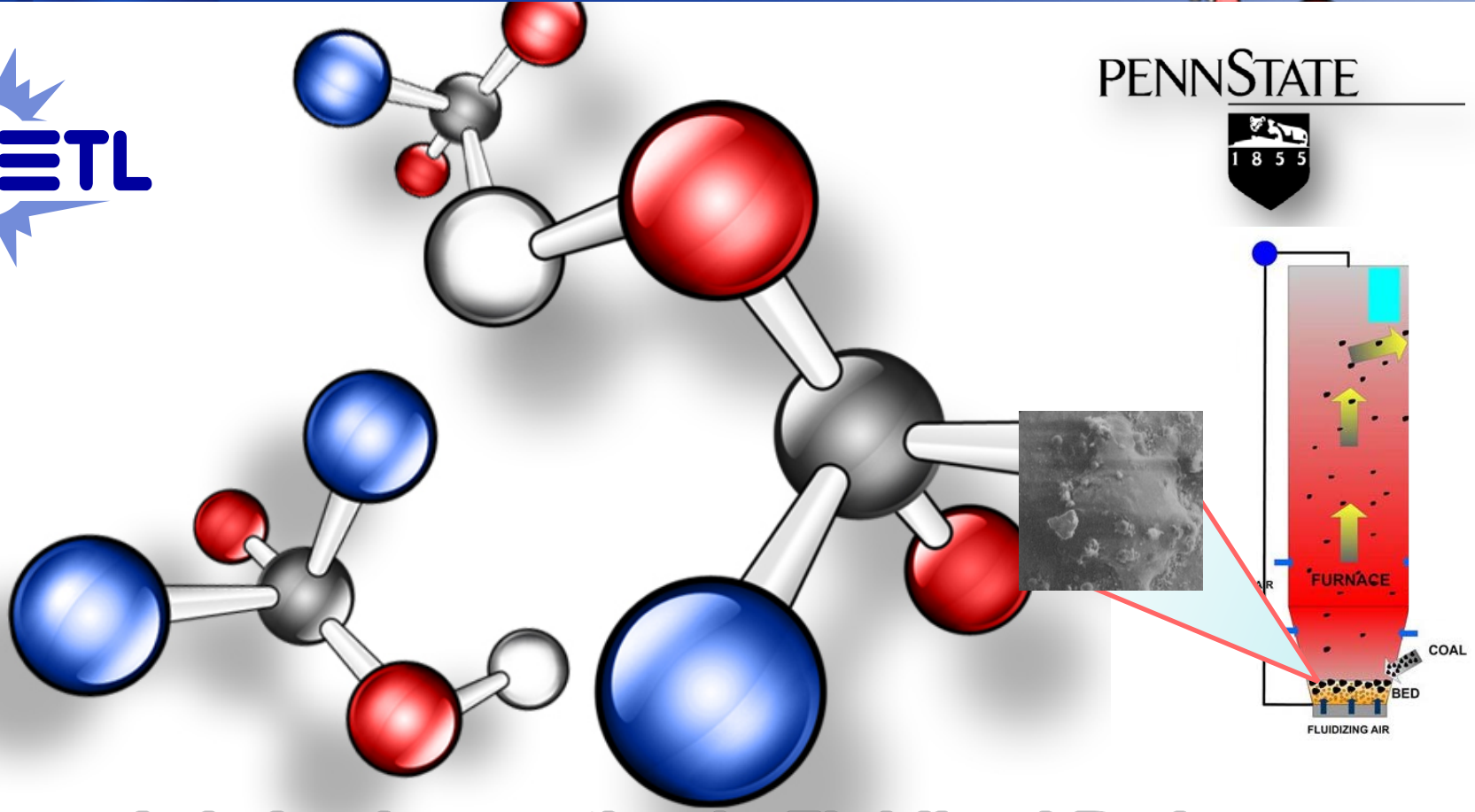


Ash Agglomeration in Fluidized Beds

Sarma V. Pisupati
Professor and Chair, Energy Engineering Program
Penn State University

Ash agglomeration causes industrial problems and is difficult to predict

Reduced efficiencies

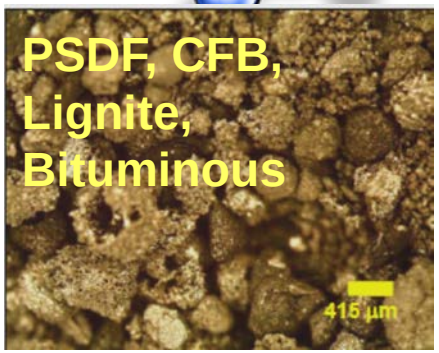
Operational problems

Reactor down-time

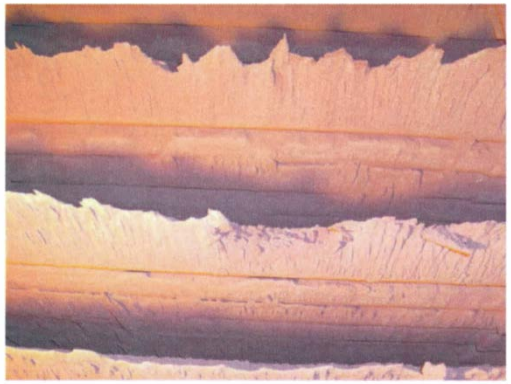
Monetary losses

Lack of quick and accurate prediction

C. Pete et al. 2001



Power Systems Development Facility topical report



K. John et al., 2012

PFBC systems - agglomeration in bed area, deposits on heat exchangers and cyclones

Need to conduct a systematic study of agglomeration in fluidized beds

PENNSTATE

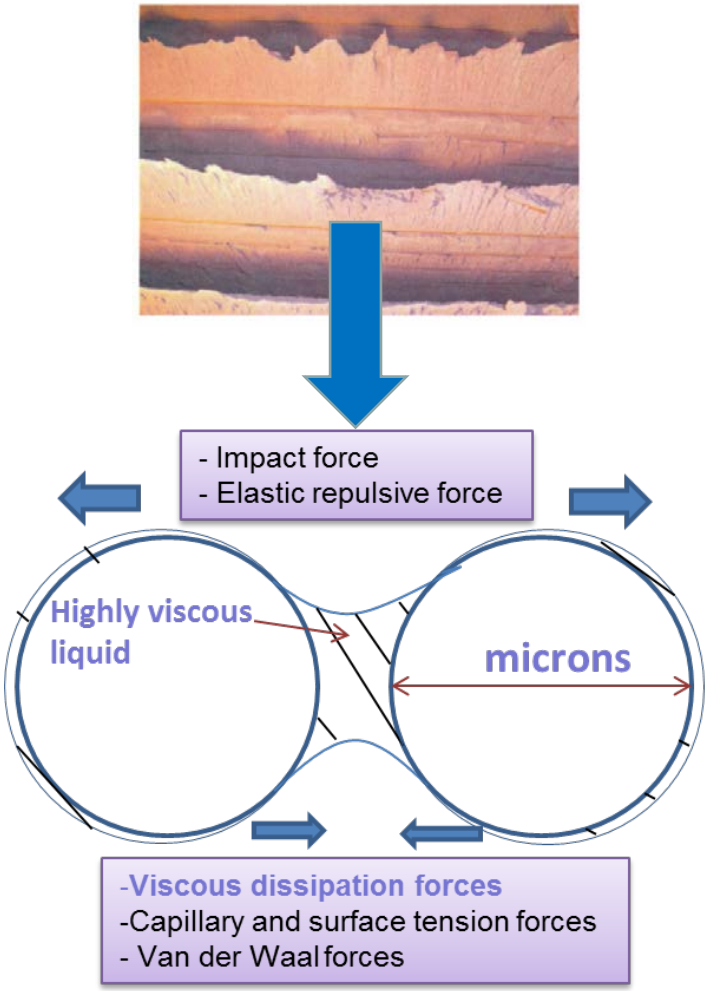
Non-uniformities throughout the reactor promote local initiation of agglomeration

Particle size	• Bed ash is polydisperse
Temperature	• Distribution of temperature among bed particles • Particle temperature often 100 ^{o}C higher
Chemical Composition	• Ash is heterogeneous
Gaseous atmosphere	• Combustion and Gasification • Pockets of reducing conditions
Hydrodynamics	• Distribution of particle velocities, granular temperatures, collision frequencies

<u>Prediction of agglomeration</u>
Only bulk properties - inadequate
Spatial and temporal variations - important
Above parameters - interdependent – net effect on agglomeration

PENNSTATE

Integration of particle-level chemistry and physics is required to predict agglomeration in FB gasification



Particle-level non-uniformities

Integration of ash chemistry and particle hydrodynamics

A.D. Salman, 2007., M.J. Adams, 1994.,B.J. Ennis, G. Tardos, R. Pfeffer, 1991. S. M. Iverson, J. D. Litster, 1998.

Existing models are for uniform granulation applications

Dry Collisions

- Hertzian
- Moseley et al.
- Zhou et al.

Mainly theoretical value (wet collisions)

-Ennis et al.
-He

Hydrodynamics

- Cryer - collision velocities
- Korina Terrazas et al. - only collision frequency
- Tan et al.

Chemical composition

- Shin-Won Kang et al.
- Shiyuan Li et al.

Models do not adequately account for interdependencies and non-uniformities of the various parameters that affect agglomeration

Khadilkar A., Rozelle P., Pisupati S., Models of agglomerate growth in fluidized bed reactors: critical review, status and applications, *Powder Technology*, 264, 2014, 216-228.

Overall Objective: Development of a unified method to predict fluidized bed agglomeration

FactSage™

Amount of Slag

Viscosity

+

CFD

Collision frequency

Granular temperature

Bed volume

Collision velocity

→

Mathematica

Mathematical model to predict resultant particle growth rate

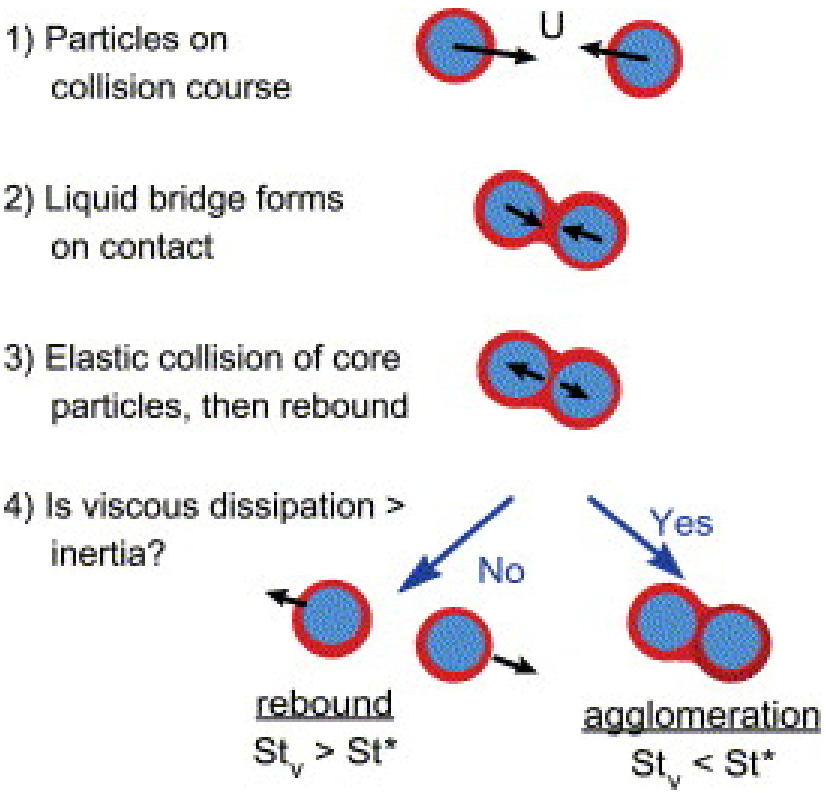
- Polydispersity
- Probability of wet collision
- Collision frequency
  (particle number, granular temperature)
- Kinetics and particle temperature distribution in bed
  (Burn out time, fuel addition rate)
- Stokes' criterion

Stokes' criterion used as basis for the energy dissipation

St → Inertial forces/ Viscous forces

$$St = \frac{mU}{12\pi\mu d^2}$$

St- Stokes number
U – Particle collision velocity
m- Particle mass
d- Particle diameter
μ- Liquid layer viscosity



A.D. Salman, Granulation (Handbook of Powder Technology- Vol 11, Elsevier, 2007.
S. A. Cryer, Modeling agglomeration processes in fluid-bed granulation, *AIChE Journal*, (1999) 45, 2069–2078.

FactSage Thermodynamic Simulation

Gaseous Atmosphere →

Ash Chemical Composition →

FactSage

→ Equilibrium phase composition
Solids
Slag
Gases

Gaseous Atmosphere

<u>Oxidizing-</u>
3% O_2, 15% CO_2, 72% N_2 and 10 % water vapour

<u>Reducing-</u>
32.6 % CO, 27.6 % H_2, 14.3 % CO_2 and balance water vapor

Ash Chemical Composition
Gravity Separated fractions of Pittsburgh Seam Coal

Khadilkar A., Rozelle P., Pisupati S., Modeling Agglomeration during Fluidized Bed Combustion and Gasification, *Proceedings of the International Conference of Coal Science and Technology*, 2013,

Gravity fractions with distinct chemical compositions were studied

Pittsburgh Seam coal fuel ash composition

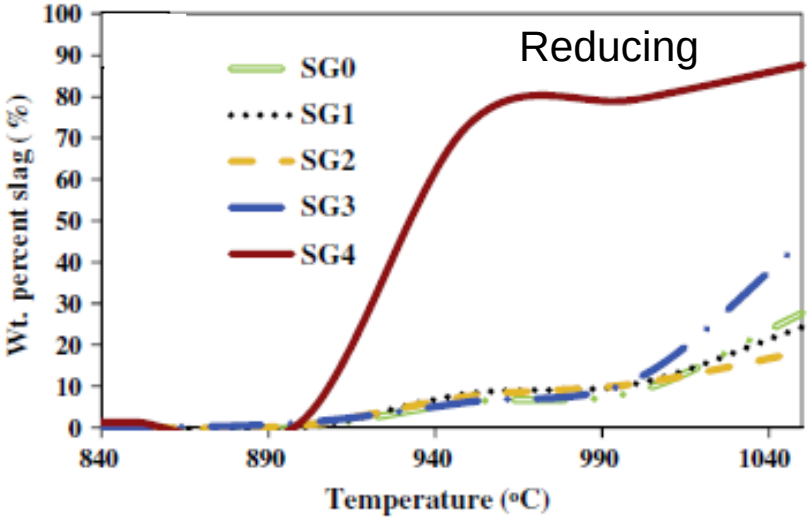
As obtained from X-ray fluorescence ash analysis

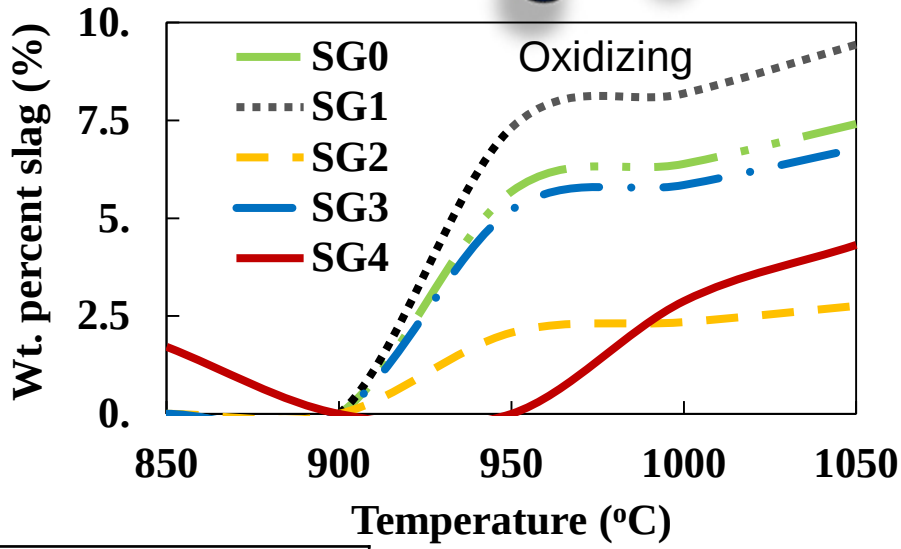
Species	Wt. percent in fuel ash			
	SG1 [1.3 float]	SG2 [1.3 sink, 1.6 float]	SG3 [1.6 sink, 2.6 float]	SG4 [2.6 sink]
SiO_2	49.9	55.3	51.8	12.5
Al_2O_3	28.7	25.2	20.8	4.67
Fe_2O_3	9.41	11.3	18.9	76.0
CaO	5.05	2.78	4.87	5.79
TiO_2	2.47	1.22	0.74	0.21
K_2O	1.85	1.98	1.48	0.24
MgO	1.32	1.08	0.76	0.29
Na_2O	0.76	0.91	0.52	0.13
SrO	0.34	0.10	0.04	0.29
BaO	0.17	0.07	0.03	0.03
MnO	0.02	0.03	0.02	0.07

Fourth gravity fraction rich in iron oxide; second fraction in alumino-silicates

G.N. Shannon, H. Matsuura, P. Rozelle, R.J. Fruehan, S. Pisupati, S. Sridhar, *Fuel Processing Technology*, 2009, 90, 1114–1121.

SG4 tends to slag more and slagging begins at lower temperatures

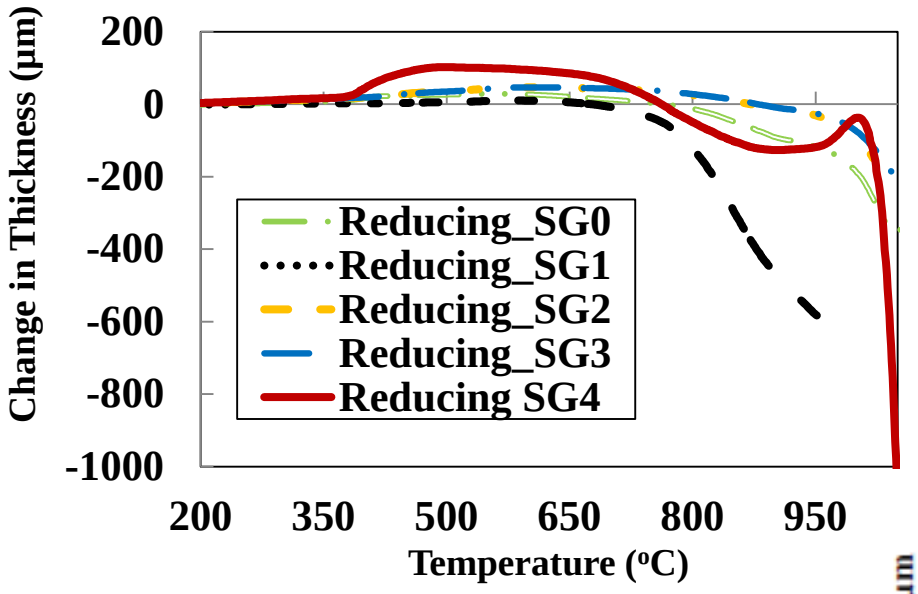


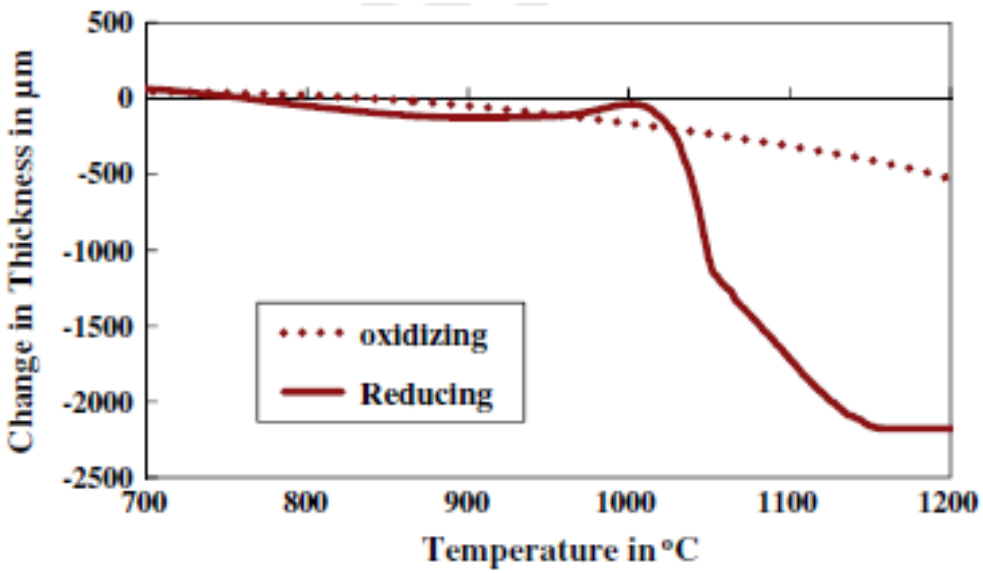


Ash	Density fraction	Slag-liquid formation onset Temperature (°C)	
		Reducing	Oxidizing
SG0	Whole	910	920
SG1	<1.3	910	940
SG2	1.3-1.6	890	930
SG3	1.6-2.6	890	920
SG4	> 2.6	840	850

Khadilkar A., Rozelle P., Pisupati S., A Study on initiation of ash agglomeration in fluidized bed gasification systems, *Fuel*, 2014, (In Press).

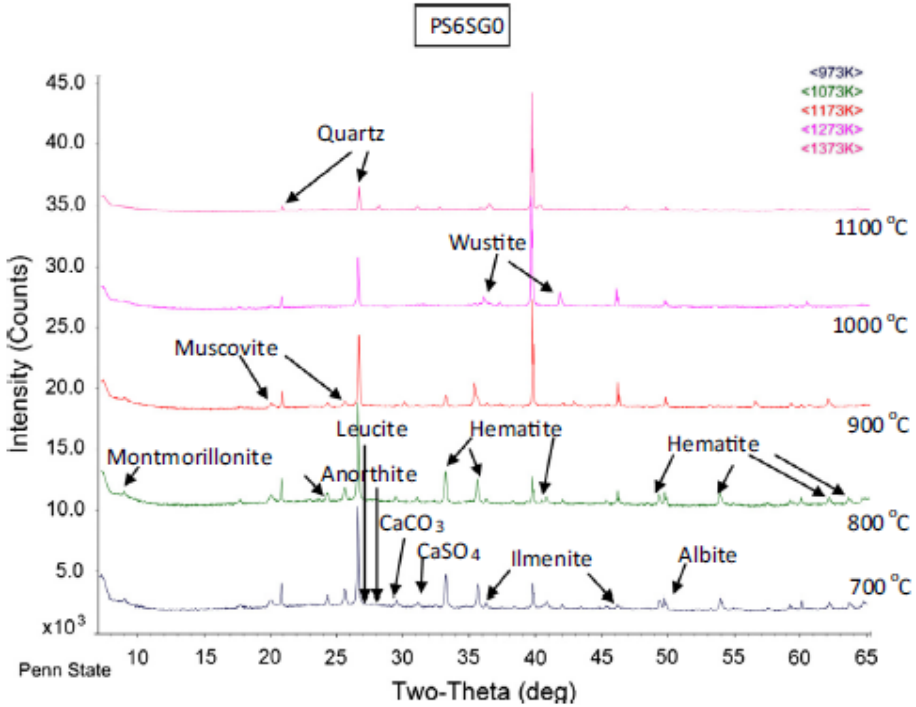
Thermo-mechanical analyses validates FactSage results



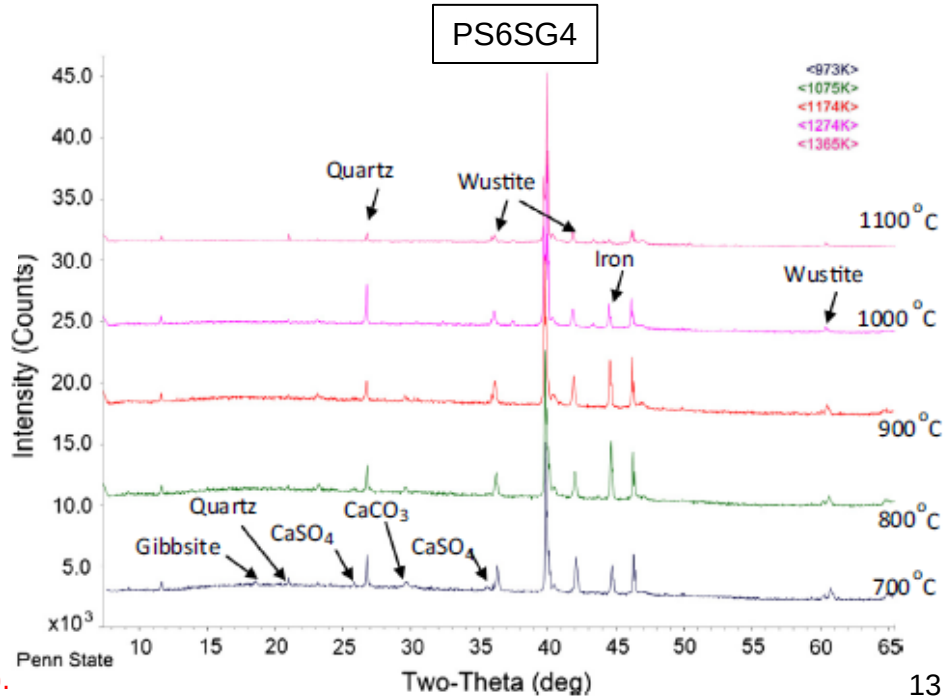


Khadilkar A., Rozelle P., Pisupati S., A Study on initiation of ash agglomeration in fluidized bed gasification systems, *Fuel*, 2014, (In Press).

Reduced iron-containing phases are not detected in whole coal

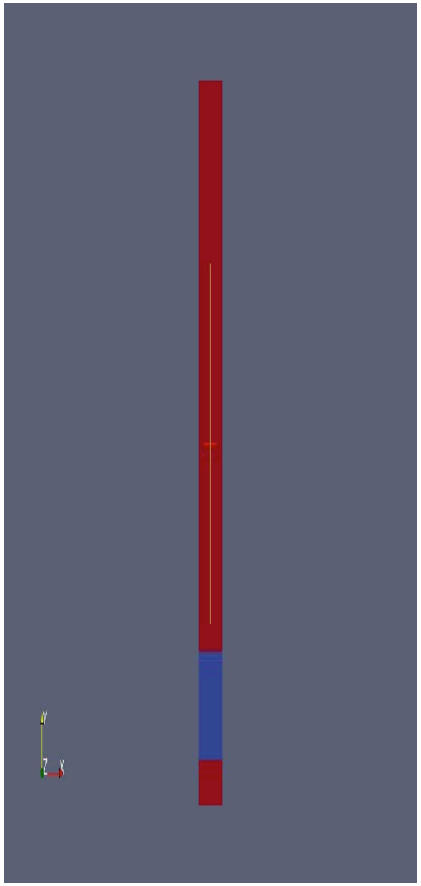


Slag formation due to iron based eutectics may not be detected by bulk analysis



Khadilkar A., Rozelle P., Pisupati S., A Study on initiation of ash agglomeration in fluidized bed gasification systems, *Fuel*, 2014, (In Press).

Methodology to obtain hydrodynamics



Particle size distribution, specific gravity
Reactor dimensions
Velocity at the jet

↓

MFIX (Finite volume method)

Eulerian-Eulerian, 3 D with cut cells

Mass, Momentum balance, Wen-Yu Drag law, Princeton friction model, Lun et al. Kinetic theory of granular flow

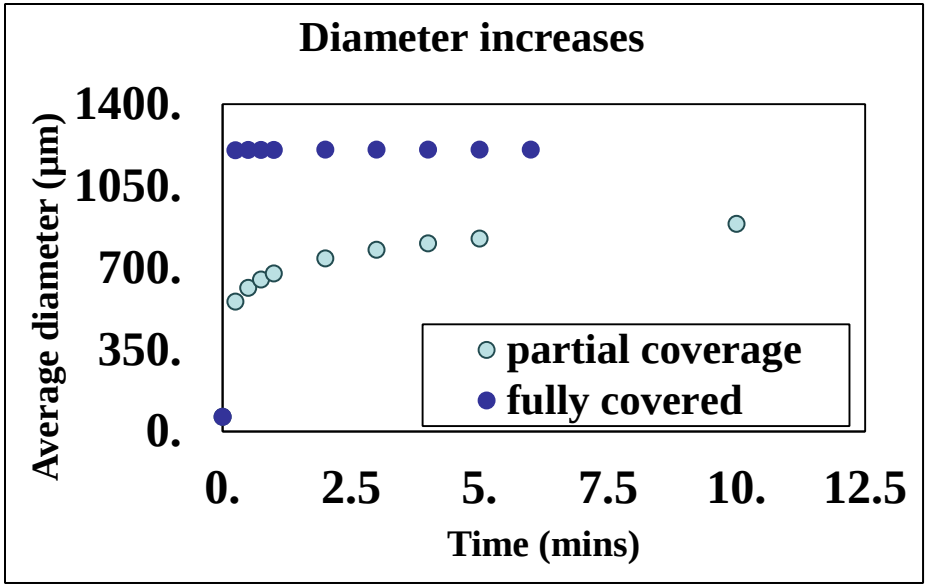
↓

Granular temperature
Particle velocity
Voidage
Bed volume

Higher particle coverage, increases agglomeration

Initial PSD used

Interval	Passing (µm)	Retained (µm)
1	1200	707
2	707	354
3	354	149
4	149	90
5	90	53
6	53	45
7	45	40

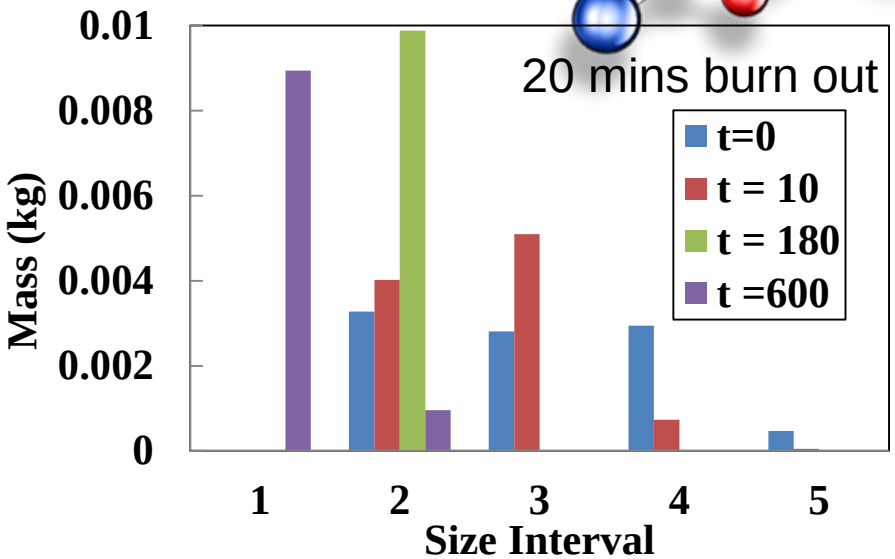


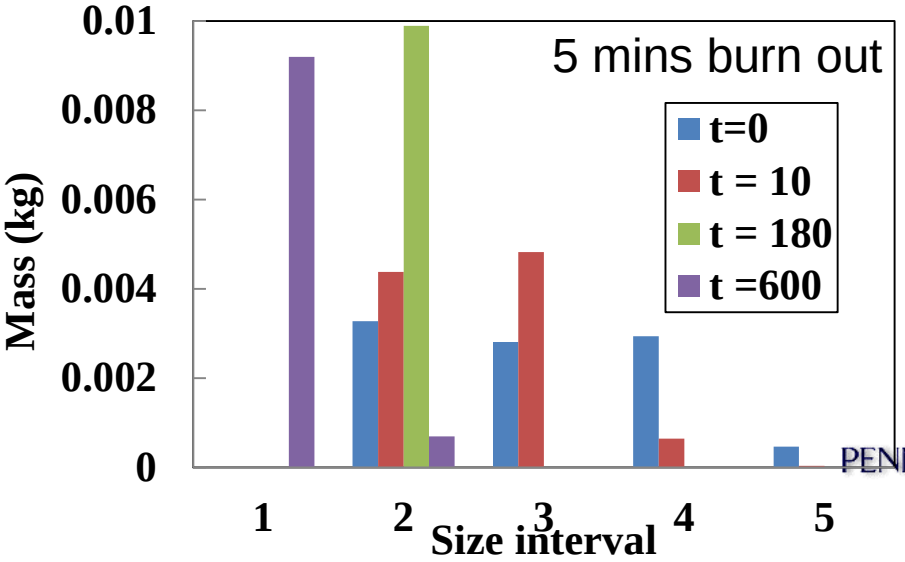
Aditi B. Khadilkar, Peter L. Rozelle, Sarma V. Pisupati, Critical Factors in Understanding the Mechanism of Ash Agglomeration in Fluidized Bed Systems, International Pittsburgh Coal Conference, USA, 2014.

Smaller burn out time, increases agglomeration

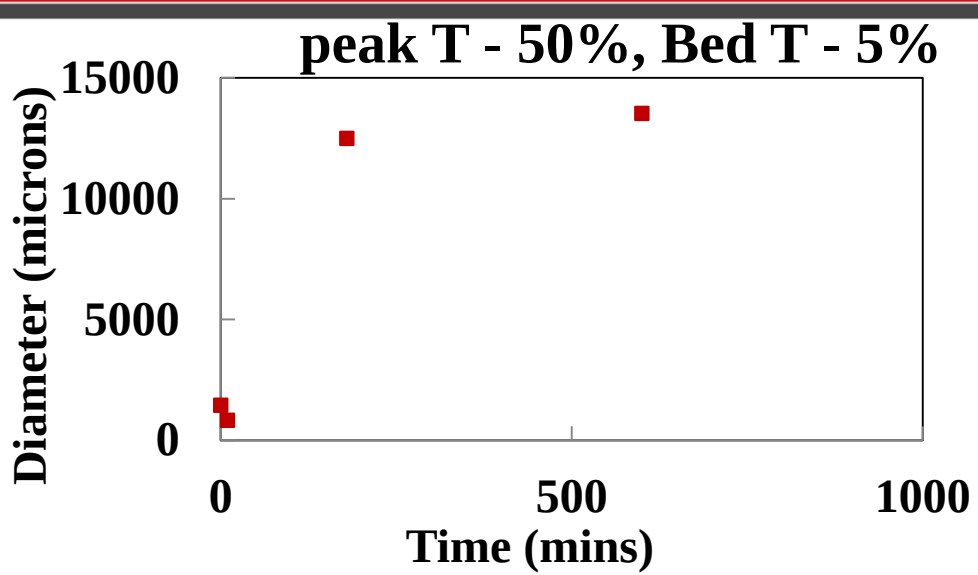
Burn out time	20 mins for 5 g sample	5 mins for 5 g sample
t (mins)	Avg. diameter (microns)	Avg. diameter (microns)
0	1448.91	1448.91
10	1694.24	1808.14
180	2979.75	3788.17
600	12605.7	12682.8

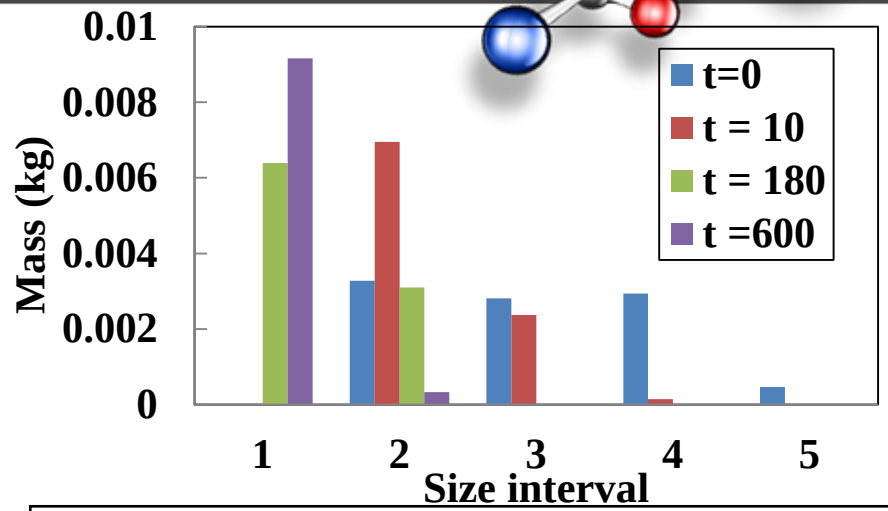
Particle class	Passing	Retained	Size (microns)
1		12700	Defluidized
2	12700	707	3500
3	707	354	531
4	354	149	252
4	149	90	120



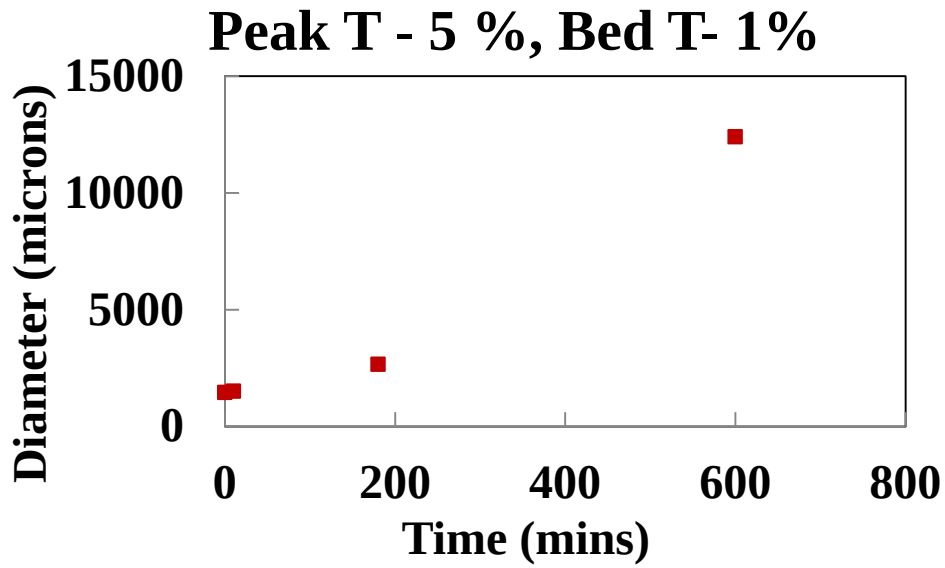


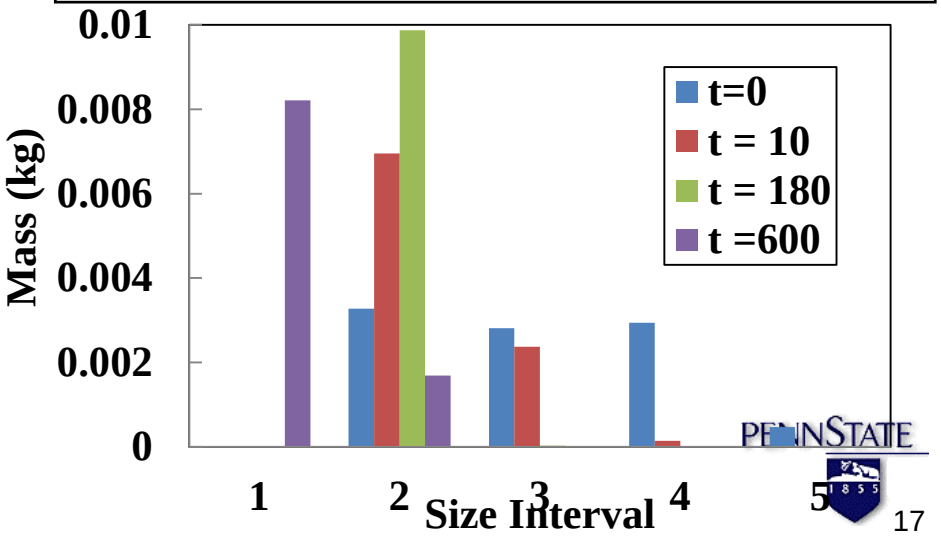
Higher slag amount, increases agglomeration



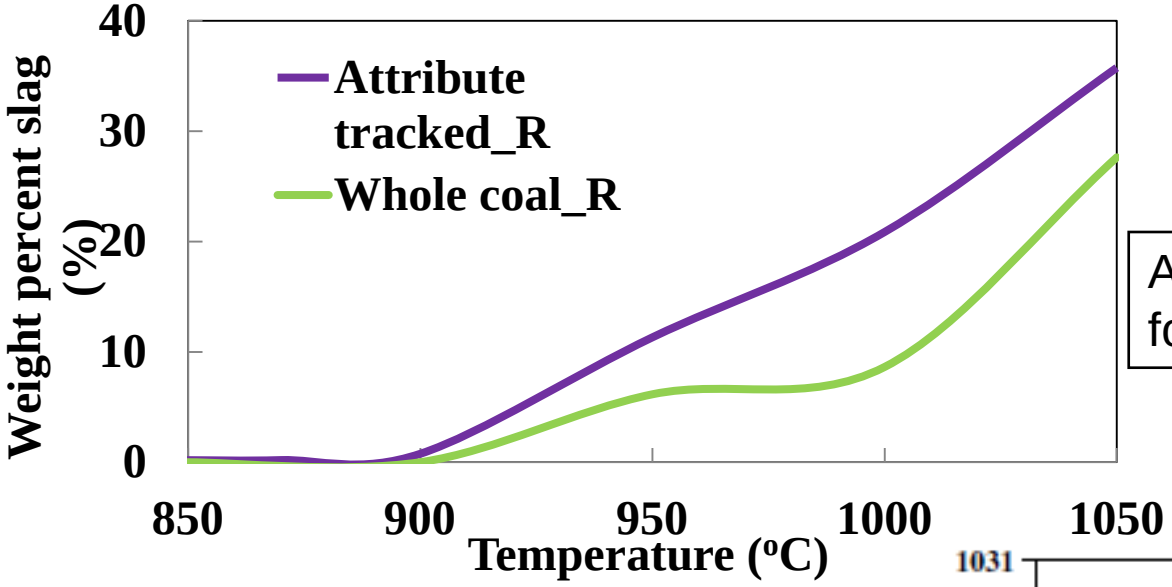


Most particles defluidize after 10 hours when 50 % slag is present



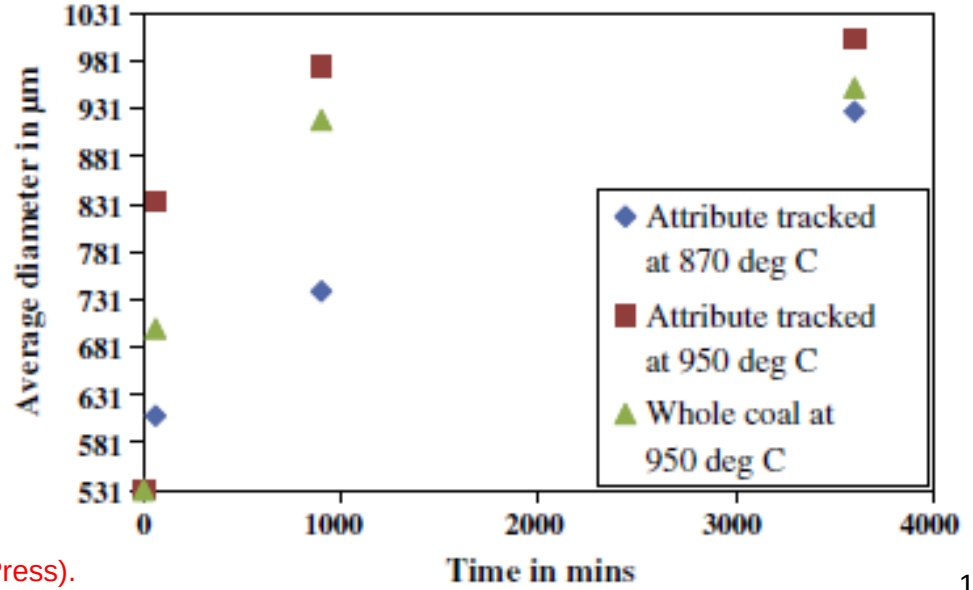


Heterogeneities in ash chemical composition are critical in determination of agglomeration rate



Attribute tracking helps to account for particle-level non-uniformities

Higher agglomeration rate is obtained from attribute tracking than bulk coal analysis



Khadilkar A., Rozelle P., Pisupati S., A Study on initiation of ash agglomeration in fluidized bed gasification systems, *Fuel*, 2014, (In Press).

Summary

- Penn State study has shown that certain particle classes are responsible for initiating agglomeration which the bulk analysis alone cannot detect.
- Particles rich in iron compounds such as those in the SG4 fraction initiate agglomeration at low fluidized bed operating conditions.
- FactSage thermodynamic analysis of gravity separated fuel fractions, along with attribute tracking, helps to predict particle-class level initiation of agglomeration.
- The Penn State Ash Agglomeration Model integrates both fuel chemistry and particle physics to predict agglomerate growth kinetics.
- This model accounts for heterogeneities in ash chemical composition and particle temperatures as well as polydispersity in the bed.

Application of this work extends to several related industries

<u>Agglomeration model</u>

- Chemical Looping
- Direct iron reduction
- Agglomeration during biomass combustion and gasification
- Agglomeration due to low rank coals such as in TRIG (KBR)
- Bed agglomeration during oxy-fuel combustion (Aerojet RocketDyne)
- Flow assurance in petroleum industry
- Fluidized catalytic cracking
- Fluidized bed drying
- Granulation in pharmaceuticals and nano particle agglomeration

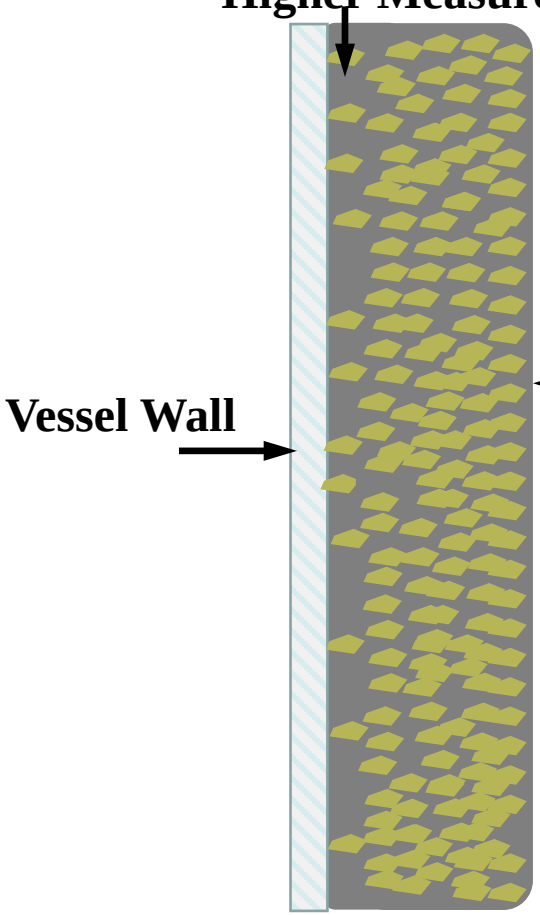
<u>Characterization Techniques involved</u>

- Slag viscosity measurement – Reliance India Ltd.
- SEM-EDX- Post mortem agglomerate analyses- Integrated Waste Treatment Units

Structural and compositional differences were observed across the deposit layer

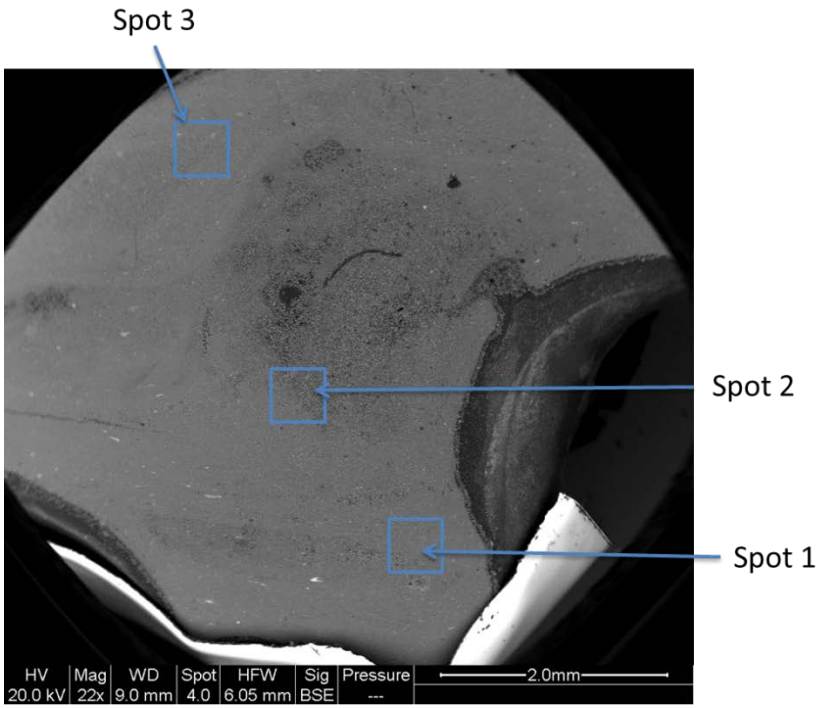
Dark Zone Near Wall

- **Visually Less Dense Population of Aggregate**
- **Lower Measured Al Content**
- **Higher Measured Na Content**

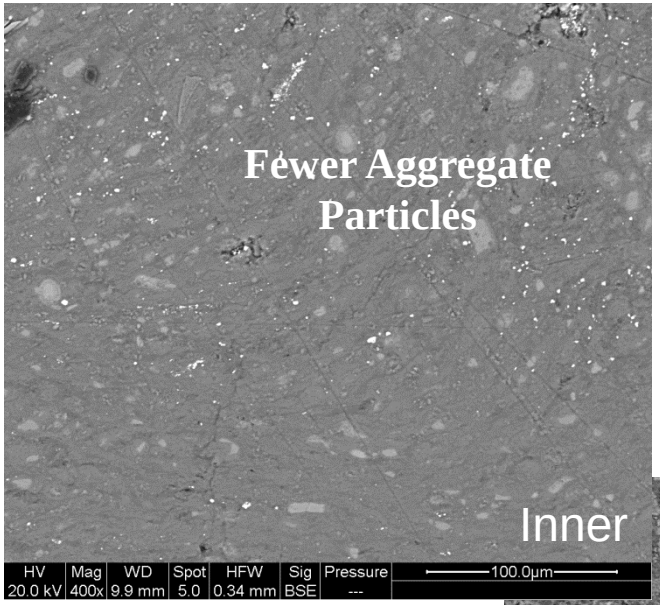


Lighter Zone Further from Wall

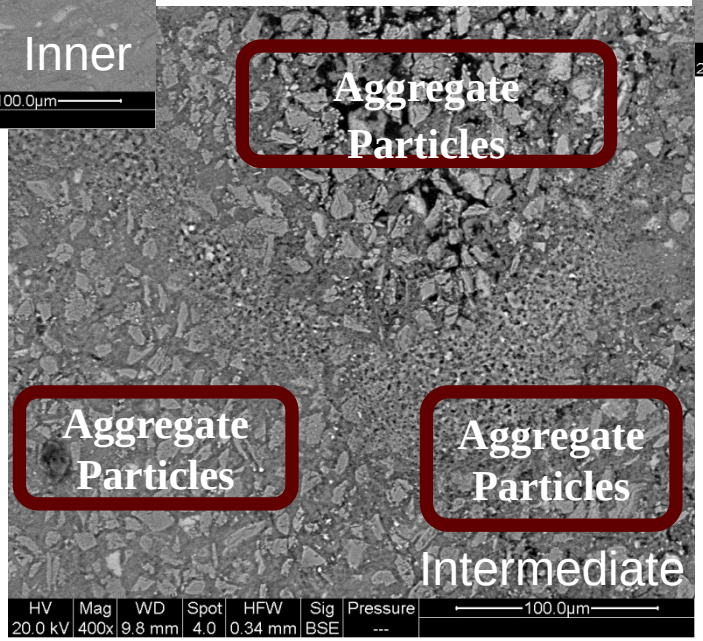
- **Visually Denser Population of Aggregates**
- **Higher Measured Al Content**
- **Lower Measured Na Content**



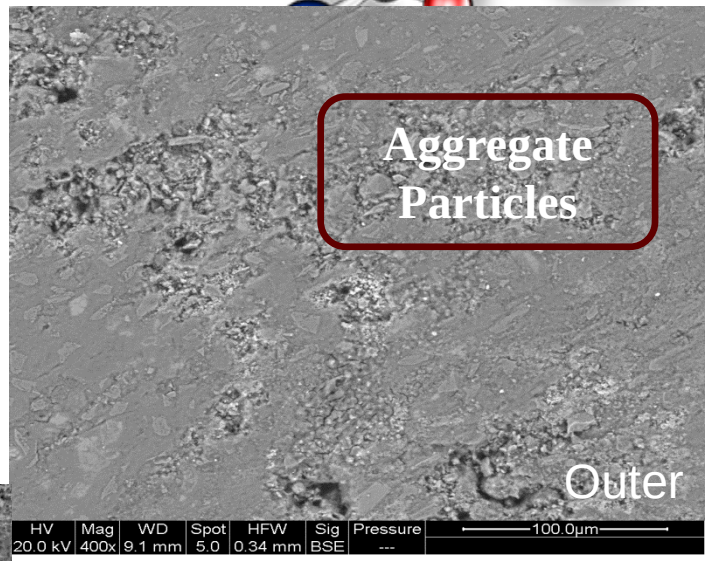
SEM results showing sticky inner layer followed by aggregate rich layers



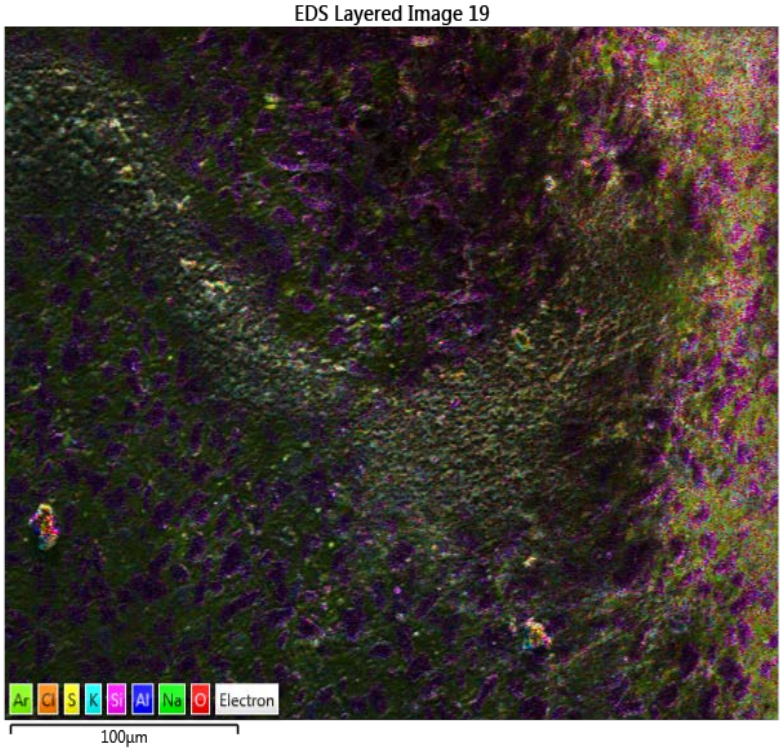
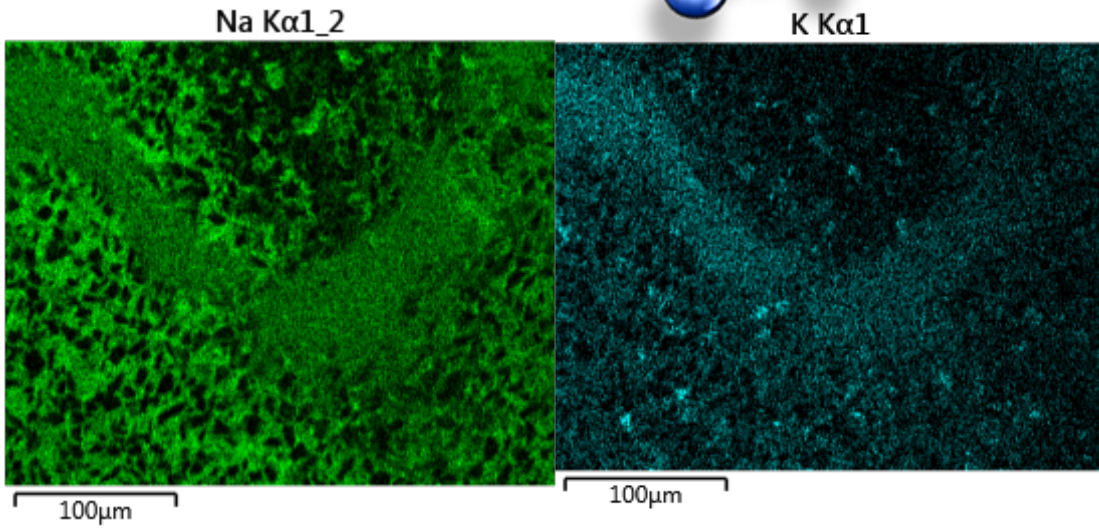
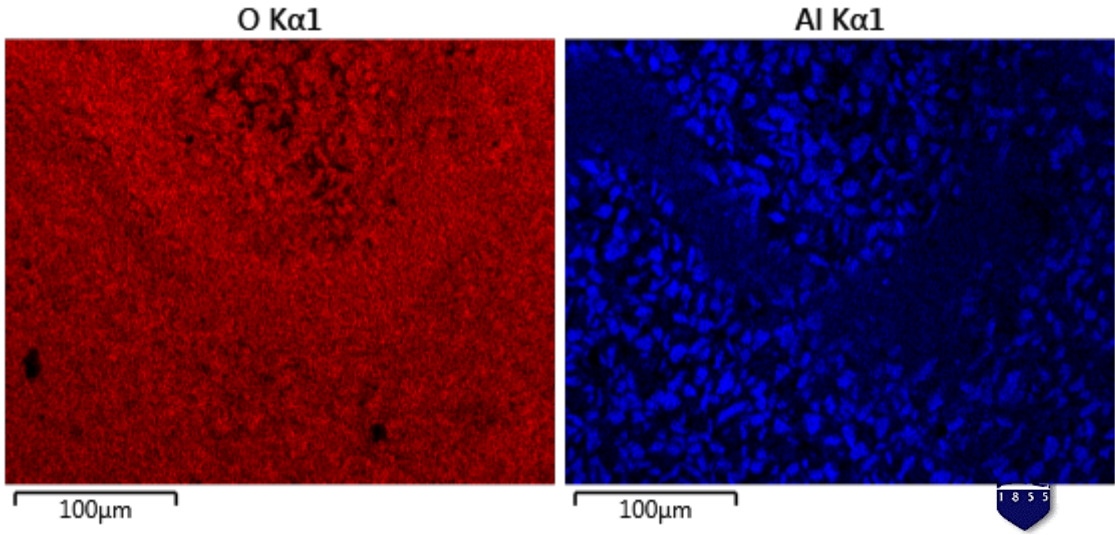
6.5 -7.5% Al
21-23.2 % Na



9.8 -11.0% Al
11.1-12.2 % Na



7.3 -7.6% Al
12.6 – 15. 4% Na

PENNSTATE

EDX shows Al rich particles surrounded by Na rich matrix