Deposit Formation Fundamentals: Experiments Reconciled with Models

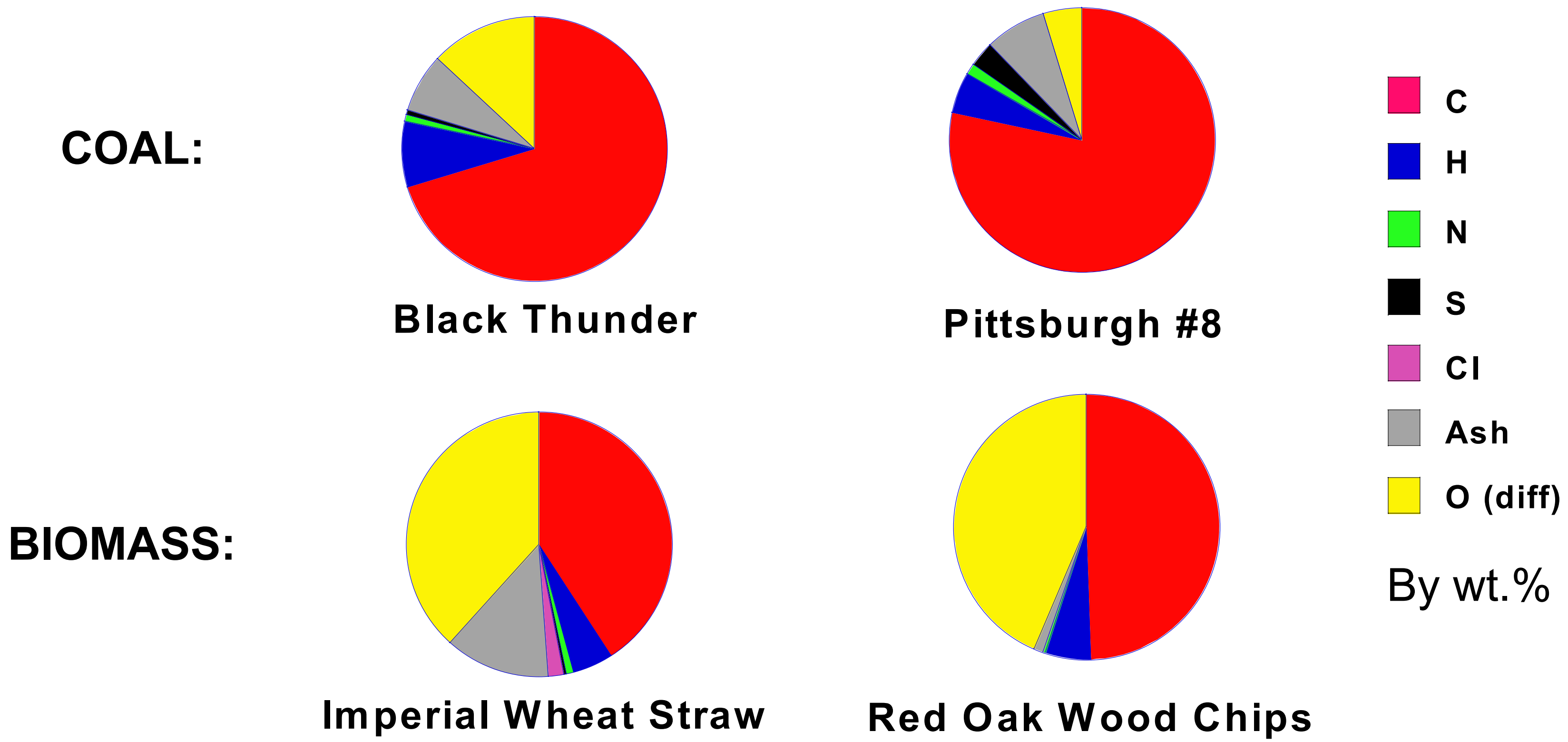
Shrinivas Lokare, Brent Poole, Bob Chan, Dale Tree, Larry Baxter

Brigham Young University, Provo, UT

Coal/Biomass Combustion

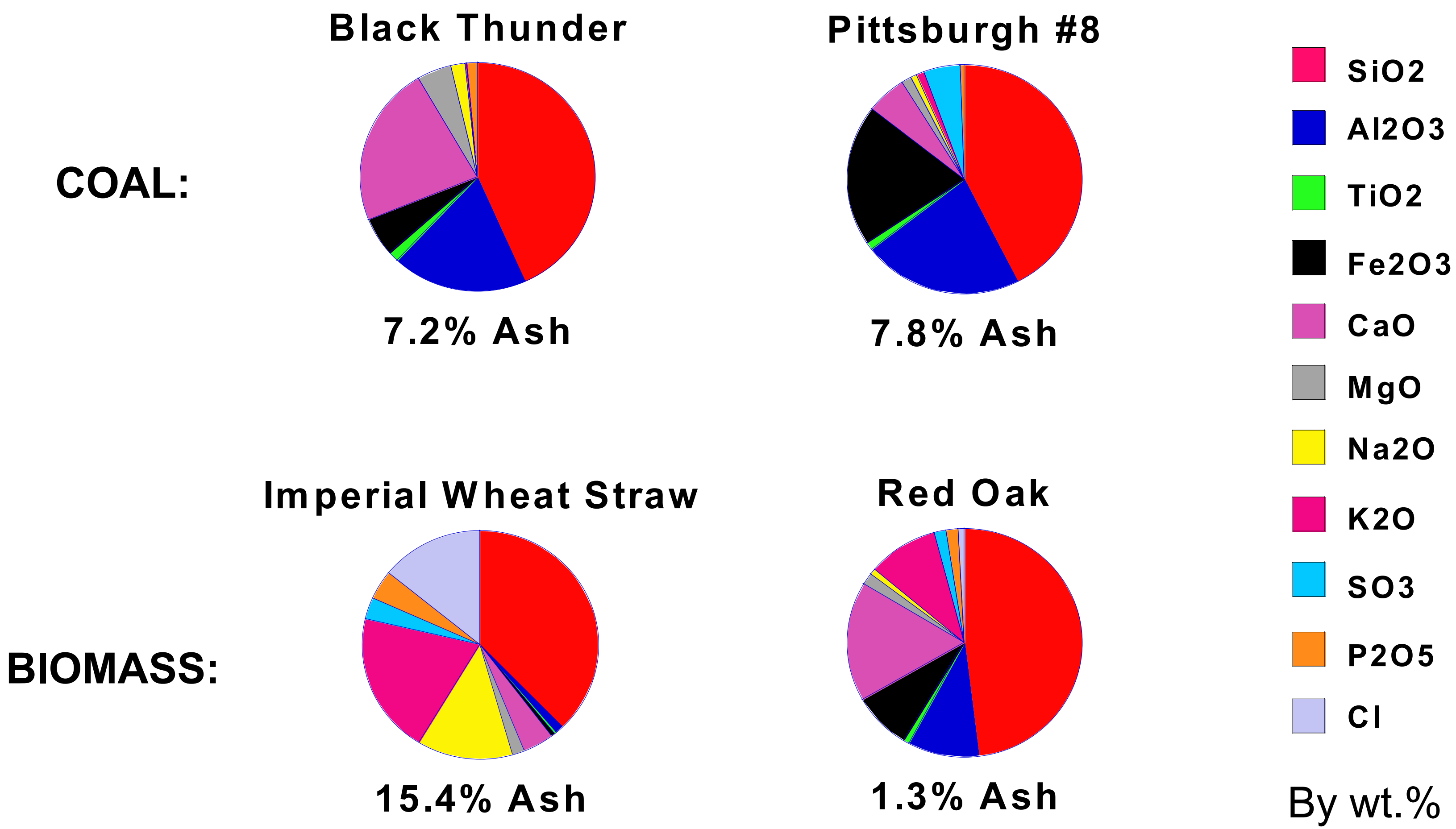
- Coal's environmental impacts
- Selection of biomass fuels
- Role of inorganic material in boiler design and operation
- Ash deposition processes involved

Fuel Chemistry



Variation in ash content and key elements such as S, Cl

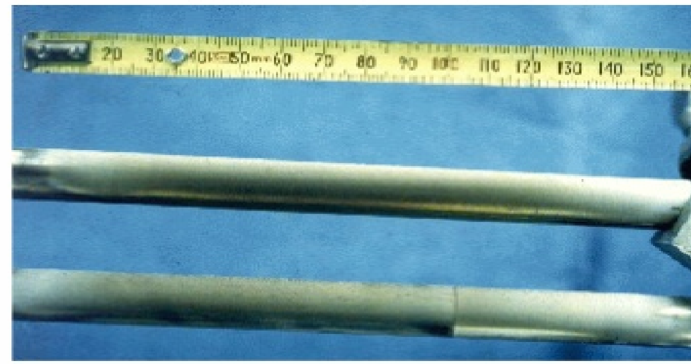
Fuel Ash Chemistry



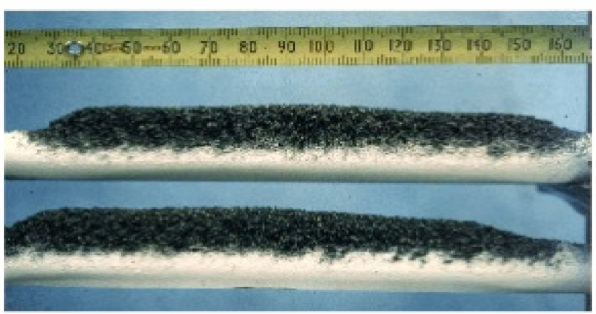
Ash Deposition Behavior

Pittsburgh #8 (1 hr)

Red Oak Wood (1 hr)



Danish Wheat Straw (1hr)

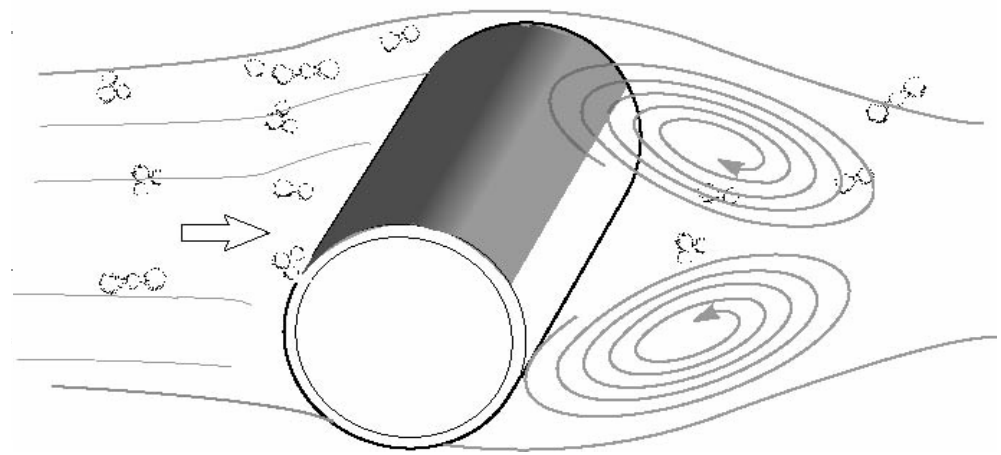


85% Pitt. #8 – 15% Imperial Straw (4 hrs)

Variation in ash content and composition - a major challenge in ash deposition

Ash deposition Mechanisms

$$\frac{dm}{dt} = \boxed{I \cdot G} + \boxed{T} + \boxed{C} + \boxed{R} + E$$

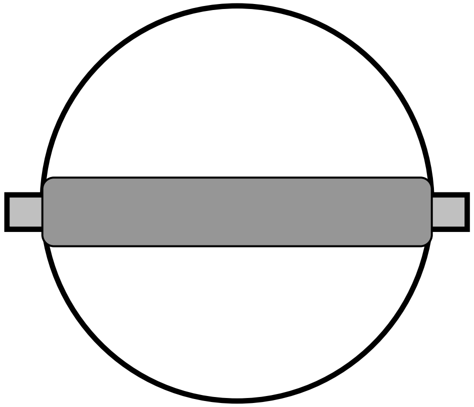


Capture Efficiency (*G*) is the fraction of particles that stay on the surface after impaction.

Investigated Mechanisms

- Inertial Impaction
  - Major contribution to mass accumulation
- Condensation
  - Impacts on enhanced ash deposition and corrosion process

Impaction Model



$$m_{ashflow} = \frac{m_{fuel} \cdot x_{ash} \cdot A_{projected}}{A_{reactor}}$$

$$m_{impaction} = m_{ashflow} \cdot \eta$$

$$m_{capture} = m_{impaction} \cdot G$$

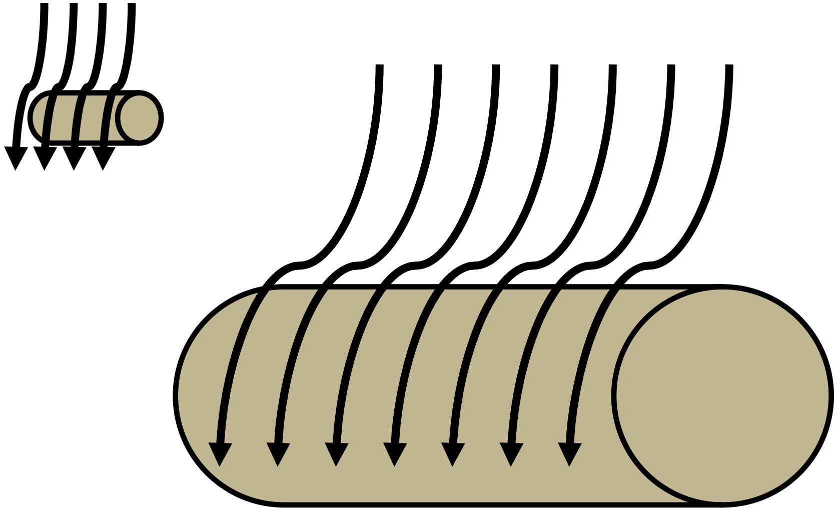
$$\zeta = \eta G$$

n = Impaction efficiency

G = Capture efficiency

ζ = Collection efficiency

Impaction model



Stokes Number

(Modified Reynolds Number)

$$Stk = \frac{\rho_p d_p^2 V_p}{9 \mu_g d_c} \psi$$

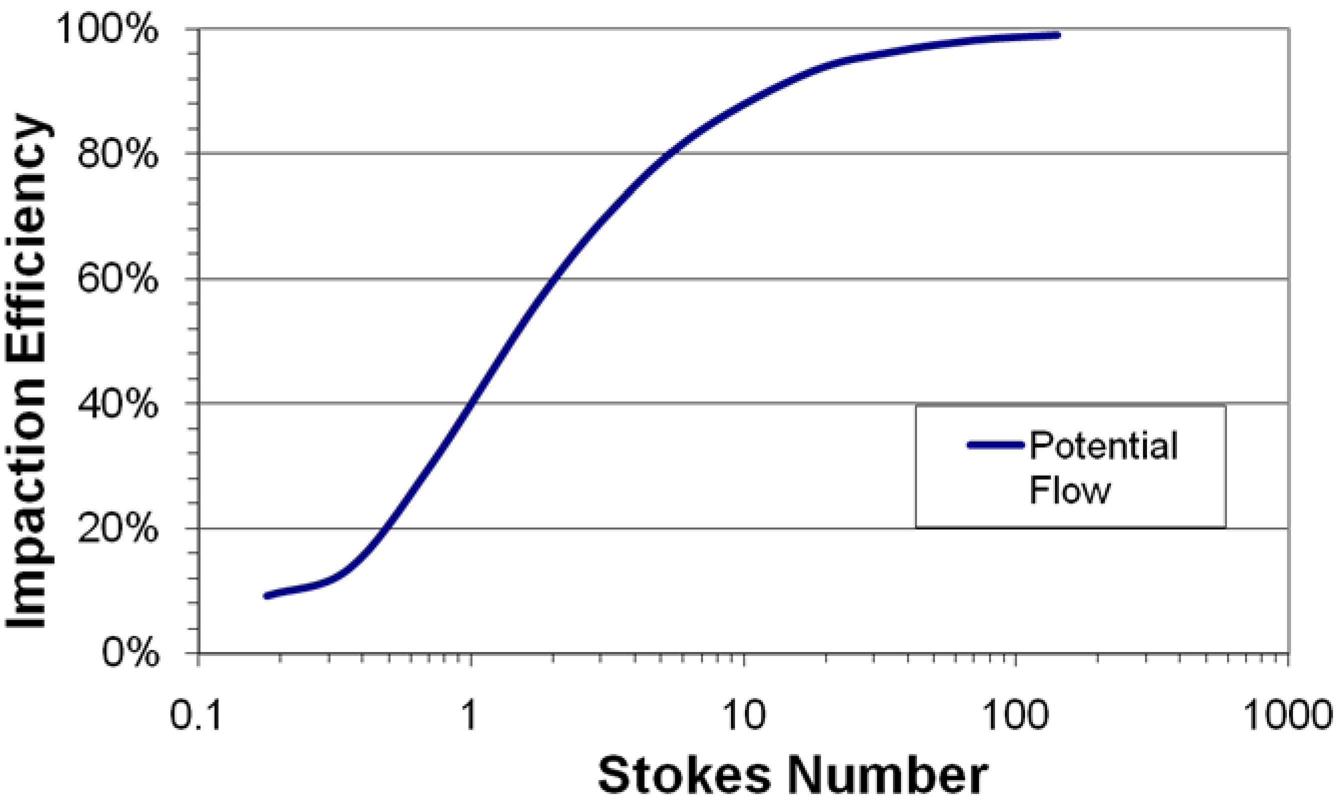
Ψ = Non-Stokesian Drag Correction

Impaction efficiency: The fraction of particles that impact on a deposition surface.

$$\eta(Stk) \cong \left[1 + b(Stk - a)^{-1} - c(Stk - a)^{-2} + d(Stk - a)^{-3}\right]^{-1}$$

Where a, b, c and d are empirically-derived parameters.

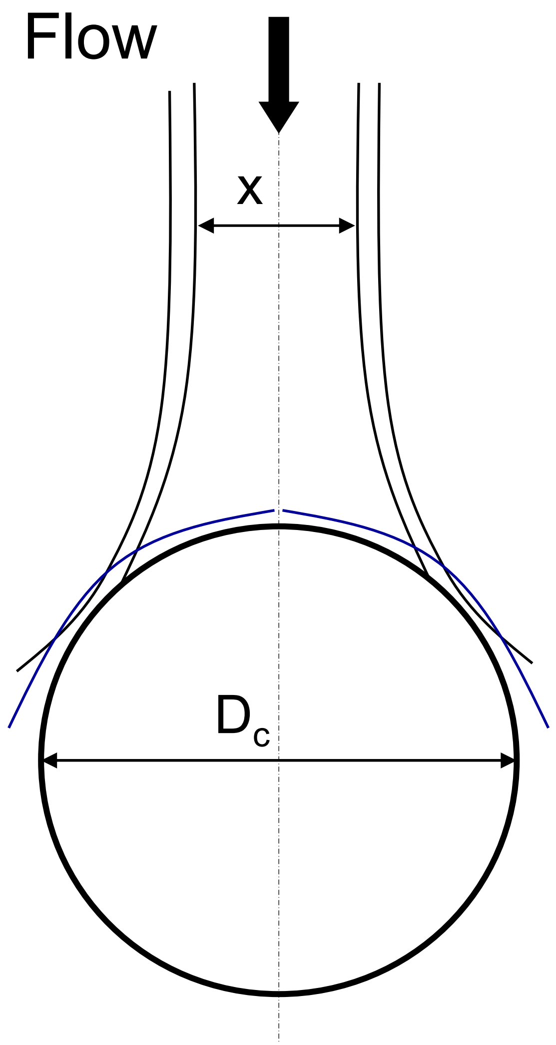
Impaction in Potential Flow



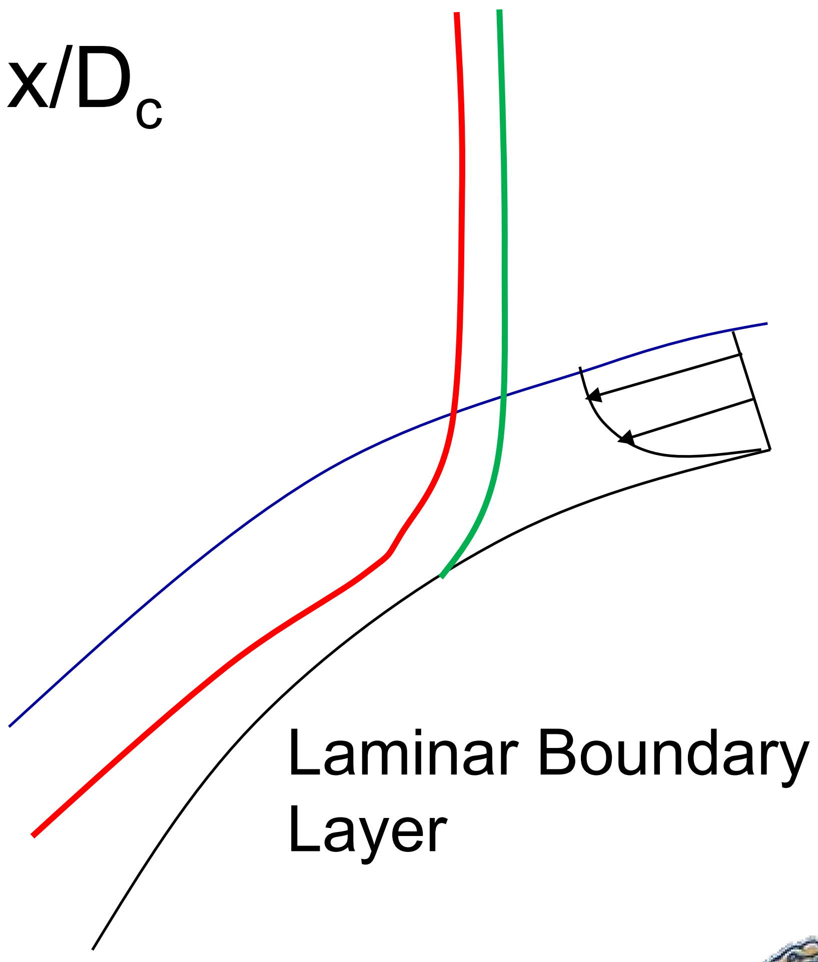
$$\eta(Stk) \cong \left[1 + b(Stk - a)^{-1} - c(Stk - a)^{-2} + d(Stk - a)^{-3}\right]^{-1}$$

	a	b	c	d
Potential Flow	0.1238	1.34	-0.034	0.0289

Impaction Efficiency

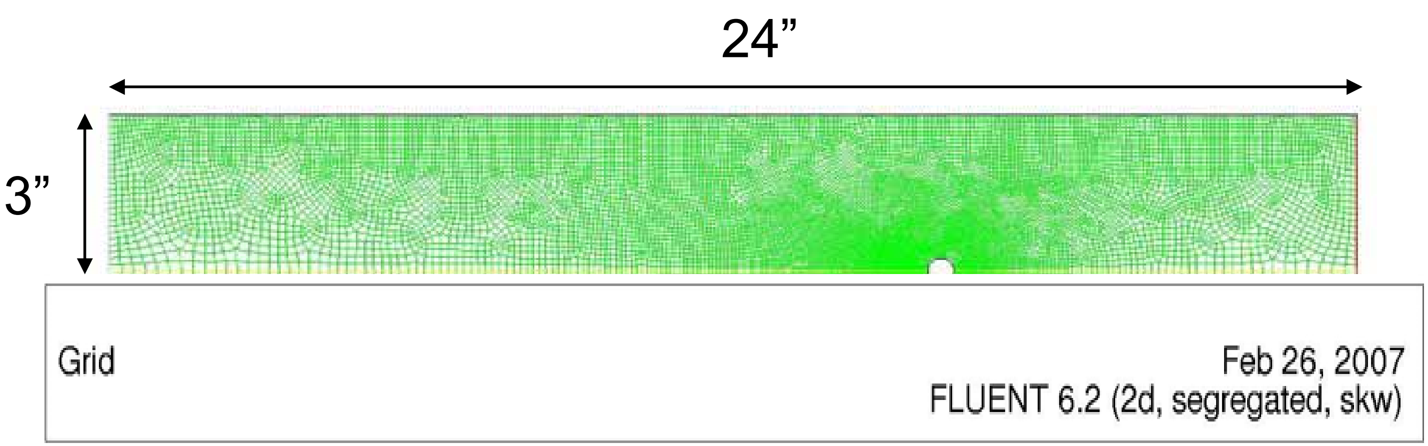


$$n = x/D_c$$



Impaction Model

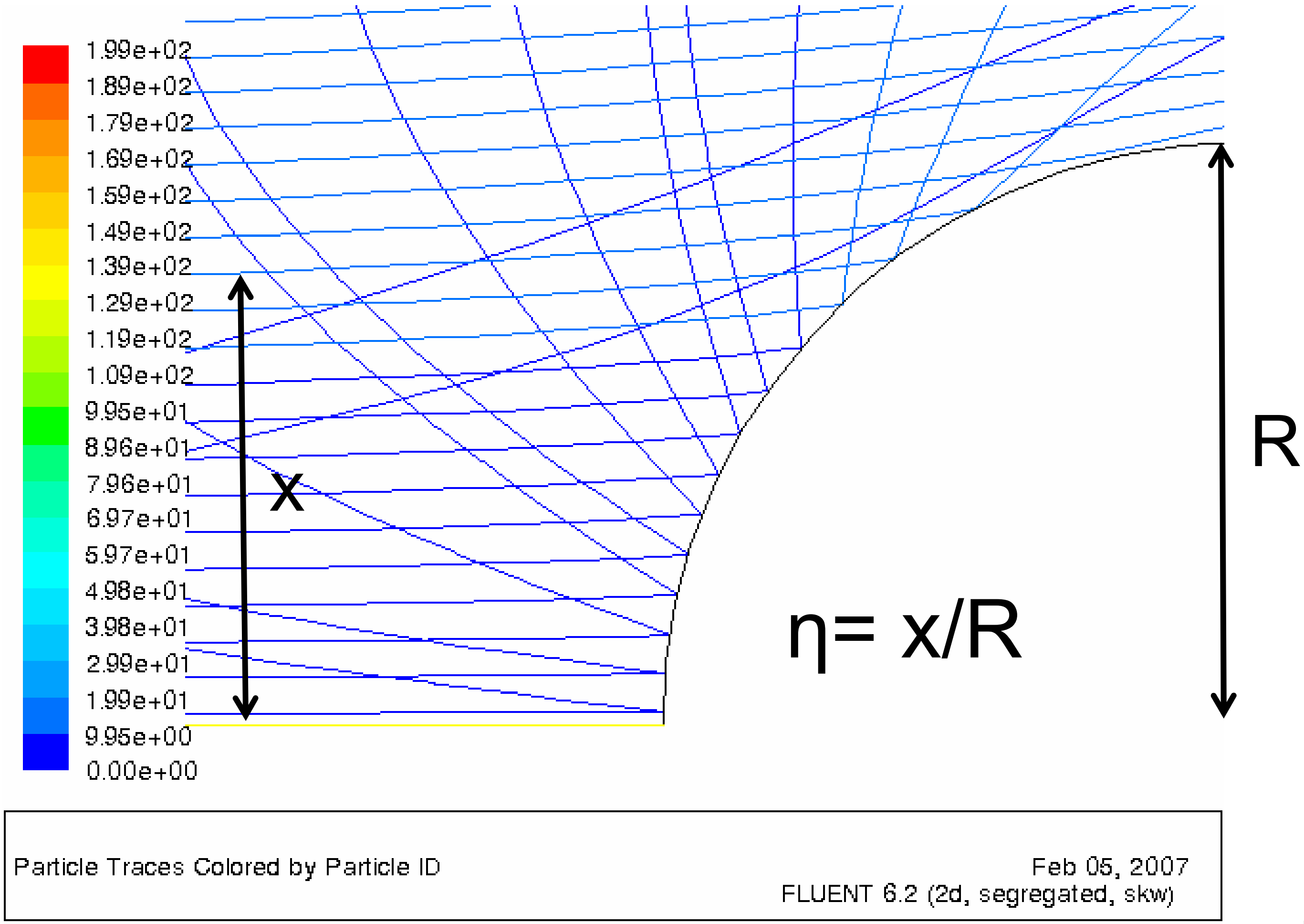
- Solver – 2D, segregated
- Grid – Quadrangular, Paved
- Cells – 12308
- Viscous model – Standard k-w (2 equation)



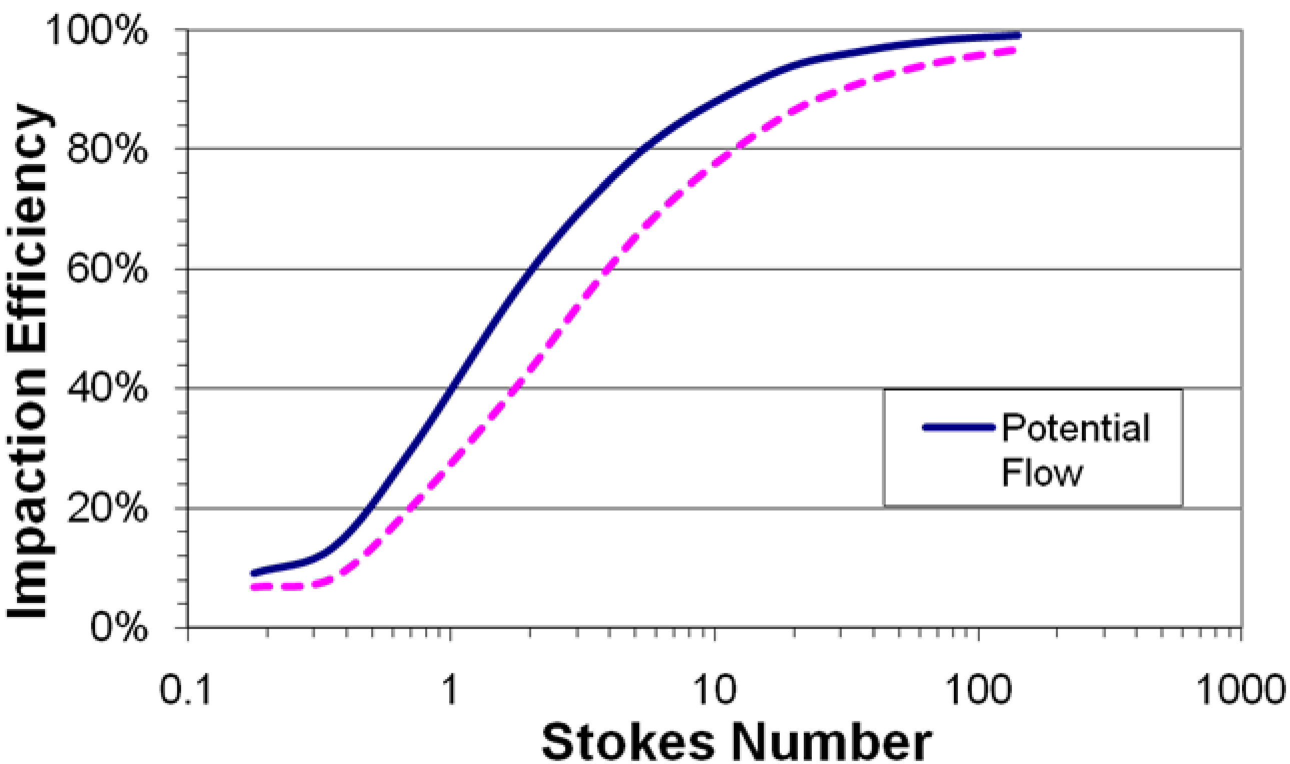
Impaction model

- Operating Parameters
  - Particle diameter : 5 – 2000 microns
  - Approximate $V_p = V_g + V_t$
  - Gas Temperature : 1300 K
  - Particle Temperature : 1400 K
  - Probe Surface Temperature : 800 K
- Combination of particle velocity and particle diameter selected for Stokes number range: 0.01 – 150.

Calculation of n



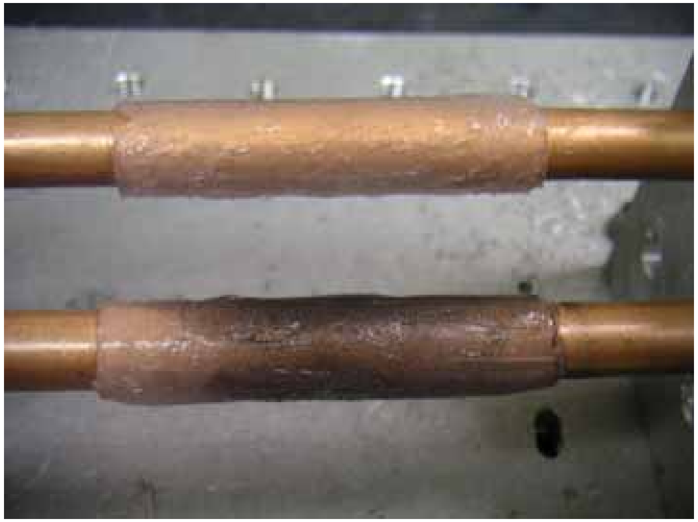
Impaction in Viscous Flow



$$\eta(Stk) \cong \left[1 + b(Stk - a)^{-1} - c(Stk - a)^{-2} + d(Stk - a)^{-3}\right]^{-1}$$

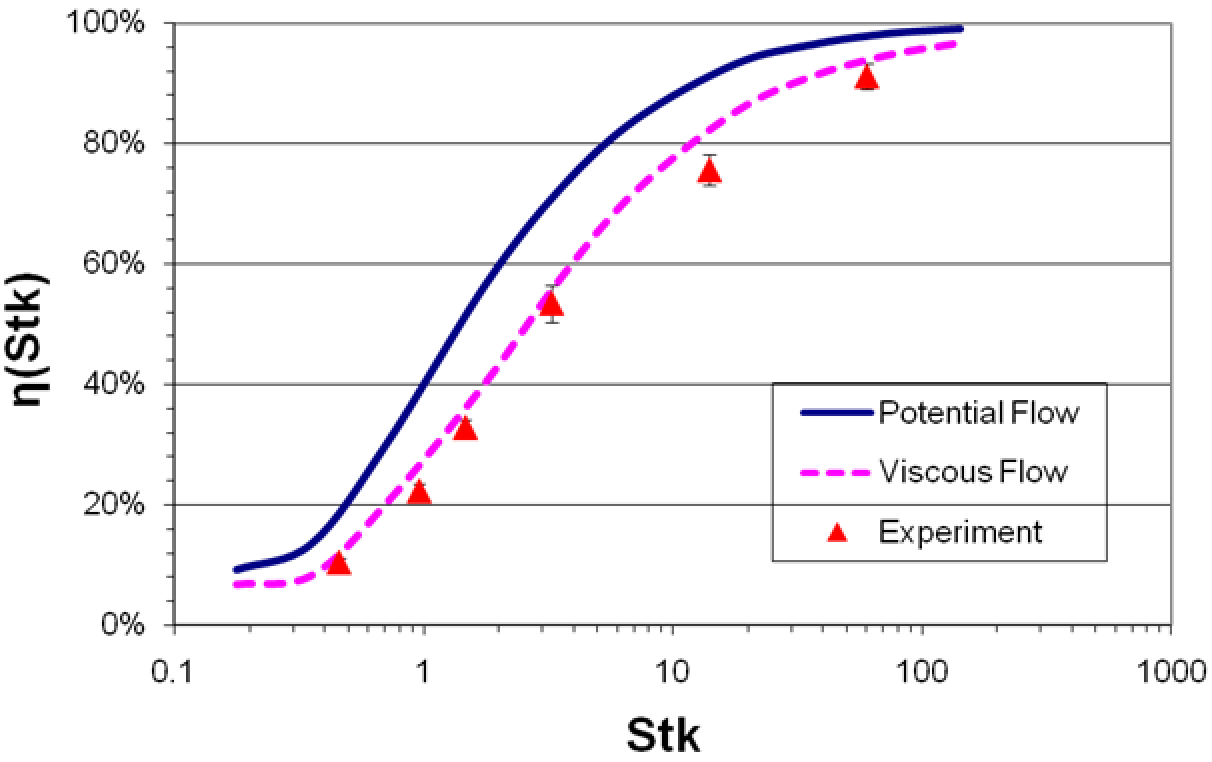
	a	b	c	d
Potential Flow	0.1238	1.34	-0.034	0.0289
Viscous Flow	**0.0868**	**1.9495**	**-0.457877**	**-0.047**

Particle Impaction Set Up



High temperature vacuum grease provides 100% particle capture system.

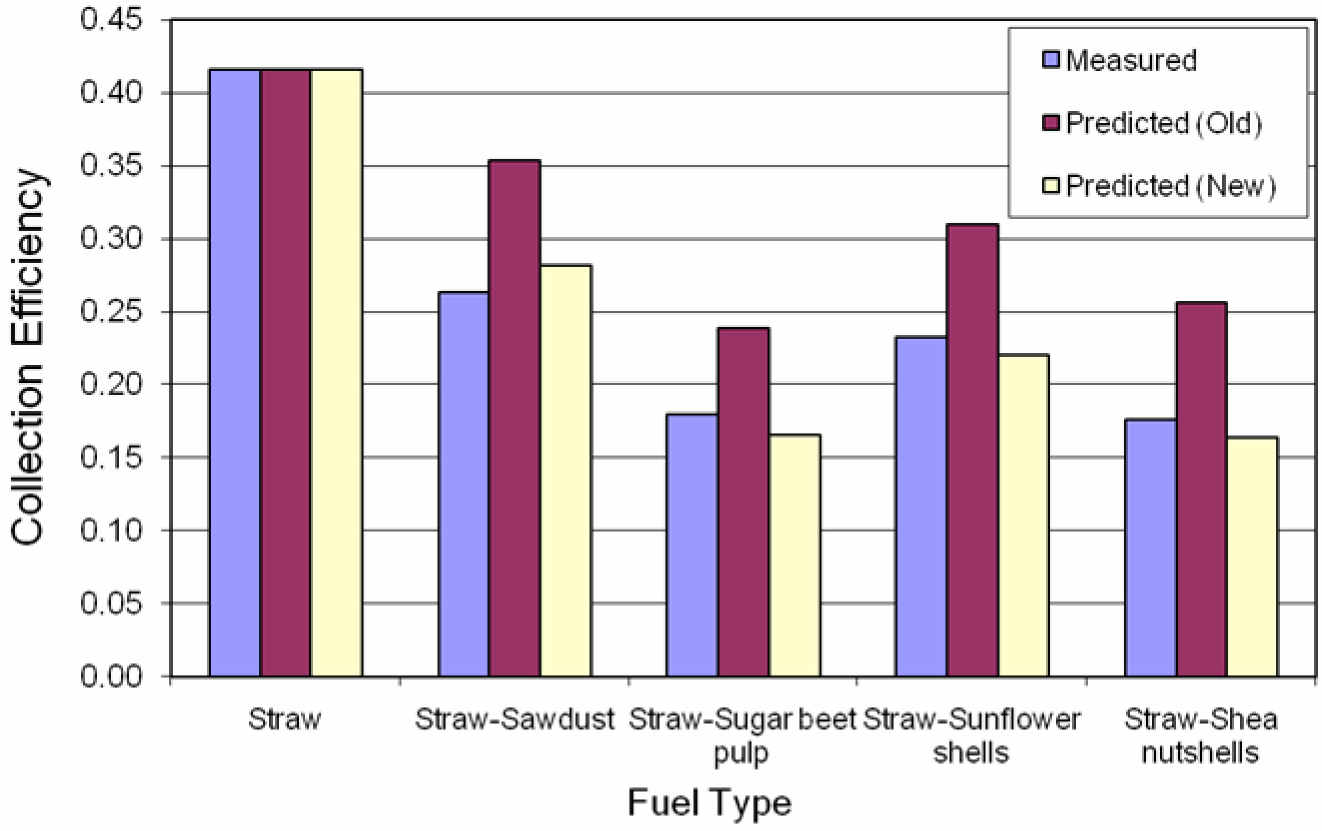
Impaction Efficiency



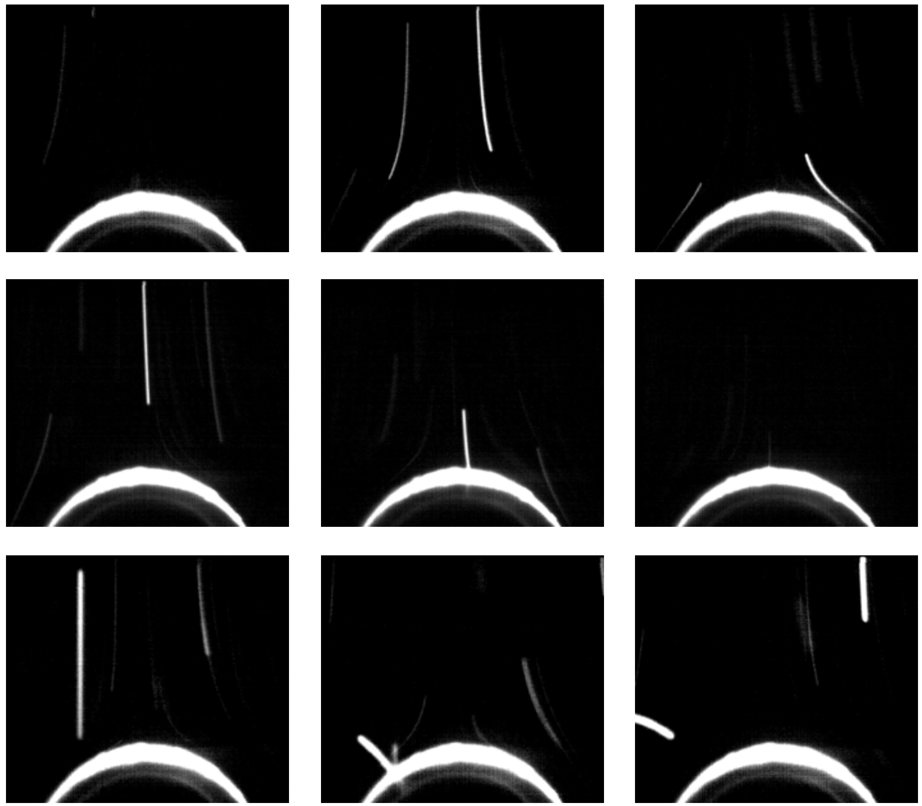
$$\eta(Stk) \cong \left[1 + b(Stk - a)^{-1} - c(Stk - a)^{-2} + d(Stk - a)^{-3}\right]^{-1}$$

	a	b	c	d
Potential Flow	0.1238	1.34	-0.034	0.0289
Viscous Flow	**0.0868**	**1.9495**	**-0.457877**	**-0.047**

Model Results with New ‘η’



To Stick or Not to Stick?



Particle Escape $V_p < V_{threshold}$

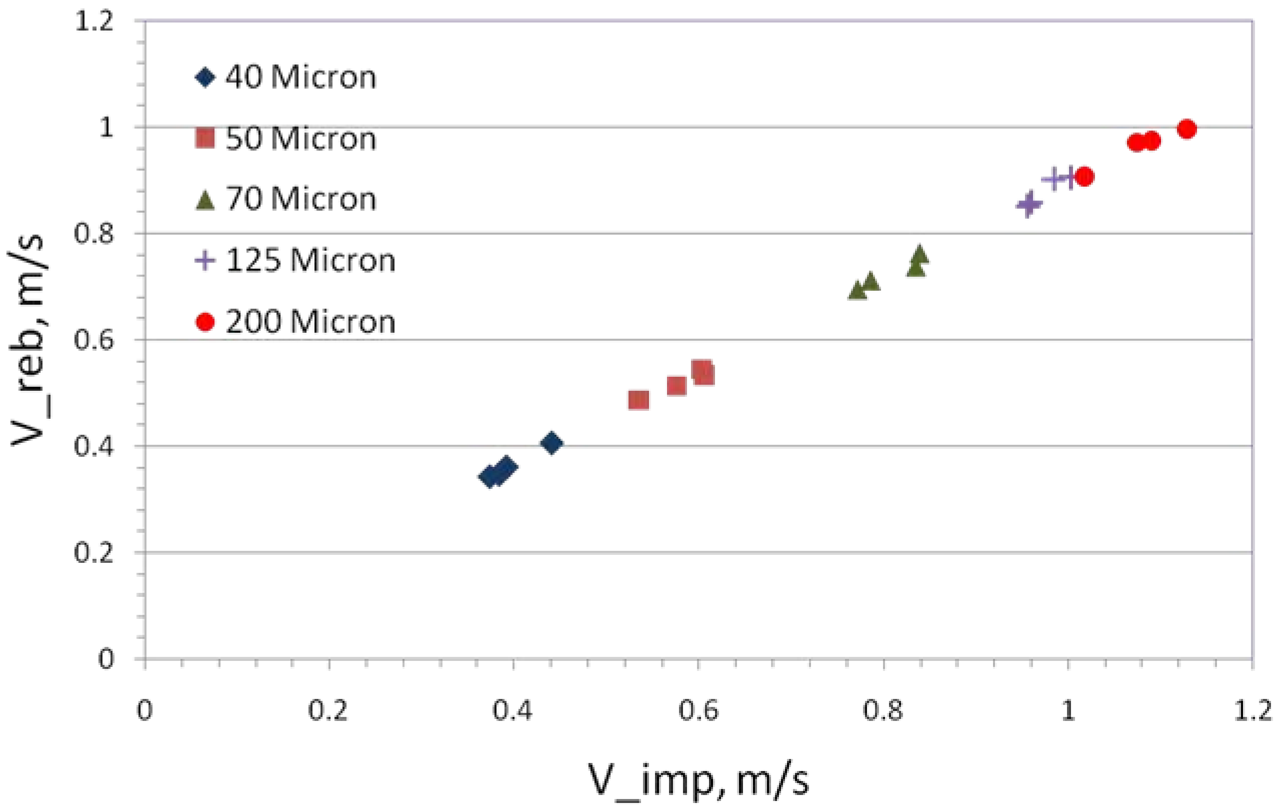
Particle Capture $V_p = V_{threshold}$

Particle Rebound $V_p > V_{threshold}$

Particle Impaction

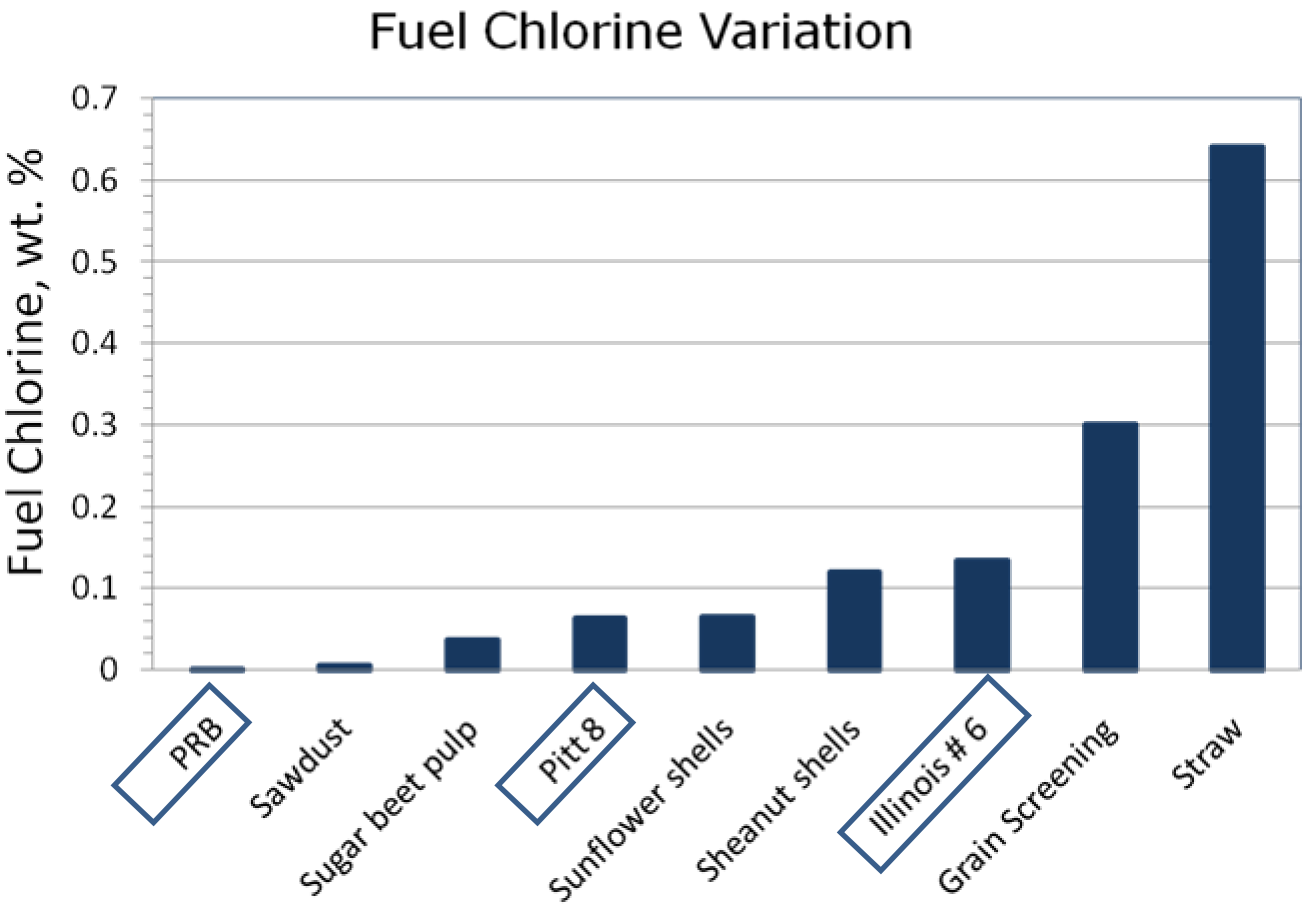
- Rigid Surface
- Powdery Layer

Impaction – Rigid Surface



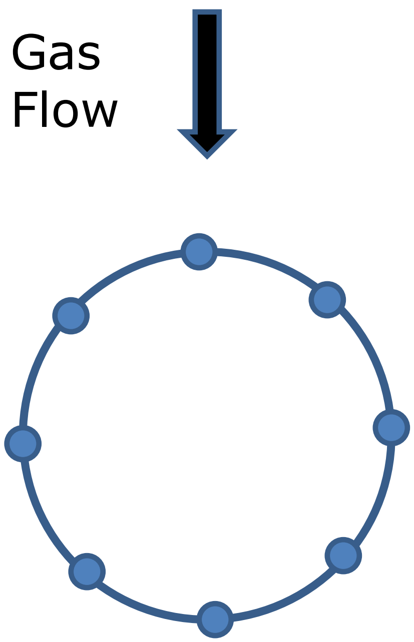
Coefficient of restitution ~ 0.9

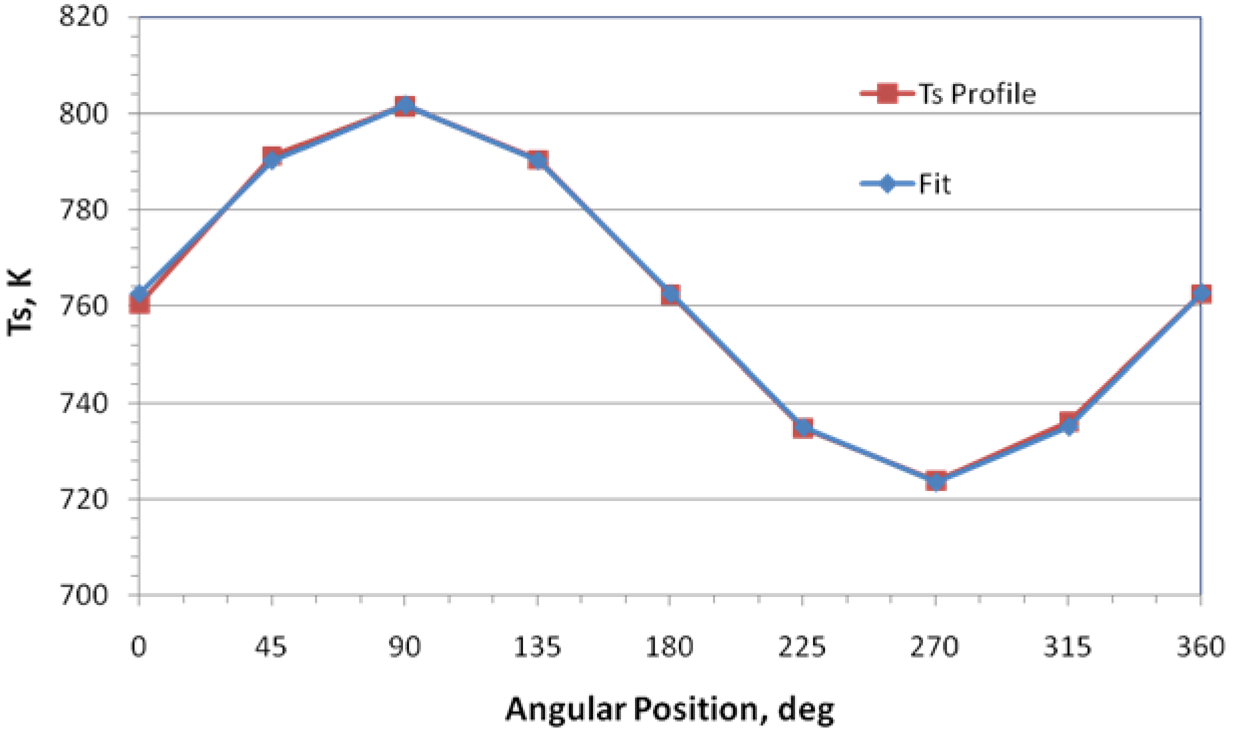
Vapor Condensation



Condensation Rate Model

$$N_{NaCl} = \frac{\theta_m k_m c(x_s - x_b)}{1 - x_b} = k_m c \ln\left(1 + \frac{x_s - x_b}{1 - x_b}\right)$$

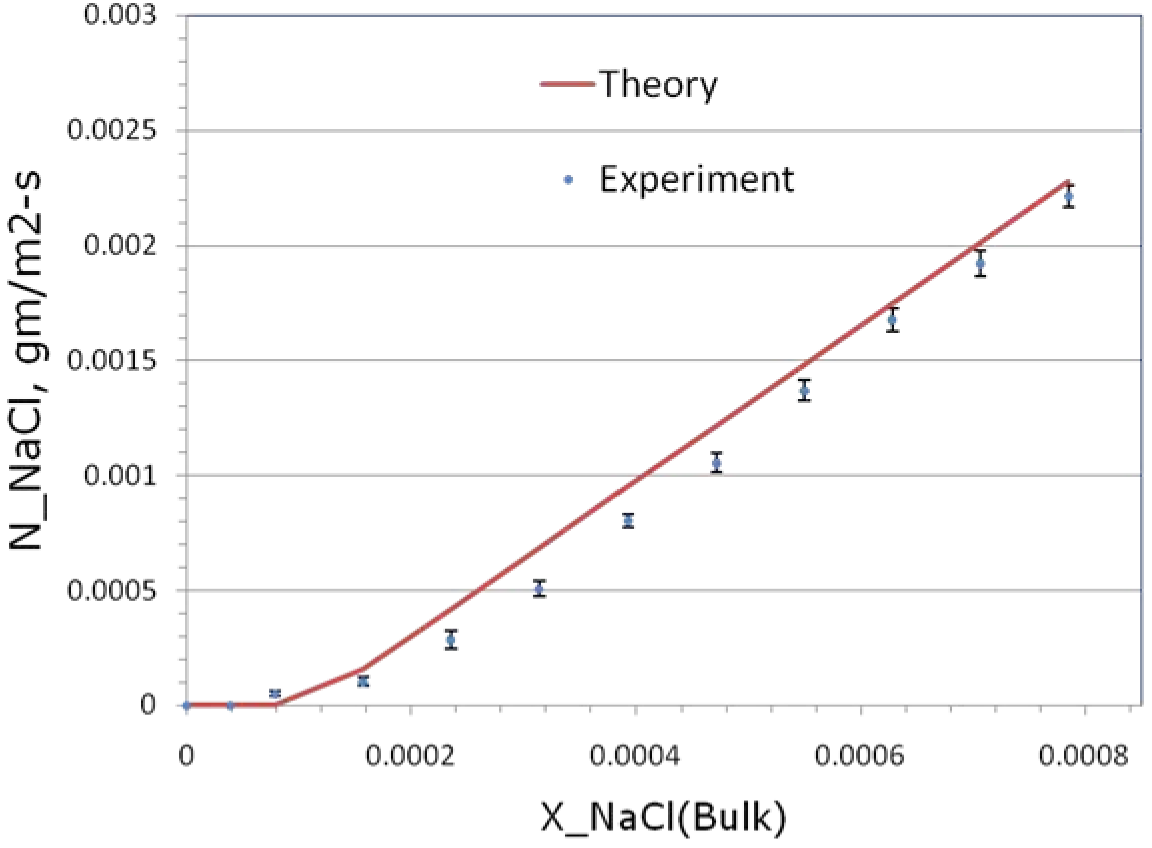




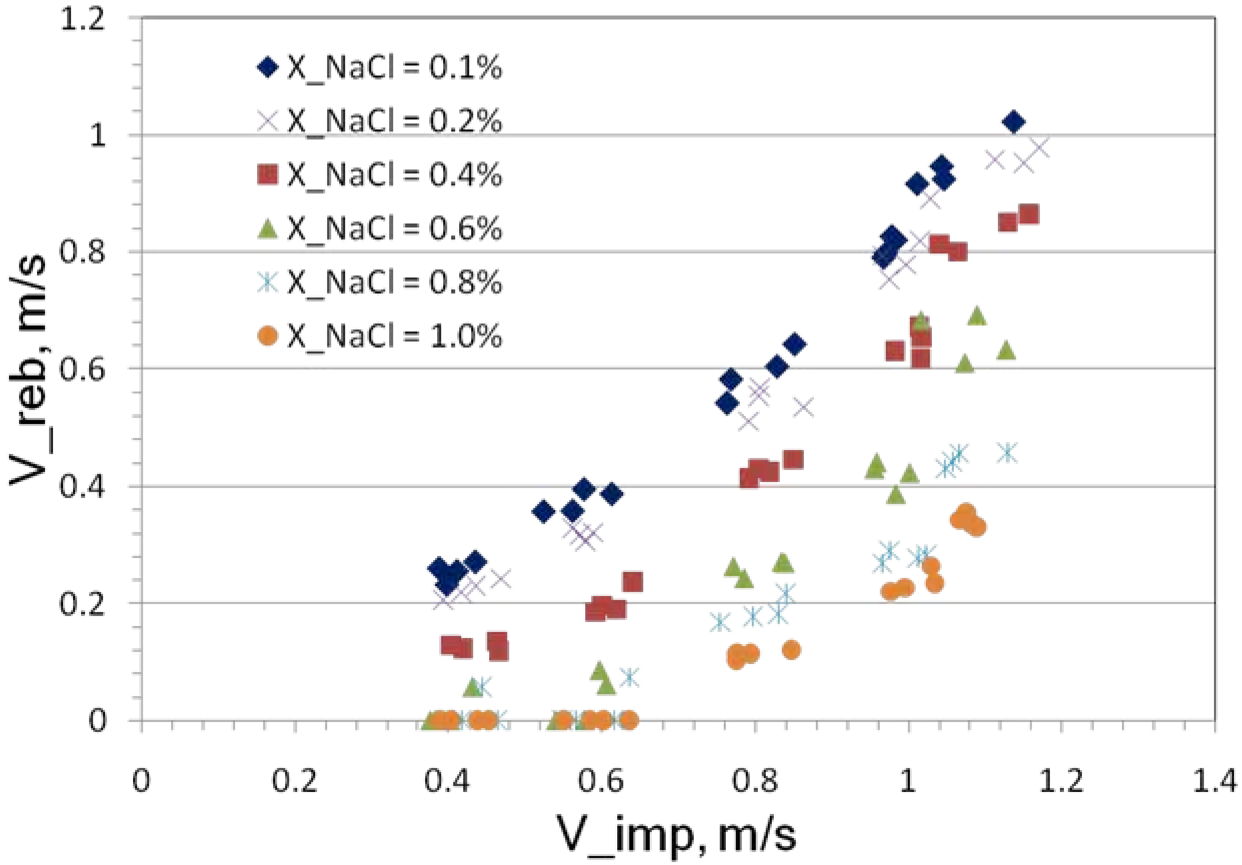
$$T_S(\theta) = T_0 + T_1 \sin\theta$$

T_0	762.625
T_1	39.0292

Vapor Condensation Rate



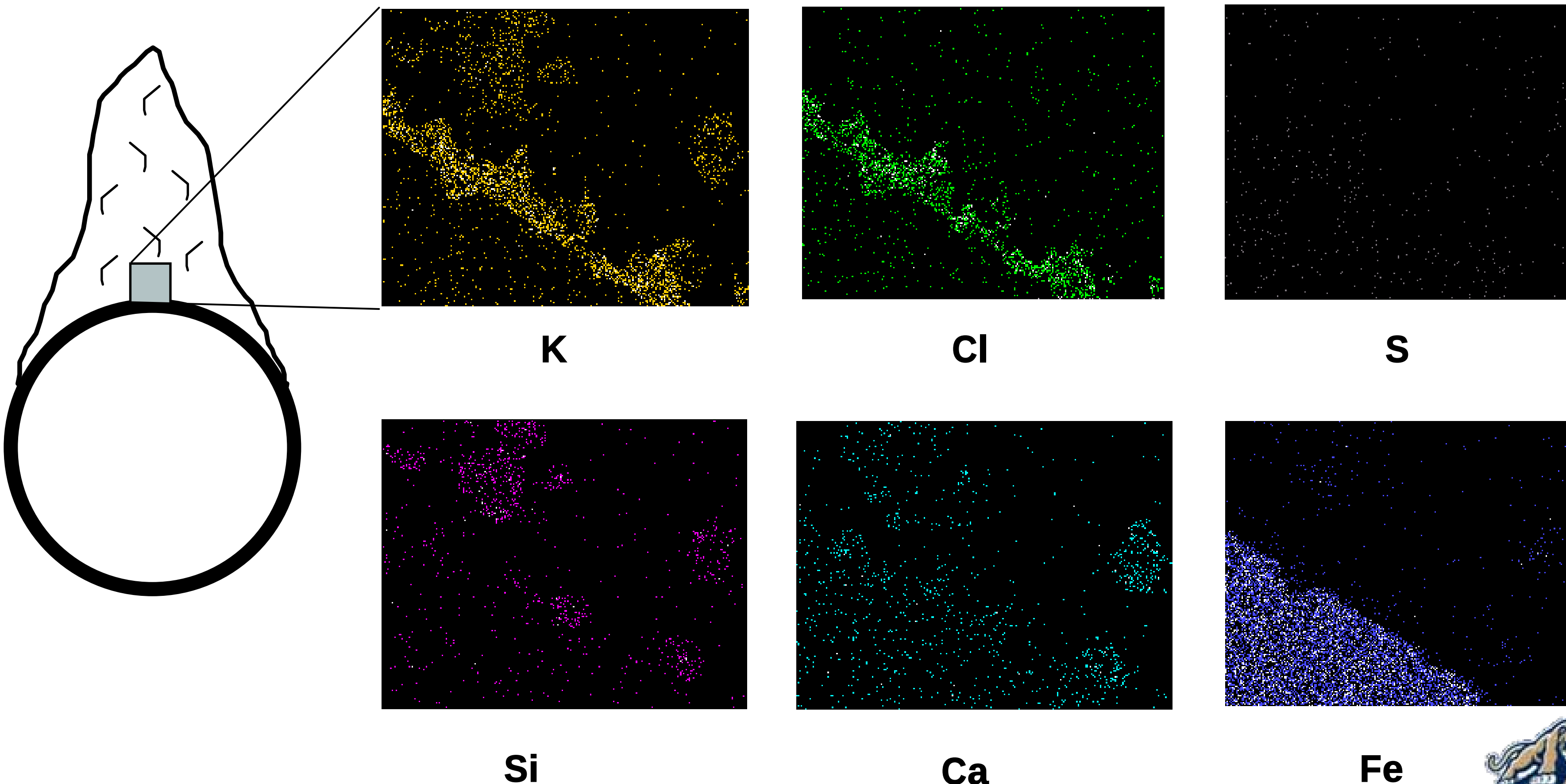
Impaction – Powdery Layer



Higher particle loading on surface induces particle capture

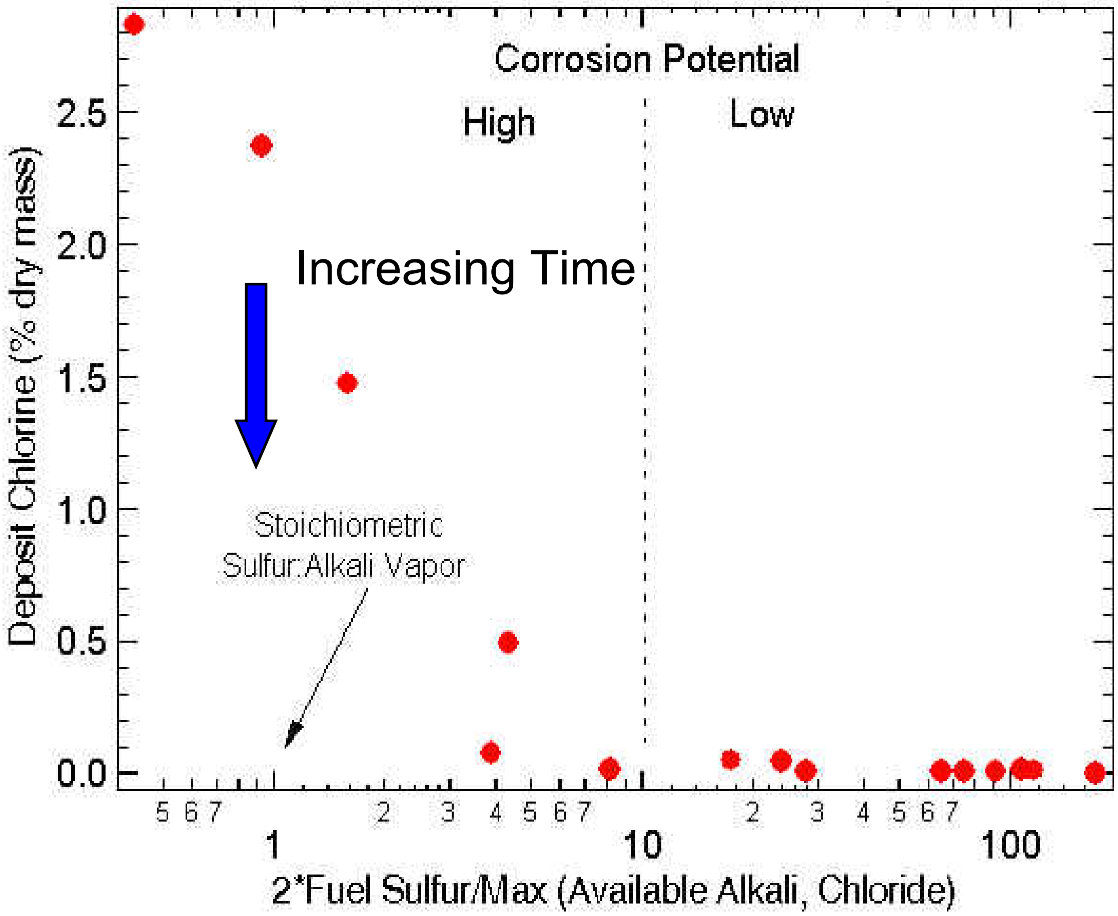
Corrosion potential

Chlorides condensation is a major step in corrosion initiation



Corrosion Chemistry

- Deposit chlorine content near zero for most commercially relevant biomass-coal blends.
- Fuel-based parameter predicts deposit chlorine content.



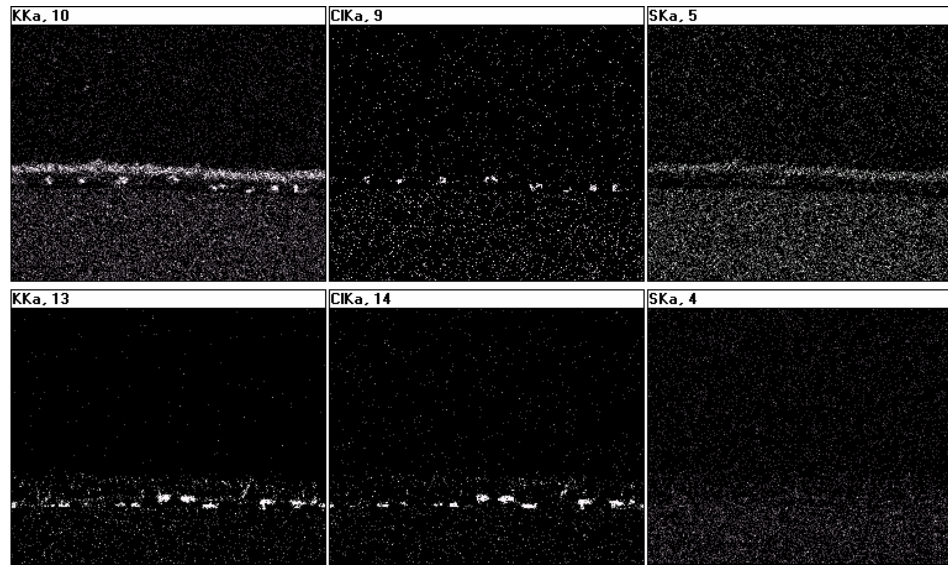
Corrosion Results

% w/w	Straw	Sunflower shells
SiO_2	52	1.1
Al_2O_3	0.6	0.5
Fe_2O_3	1.1	0.9
CaO	9.2	16
MgO	1.8	13.1
Na_2O	0.3	< 0.2
K_2O	21.9	45.1
SO_3	4	11.7
P_2O_5	3.2	10.1
Cl	5.6	1.2
Other	0.3	0.3
Sum	100	100

K Cl S

Sunflower Shells

Straw



Conclusions

- The improvement of previous representations resulted in up to 40% decrease in impaction efficiency
- Condensation theory and experimental results provide mechanistic and accurate deposit descriptions
- Particle capture mechanisms on different surfaces (e.g. rigid metal wall, fine particulate layer) provide quantitative capture efficiencies, rates and structures that compare well with experimental data.

Acknowledgements

- Industrial Sponsors
- BYU Ash Deposition Group
- Larry Baxter, Dale Tree