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May 21, 2009

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Outline

- Test purpose & design
- Invaluable literature information
- Stability map concept development
- Results/sedimentation observations
- General conclusions

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M-1 Initiative Testing: Purpose & Design

- Investigate critical deposition velocity for slurries with wide range of properties to mimic large cross section of Hanford waste to be processed (WTP-RPT-175, Rev 0)
  - Particle density (2.5 g/cc - 8 g/cc)
  - Particle size (10 µm - 100 µm)
  - Rheology (0, 3, 6 Pa) koalin composition
- Investigate influence of complex piping geometry (WTP-RPT-178, Rev 0)
- Investigate critical deposition velocity for a representative complex simulant (WTP-RPT-189, Rev D – to be released shortly)
  - Engineered AZ-101 HLW pretreated simulant (<1 to 30 Pa)
- Investigate possible flushing techniques

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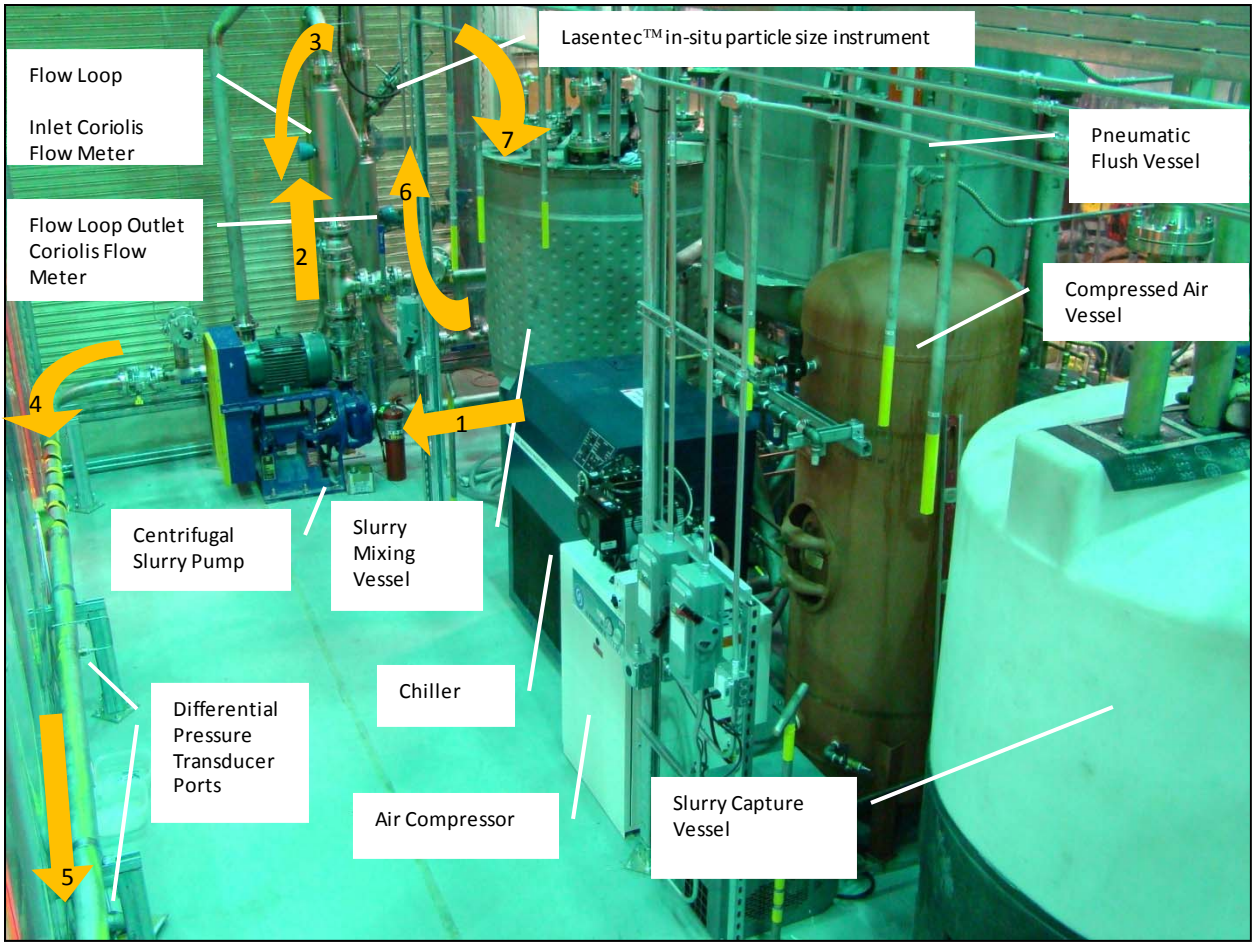
Flow Loop Configuration

- Slurry pumped through 3” sch. 40 Sst pipe
- Flow rate monitored via dual Coriolis flow meter
- Pressure/length of pipe monitored via differential pressure transducers
- Electrical Resistance Tomography probe
- Lasentec focused beam reflectance measurement (FBRM) sensor
- Simulants tested
  - RPT-175 (0 to 6 Pa yield stress)
    - 10 µm glass beads
    - 10 µm stainless steel
    - 50 µm alumina
    - 100 µm glass beads
    - 100 µm stainless steel
  - RPT-189 (<1 to 30 Pa yield stress)
    - 150 µm glass beads
    - AZ-101 HLW pretreated simulant



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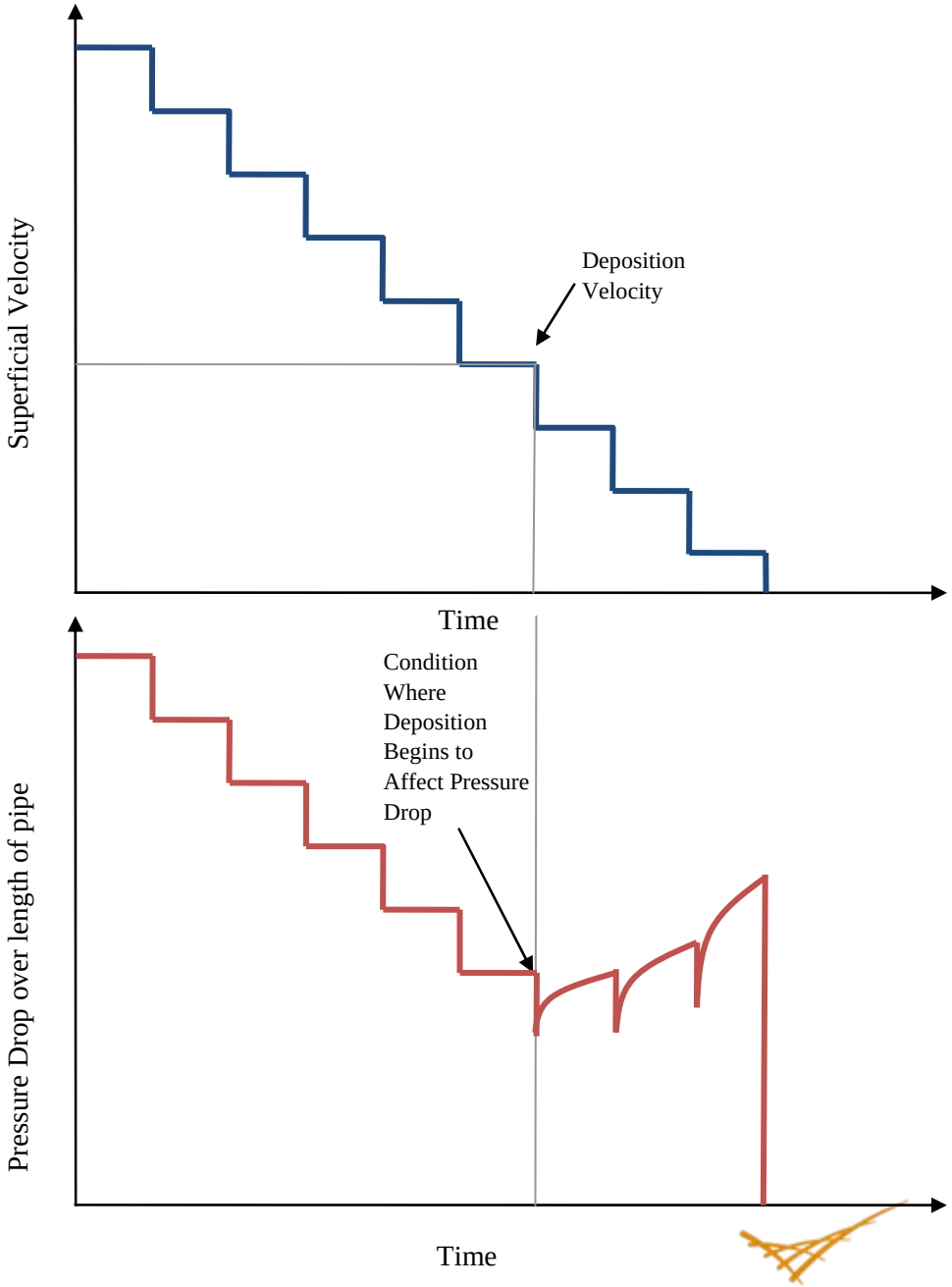
Test Process

- Velocity was decreased in 0.5 ft/sec increments starting at 8-10 ft/sec
- Deposition is indicated by an increase in the pressure/time signature
- Whether the unstable pressure condition surpasses the previous pressure measurement depends on the selected velocity step size and test duration
- Conclude testing by flushing loop



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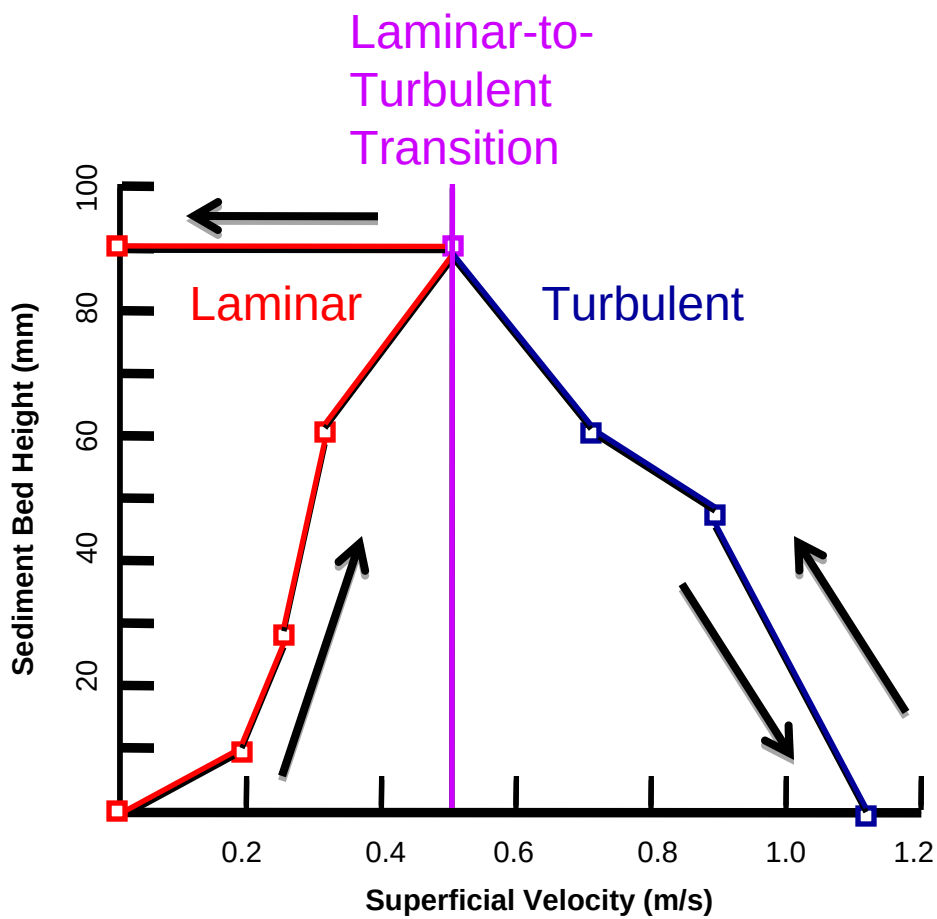
Invaluable Literature Information Summary

- Turbulent-to-laminar transition promotes particle settling (especially coarse even among fines) and Darby yield stability parameter, *Y* not reliable in predicting this behavior Newtonian or non-Newtonian)
  - Shah & Lord (1991), Shook et al. (2002), Gillies et al. (2007), Cooke (2002), Thomas et al. (2004), and Gaskill et al. (1996)
- Some laminar flows lead to settling, some don't and particles typically stable until sheared
  - Paterson & Cooke (2008), Cooke (2002), Gillies et al. (2007)
- Some non-Newtonian turbulent regimes display early onset particle settling (above turbulent-to-laminar transition)
  - Cooke (2002)

Significance of the Laminar-to-Turbulent Transition-Experimental Data

- Data from Song and Chiew[1] (1997)
- Bingham Plastic Slurry with Clay (4.5 µm) and Sand (150 µm)
- At zero flow the slurry is stable.
- As flow is ramped up, a bed deposits while in laminar flow (red)
- When transition velocity (magenta) is reached, the bed height peaks
- The bed height then decreases while in turbulent flow (blue) as velocity increases
- As flow is decreased while in turbulent flow (blue), the bed begins to reform
- As flow is decreased while in laminar flow, the bed height remains at the maximum level



[1]Song T. and Y-M Chiew. 1997. "Settling Characteristics of Sediments in Moving Bingham Fluid." *J of Hyd. Eng.*, 123:9, September, ASCE.

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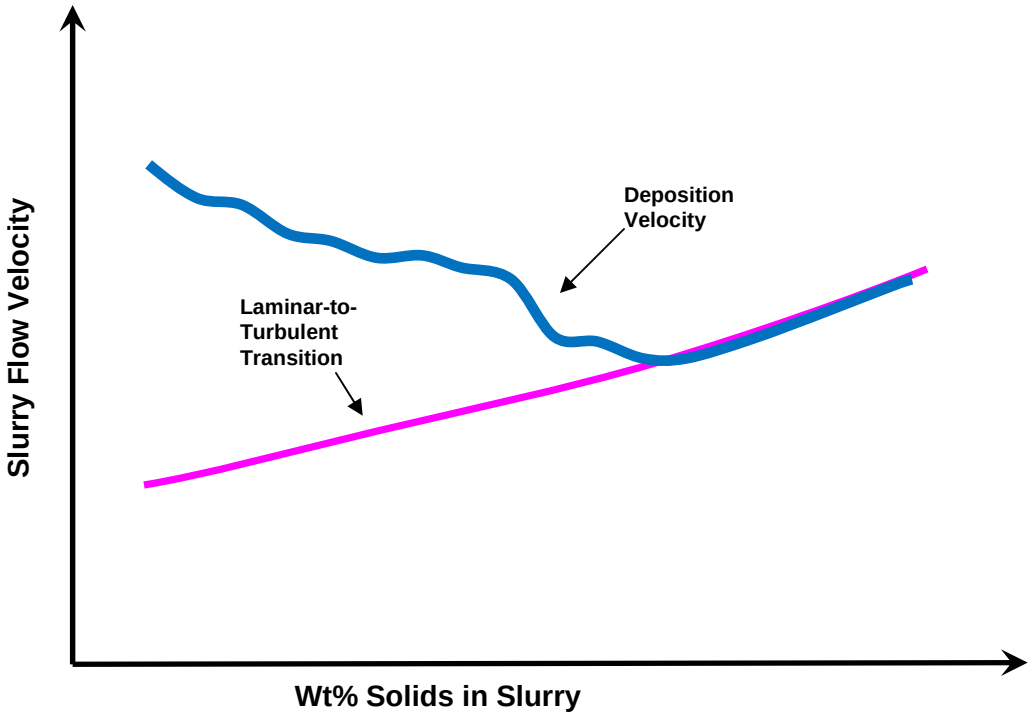
Significance of the Laminar-to-Turbulent Transition-Experimental Data

- Plot adapted from Mular et al. (2002)[1]
- Increasing solids loading raises rheological properties
- Eventually the flow will become laminar and deposition occurs
- Deposition velocity then follows the transition velocity and increases with solids loading
- Warn of excessive pipe wear at pipe bottom due to moving bed



[1]Andrew L. Mular, Doug N. Halbe, Derek J. Barratt Contributor Andrew L. Mular, Doug N. Halbe, Derek J. Barratt, "Mineral Processing Plant Design, Practice and Control: Proceedings" Published by SME, 2002

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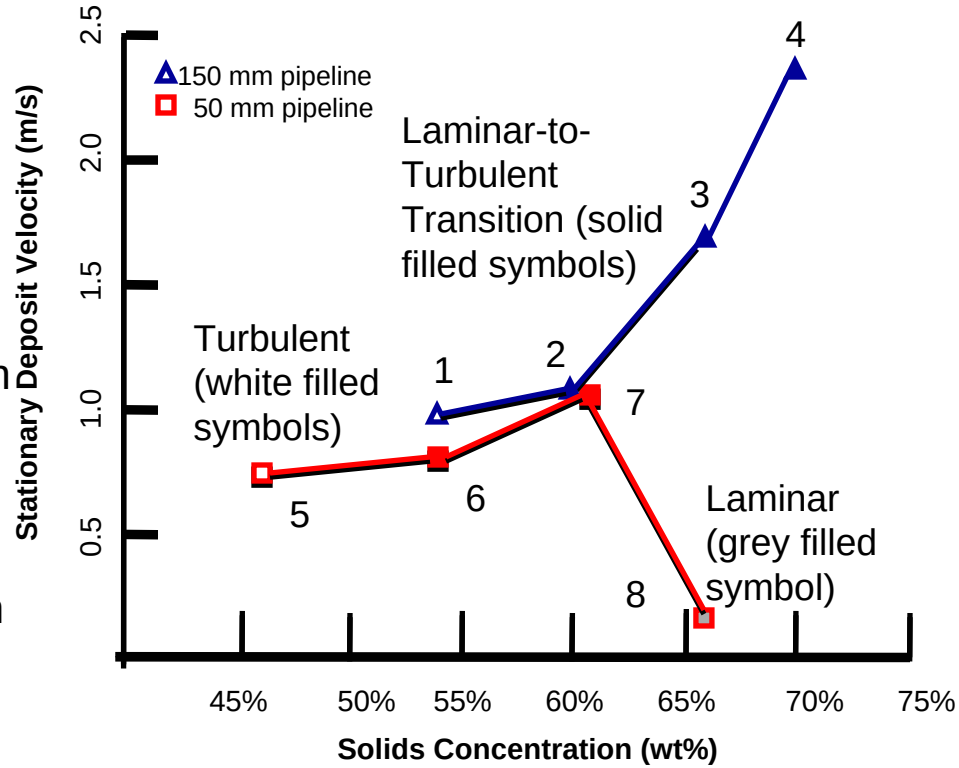
Significance of the Laminar-to-Turbulent Transition-Experimental Data

- Data from Cooke[1] (2002)
- Two pipelines tested
  - 50 mm ~2 in; square symbols
  - 150 mm ~ 6 in; triangle symbols
- Points 1 & 5 exhibit deposition in turbulent flow
- Points 2,3,4, 6, & 7 exhibit deposition occurring at the transition from turbulent to laminar flow
- Point 8 shows stable laminar flow occurring in the smaller diameter pipe due to increased shear to extrude the settled particles through the pipe
- Author concludes that pipe tests with only 50 mm diameter would incorrectly find that operation at high solids concentrations is safe



[1]Cooke R (2002) "Laminar flow settling: the potential for unexpected problems." BHRG 15th International Conference on Slurry Handling and Pipeline Transport, *Hydrotransport 15*; Banff, June. 121-133.

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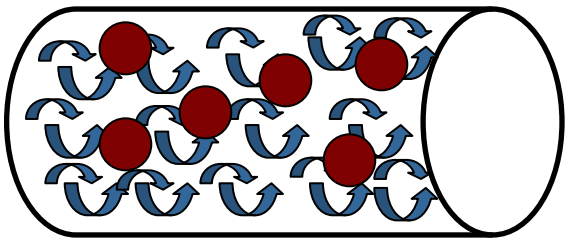
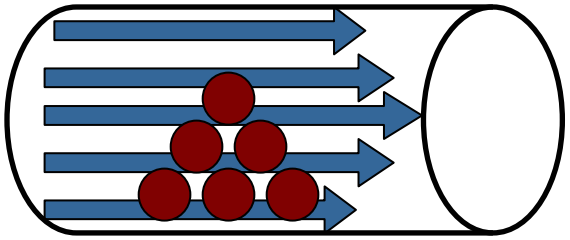
Flow Regions



- Region A: Stable Turbulent
  - Turbulent eddy drag forces are sufficient to suspend the particle buoyant mass



- Region C: Unstable Laminar
  - Turbulent eddy forces are dissipated by viscous forces

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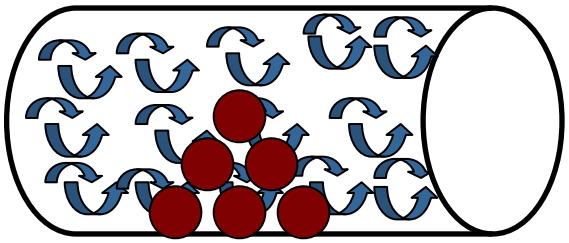
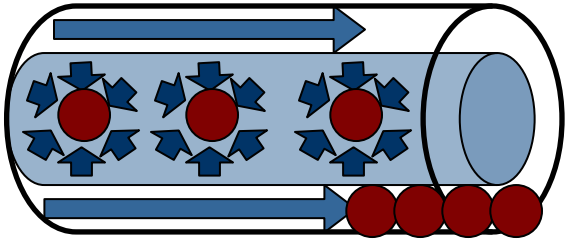
Flow Regions



- Region B: Unstable Turbulent
  - Turbulent eddy drag forces are not sufficient to suspend the particle buoyant mass



- Region D: Stable Laminar
  - Yield stress forces dominate the unsheared core region of the pipe flow
  - Yield stress supports particles during transfer
  - Wall shear stress push particles deposited along pipe wall

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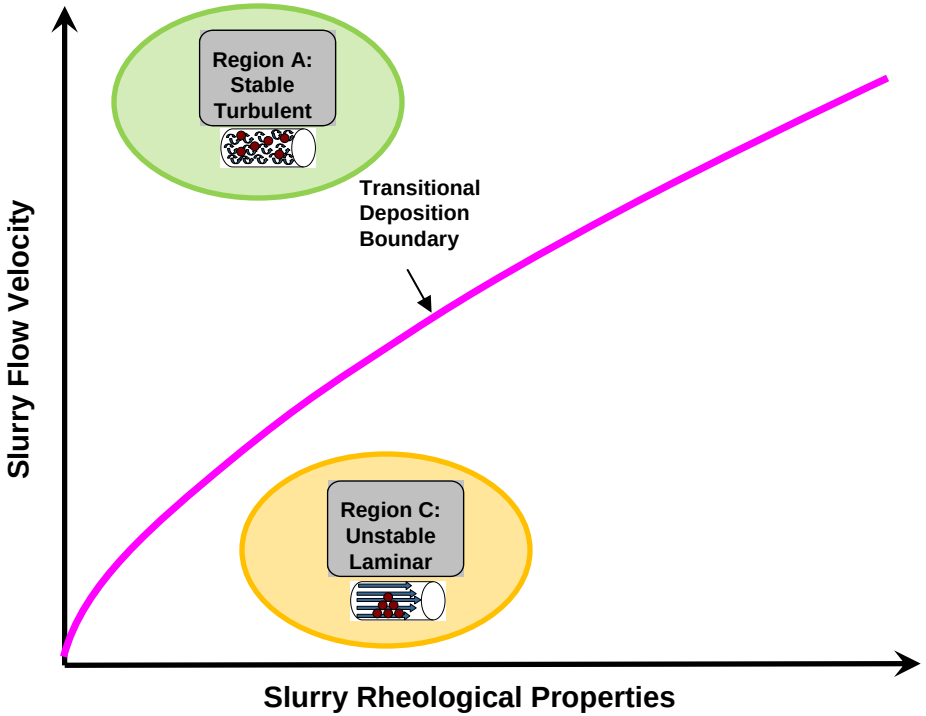
Stability Maps: Transitional Deposition Boundary

- As slurry rheology increases, viscous forces dampen formation of turbulent eddies
- Homogeneous Transport not possible without turbulent eddies
- Two regions are proposed
  - Stable Turbulent
  - Unstable Laminar Flow
- Develop via *He* for Bingham or *Ca* for Casson, and general critical Reynolds number relationship



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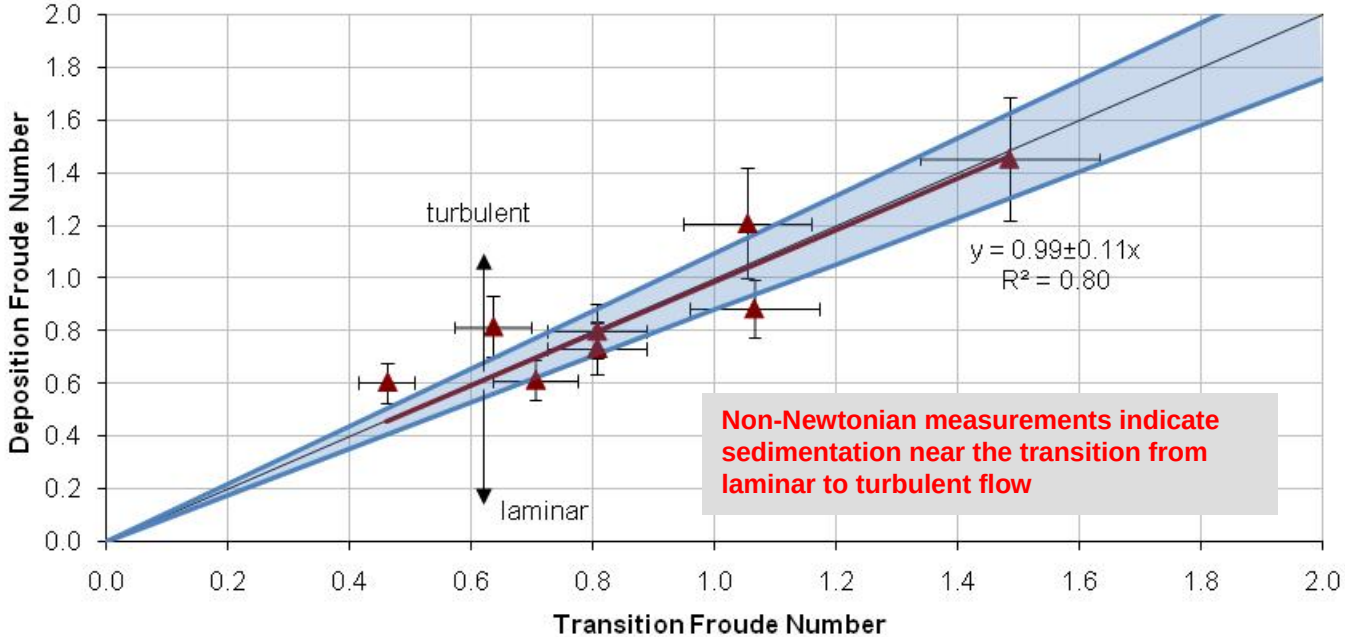
M1 Experimental Data on Laminar-to-Turbulent Transition



- 9 M-1 data points support the correlation
- Error bands are based on 95% confidence on correlation parameters
- Error bars based on propagation of error on measurement uncertainty
- Stability unique to each particle size, density, and rheology combination
  - With these parameters defined the Archimedes number and laminar-to-turbulent flow velocity can be computed
  - Froude number can be predicted and used to calculate a predicted deposition velocity

$$Fr = \frac{V_c}{\sqrt{gD(S-1)}} \propto \frac{\text{inertial forces}}{\text{gravitational forces}}$$

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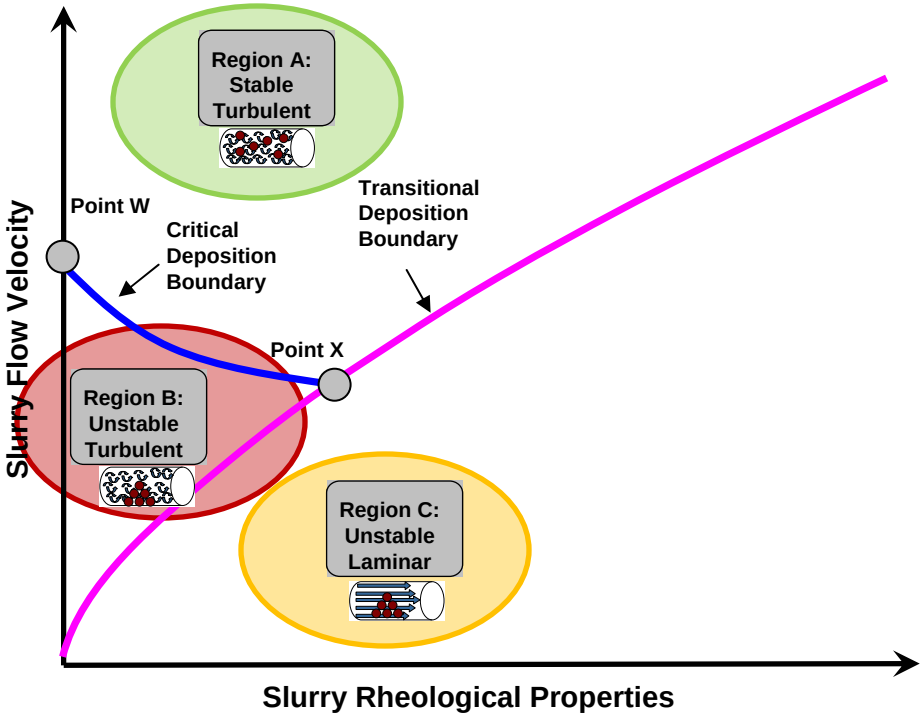
Stability Maps

- Turbulent Region can be divided into two areas
  - Stable Turbulent and Unstable Turbulent
- Point W – Newtonian Fluid Critical Velocity
  - Predicted with traditional transport correlations (Liddell & Burnett)
- As slurry rheology increases for a given density/particle size distribution,
  - Increasing viscosity increases drag on particles and promotes transport
  - Critical velocity requirements drop following curve WX - Critical Deposition Boundary
- Similar to Mular et al. (2002) plot on slide 8



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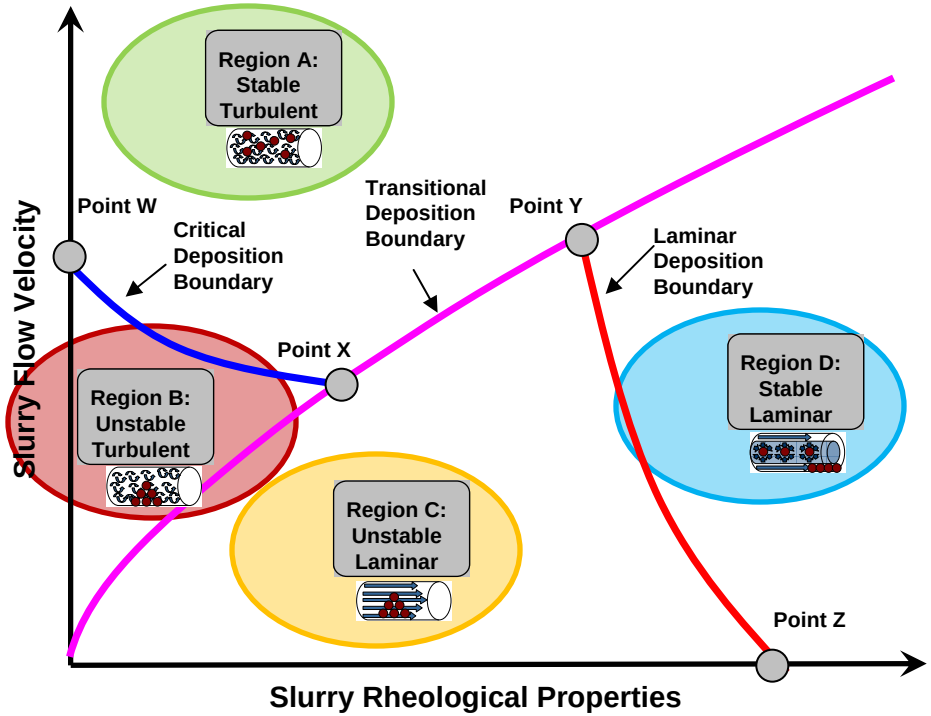
Laminar Flow: Particle Settlement

- **Under what conditions will the particles be transported?**
- **Thomas (1977)**
  - Deposition occurs at a constant pressure gradient regardless of pipe size.
- **Gillies *et al* (1999)**
  - Pressure gradient of about 2 kPa/m required to transport sand particles in a viscous Newtonian oil.
- **Gillies *et al* (2007)**
  - Propose that the criterion for transport is based on the ratio of the mean wall shear stress to the mean surficial particle stress.
- **This is an area of ongoing research**

Stability Maps

- As slurry rheology increases still further,
  - Another limit is reached at Point Y – maximum non-Newtonian Critical Velocity
  - Yield stress and pressure gradient forces are sufficient to push settled particles through the piping system
- Critical velocity requirements drop, usually dramatically, along curve YZ-Laminar Deposition Boundary
  - Gillies et al. (2007)[1]
  - The parameter α defines this boundary and current (limited) knowledge is that the stability boundary exists when $50 < \alpha < 100$ (α = wall shear / surficial shear)



[1]Gillies RG, R Sun, RS Sanders, and J Schaan. 2007. "Lowered Expectations: The Impact of Yield Stress on Sand Transport in Laminar, Non-Newtonian Flows." *Journal of the South African Institute of Mining and Metallurgy* 107(6):351–357.

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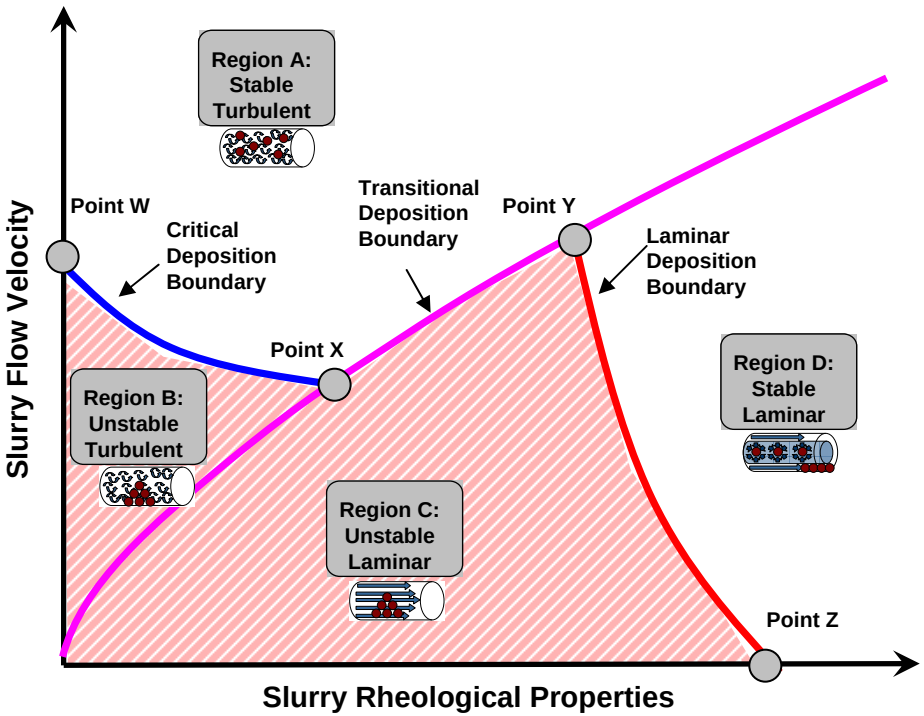
Stability Map Example

- The four flow regions (slides 10 & 11) correspond to regions on the stability map
  - Labeled as Region A, B, C, & D
- Operation in red areas will lead to eventual line plugging if a flush is not implemented soon enough
- When Point W > Point Y, Newtonian correlations are conservative for non-Newtonian transport
- When Point Y > Point W, Newtonian correlations are not conservative for non-Newtonian transport
- Again, region sizes are unique to particle density, particle size, and pipe diameter combinations.



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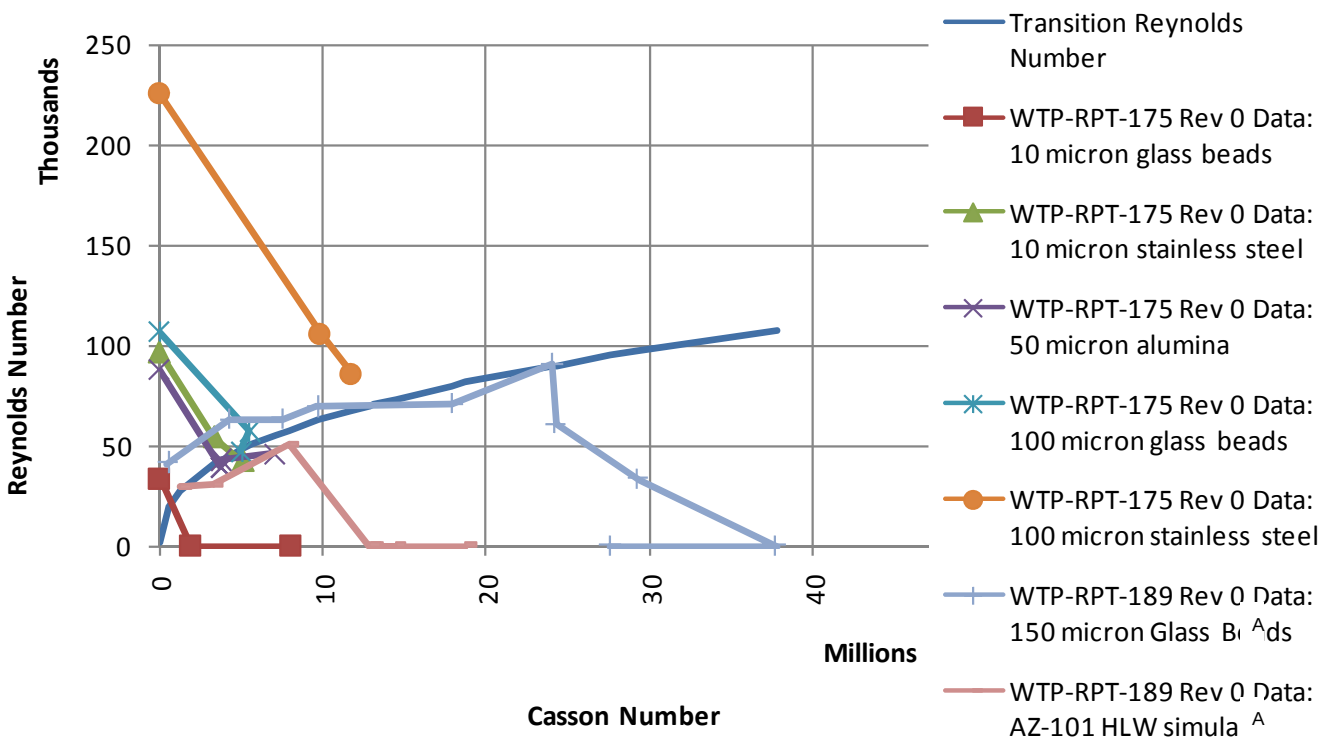
Summary of Results



- For Newtonian data (Ca = 0) deposition occurs in highly turbulent flow
- For non-Newtonian data (Ca > 0) deposition occurs along laminar to turbulent transition
- Non-Newtonian Reynolds numbers on the order of tens of thousands needed to prevent deposition
- Under highly non-Newtonian conditions, flow restabilizes

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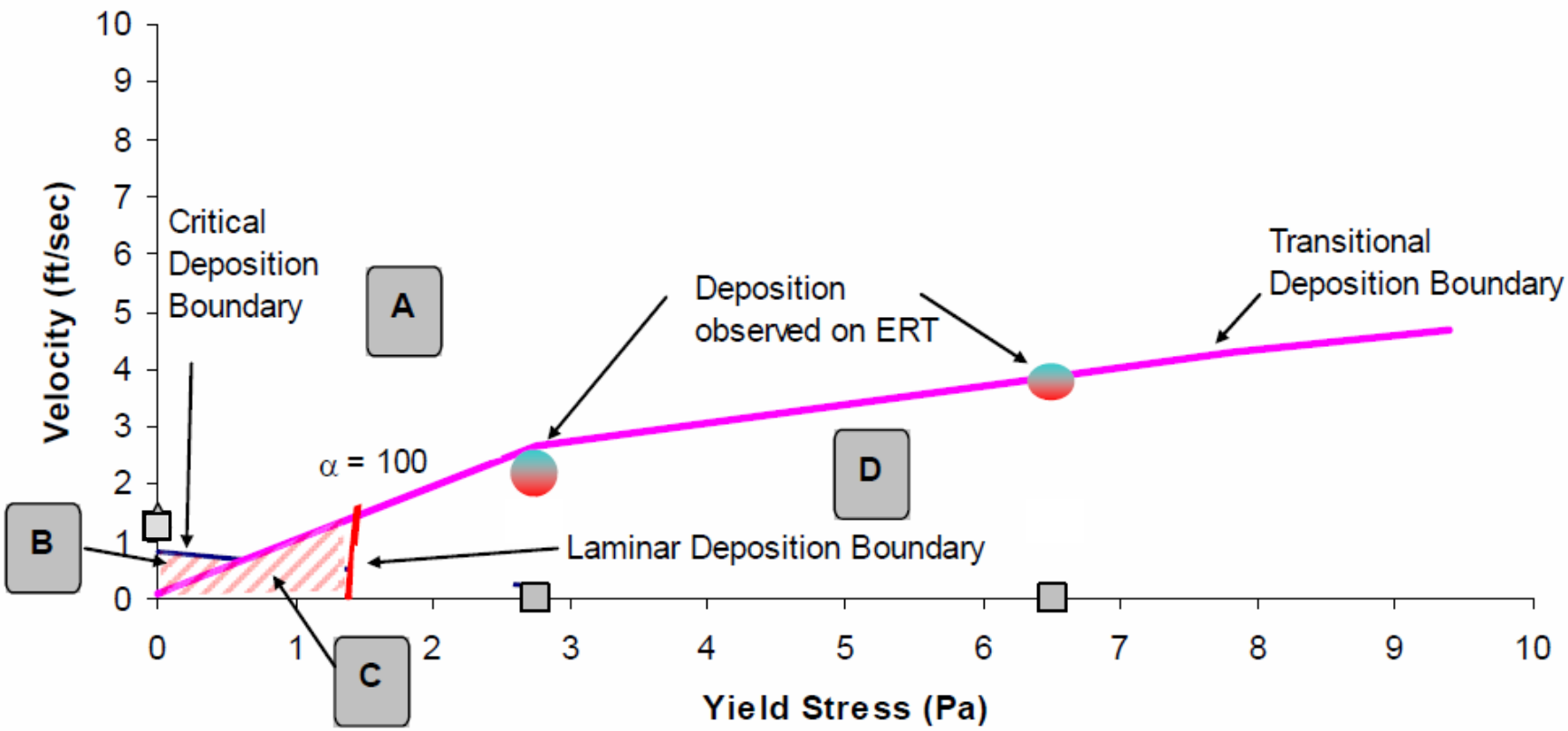
Stability Map Result for 10 micron Glass Beads in Water, and Thin & Thick Kaolin Slurry



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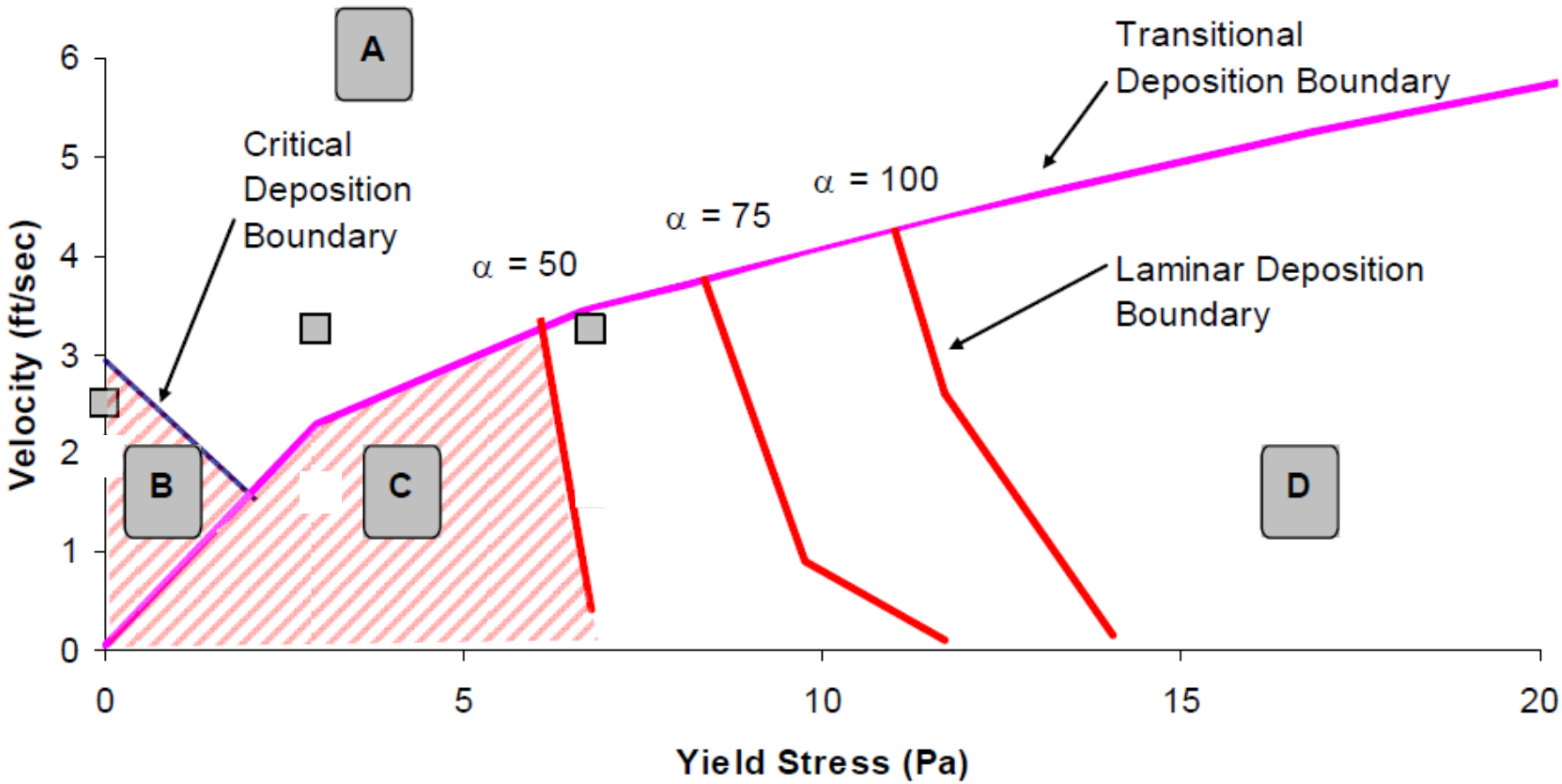
Stability Map Result for 10 micron Stainless Steel Beads in Water, and Thin & Thick Kaolin Slurry



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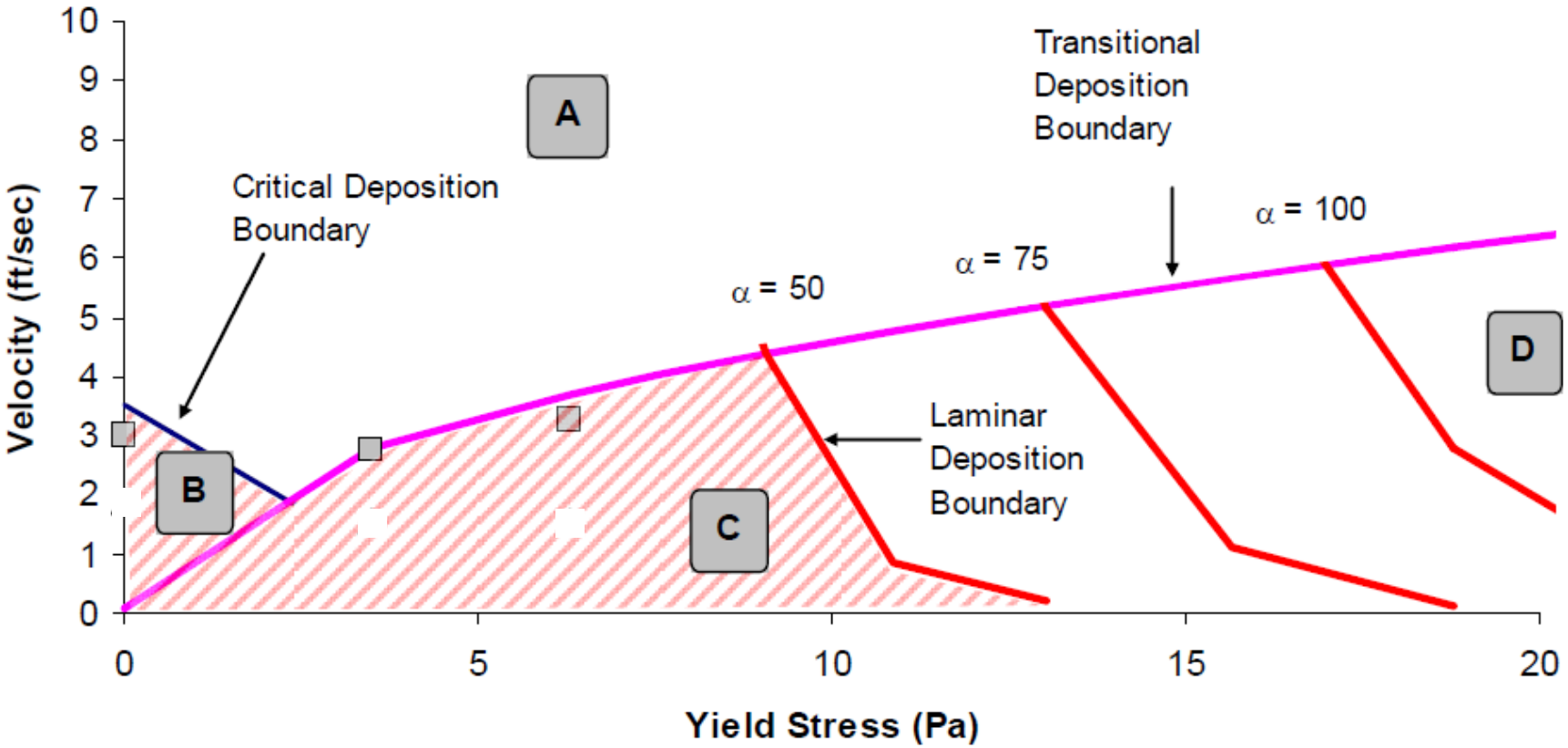
Stability Map Result for 50 micron Alumina in Water, and Thin & Thick Kaolin Slurry



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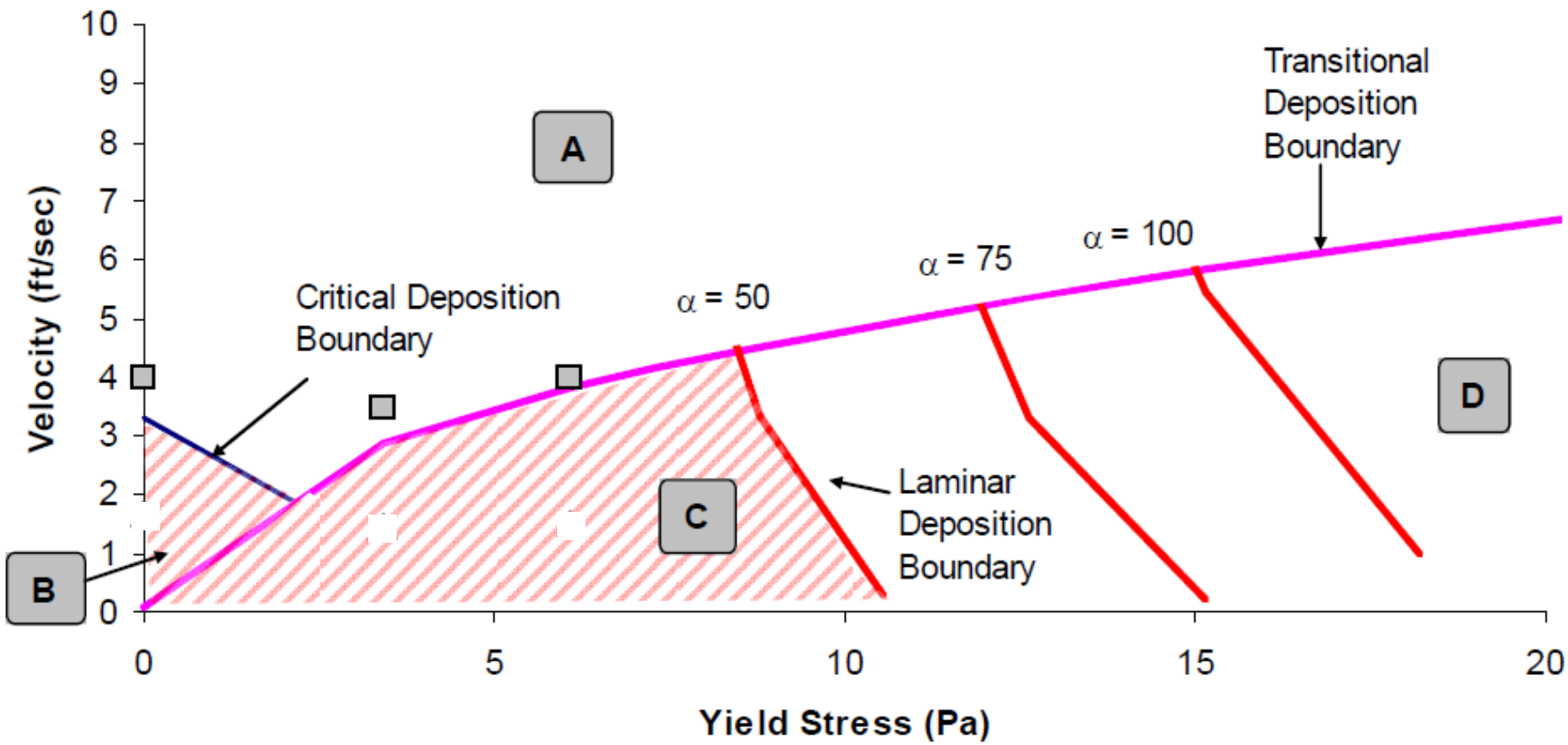
Stability Map Result for 100 micron Glass Beads in Water, and Thin & Thick Kaolin Slurry



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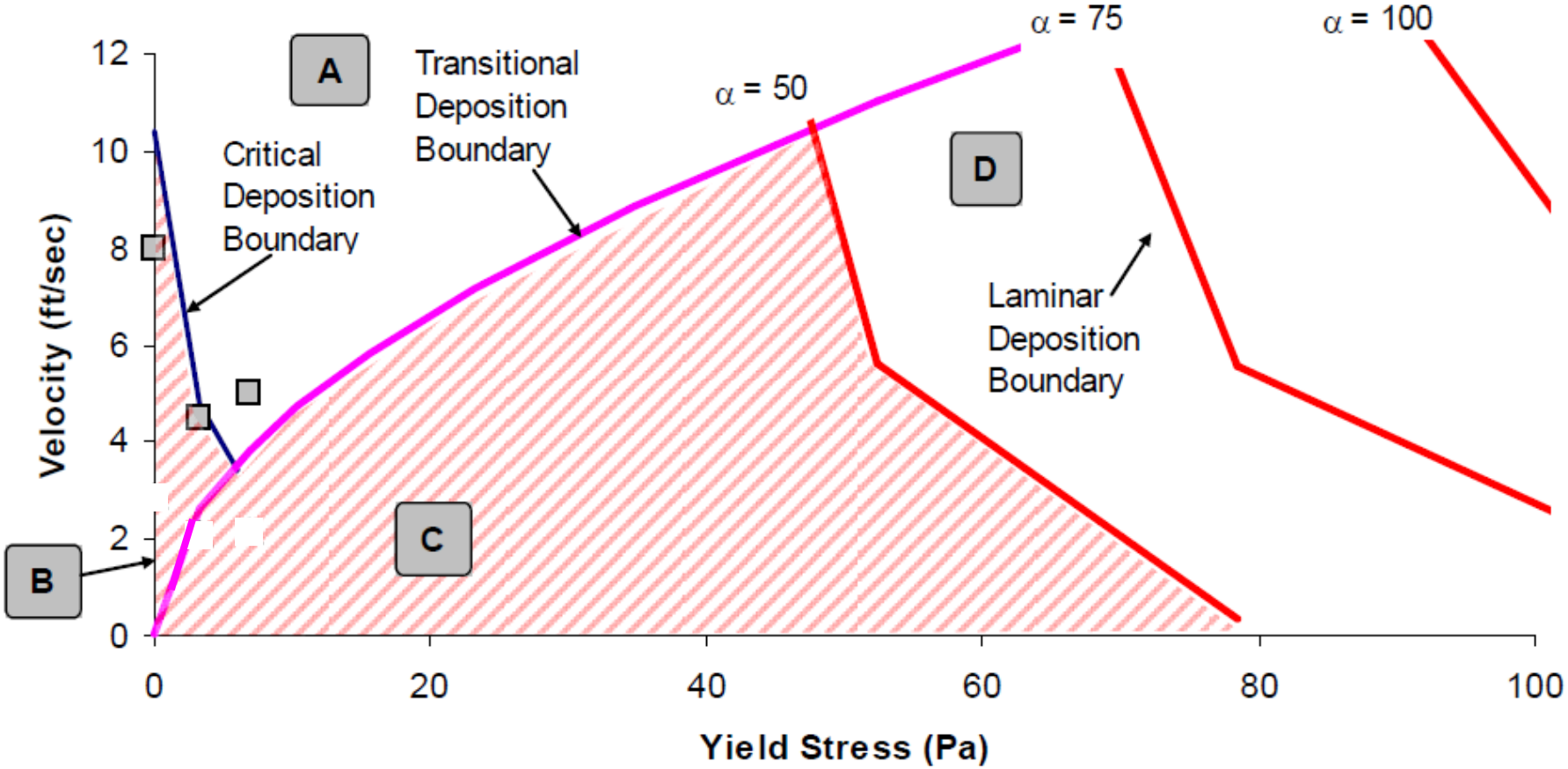
Stability Map Result for 100 micron Stainless Steel Beads in Water, and Thin & Thick Kaolin Slurry



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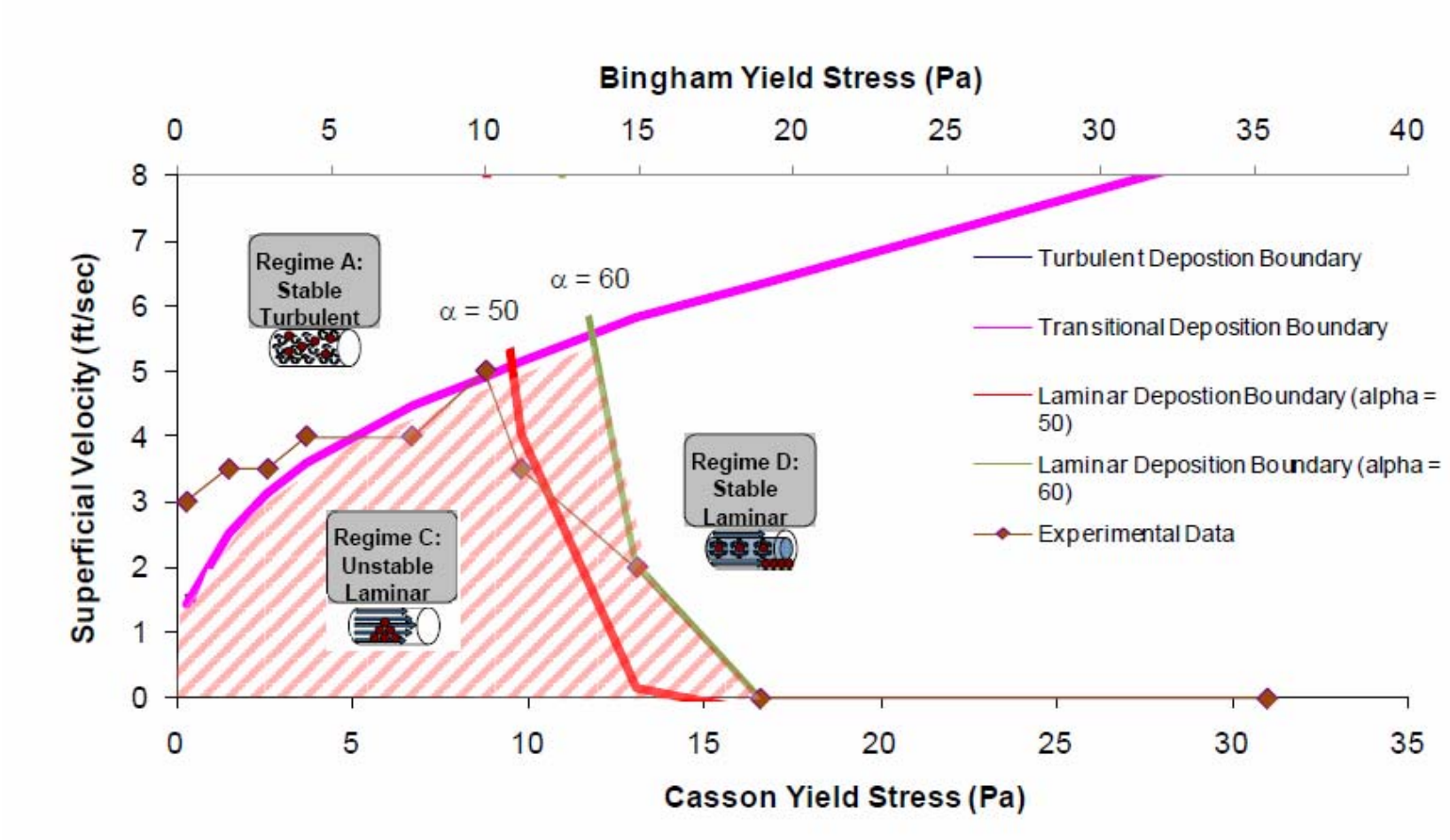
Stability Map Result for 150 micron Glass Beads in Kaolin Slurry



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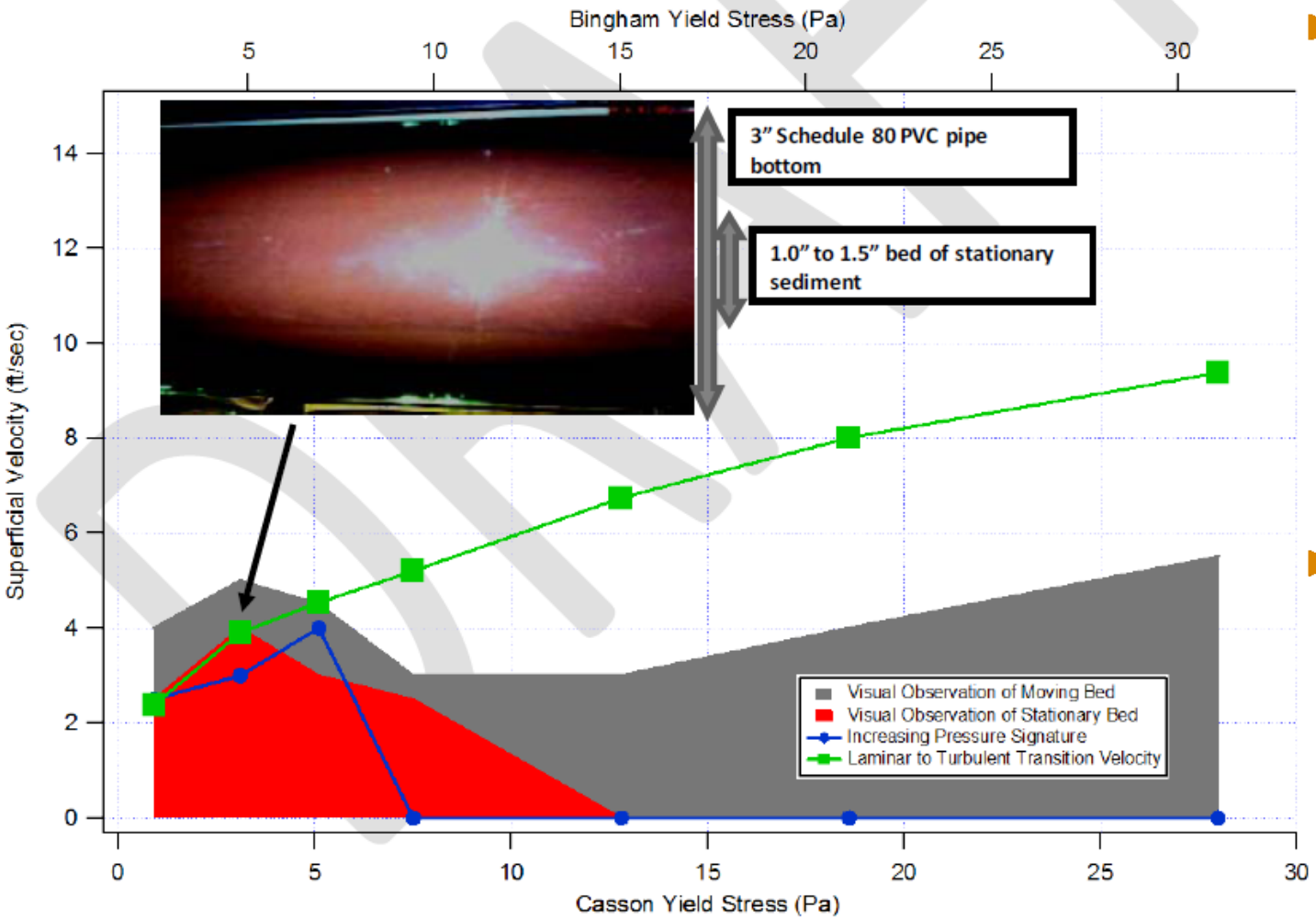
AZ-101 HLW Pretreated Sludge Simulant Stability Results



- Stability map features are observed but the controlling particle for the stability map is unknown since the PSDD is not characterized
  - controlling particle is greater than $\{d_{50}, \rho_{50}\}$
- Deposition follows laminar transition velocity

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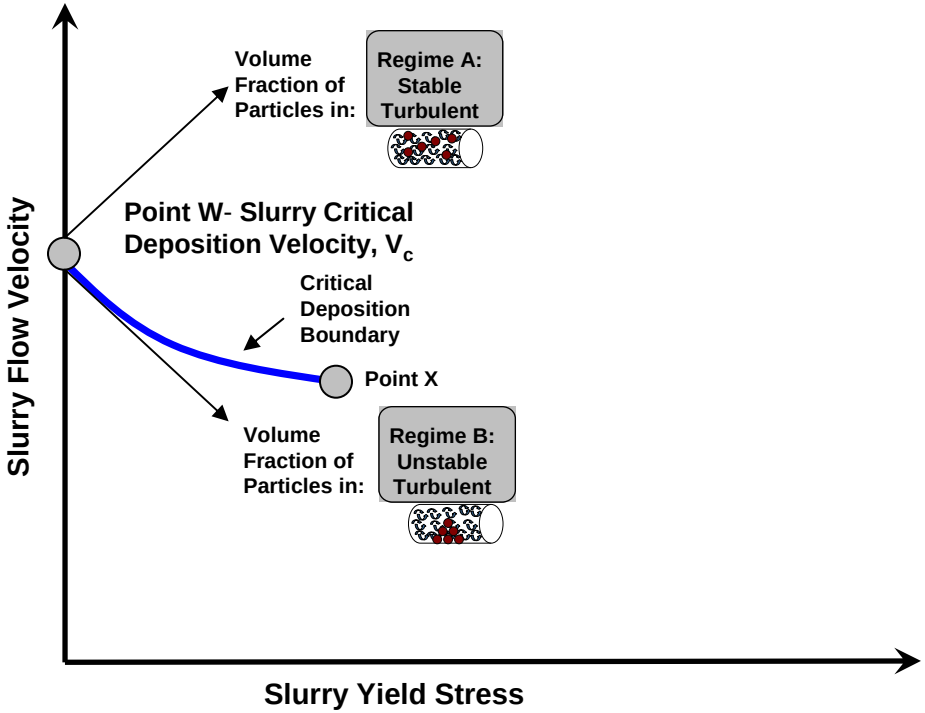
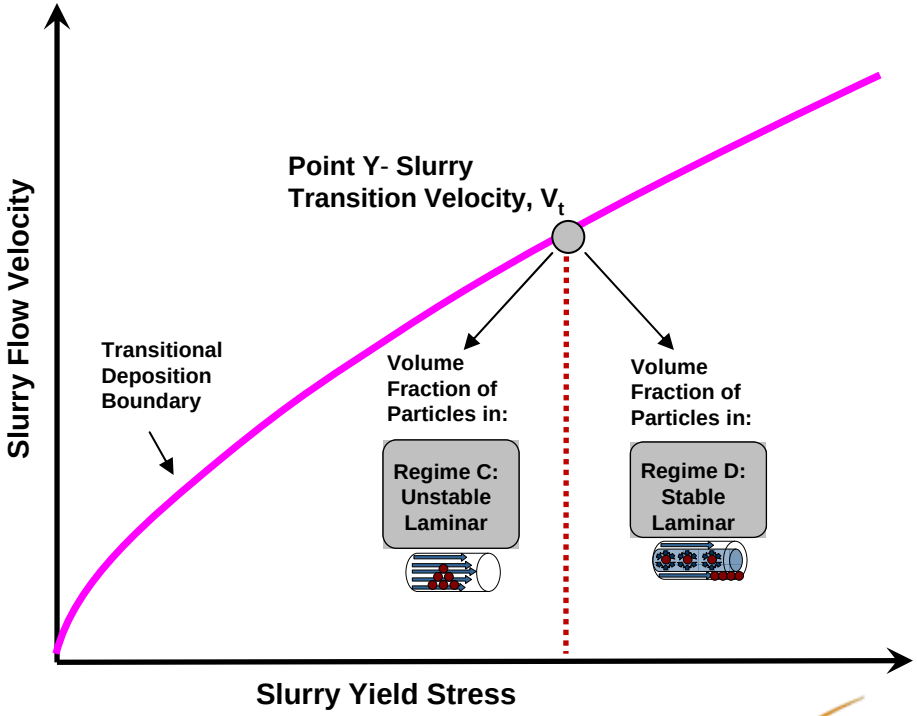
Selection of Minimum Transport Velocity

- Two maximums observed on stability map:
  - Point W: Newtonian Design Basis for turbulent flow
  - Point Y: non-Newtonian Design Basis for transition to Laminar flow





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Conclusions

- Critical velocity Vs. rheology can be non-intuitive for non-Newtonian flows (greater for high rheology than medium rheology)
- Darby yield stability parameter, *Y*, yields unreliable predictions – particles drop out in sheared mediums (even laminar, highly non-Newtonian slurries)
- A significant fraction of particles are predicted to settle to a stationary bed in the 4-6 ft/sec range under both Newtonian and non-Newtonian conditions for simulants evaluated.
- Under typical conditions settled particles will be predominately of high density or large particle size.
- Laminar flow stability criteria (α) needs further development/vetting to be relied upon (α>100 seems fine).
- A transport velocity of approximately 10 ft/sec will typically maintain turbulent flow in a 3” pipe at the upper end of the rheological operating window (30 Pa, 30 cP Bingham plastic yield stress and consistency, respectively).
  - If this is not achievable a minimum velocity of 6 ft/sec or greater is recommended for operation under laminar conditions.

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Conclusions and Recommendations

- Situations where a sediment bed is expected to slowly develop over time must be aggressively flushed to mitigate potential line plugging. Sediment beds are expected to develop faster in larger diameter pipes but the deposition rate is unknown.
  - Development of a basis for an aggressive flushing frequency should be supported by further testing.
- Flushing at 10 ft/sec or greater should be sufficient to remove the sediment beds. However, re-suspension of particles from a stationary bed involves different mechanics than deposition and is not well understood.
  - A design basis value for the minimum flush velocity to remove a stationary bed should be supported by further testing.
- Flushing should be performed from the back of the process line forward. Back flushing pipes to source tanks should not be permitted as particles will accumulate in vessels and pipes.
- Flushing should be initiated with low flow graduating to high flow to erode the sediment bed and prevent plugging.

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Backup Slides

Significance of the Laminar-to-Turbulent Transition

- In a study that examined deposition velocities in non-Newtonian fluids, Shah and Lord (1991)[1] made the following conclusion:
  - *"In the present study, most of the critical depositional velocities correspond to the laminar or near-laminar flow conditions based on the critical value of 2,100 for the Dodge-Metzner (1959) generalized Reynolds number." (3,000 for Wasp…)*
- *Shook et al. (2002)[2] state:*
  - *"There have been many experimental investigations of non-Newtonian slurries in laminar and turbulent flow and deposition is often observed as the laminar flow condition is approached."*

[1]Shah SN, and DL Lord. 1991. "Critical Velocity Correlations for Slurry Transport with Non-Newtonian Fluids." *AIChE Journal* 37:6, 863–870.
[2]Shook CA, RG Gillies, and RS Sanders. 2002. *Pipeline Hydrotransport with Applications in the Oil-Sand Industry*. SRC Publication No. 11508-1E02, Saskatchewan Research Council, Saskatoon, Canada.

Significance of the Laminar-to-Turbulent Transition

- On the subject of deposition occurring in laminar non-Newtonian flows, Gillies et al. (2007)[1] state the following:
  - "The body of evidence suggesting that coarse particle settling can occur during the laminar pipeline transport of mixtures of this type [non-Newtonian slurries with a mixture of fine and coarse particles] is overwhelming. Cooke (2002) and Thomas et al. (2004) provide excellent reviews of such cases where coarse particle settling was observed in operating pipelines and laboratory pipeline loops. In many of these cases, static settling tests show that the mixture is stable—that is, no coarse particle settling occurs. However, when the same mixture is transported by pipeline, coarse particle settling is observed."
  - *"There should no longer be any debate about (i) the fact that coarse particle settling can occur in laminar flows and (ii) the absolute irrelevance of static settling tests in determining the tendency of coarse particles to settle during laminar pipeline transport of non-Newtonian mixtures."*

[1]Gillies RG, R Sun, RS Sanders, and J Schaan. 2007. "Lowered Expectations: The Impact of Yield Stress on Sand Transport in Laminar, Non-Newtonian Flows." *Journal of the South African Institute of Mining and Metallurgy* 107(6):351–357.

Significance of the Laminar-to-Turbulent Transition

- However, the following observation was made by Gaskill et al. (1996)[1] about the transport of 25 Pa melter feeds for HWVP:
  - *"The second reason for the decreasing flow in the melter feed line is the build-up of material in the melter feed line, thus effectively reducing the flow area and flow rate. Visual evidence of this phenomenon was observed at the end of the nozzle where material was building up and would occasionally fall off or be knocked off. Build-up of solids was also observed in the 3-way valve during a visual inspection after the run when the valve was disassembled.* It is a safe assumption that build-up occurred at other parts of the system, particularly where there is a changing cross-section, as in the 3-way valve or cross-flow strainer."

[1]Gaskill JR, Larson DE, Abrigo GP, Daume JT, Graves RE. 1996. *Hanford Waste Vitrification Plant full-scale feed preparation testing with water and process simulant slurries*, PNNL—11011, Pacific Northwest National Laboratory, Richland, Washington.

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Laminar Flow: Particle Settlement

- **Rugby Limestone pipeline**
  - Laminar flow operation
  - 92 km long, 250 mm diameter
  - Over 36 hours, 0.106 kPa/m to 0.121 kPa/m

Feed	Discharge
56.5%m	54.5%m
1.1% > 300 µm	trace
150 µm > 2.8% > 300 µm	trace

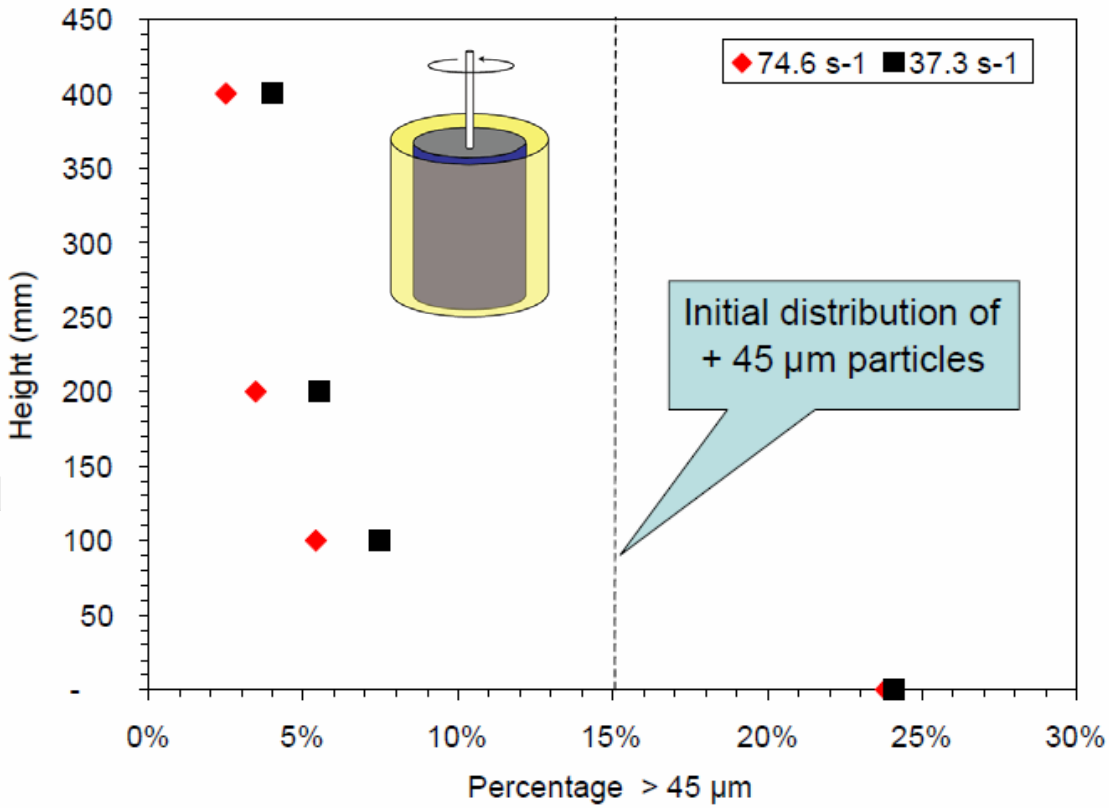
Laminar Flow: Particle Settlement

- **Belovo-Novosibirsk pipeline (Siberia)**
  - Laminar flow operation (stabilized coal)
  - 262 km (164 mile) long, 530 mm diameter
  - Pipeline blocked during commissioning
  - Pressure gradient increased with time
  - Stationary deposit on pipe invert
  - Instabilities were not observed during loop tests using a 200 mm pipeline

Laminar Flow: Particle Settlement

Significance of the Laminar-to-Turbulent Transition-Experimental Data

- Data from Cooke[1] (2002)
- Couette (annular) laminar flow experiment with 15 wt% sand particles between 45 µm and 212 µm in a clay suspension
- Bingham Plastic fluid with yield stress of 59 Pa and consistency of 8.4 cP
- Sand was stable when unsheared
- Shearing period of 30 minutes at two shear rates
- Samples withdrawn and analyzed for sedimentation at different heights
- Large particles settled to the bottom of the apparatus in both cases



[1]Cooke R (2002) "Laminar flow settling: the potential for unexpected problems." BHRG 15th International Conference on Slurry Handling and Pipeline Transport, *Hydrotransport 15*; Banff, June. 121-133.

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