# Update: Brush Scrubbing for Post-CMP Cleaning

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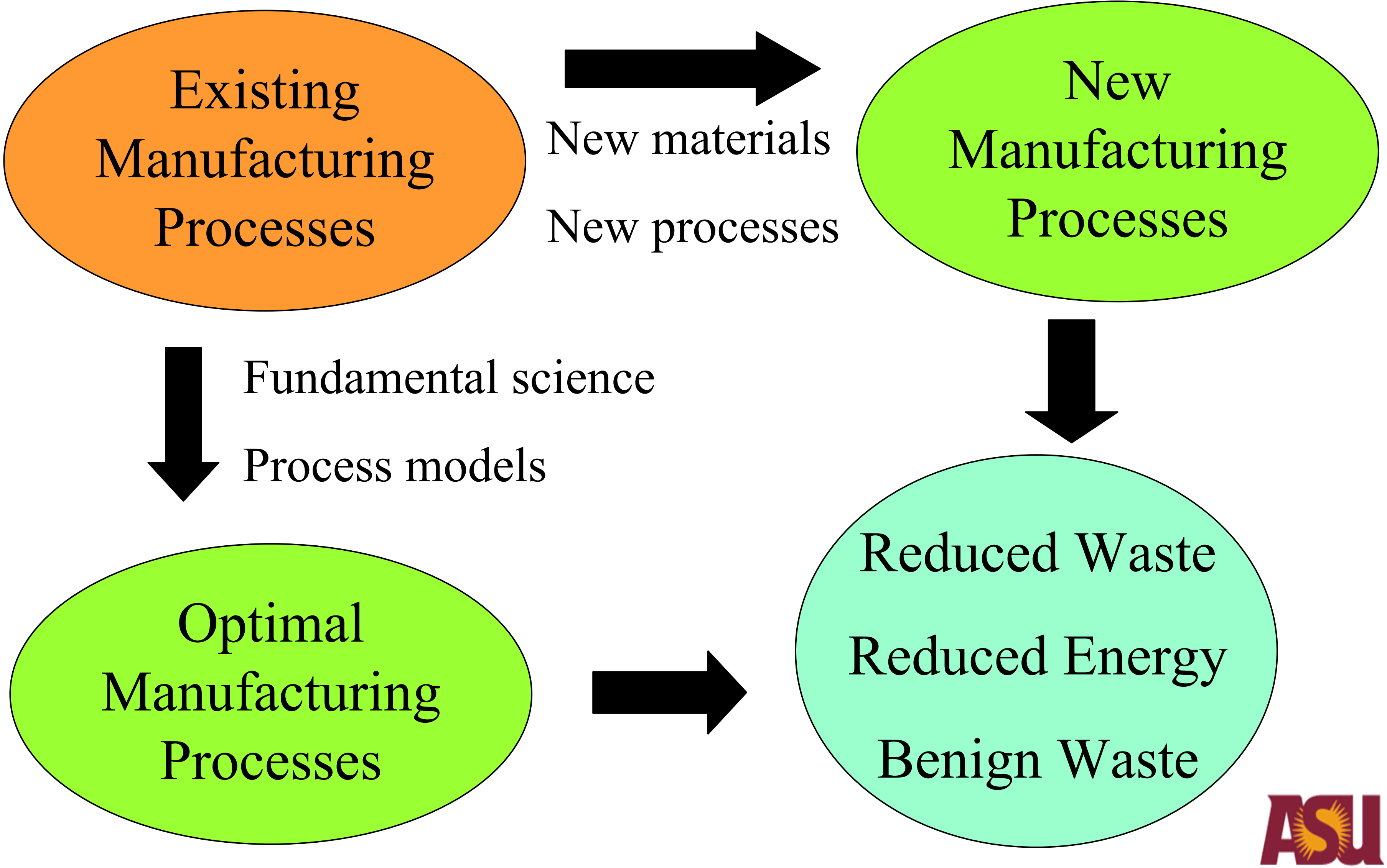
# Environmentally-Benign Semiconductor Manufacturing



Existing Manufacturing Processes

New materials

New processes

New Manufacturing Processes

Fundamental science

Process models

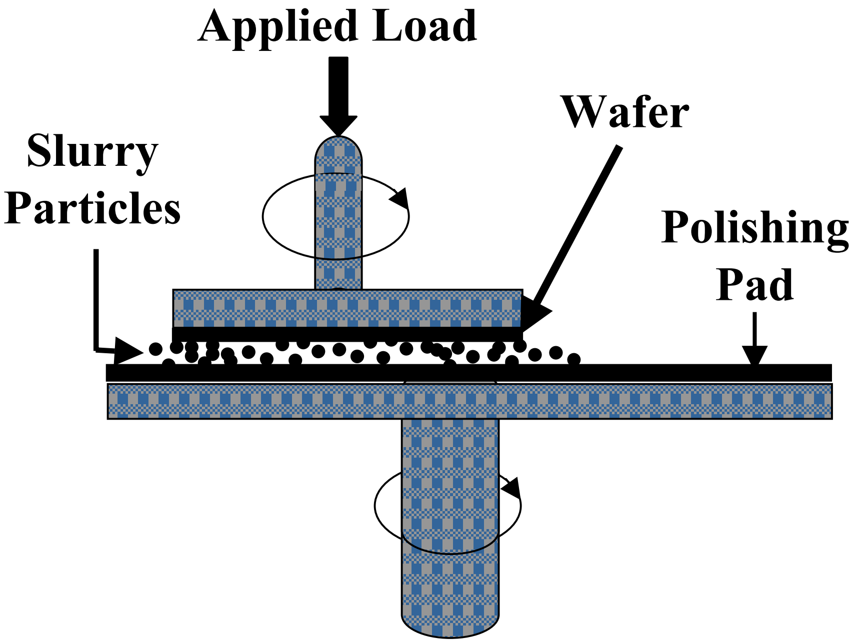
Optimal Manufacturing Processes

Reduced Waste

Reduced Energy

Benign Waste

# Chemical Mechanical Polishing (CMP)



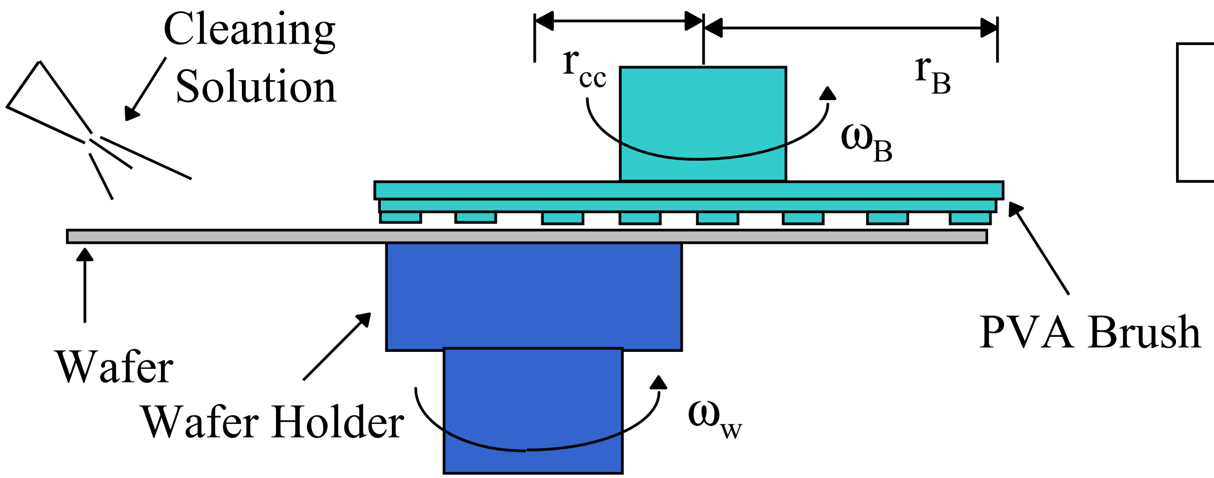
CMP Tool

- » Removes a thin surface layer to obtain planar wafers
  - Uses abrasive particles in aqueous solution in conjunction with relative motion between polishing pad and wafer
  - Surface removed mechanically and chemically
- » Introduces contaminants onto wafer surfaces
  - Pieces of polished surface and polishing pad
  - Slurry particles
  - Contamination from the handler or handling device
  - Must be removed before further processing

# Post-CMP Cleaning

- Must remove particles less than 1 micron in diameter
- Must not roughen wafer surface excessively
- Brush scrubbing and megasonic cleaning have potential for removing small particles
- Problems with
    - Resource consumption
    - Lack of understanding of cleaning mechanism
    - Inefficient and unreliable processes

**Brush Scrubber**



$r$ = radius

$\omega$ = angular speed

# Cleaning Model Objective

**Develop and validate scientifically-based cleaning models to optimize wafer cleaning processes and minimize water and chemistry use**

Adhesion Model

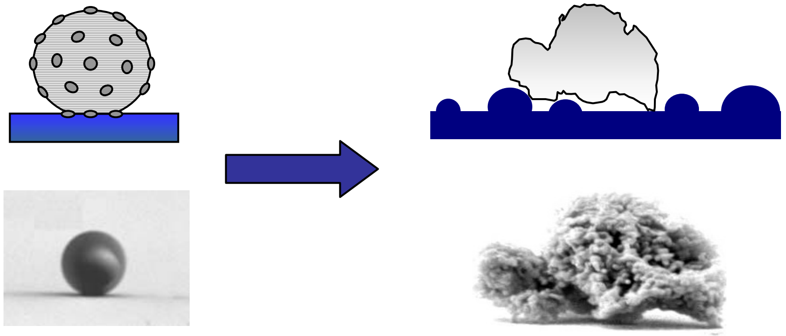
Removal Model

**<u>1st Generation</u>**

Rough deformable spherical particles interacting with a rough flat surface

**<u>2nd Generation</u>**

Asymmetrical rough particles interacting with real surfaces

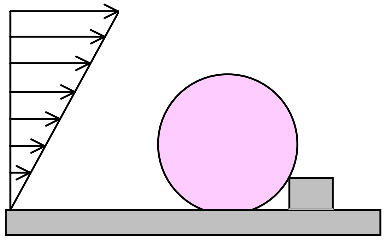


Particle size variation

Adhesion force variation

Points around which rolling occurs

Velocity profile near adhering particle



# Adhesion of Particles to Surfaces – DLVO Theory

$$F_A = F_{vdW} + F_{EDL}$$

Total Adhesion Force

van der Waals Force

$$F_{vdW} = f(A, d, a, h)$$

Electrostatic Double Layer Force

$$F_{EDL} = f(\varepsilon, \zeta, \kappa, d, h)$$

$$\zeta = f(I, pH)$$

$$\kappa = f(I)$$

A = System Hamaker constant

d = Particle diameter

a = Contact radius

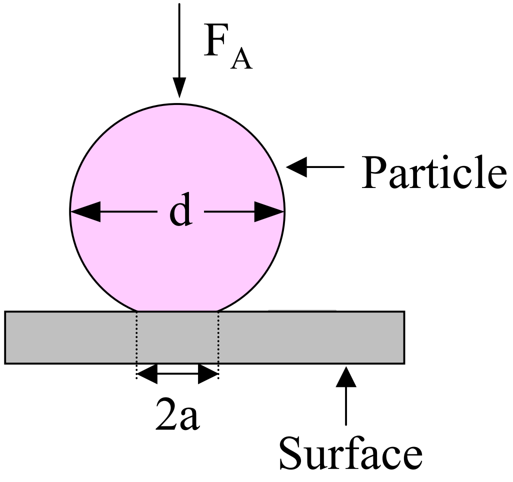
h = Particle-surface separation distance

$\varepsilon$ = Medium dielectric constant

$\zeta$ = Zeta potential

$\kappa$ = Reciprocal double-layer thickness

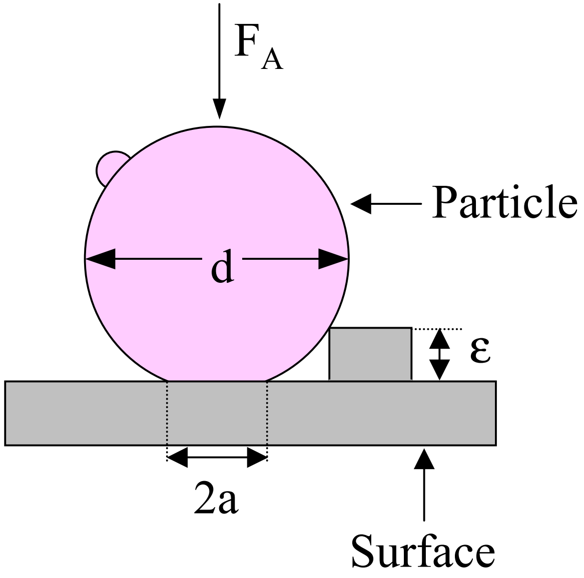
I = Medium ionic strength



# Adhesion of Particles to Surfaces – Real Systems

$$\boxed{F_A = F_{vdW}(A, h, E, P, f_s, \varepsilon_s, \sigma_s, f_p, \varepsilon_p, \sigma_p, a, d)}$$

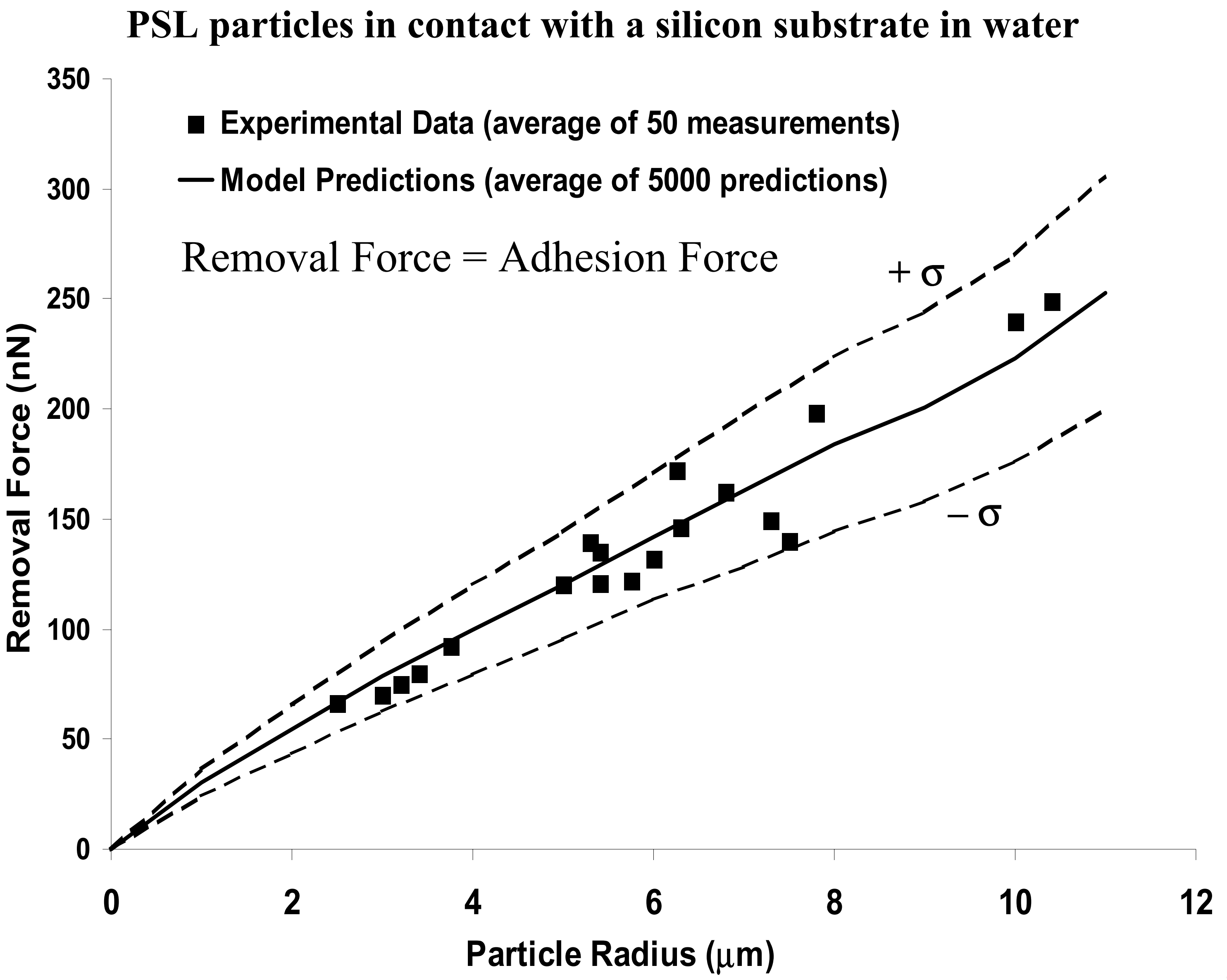
A = System Hamaker constant
h = Particle-surface separation distance
E = Elastic modulus
P = Applied load
$f_s$ = Fraction of substrate covered by asperities
$\varepsilon_s$ = Average asperity height on substrate
$\sigma_s$ = Standard deviation in asperity height on substrate
$f_p$ = Fraction of particle covered by asperities
$\varepsilon_p$ = Average asperity height on particle
$\sigma_p$ = Standard deviation in asperity height on particle
a = Contact radius
d = Particle diameter



# Adhesion Model – Gen 2

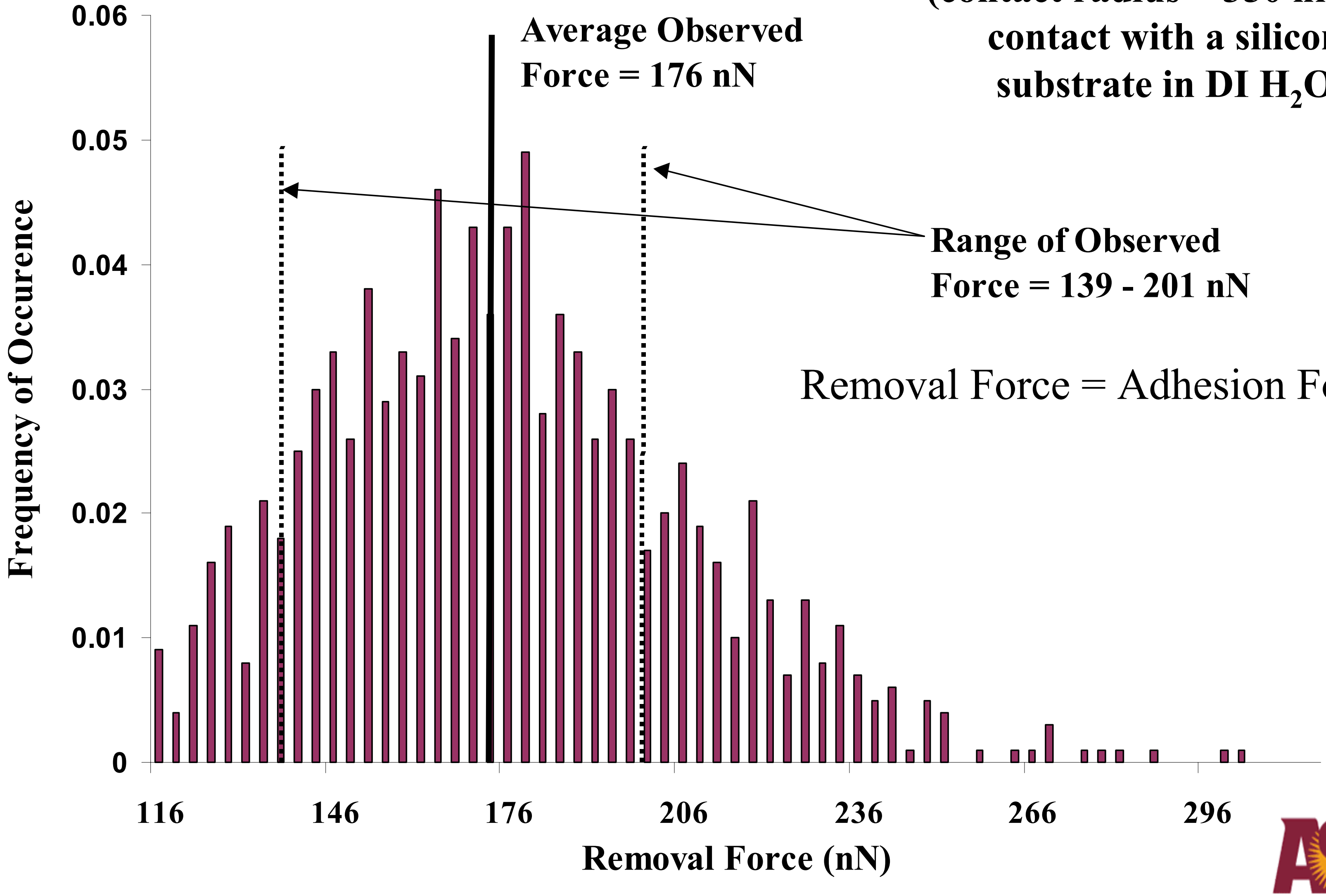
- Predicts adhesive interactions for particles on various surfaces
  - Couples computer simulation with fundamental adhesion model
  - Accounts for particle and surface:
    - Chemistry
    - Morphology
    - Mechanical properties
    - Geometry
- Validated using experimental investigations of adhesion of alumina particles and polystyrene latex spheres to copper, $SiO_2$, and tungsten substrates in a variety of environments
  - Atomic force microscopy (AFM), nanoindentation, and scanning electron microscopy (SEM) techniques applied
    - Measure force required to remove particles from the substrates
    - Characterize morphology, mechanical properties, and geometry of interacting surfaces
  - Experimental removal forces compared with model predictions
  - Measurements can be used to determine system Hamaker constant
- Predictive model for particle adhesion established

# PSL/$H_2O$/Silicon Adhesion



# Alumina/$H_2O$/Silicon Adhesion

**3 µm alumina particle (contact radius = 350 nm) in contact with a silicon substrate in DI $H_2O$**

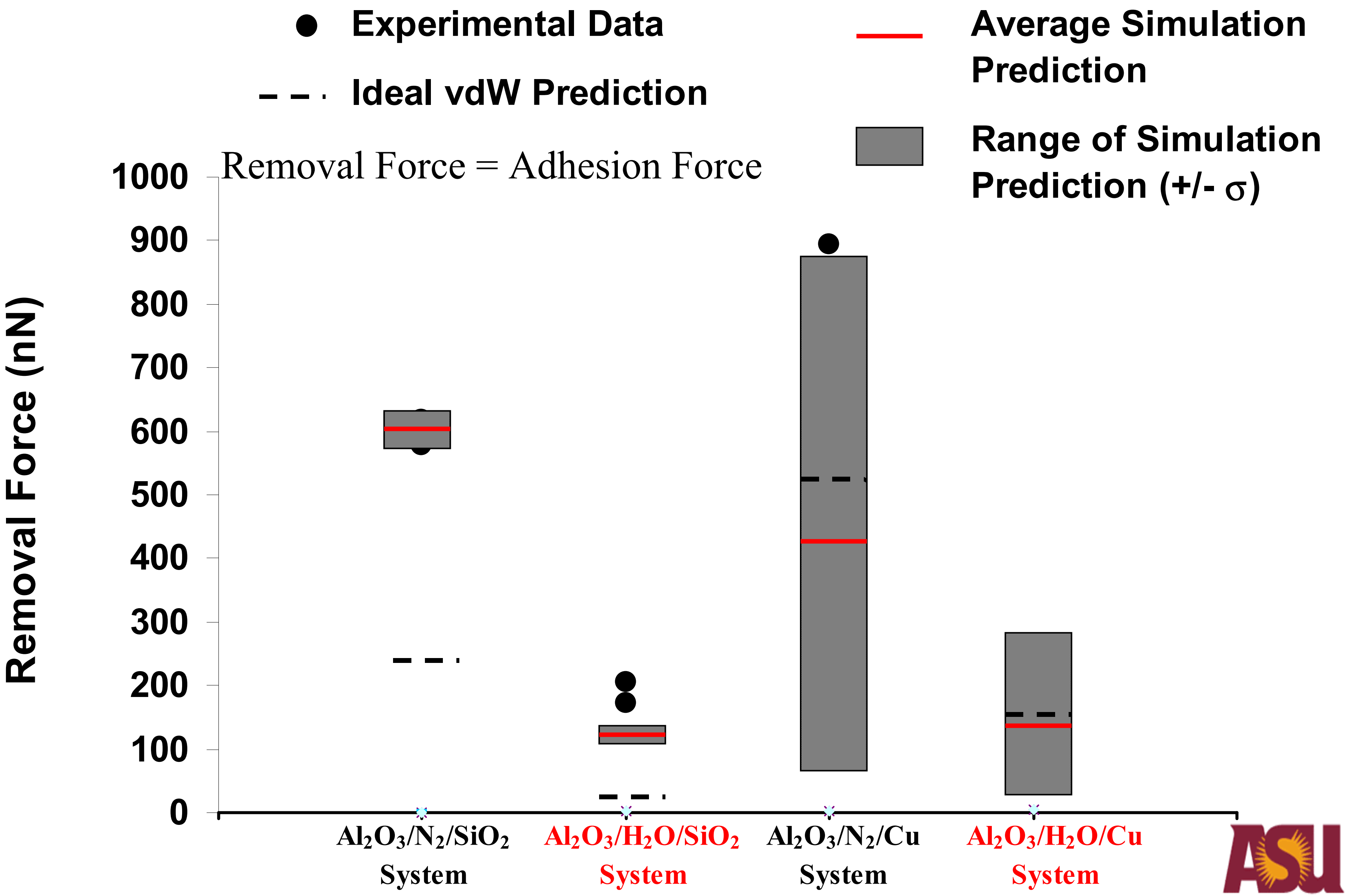


**Average Observed Force = 176 nN**

**Range of Observed Force = 139 - 201 nN**

Removal Force = Adhesion Force

# Substrate, Media Effects: Alumina Adhesion


Removal Force = Adhesion Force

# Removal Model Objective

Assess mechanism(s) of micron-scale particle removal from semiconductor wafer surfaces using a critical particle Reynolds number approach

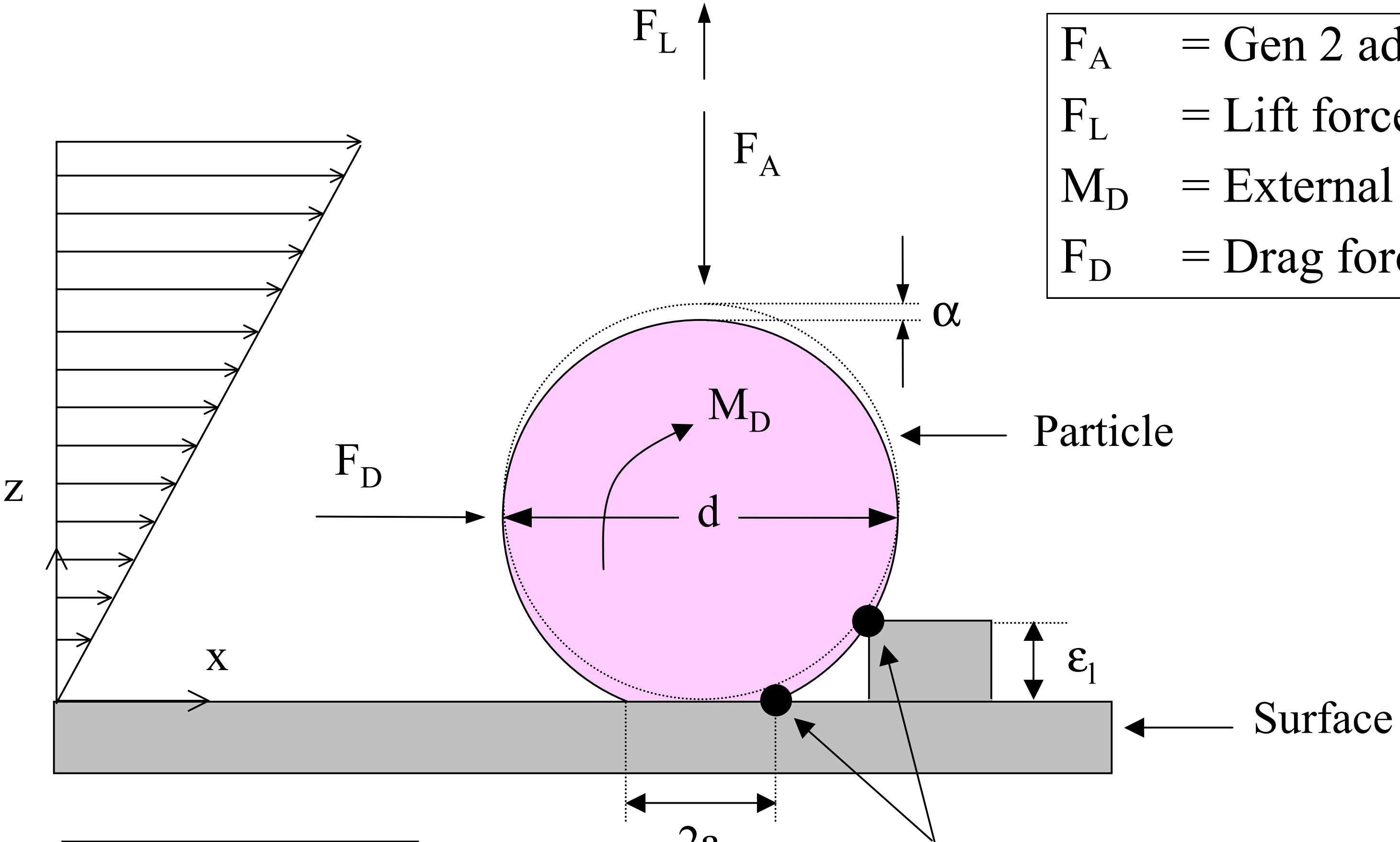
- Relate adhesion models to particle removal
- Relate flow characteristics to particle removal
- Develop model for removal processes by combining adhesion and flow models

# Removal Model Validation

Use experimental results from Yiantsios and Karabelas, *J. of Colloid and Interface Sci.* ***176****, 74-85 (1995)*, to assess validity of critical particle Reynolds number approach

- Studied detachment of spherical glass particles from a flat glass surface
- Used laminar channel flow over a range of flow rates to remove adhering particles
- Percentage adhering as a function of wall shear stress ($\tau_w$) presented graphically
- System Properties
  - Fluid: solution of distilled water, $HNO_3$, and $NaNO_3$
  - Particle (mean) diameters: 2, 5, 10, 15 μm ($\sigma_d \sim 12\%$)

# Particle Adhesion/Removal Model



Points around which rolling can occur

$F_A$ = Gen 2 adhesion force
$F_L$ = Lift force
$M_D$ = External moment
$F_D$ = Drag force

$$\mathrm{Re}_p = \frac{d\rho V_p}{\mu}$$

# Rolling Particle Removal Criteria

$$\vec{M}_R\left(\vec{M}_D,\vec{F}_D,\vec{F}_L,l_1,l_2\right)\geq \vec{M}_A\left(\vec{F}_A,l_2\right)$$

| | |
|---|---|
| External moment of surface stresses about center of particle | $M_D \propto d\,Re_p$ |
| Drag force | $F_D(Re_p < 1) \propto Re_p$ |
| Lift force | $F_L \propto d\left.\frac{du}{dz}\right\|_{\frac{d}{2}} Re_p$ |
| Adhesion force | $F_A \propto Ad$ |
| Vertical lever arm | $l_1(d, a, \alpha, \varepsilon_1)$ |
| Horizontal lever arm | $l_2(d, l_1)$ |

# Assessing Particle Removal

» Removal occurs when $Re_p(Flow) \geq Re_{pc}(Rolling)$

$Re_p$(Flow) constant at constant flow rate (for this system)

» ***Ideal system*** of smooth, deformable spherical particles of identical radius adhering to a smooth, flat, deformable surface

→ Single adhesion force

⇒Single value of $Re_{pc}$

⇒All or none of the adhering particles should be removed

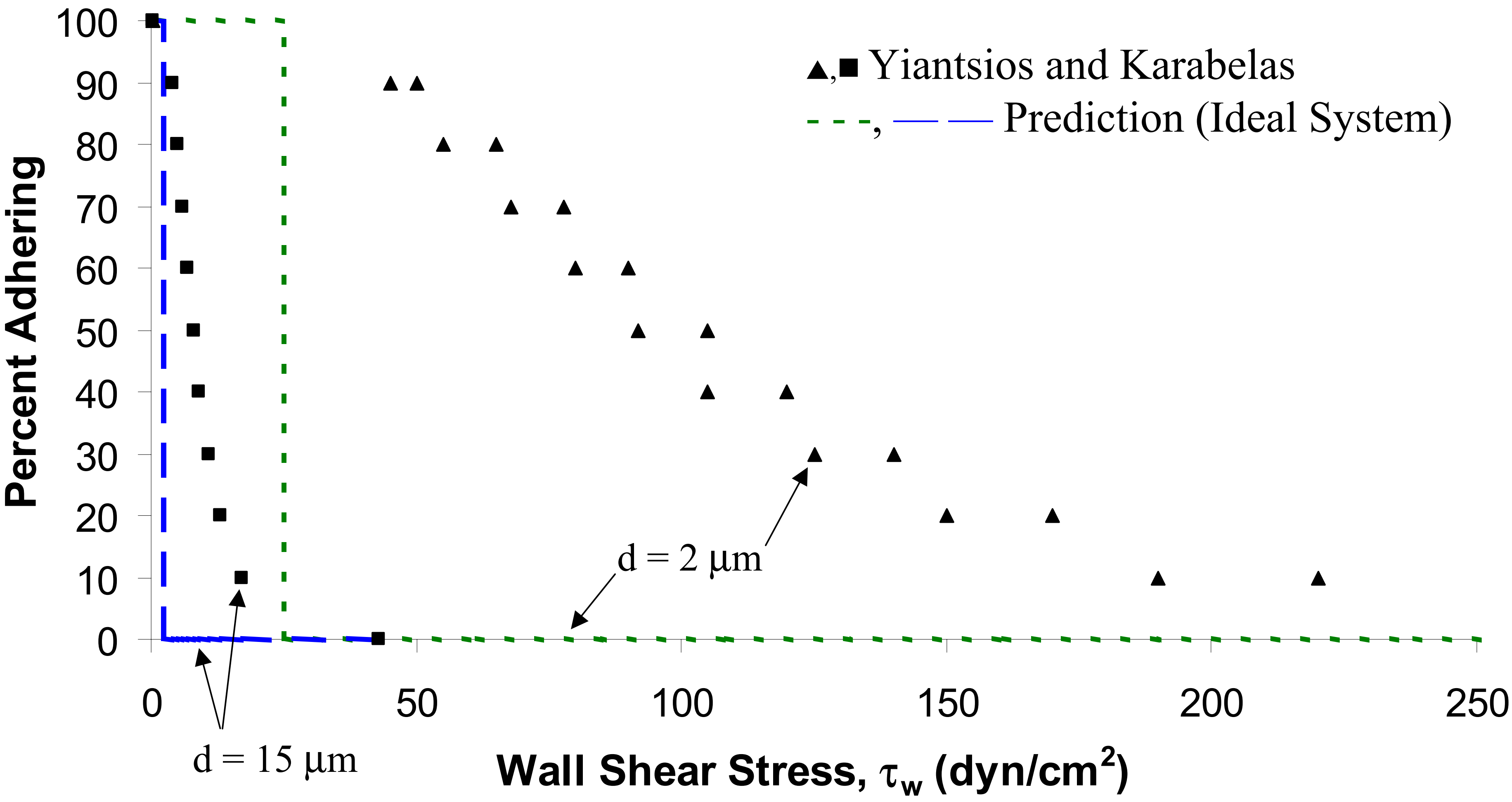
» ***Real system*** of deformable particles with non-uniformly distributed roughness and a finite size distribution adhering to a deformable surface with a non-uniform roughness distribution

→ Multiple adhesion forces and multiple points around which rolling can occur

⇒Multiple values of $Re_{pc}$

⇒All, some, or none of the adhering particles can be removed

# Adhesion Profile – Ideal System, d = 2 and 15 μm

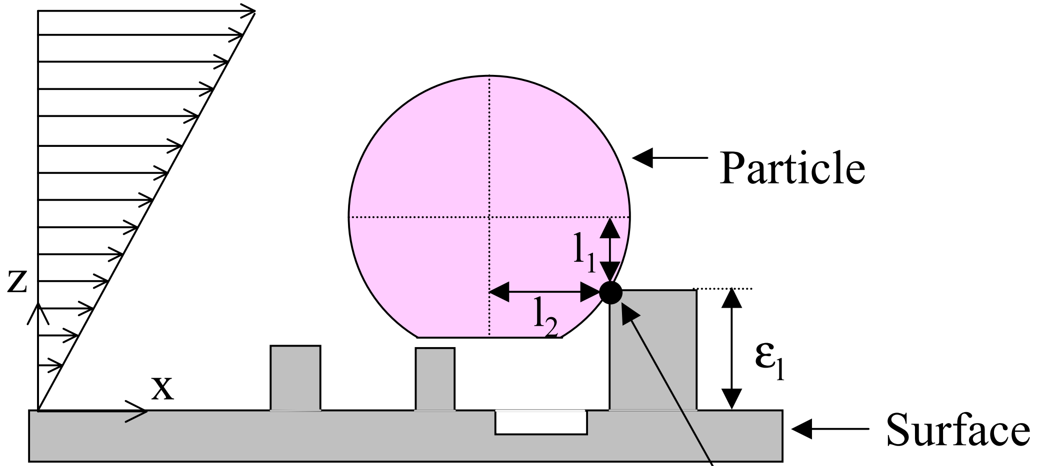


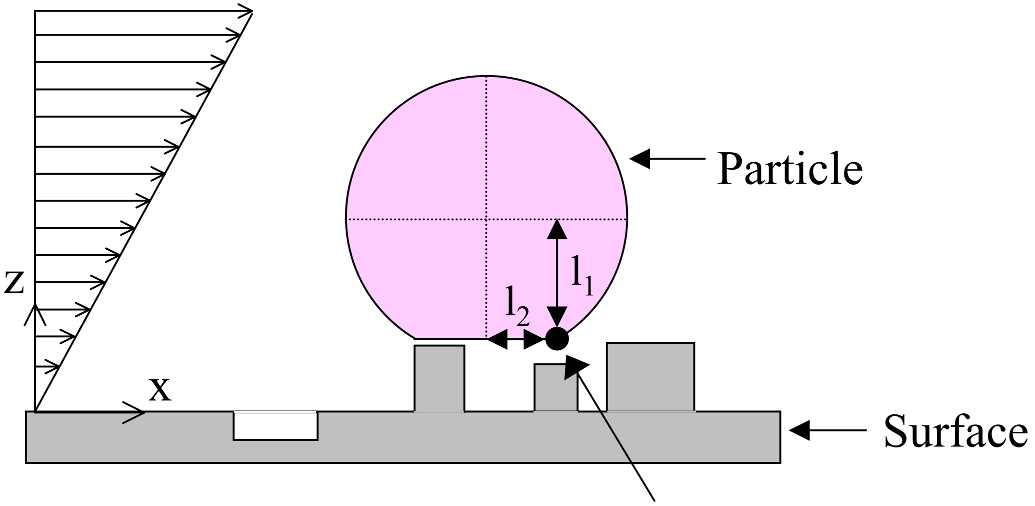
$\tau_w \propto Q$ (cm$^3$/s)

# Effect of Roughness on $Re_{pc}$

Roughness affects $Re_{pc}$ by affecting

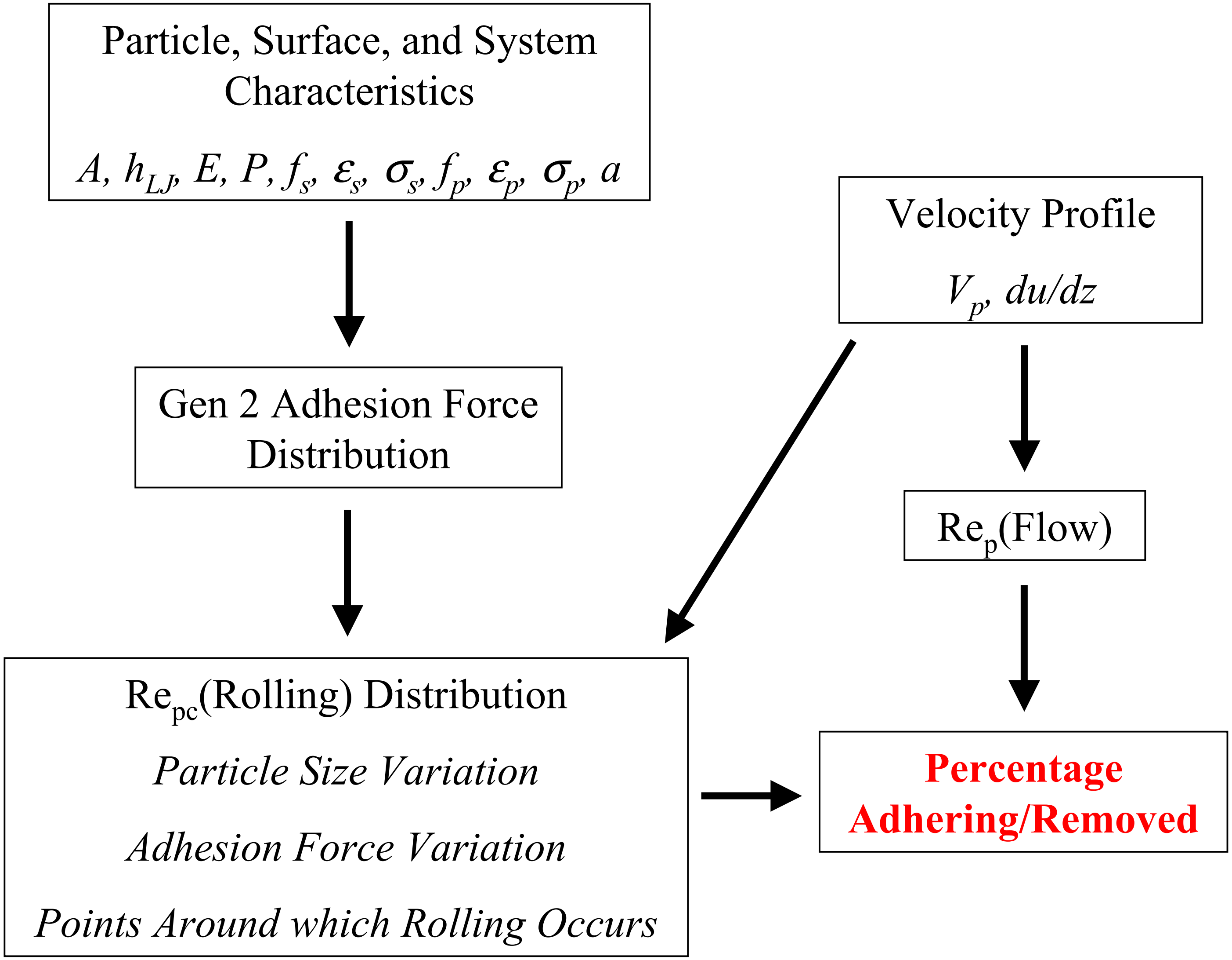
- Adhesion force
- Point around which rolling can occur





Length of horizontal and vertical lever arms ($l_1$ and $l_2$) depend on $\varepsilon_1$

# Removal Analysis Procedure



Particle, Surface, and System Characteristics

$A, h_{LJ}, E, P, f_s, \varepsilon_s, \sigma_s, f_p, \varepsilon_p, \sigma_p, a$

Velocity Profile

$V_p$, $du/dz$

Gen 2 Adhesion Force Distribution

$\mathrm{Re}_p$(Flow)

$\mathrm{Re}_{pc}$(Rolling) Distribution

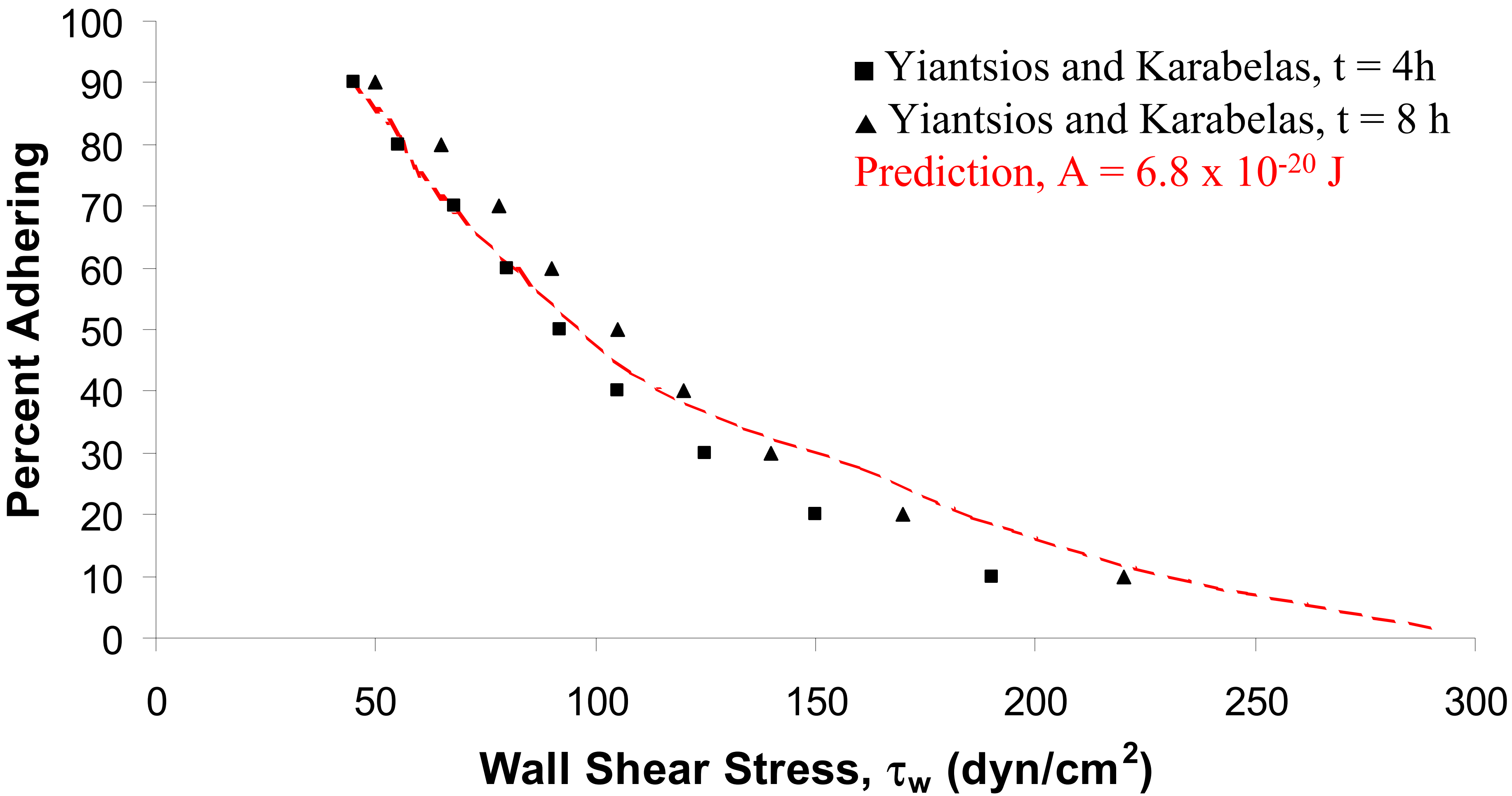
*Particle Size Variation*

*Adhesion Force Variation*

*Points Around which Rolling Occurs*

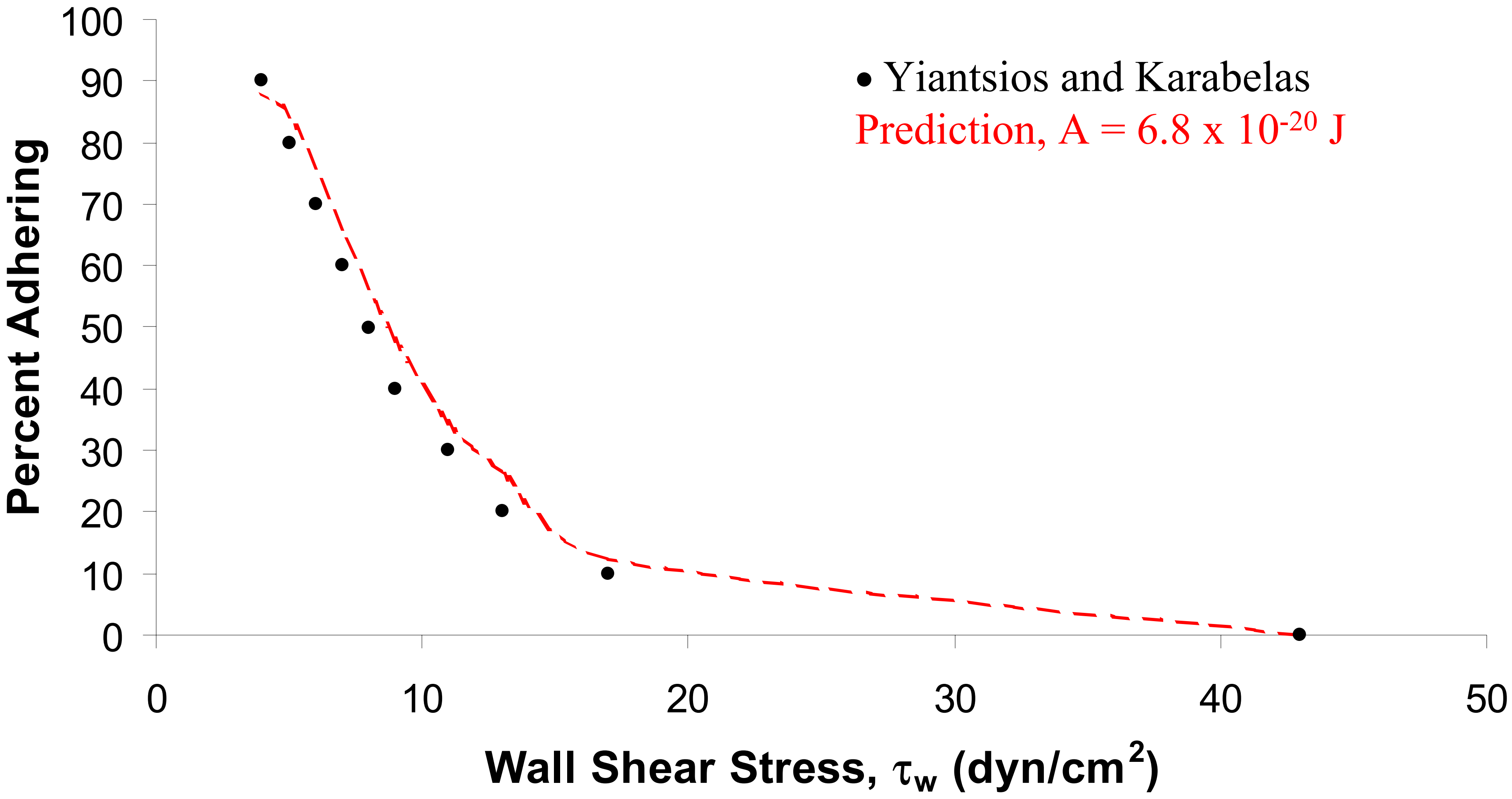
**Percentage Adhering/Removed**

# Adhesion Profile – Real System, $d_{mean} = 2\ \mu m$



$\tau_w \propto Q\ (cm^3/s)$

# Adhesion Profile – Real System, $d_{mean}$ = 15 μm



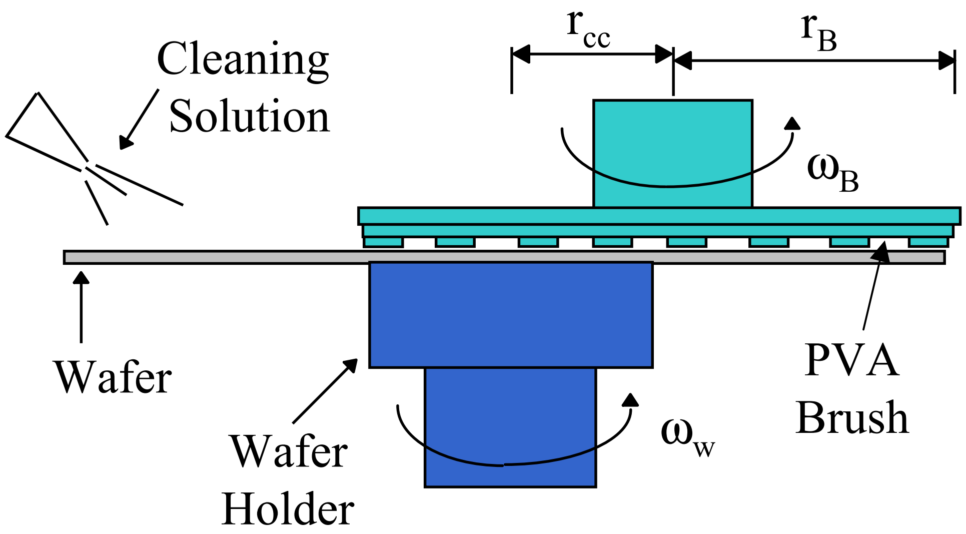
$\tau_w \propto Q$ (cm$^3$/s)

# Removal Model Conclusions

- » Accurate particle removal models require accurate particle adhesion models
- » Rolling is the controlling removal mechanism
- » Roughness and particle size distribution affect the point around which rolling can occur
- » (Rolling) theoretical adhesion profiles for real adhesion system in agreement with those of Yiantsios and Karabelas
- » Critical particle Reynolds number approach validated
- » Predictive model for particle removal established
  - Independent of particle size and cleaning (flow) system

# Brush Scrubbing Analysis Objective

Use critical particle Reynolds number ($Re_{pc}$) approach to assess particle removal from wafer surfaces during brush scrubbing



r = radius

ω = angular speed

**Typical Operating Conditions**

$\omega_B$ = 200 rpm  $\omega_w$ = 90 rpm

$r_{cc}$ = 5 cm  $r_B$ = 5.7 cm

Total cleaning time, t:  20 s

Brush Pressure, $P_B$:  3 psi

Finger diameter, $d_f$:  0.6 cm

Number of fingers per brush, $N_f$:  85

Total area covered by fingers:  66,000 $cm^2$

**System Properties**

Particles:  asymmetrical alumina

Surfaces:  polished silicon dioxide and copper

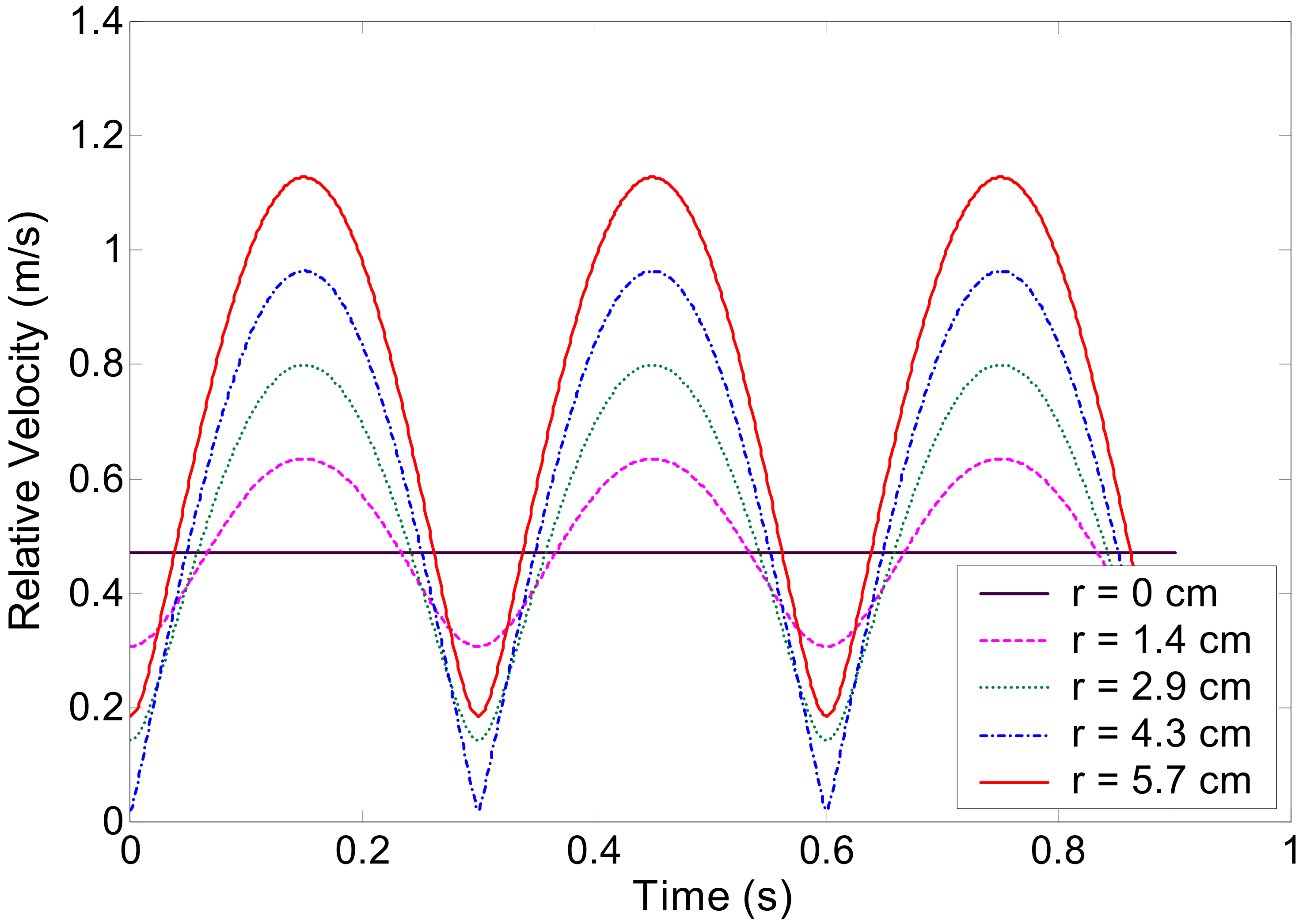
# Brush Scrubbing Analysis Objective, cont'd

- Assess whether hydrodynamic forces can remove adhering particles from wafer surfaces during brush scrubbing, or whether brush-particle contact must occur
  - Systems of 0.1 and 1.0 μm diameter alumina particles adhering to polished silicon dioxide and copper surfaces considered
  - Two approaches: time-dependent and time-averaged
- Calculate particle Reynolds numbers as a function of
  - Time (t)
  - Brush radial position (r)
  - Brush-wafer separation distance (D)
  - Brush and wafer angular speed ($\omega_B$ and $\omega_w$)
- Consider the effects of
  - Substrate chemistry
  - Particle and substrate morphology and mechanical properties
  - Geometry of the interacting surfaces
  - Fluid properties
  - Velocity profile near adhering particle

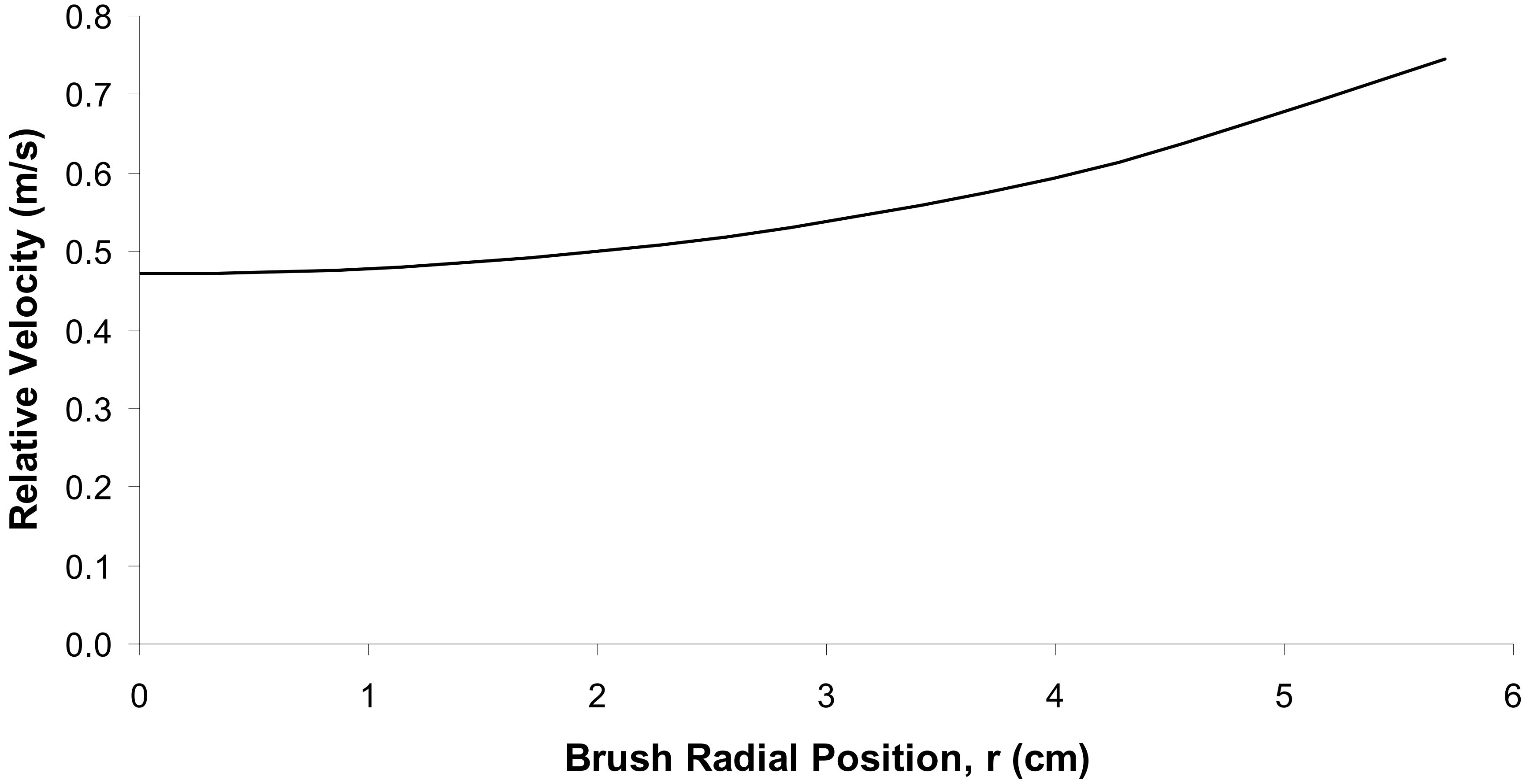
# Velocity Profile

- » Two approaches
  - Use time-dependent relative velocity ($V_{rel}$) to calculate $V_p$ and $Re_p$
  - Use time-averaged relative velocity ($V_{rel}$) to calculate $V_p$ and $Re_p$
- » Calculate boundary layer thickness ($\delta$) on brush finger
  - Determines relationship between $V_p$, $V_{rel}$, and D
  - If $D \leq \delta$: $V_p = \frac{\left|\vec{V}_{rel}\right|}{D} \cdot \frac{d}{2}$ $\quad Re_p = \frac{\rho}{\mu} \frac{\left|\vec{V}_{rel}\right|}{D} \cdot \frac{d^2}{2}$

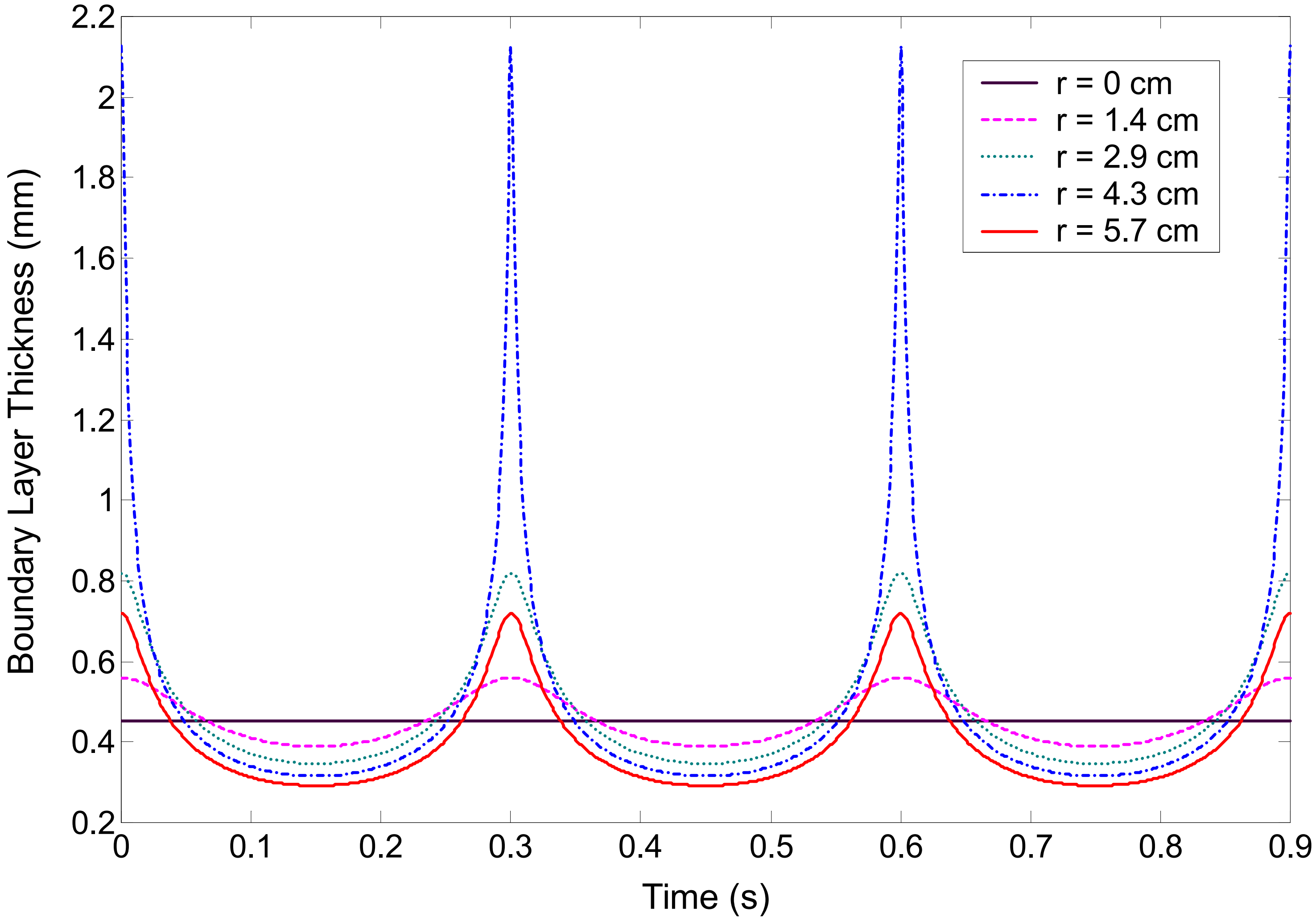
# Time-Dependent Velocity Profile



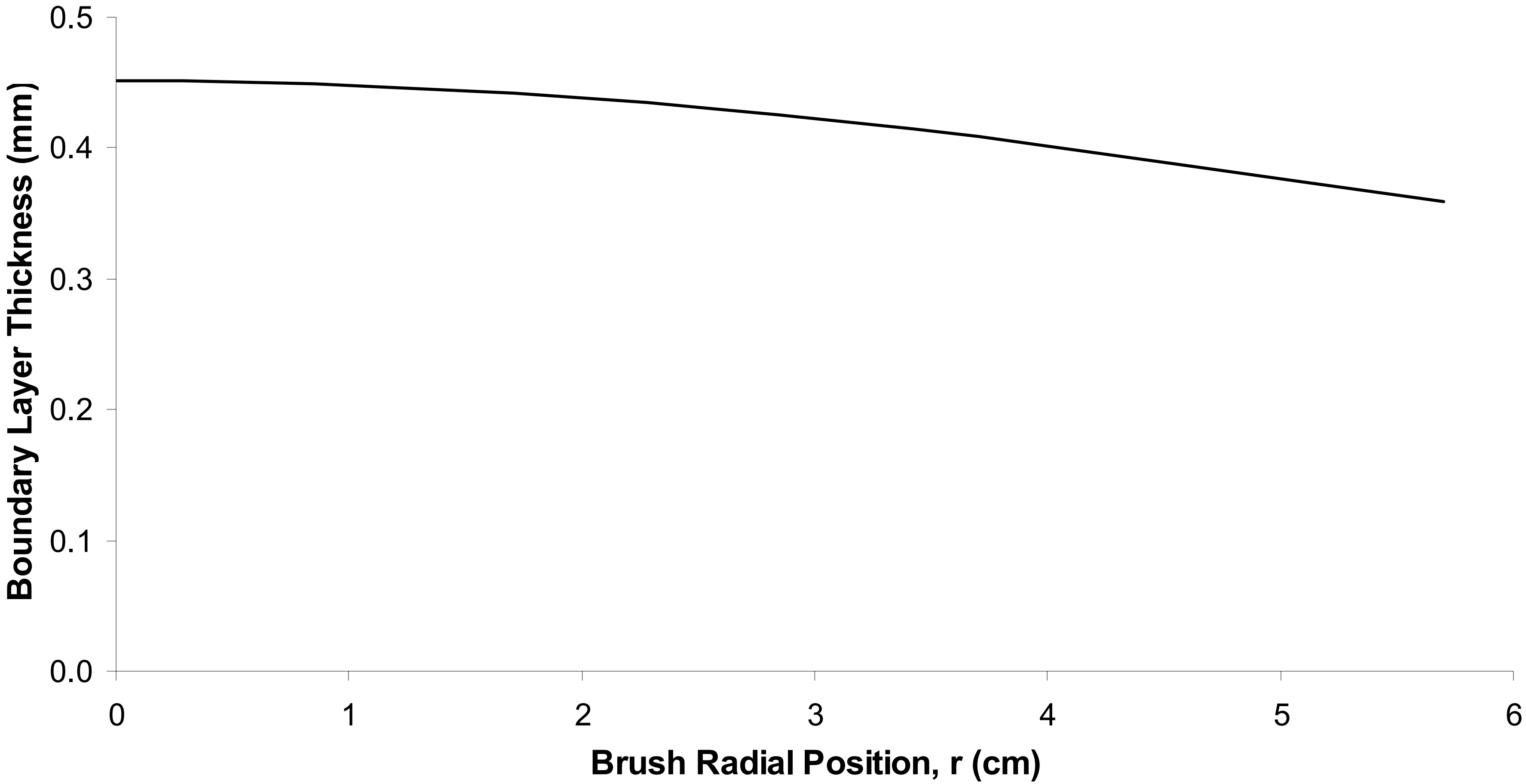
# Time-Averaged Velocity Profile



# Time-Dependent Boundary Layer Thickness

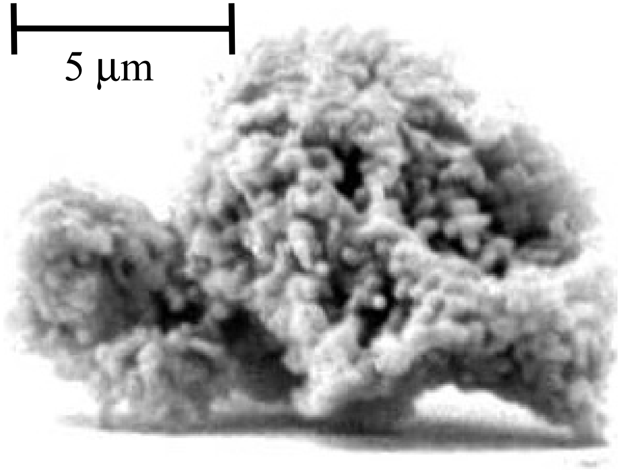


# Time-Averaged Boundary Layer Thickness



# System Properties

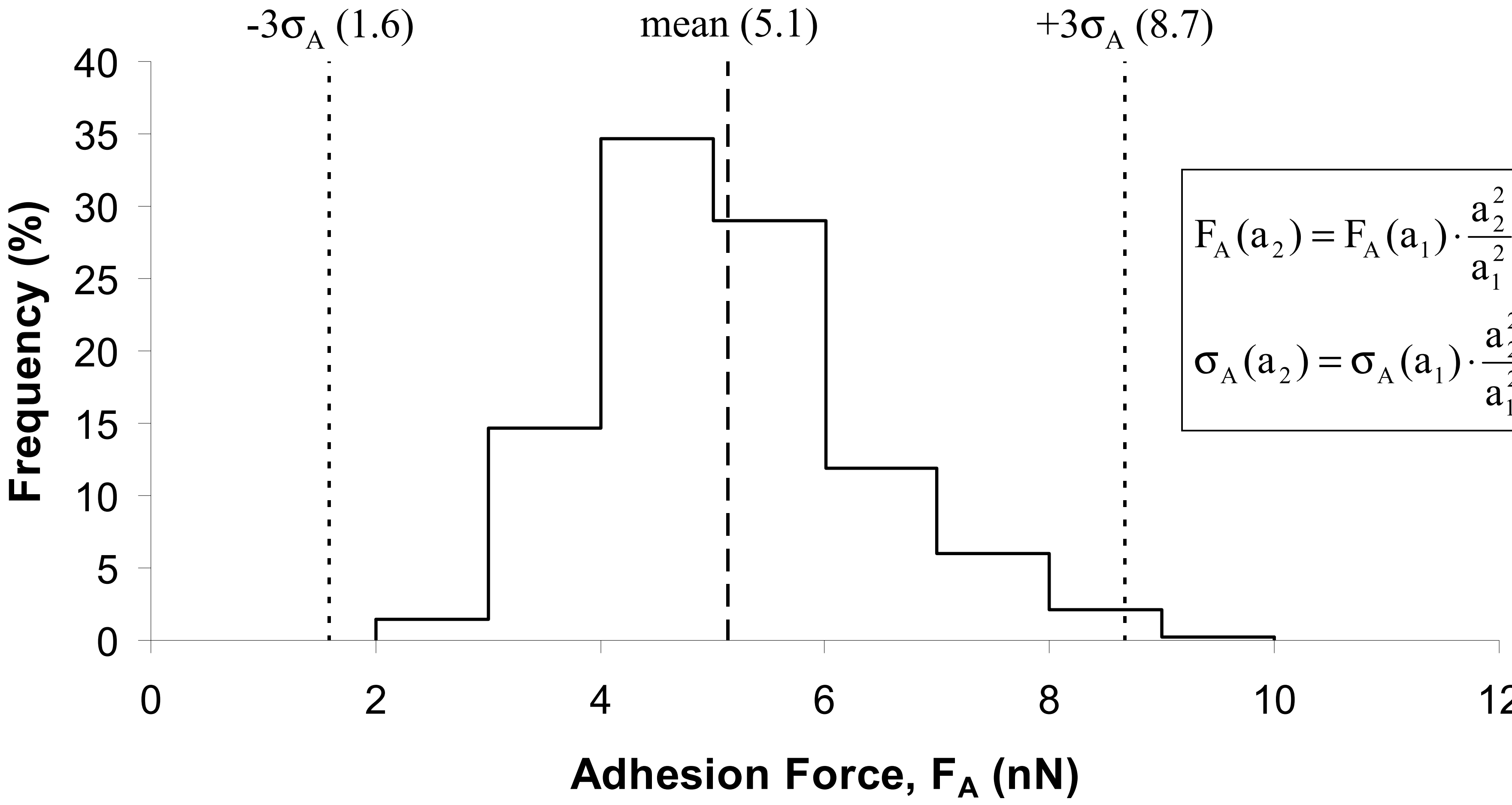
| **Particle size (μm)** | **Contact Radius, a (nm)** |
|---|---|
| 0.1 | 22.6 |
| 1.0 | 226 |



| **Parameter** | **$Al_2O_3$ Particle** | **$SiO_2$** | **Cu** |
|---|---|---|---|
| Average asperity height, ε (nm) | 1.6 | 1.7 | 0.8 |
| Standard deviation in asperity height, σ (nm) | 0.7 | 0.7 | 0.5 |
| Fraction of surface covered in asperities, f | 0.33 | 0.56 | 0.45 |
| Elastic modulus, E ($N/m^2$) | $5.0\times 10^{11}$ | $5.6 \times 10^{11}$ | $7.8 \times 10^{10}$ |

# $Al_2O_3$-$H_2O$-$SiO_2$ Adhesion Force

**1.0 μm alumina particle adhering to polished silicon dioxide in deionized water**



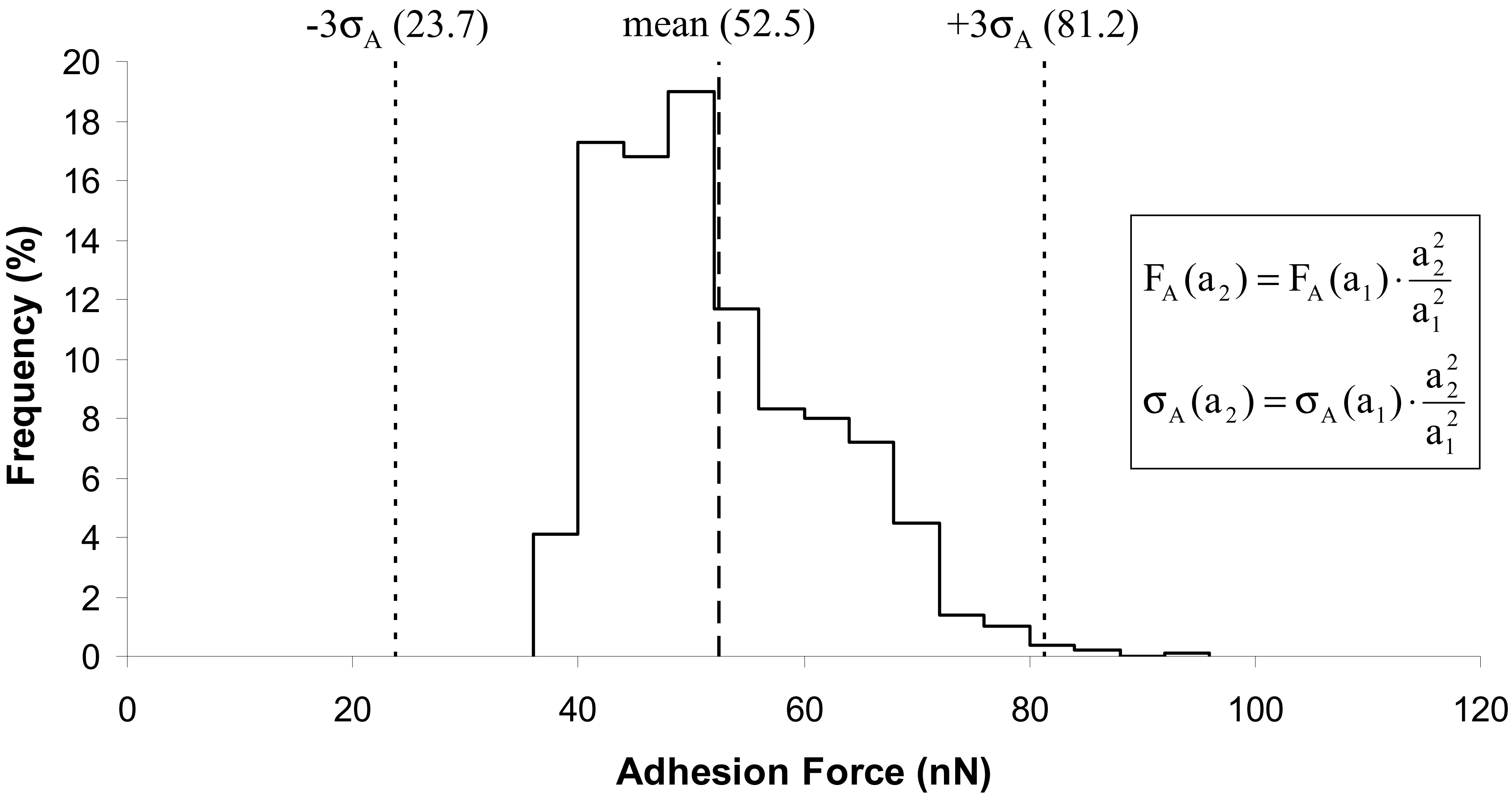
$$F_A(a_2) = F_A(a_1) \cdot \frac{a_2^2}{a_1^2}$$

$$\sigma_A(a_2) = \sigma_A(a_1) \cdot \frac{a_2^2}{a_1^2}$$

$\sigma_A = 1.2$ nN

# $Al_2O_3$-$H_2O$-Cu Adhesion Force

**1.0 μm alumina particle adhering to copper in deionized water**



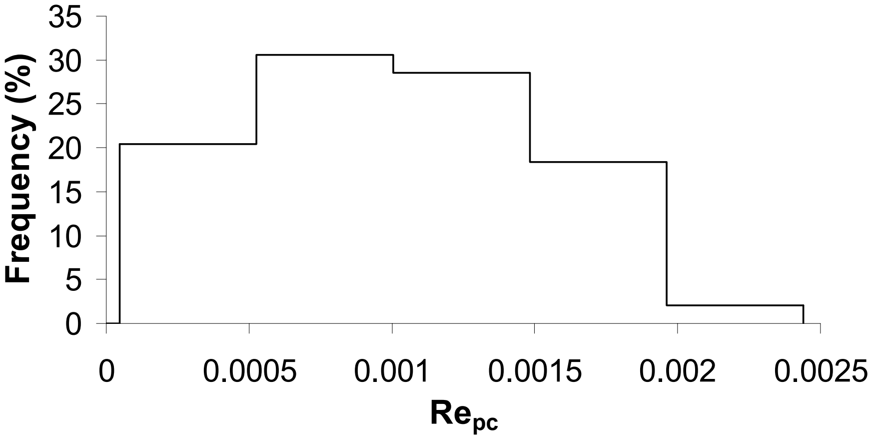
$$F_A(a_2) = F_A(a_1) \cdot \frac{a_2^2}{a_1^2}$$

$$\sigma_A(a_2) = \sigma_A(a_1) \cdot \frac{a_2^2}{a_1^2}$$

$\sigma_A = 9.6$ nN

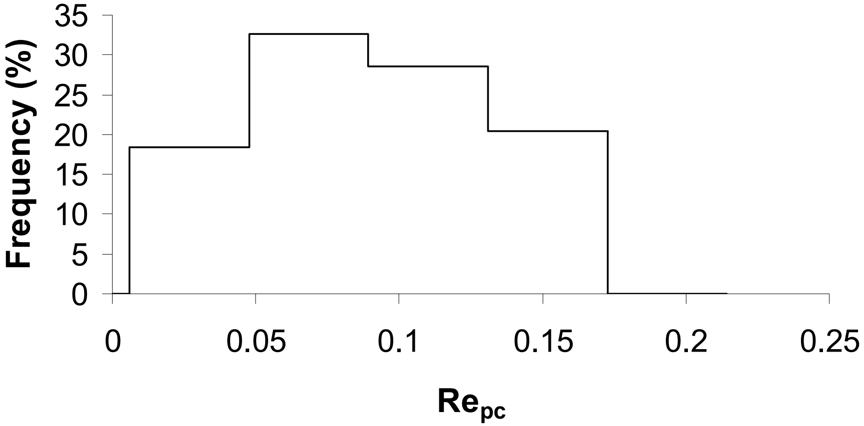
# $Al_2O_3$-$H_2O$-$SiO_2$ Critical Particle Reynolds Number

$Re_{pcmean} = 0.0010$
$\sigma_{Re} = 0.00048$



**0.1 µm alumina particle adhering to polished silicon dioxide in deionized water**

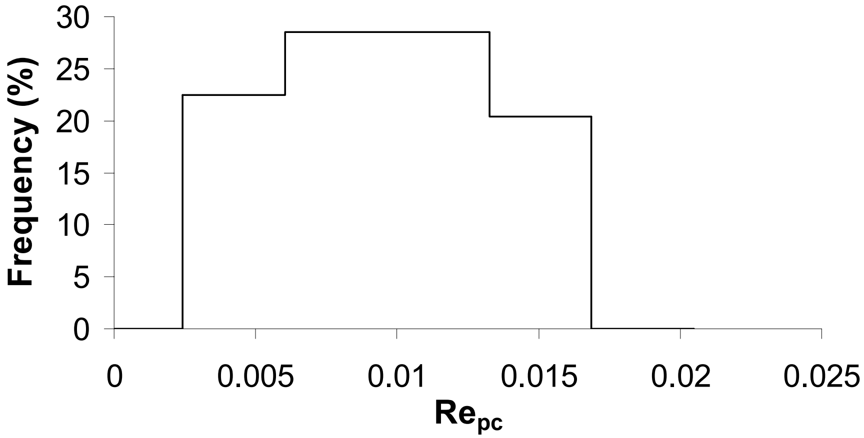
$Re_{pcmean} = 0.089$
$\sigma_{Re} = 0.042$



**1.0 µm alumina particle adhering to polished silicon dioxide in deionized water**

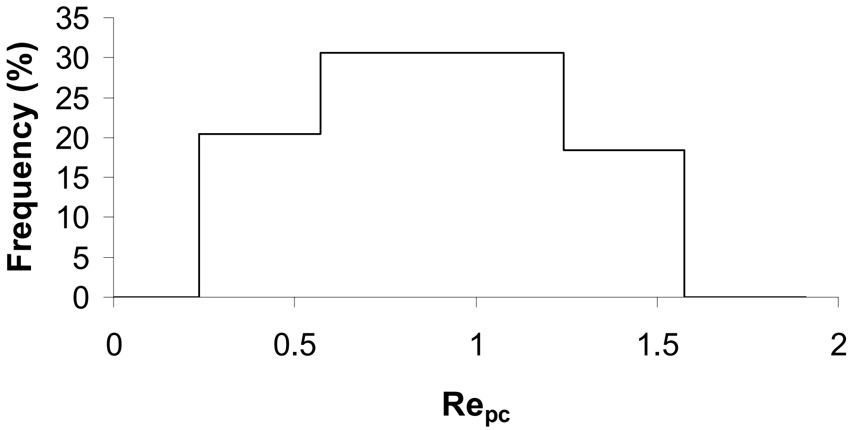
# $Al_2O_3$-$H_2O$-Cu Critical Particle Reynolds Number

$Re_{pcmean} = 0.0096$
$\sigma_{Re} = 0.0036$



**0.1 μm alumina particle adhering to copper in deionized water**

$Re_{pcmean} = 0.91$
$\sigma_{Re} = 0.33$



**1.0 μm alumina particle adhering to copper in deionized water**

# Analysis Algorithms

## Time-Dependent

1. Calculate $\left|\vec{V}_{rel}(t,r)\right|$
2. Calculate $Re_p(V_{rel}(t,r),D)$
3. Set $Re_{pc}$ distribution, $Re_{pc}(i) = Re_{pc}(mean) + i\sigma$ ($i = 0, \pm1, \pm2, \pm3$, $\sigma$ = standard deviation)
4. Calculate the fraction (R) of $Re_p$ greater than $Re_{pc}$ over a given interval ($\sigma$) using†

$$R(i,i+1) = \frac{\int_0^t \left[\left(Re_p(t,r,D) - Re_{pc}(i)\right) - \left(Re_p(t,r,D) - Re_{pc}(i+1)\right)\right] dt}{\sigma \int_0^t dt}$$

5. Calculate the percentage of particles removed using

$$\%\ \text{Removed} = \sum_i R(i,i+1) \cdot F(i,i+1)$$

where F is the frequency (%) from the $Re_{pc}$ distribution

## Time-Averaged

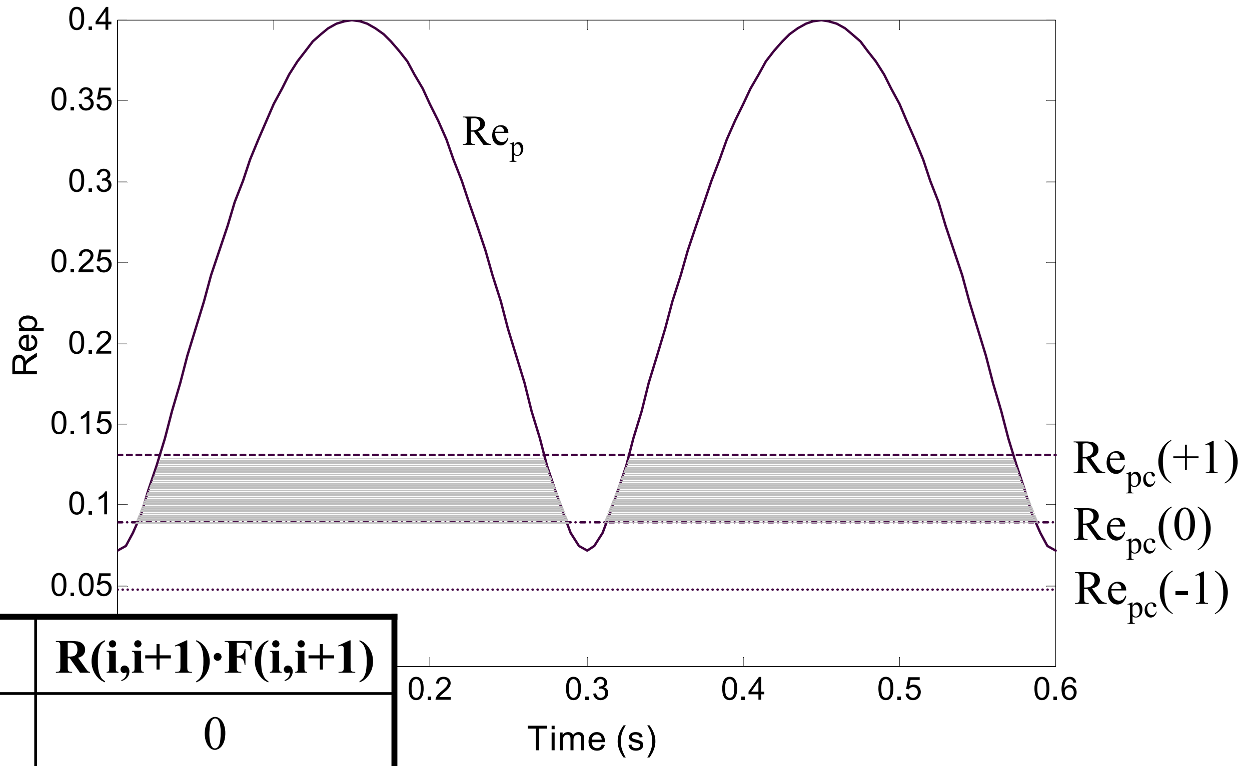
1. Calculate $\overline{V}_{rel}(r)$
2. Calculate $Re_p(V_{rel}(r),D)$
3. Compare $Re_p$ with the $Re_{pc}$ distribution and calculate the percentage of particles removed

† Integral in numerator calculated only for the time when $Re_p > Re_{pc}$

# Time-Dependent Analysis – Example, r = 2.85 cm

**1.0 μm alumina particle adhering to polished silicon dioxide in deionized water**

D = d = 1.0 μm



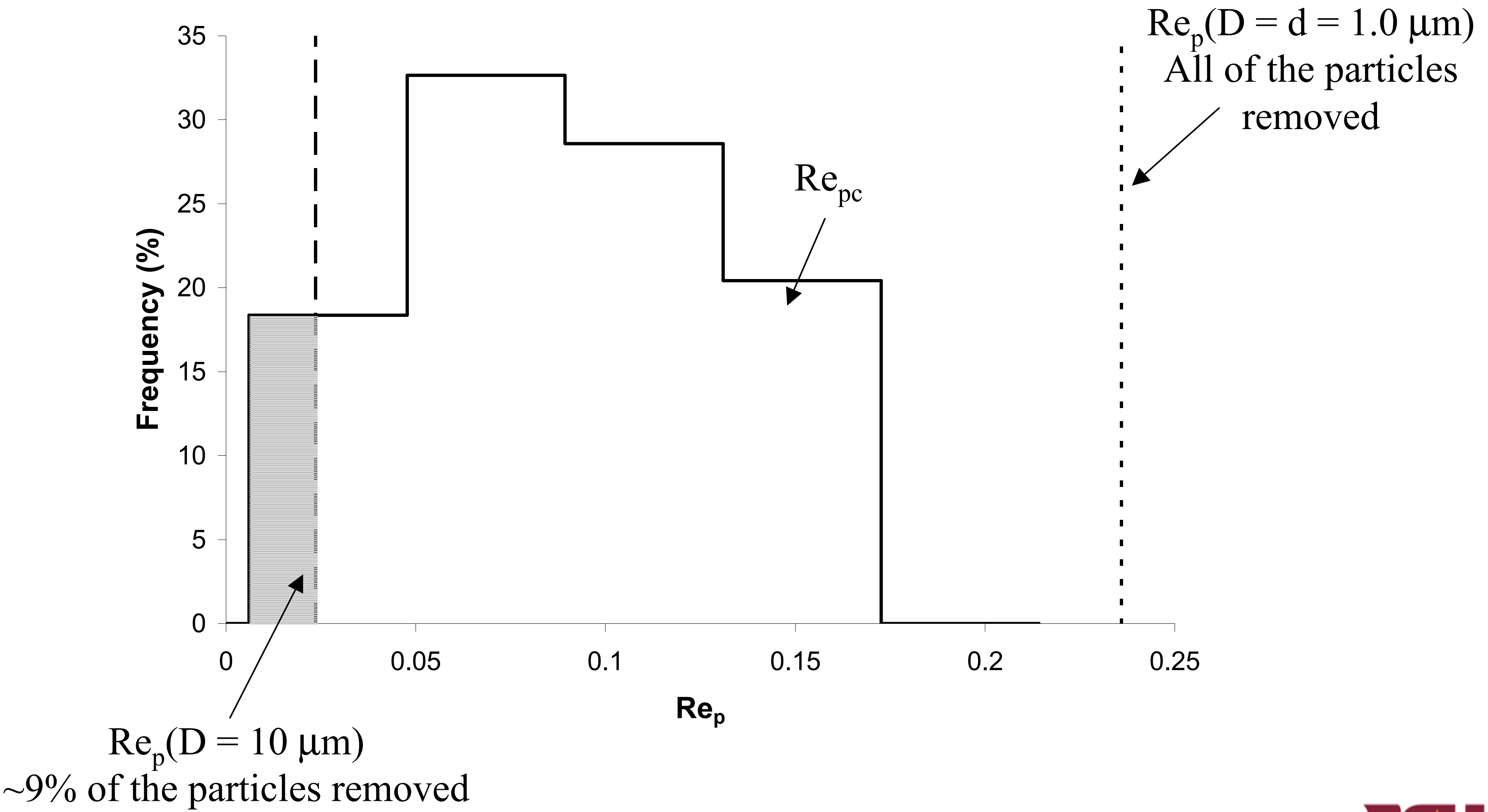
| i,i+1 | R(i,i+1) | F(i,i+1) | R(i,i+1)·F(i,i+1) |
|---|---|---|---|
| -3,-2 | 1.0 | 0 | 0 |
| -2,-1 | 1.0 | 18.37 | 18.37 |
| -1,0 | 0.98 | 32.65 | 32.00 |
| 0,1 | 0.86 | 28.57 | 24.57 |
| 1,2 | 0.78 | 20.41 | 15.92 |
| 2,3 | 0.70 | 0 | 0 |
| % Removed $=\sum_{i} R(i,i+1)\cdot F(i,i+1)$ | | | 91 |

R = fraction of $Re_p$ greater than $Re_{pc}$ over a given interval

F = frequency (%) from $Re_{pc}$ distribution

# Time-Averaged Analysis – Example, r = 2.85 cm

**1.0 µm alumina particle adhering to polished silicon dioxide in deionized water**



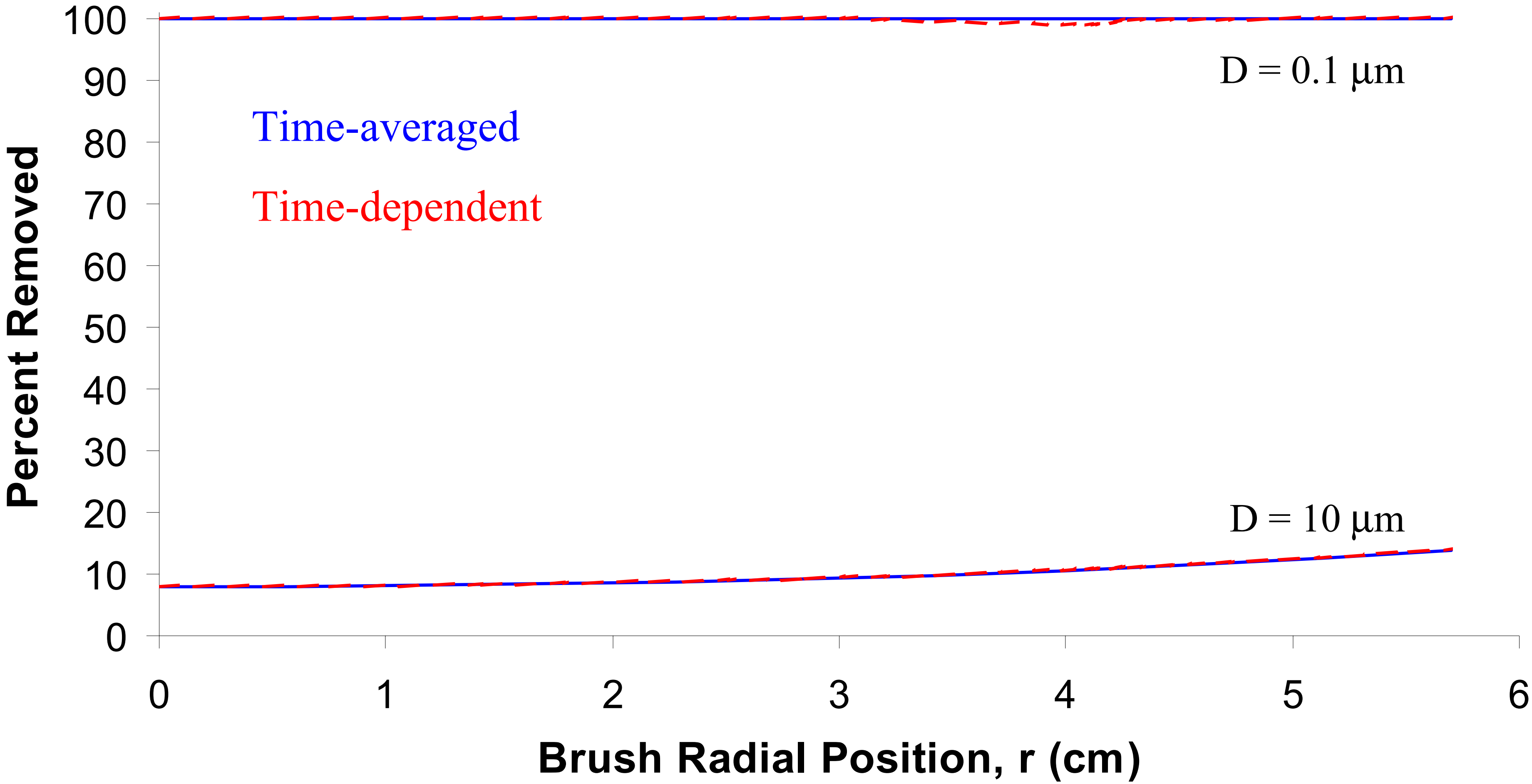
$Re_p$(D = d = 1.0 µm)
All of the particles
removed

$Re_{pc}$

$Re_p$(D = 10 µm)
~9% of the particles removed

# Silicon Dioxide Removal Profiles, d = 0.1 µm

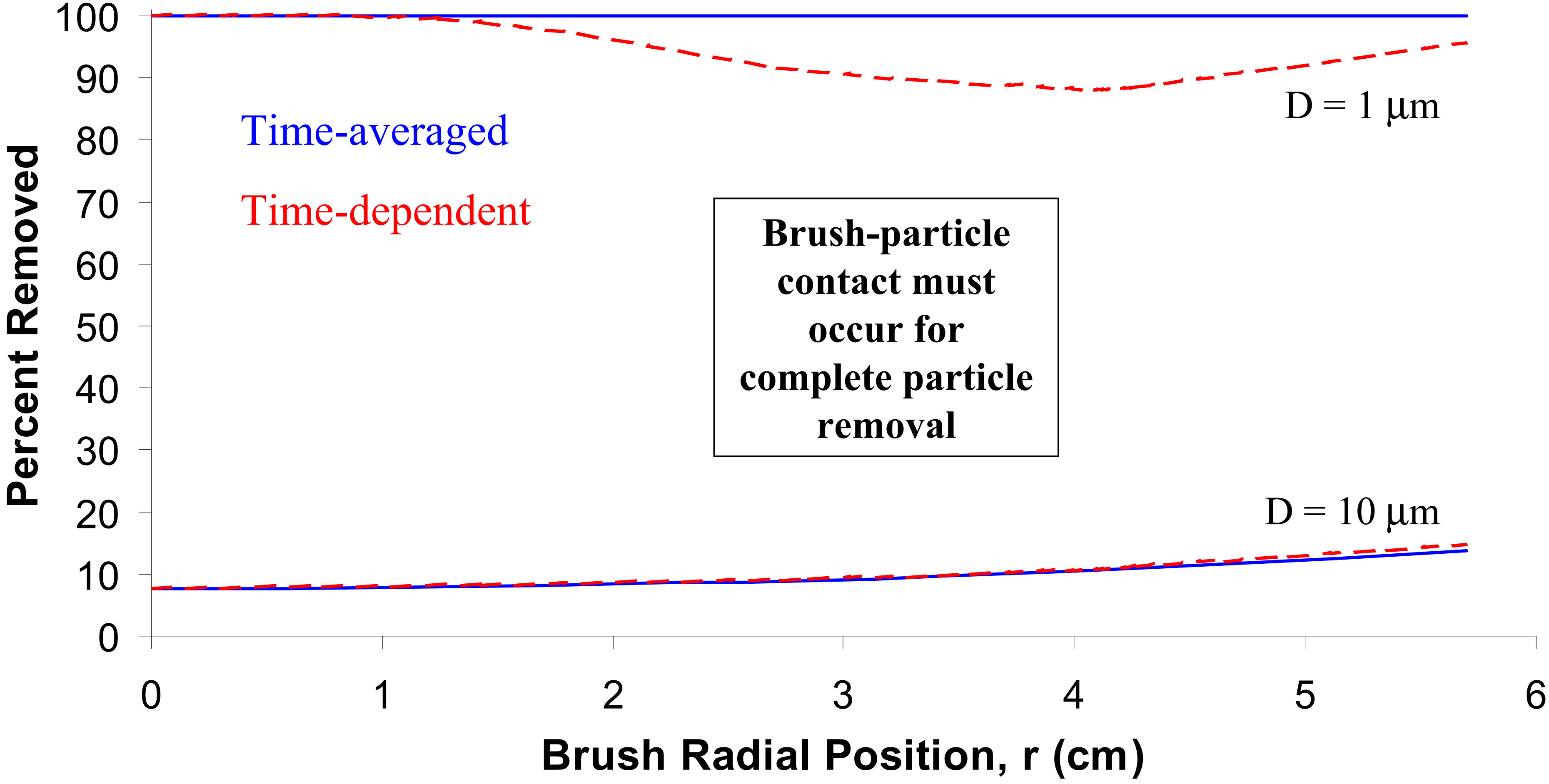
**0.1 µm alumina particles adhering to polished silicon dioxide in deionized water**



**A = 6.2 x 10$^{-20}$ J**

# Silicon Dioxide Removal Profiles, d = 1.0 µm

**1.0 µm alumina particles adhering to polished silicon dioxide in deionized water**

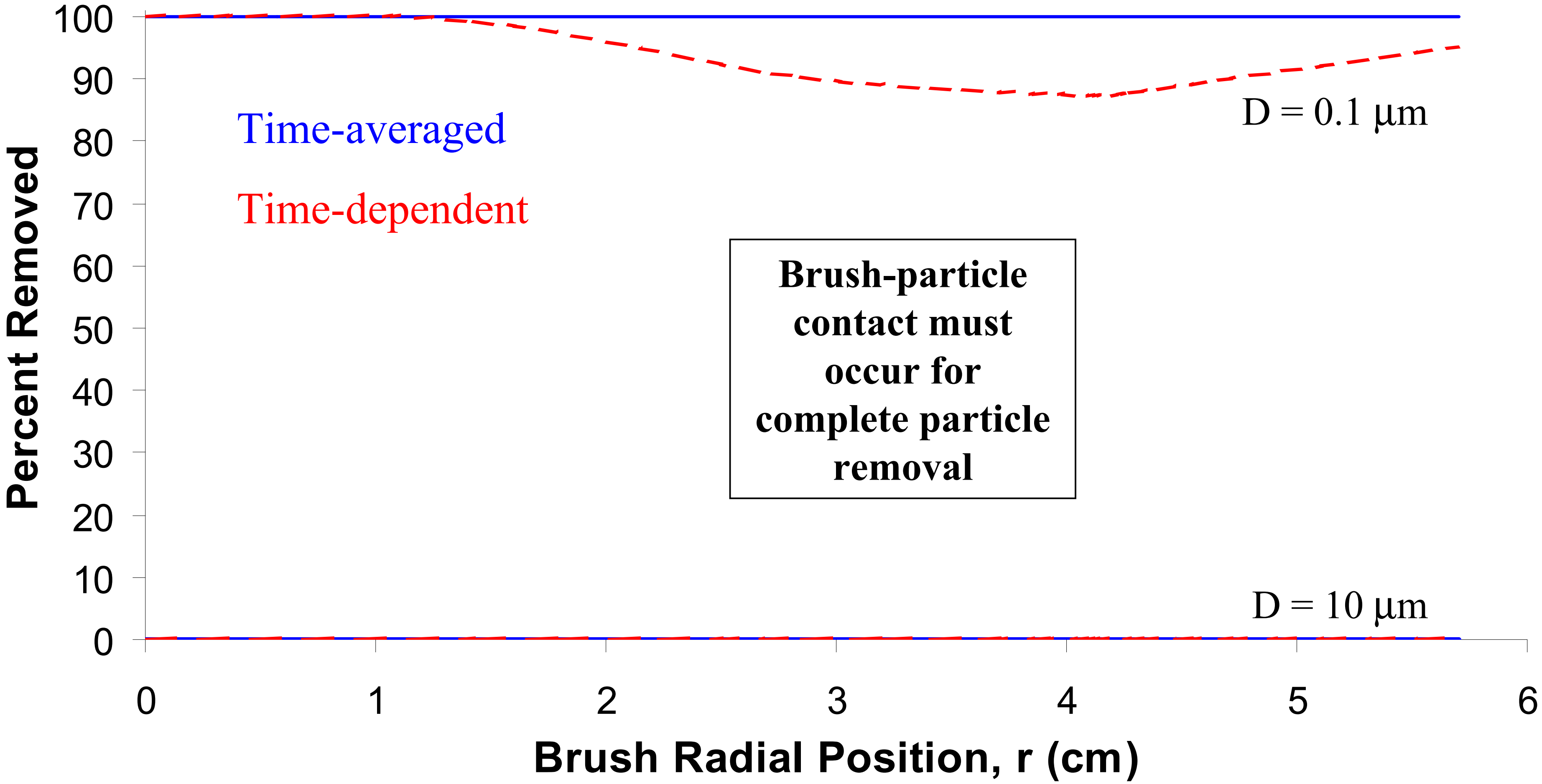


**Brush-particle contact must occur for complete particle removal**

**$A = 6.2 \times 10^{-20}$ J**

# Copper Removal Profiles, d = 0.1 μm

**0.1 μm alumina particles adhering to copper in deionized water**

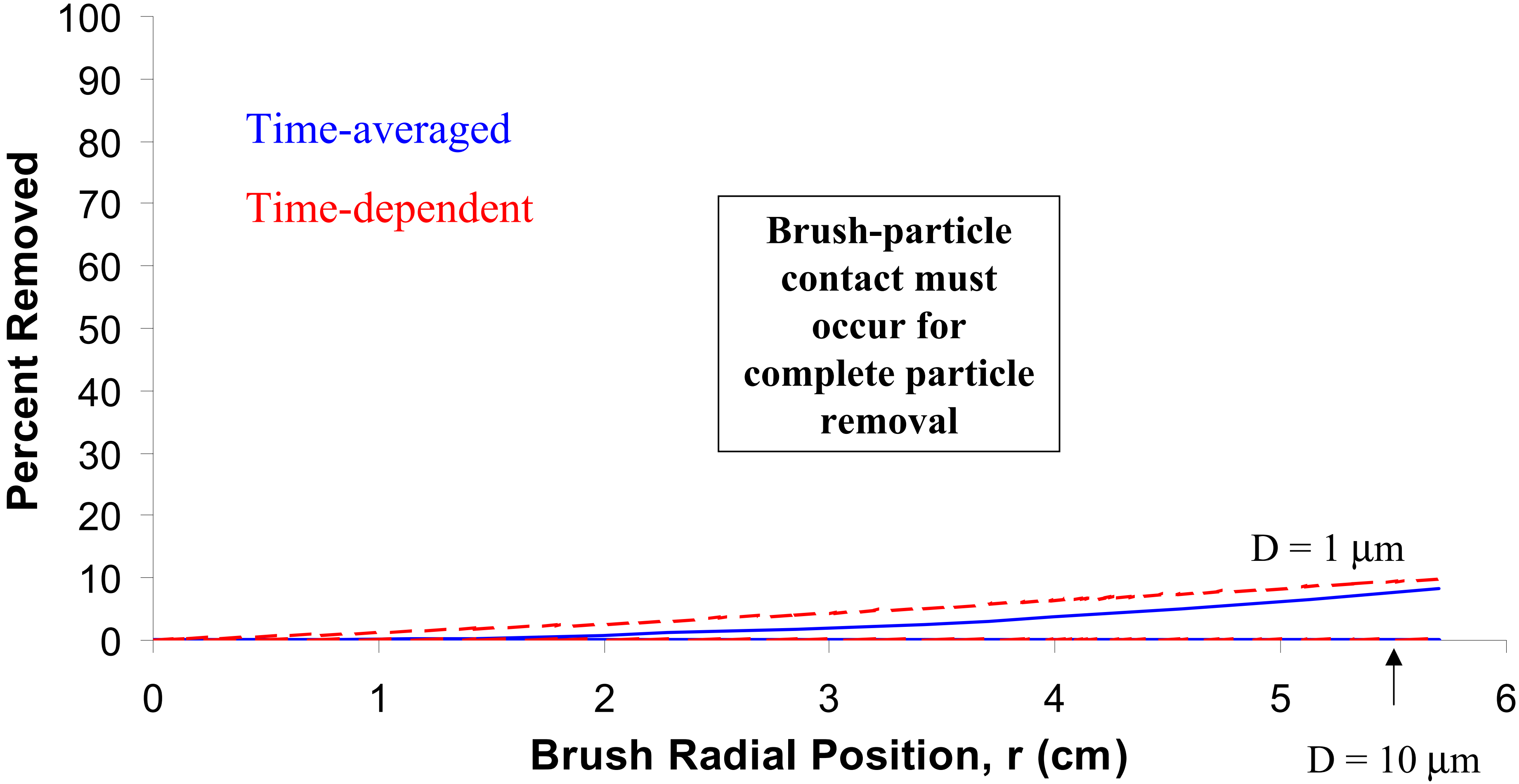


**Brush-particle contact must occur for complete particle removal**

**A = 6.2 x $10^{-20}$ J**

# Copper Removal Profiles, d = 1.0 µm

**1.0 µm alumina particles adhering to copper in deionized water**



**Brush-particle contact must occur for complete particle removal**

**A = 6.2 x $10^{-20}$ J**

# Brush Scrubbing Analysis Conclusions

- » Under limited conditions (i.e., particle size, brush radial position, and brush-wafer separation distance), the time-averaged analysis predicts almost identical results to the time-dependent analysis
- » Time-averaged analysis predicts that as brush radial position increases and brush-wafer separation distance decreases, the percentage of particles removed increases
- » Time-dependent analysis predicts that as brush-wafer separation distance decreases, the percentage of particles removed increases, but follows no overall trend as a function of brush radial position

# Brush Scrubbing Analysis Conclusions, cont’d

- Based on mechanics alone more particles are expected to be removed from the silicon dioxide surface than from the copper surface since the copper system has a larger $Re_{pc}$ under the same flow conditions
- In many cases brush-particle contact must occur for complete particle removal
- Larger particles are more difficult to remove
  - $Re_p$ and $F_A$ both proportional to $d^2$, therefore contact radius controls the level of difficulty in removing a particle
  - Larger particles, having a larger contact radius, are more difficult to remove since there is more mass interacting at the particle-wafer interface than for smaller particles
  - $Re_p$ must increase proportionally to remove these particles
- Hydrodynamic particle removal is system dependent

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