CMP Fluid Dynamics and Tribology

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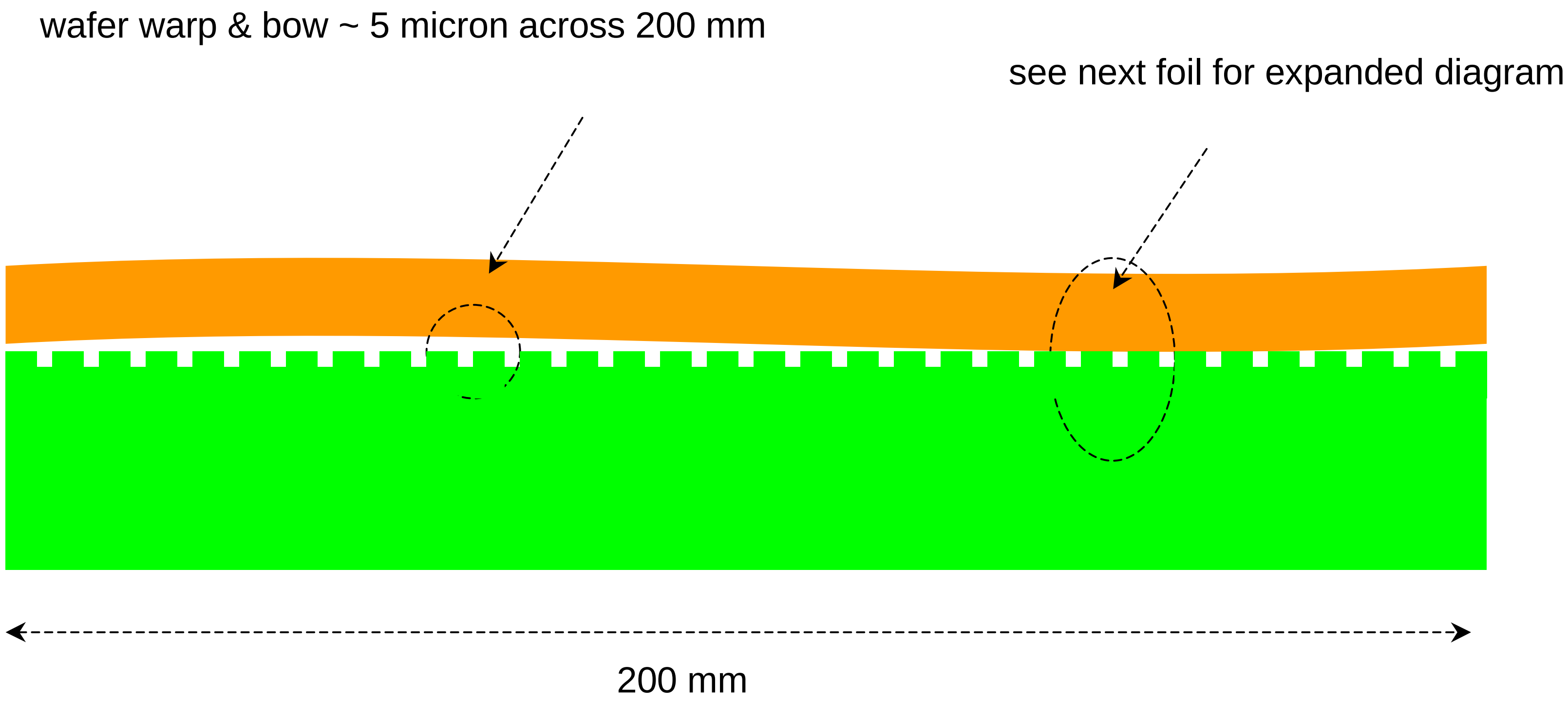
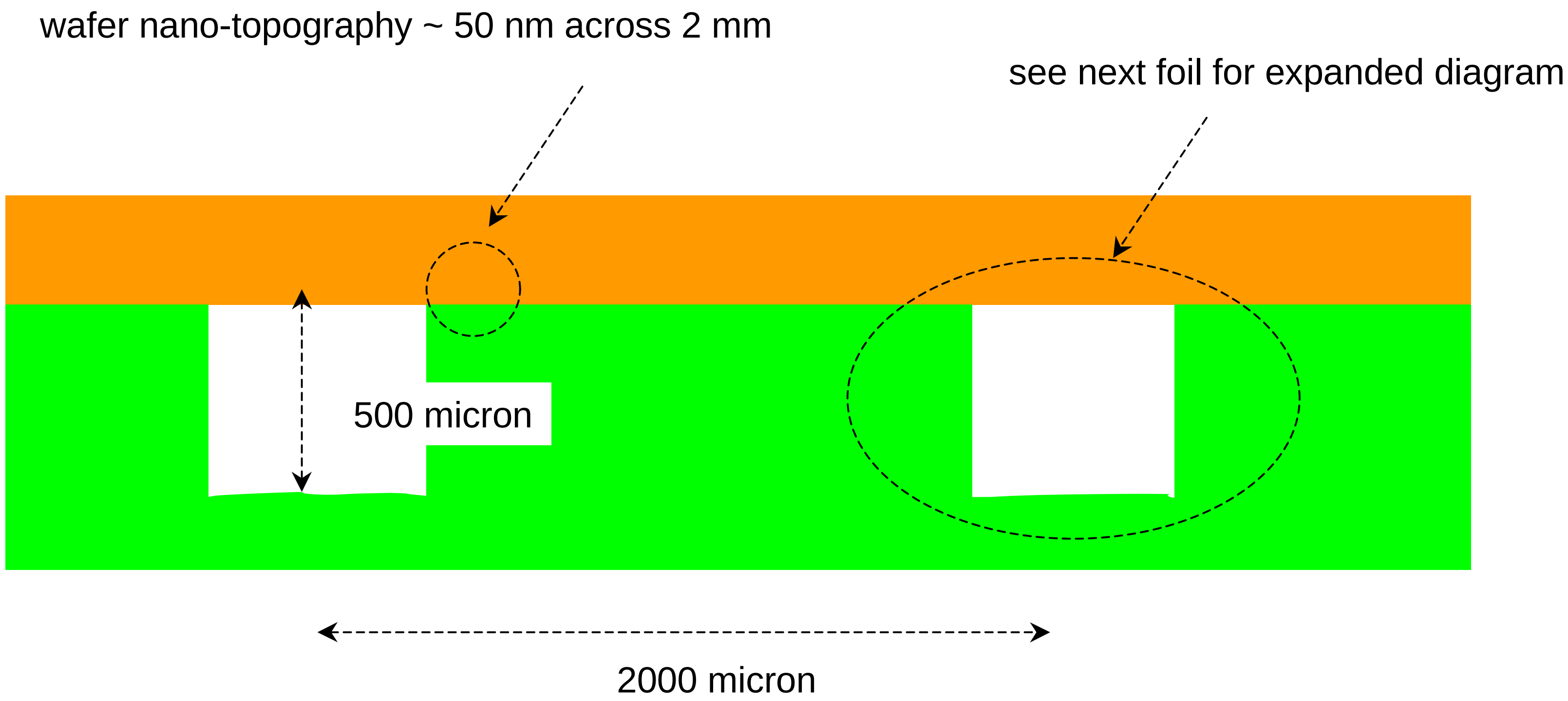
Particle Settling & Pad Geometry

- Slurry:
  - How do abrasive particles flow during CMP?
  - Which types of abrasives tend to settle during flow?
  - Is abrasive settling a good thing or a bad thing?
  - How does abrasive flow pattern depend on process, slurry type and pad properties?
  - What is the critical abrasive size for determining defectivity?
- Pad:
  - How do grooves affect the overall fluid dynamics of the CMP process?
  - Is there an optimum groove design?
  - How do grooves and abrasive particles interact?
  - Can grooves act as particle gettering devices?

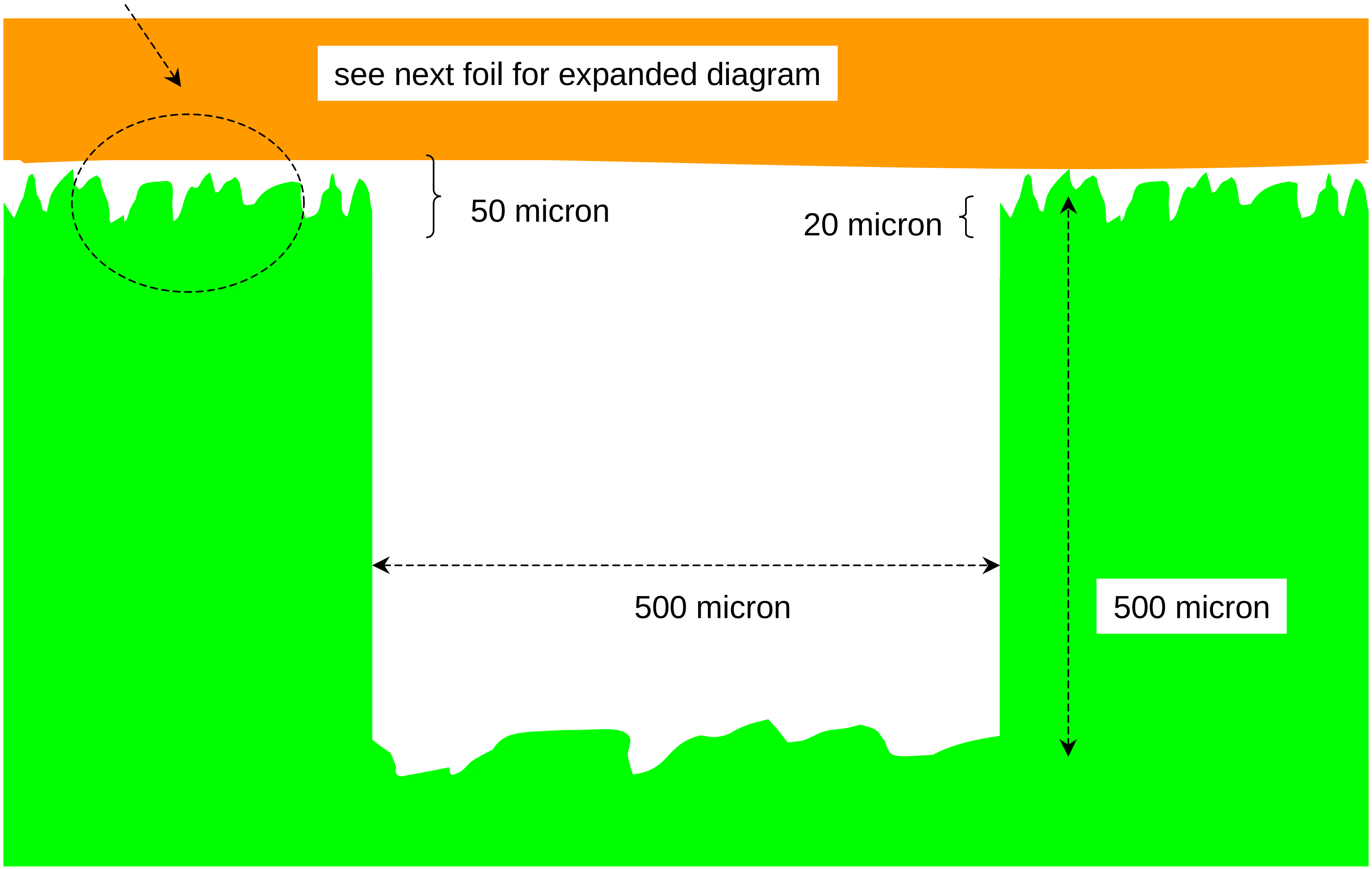
Scaled Schematic No. 1 (Macro-Scale)



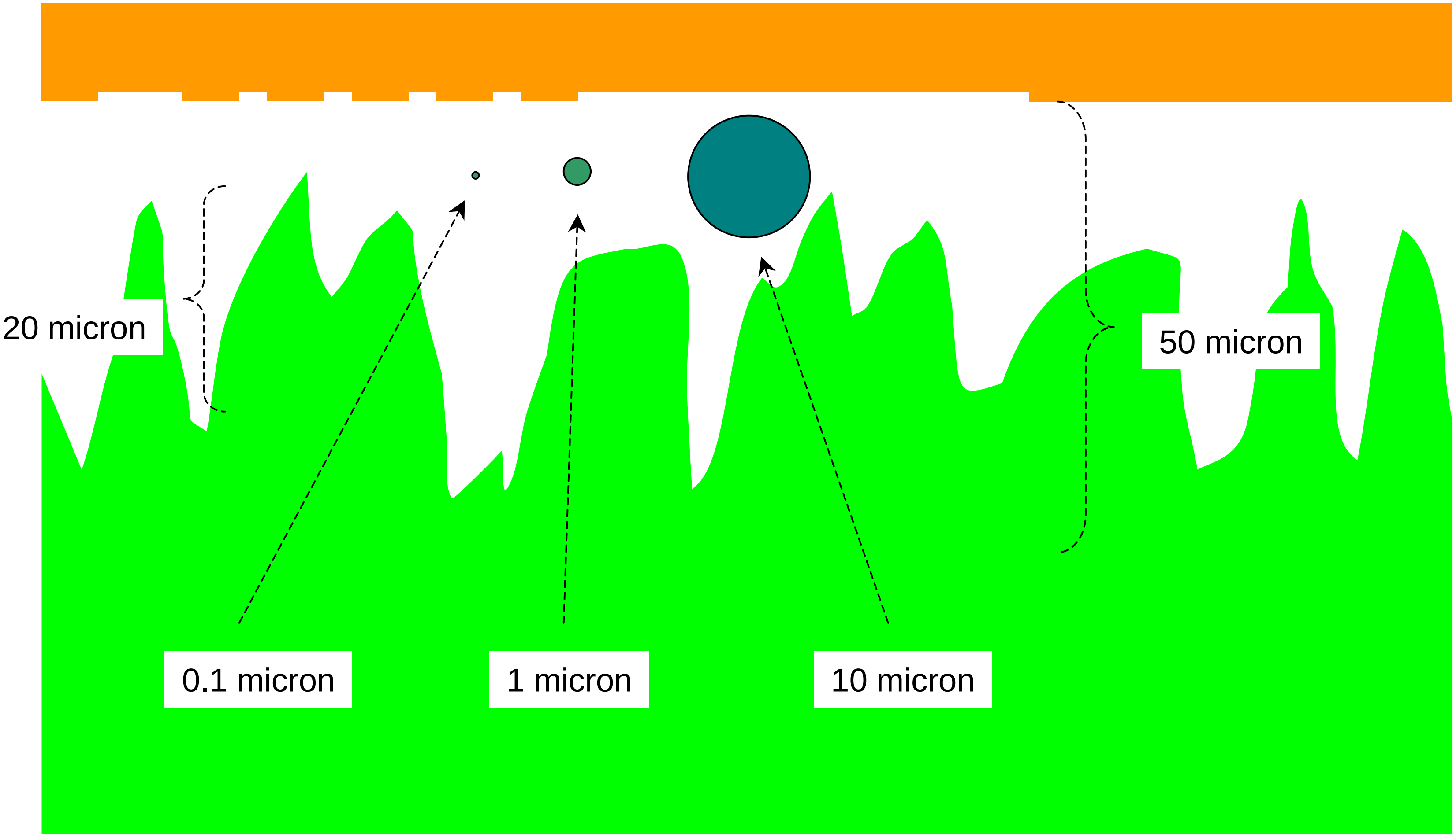
Scaled Schematic No. 2 (Macro-Scale)



Scaled Schematic No. 3 (Feature-Scale)



Scaled Schematic No. 4 (Micro-Scale)



Stokes Number

Response time of particle relative to response time of fluid

$$St = \frac{\rho_p D^2 u}{\mu L}$$

- St < 0.1 particles do not have inertia and they follow the flow field
- St > 0.1 particles have inertia and they most likely do not follow the flow field

ρ_p	density of abrasive particle
D	mean aggregate diameter
u	relative pad-wafer linear velocity
μ	slurry viscosity
L	hydraulic diameter of groove (cross sectional area ÷ wetted perimeter)

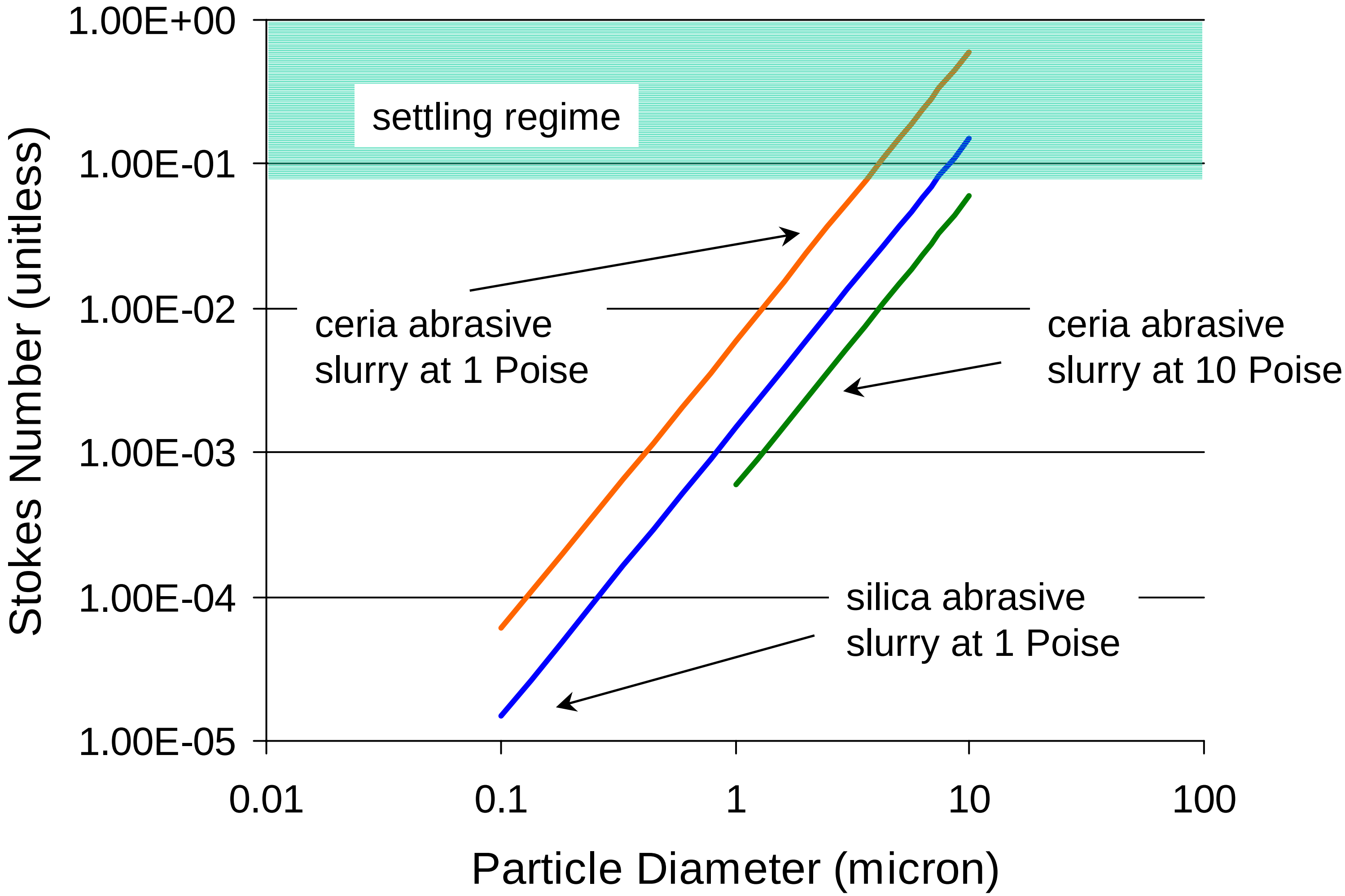
Assumptions:

Creeping flow (i.e. Reynolds Number < 0.1)
No particle-particle interactions
No chemistry effects

No gravitational effects

Stokes Number Calculations

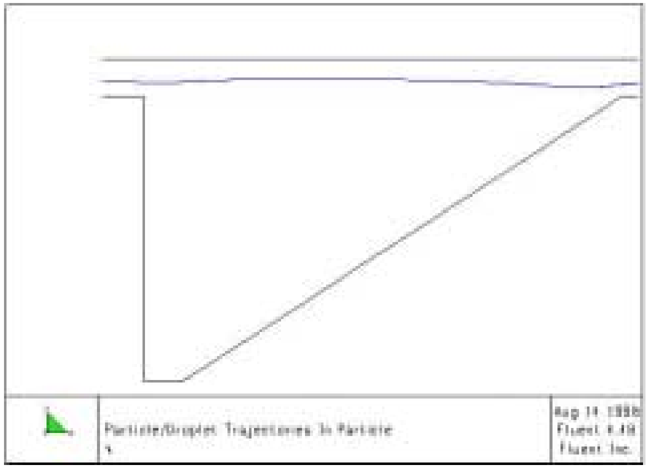
groove W X H = 500 X 300 micron ; u = 0.44 meter per second

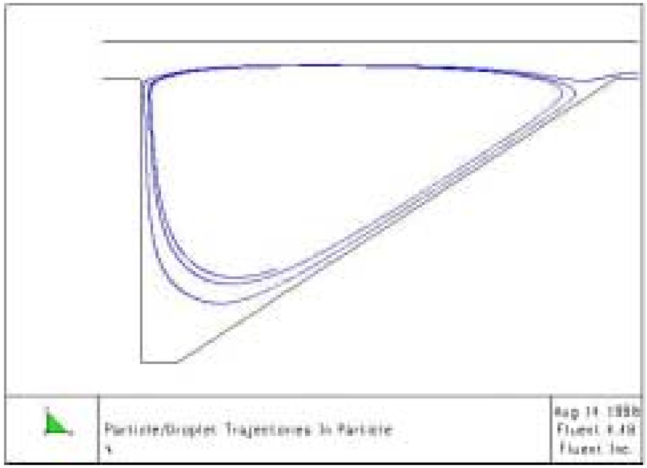


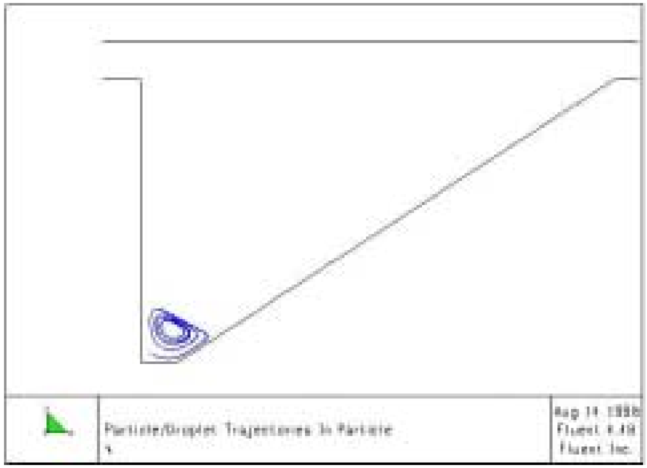
General Observations Regarding Stokes Number

- For most slurry systems, particles with diameters of 1 micron or less are predicted to follow the flow field:
  - Chances of coming into contact with the wafer surface is greater
  - 1 micron particles may cause scratches
- Particles larger than 1 micron are more likely to settle down into grooves or away from the wafer surface:
  - They may be less dangerous
- Changes in slurry viscosity (due to non-Newtonian or rheopectic behavior) can dramatically affect abrasive flow characteristics
- For a slurry system, both the Stokes Number and the particle size may need to be considered in order to determine the detrimental effects on surface defectivity

Selected Particle Trajectories



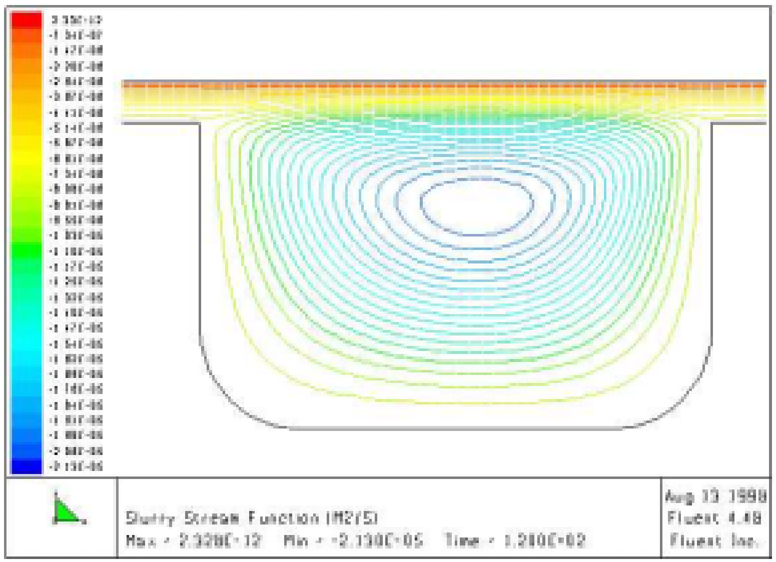




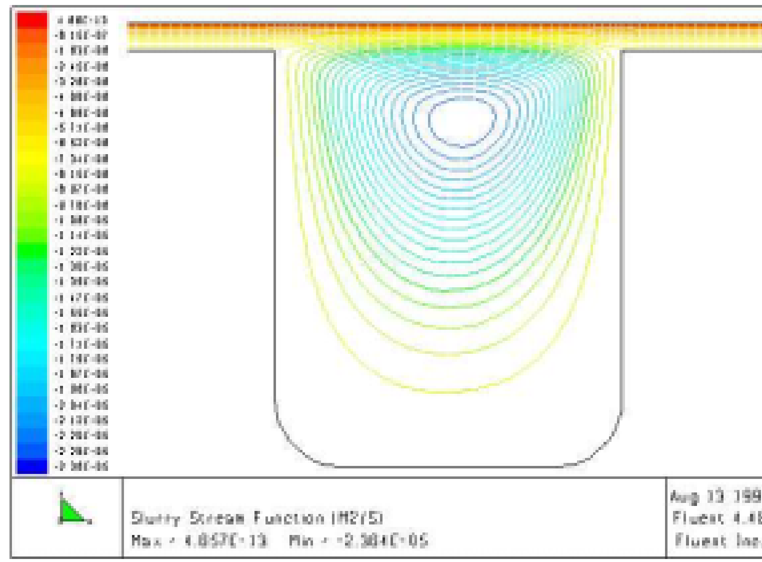
Selected Streamlines For Fully-Developed Flow

Effect of Groove Depth

Groove width = 500 micron
Groove depth = 300 micron

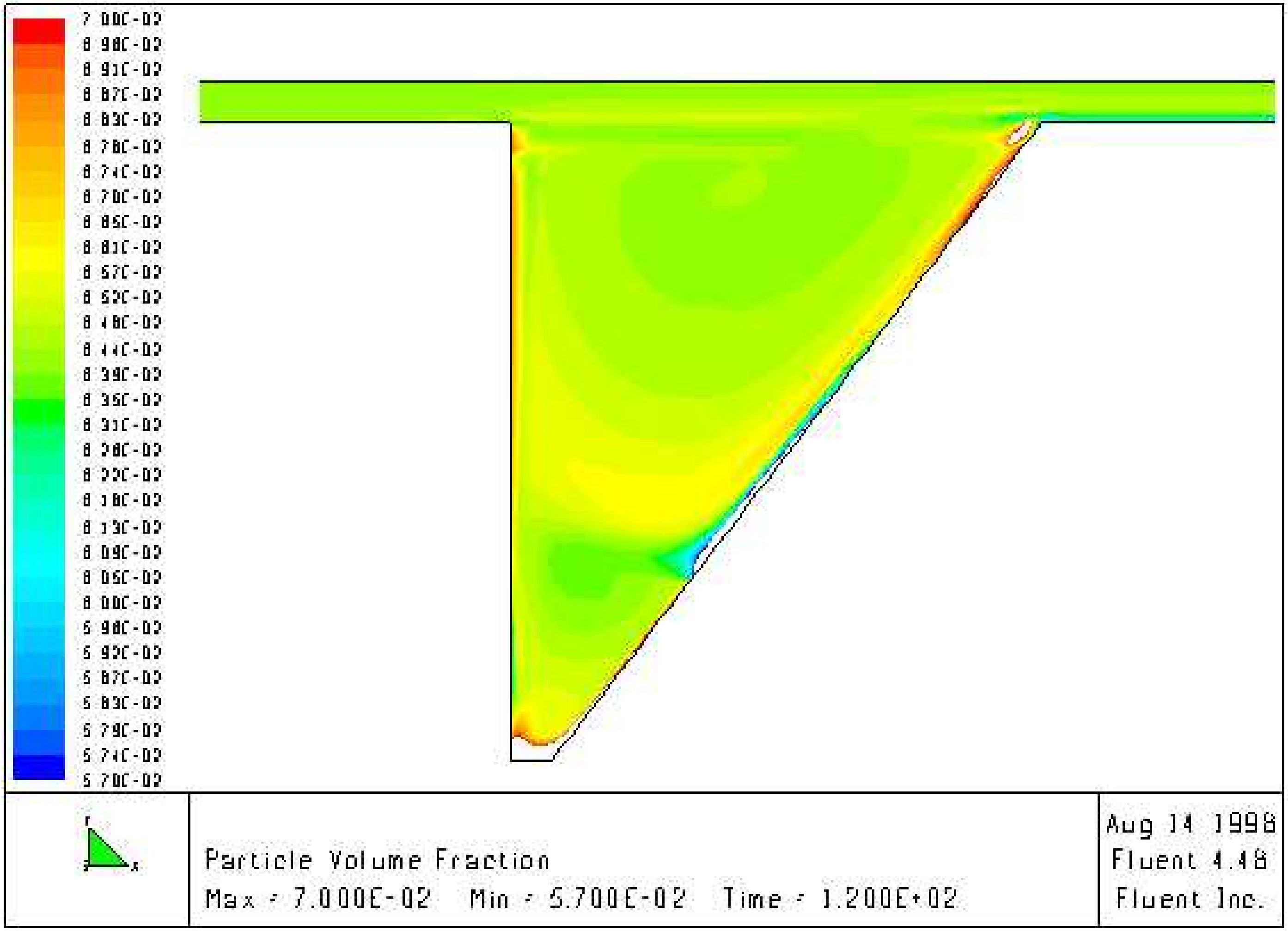


Groove width = 500 micron
Groove depth = 600 micron



Streamline imaginary curve in a mass of flowing fluid so drawn that at every point
on the curve the net velocity vector is tangent to the streamline

Ex: Volume Fraction Computation for a 2-minute Polish



Volume Fraction Data Can Be Manipulated to Provide Useful Information on Geometric and Inertial Effects

- Residence time of particle in the groove at steady state

$$\tau_{groove} = \frac{V_{groove}}{Q_{particles}}$$

V volume of groove

Q volumetric flow rate of particles

- Fraction of time particles spend in the groove

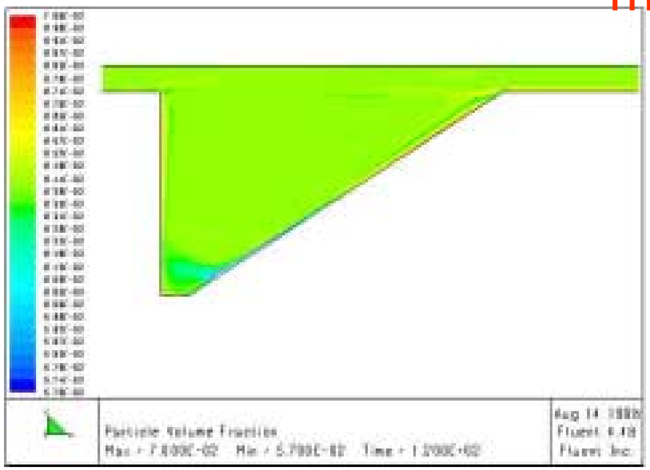
$$\tau_{groove} + \tau_{gap} = \tau_{total}$$

$$\varphi = \frac{\tau_{groove}}{\tau_{groove} + \tau_{gap}}$$

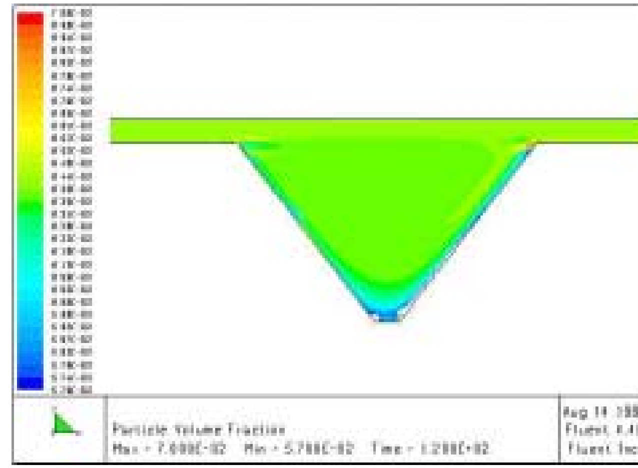
τ_{gap} residence time of particle in the gap between wafer and top surface of pad

Volume Fraction as a Function of Groove Shape

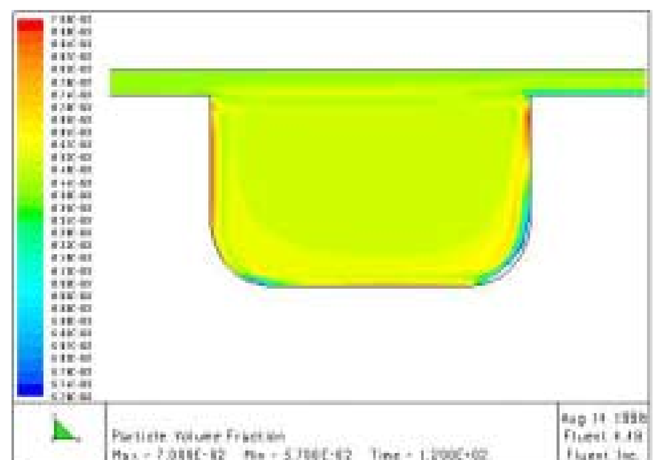
120 second polish ; 0.1 micron particles ; W X D = 500 X 300 micron



τ_{groove}	83 sec
φ	0.69



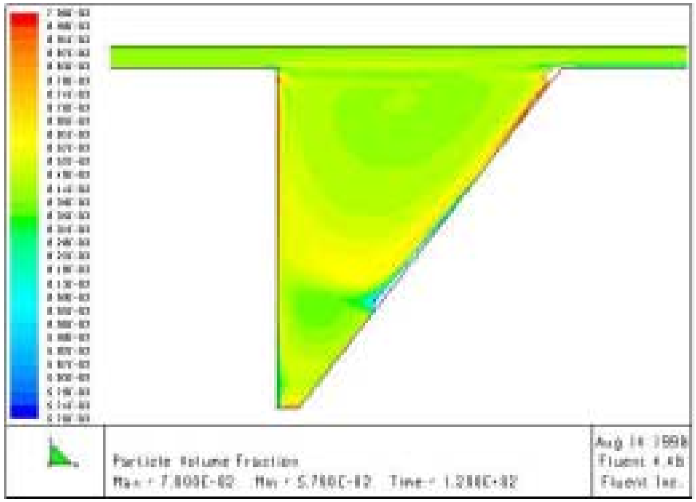
τ_{groove}	83 sec
φ	0.69



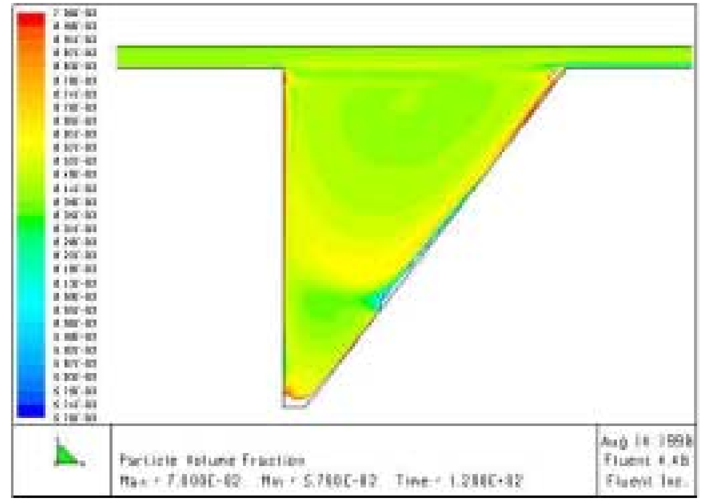
τ_{groove}	90 sec
φ	0.75

Volume Fraction as a Function of Particle Size

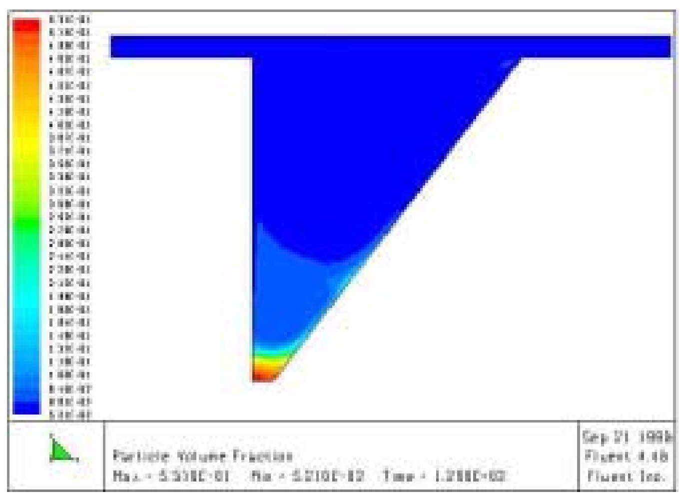
120 second polish ; W X D = 500 X 600 micron



0.1 μm



1 μm

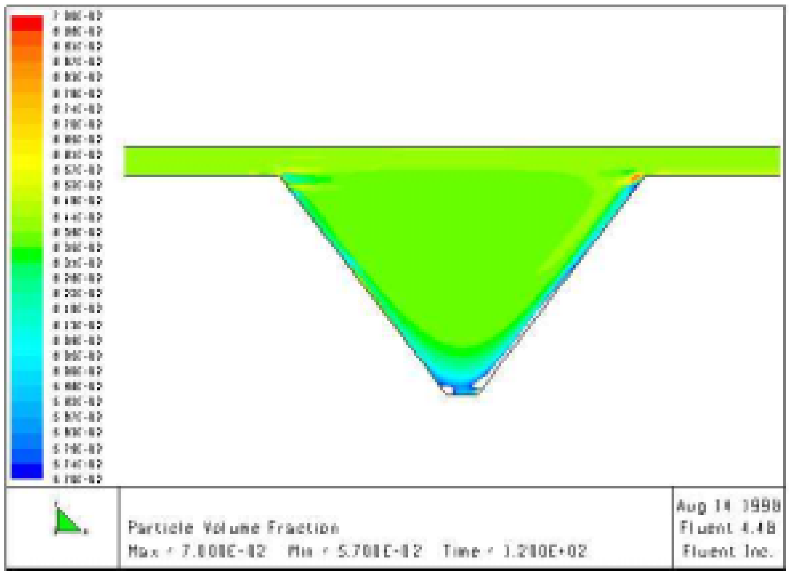


10 μm

Volume Fraction as a Function of Groove Depth

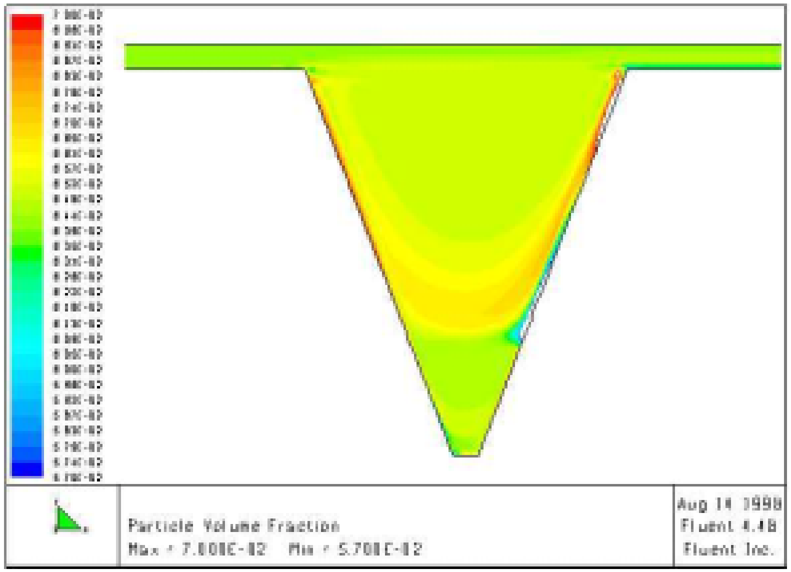
120 second polish ; 0.1 micron particles ;
Groove Width = 500 micron

Groove Depth = 300 micron



τ_{groove}	83 sec
φ	0.69

Groove Depth = 600 micron

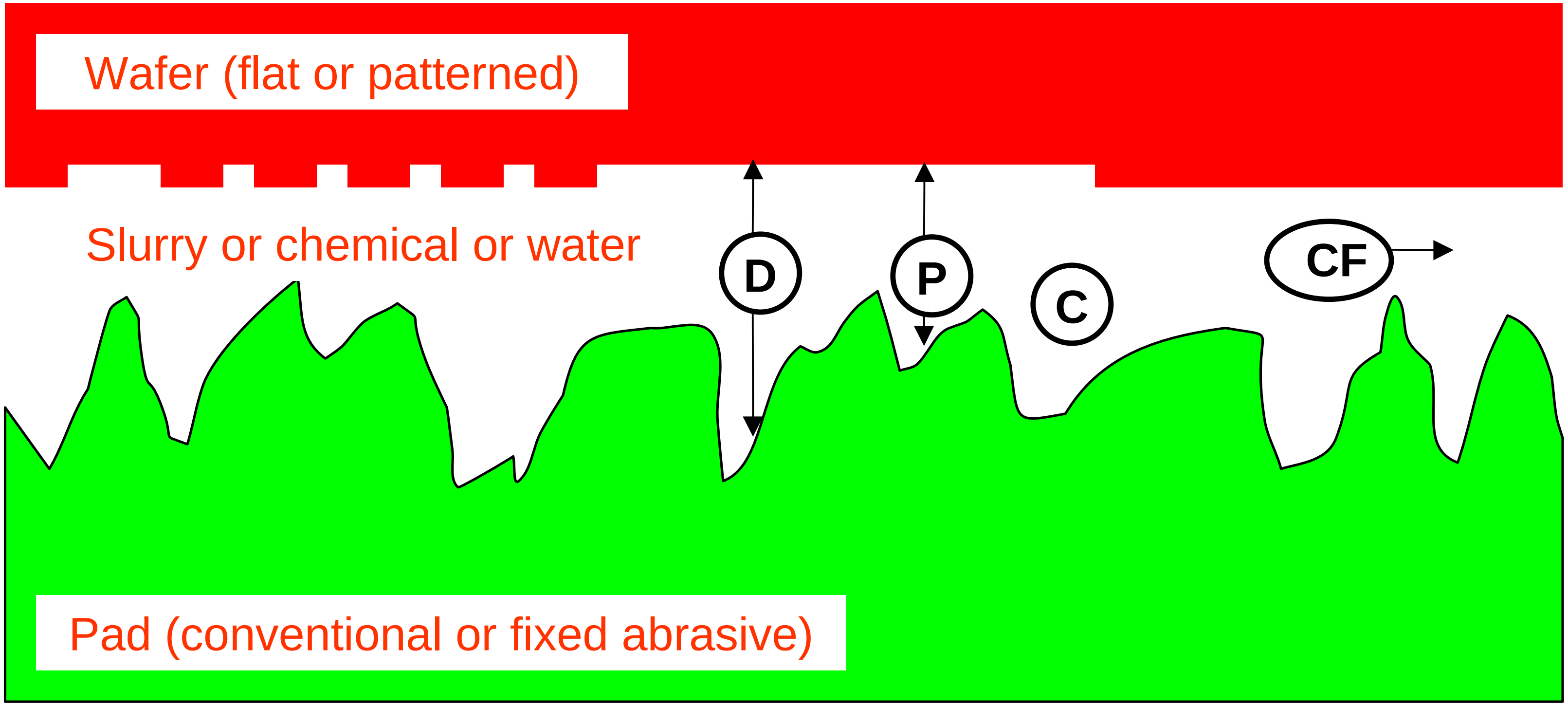


τ_{groove}	92 sec
φ	0.76

General Observations Re: Numerical Analysis

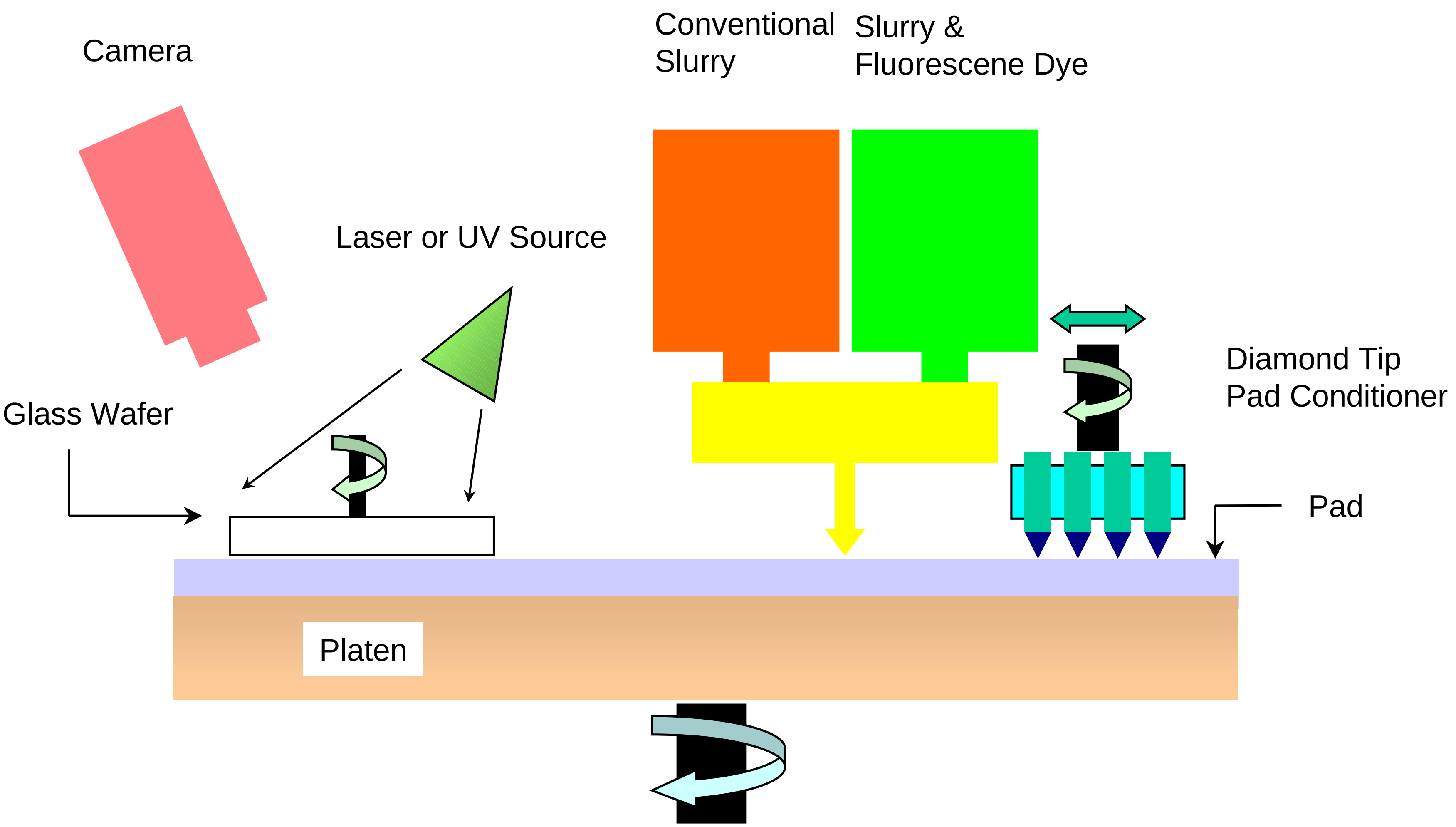
- Most differences observed at the bottom of the groove and not near the wafer-pad gap region
- V-groove results in the most even particle distribution
- U-groove results in the least even particle distribution
- Smaller aspect ratios result in more even particle distribution
- Fluid dynamics differences between 0.1 and 1 micron particles are very minor and can be ignored
- Fluid dynamics differences between 1 and 10 micron particles are major
  - Results are in qualitative agreement with the Stokes analogy presented earlier

The CMP System

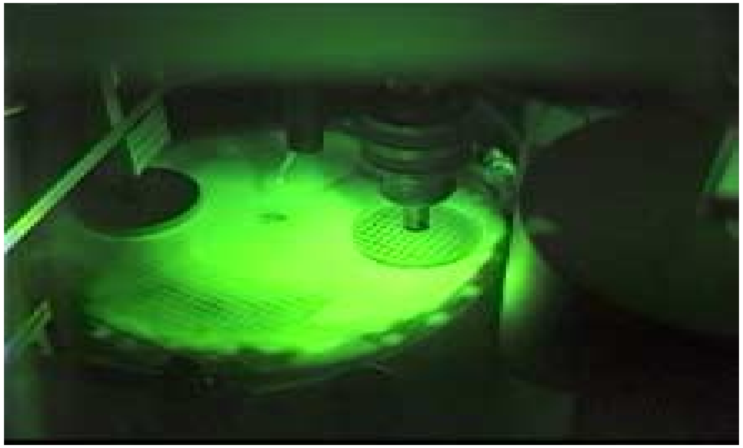


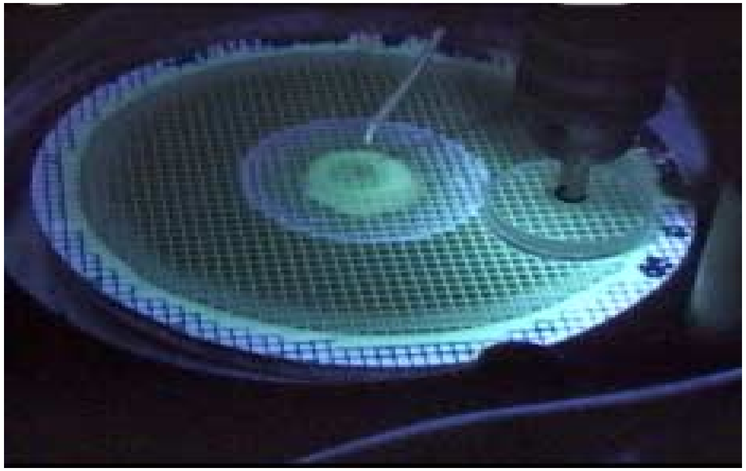
C:	Slurry (or chemical or water) concentration
D:	Apparent distance between wafer and pad
FF:	Frictional force resulting from interactions between rotating pad, rotating wafer and entrained fluid
P:	Local pressure

Dual-Emission Laser-Induced Fluorescence
(DELIF)



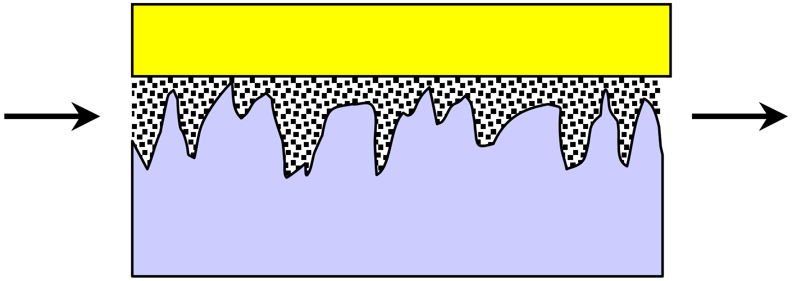
Flow Visualization using DELIF





Concentration (C)

- How does fresh fluid (i.e. slurry, chemical or water) mix with old fluid ?



- Does the CMP system behave like a CSTR (Continuously Stirred Tank Reactor), a PFR (Plug Flow Reactor), or a Dispersed Vessel ?
- What is the mean residence time of fluid in the wafer-pad gap and on the pad surface ? How much of the slurry actually enters the wafer-pad gap ?
- How do process parameters such as down-force, platen speed, carrier speed, flow rate and type of wafer being polished affect ‘C’ ?
- How do polisher parameters such as conditioning methods, fluid injection schemes and the location of the carrier and platen affect ‘C’ ?
- How do consumable parameters such as slurry type, solids content, pH, pad type, groove pitch-depth-width-shape affect ‘C’ ?

Design of Experiment (43 Runs)

Variables:

- Pad Manufacturer (Cabot, Rodel & Freudenberg)
- Pad Groove Depth (0 - 40 mils)
- Wafer Pressure (2 - 6 psi)
- Platen Speed (30 - 90 rpm)
- Slurry Flow Rate (20 - 50 ml/min)

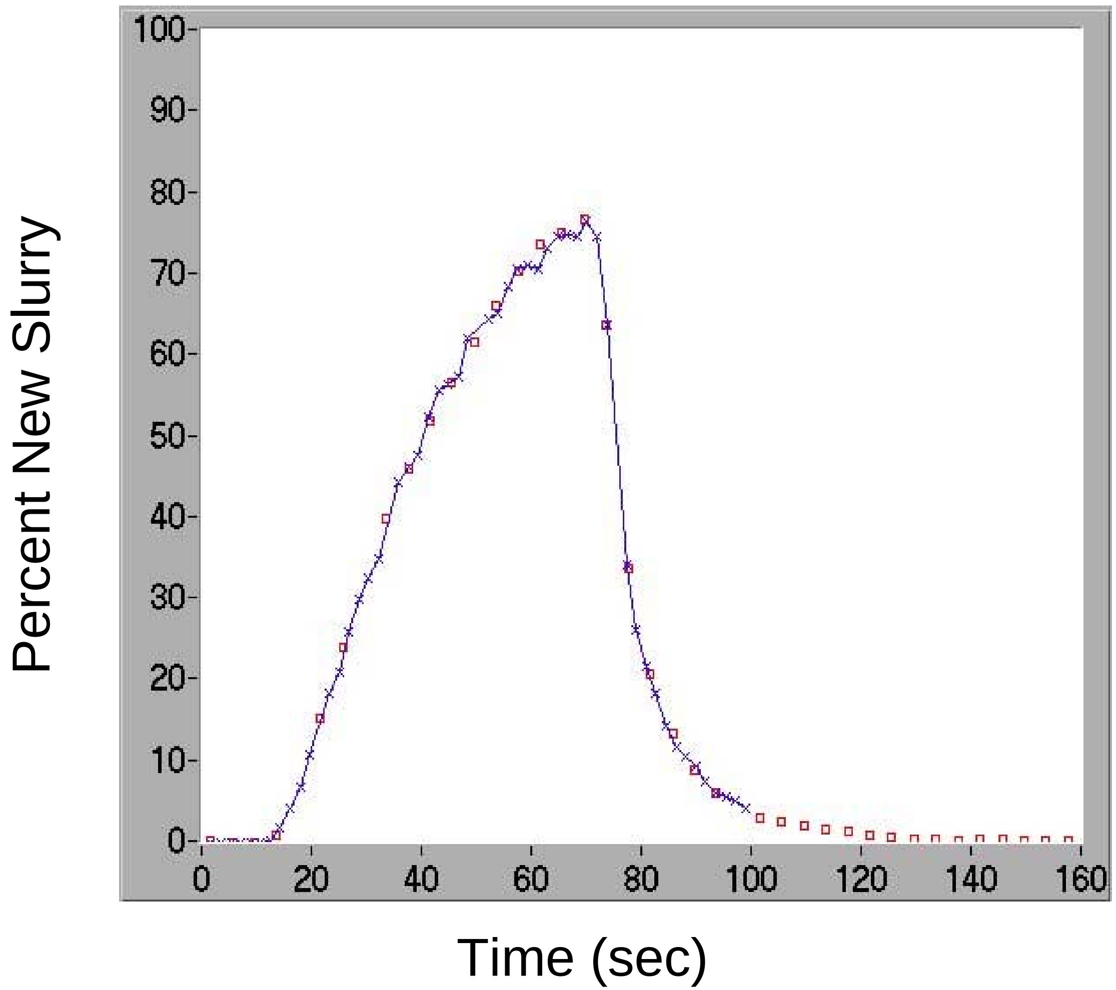
Constants:

- Groove Style (X-Y Grooving, 0.025” width)
- Head Speed (60 rpm)
- Head Position (3/4” wafer to platen edge)
- Injection Location (pad center)
- Conditioning (163 Micron diamond grit)

Response:

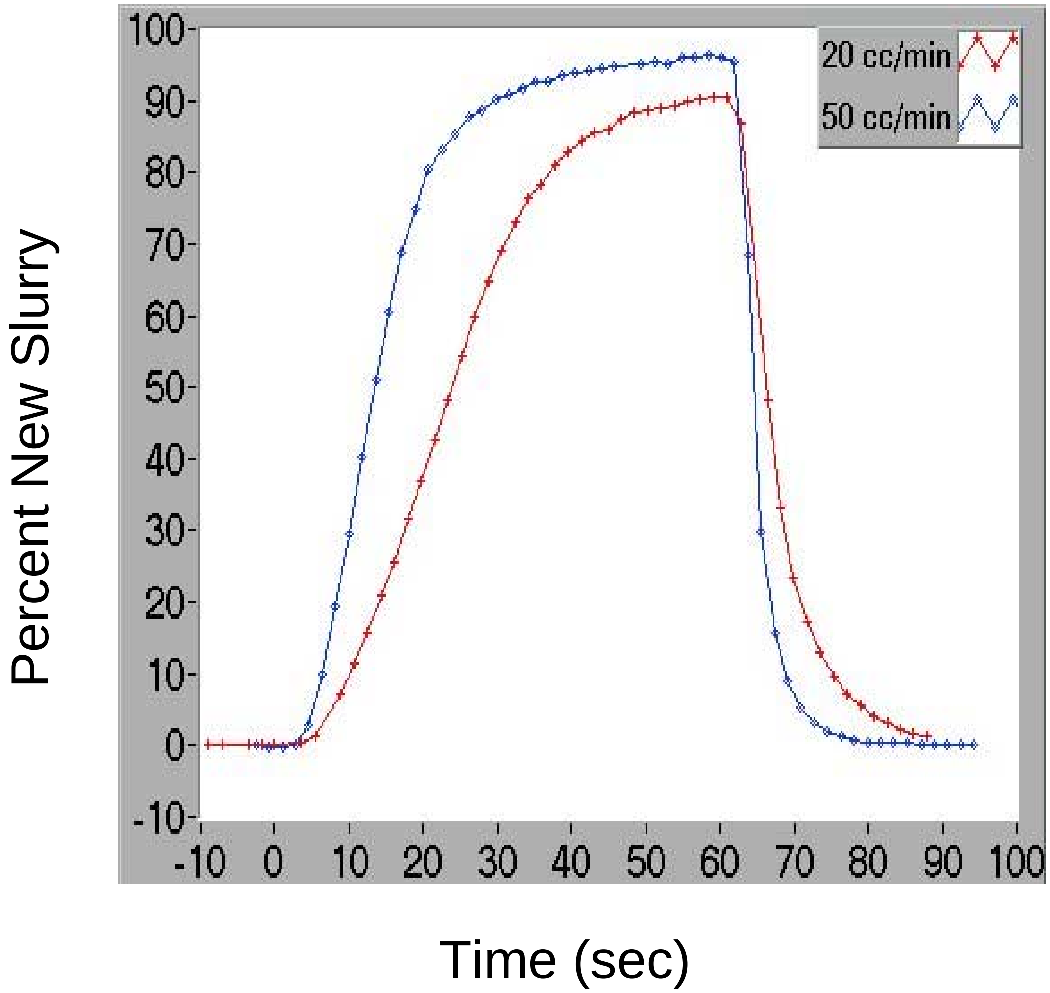
- Fresh (i.e. entering) slurry concentration vs. time

Repeatability



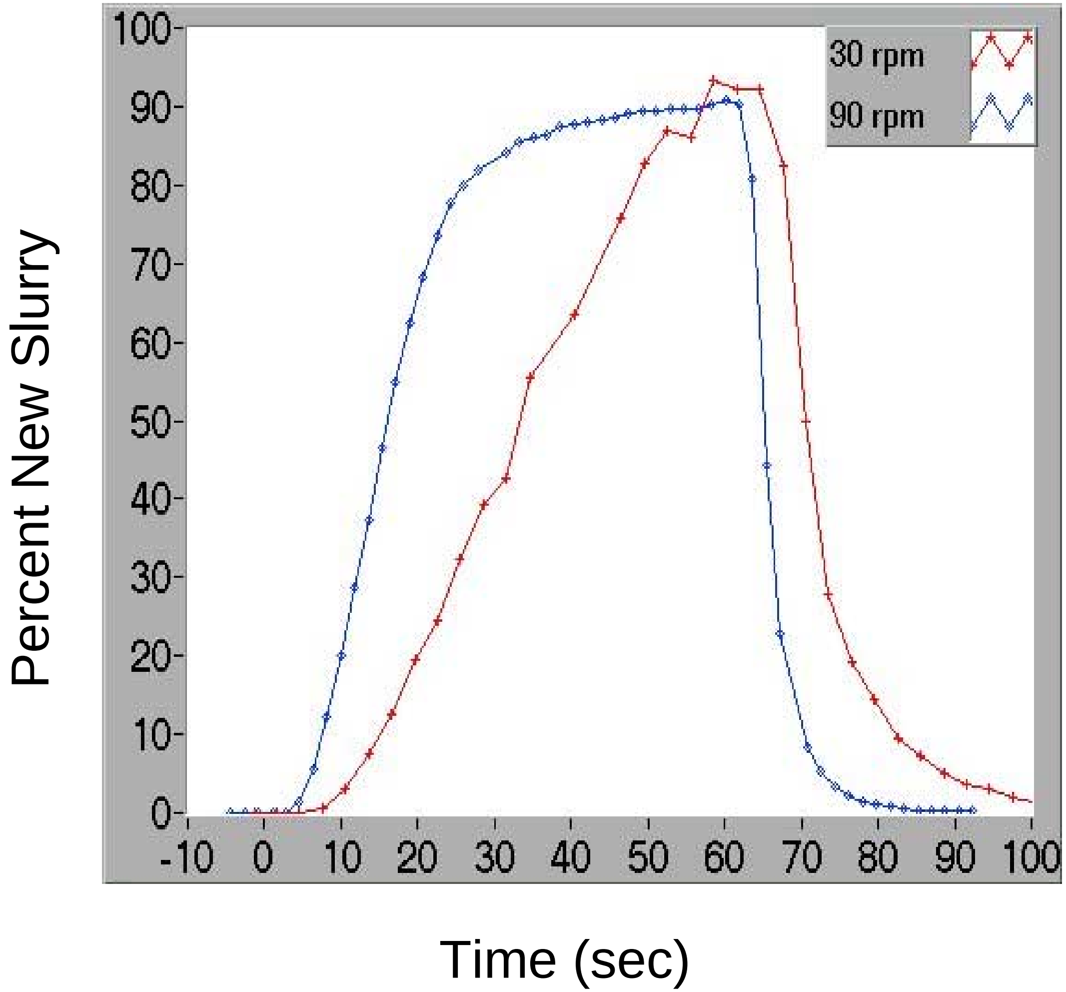
Manufacturer: **Cabot**
Slurry Flow Rate: **35 cc/min**
Wafer Pressure: **4 psi**
Platen Speed: **60 rpm**
X-Y Groove Depth: **20 mils**

Slurry Flow Rate



Manufacturer: **Rodel**
Slurry Flow Rate: **20 & 50 cc/min**
Wafer Pressure: **4 psi**
Platen Speed: **60 rpm**
X-Y Groove Depth: **20 mils**

Platen Speed



Manufacturer: **Freudenberg**
Slurry Flow Rate: **35 cc/min**
Wafer Pressure: **4 psi**
Platen Speed: **30 & 90 rpm**
X-Y Groove Depth: **20 mils**

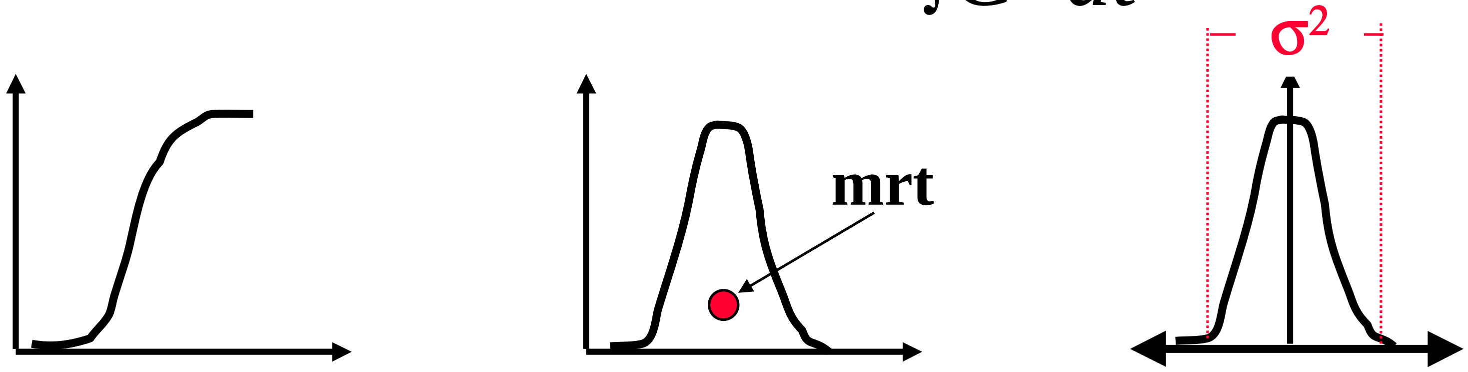
Measuring the Slurry Age

- Mean Residence Time

$$\bar{t} = \frac{\int C \cdot t \cdot dt}{\int C \cdot dt}$$

- Variance

$$\sigma^2 = \frac{\int C \cdot \left(t - \bar{t}\right)^2 \cdot dt}{\int C \cdot dt}$$



Mixing Curve | Derivative | Shifted Derivative

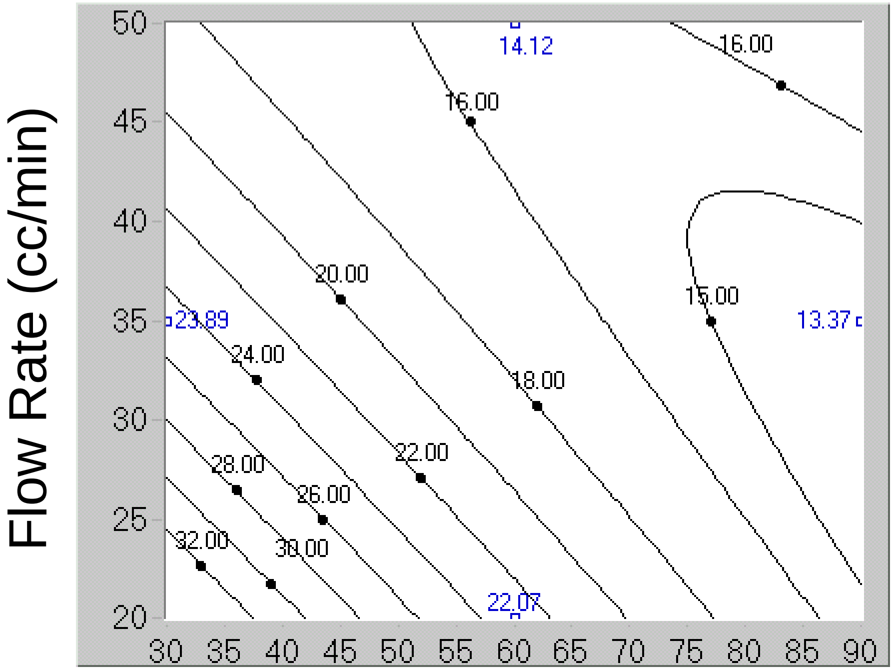
Data Analysis

Mean Residence Time Significant Factors

Factor	***In Situ Coefficient***	***Ex Situ Coefficient***
Constant	**22.63**	**13.96**
Platen Speed	**-12.69**	**-8.89**
Flow Rate	**-8.27**	**-3.70**
Pad Manufacturer	-4.391	**-4.11**
Groove Depth	**3.92**	**-2.50**
Platen Speed-Platen Speed Interaction	**8.35**	**5.73**
Platen Speed- Flow Rate Interaction	**6.39**	**4.87**
Platen Speed- Groove Depth Interaction	x	**-5.61**
Flow Rate- Flow Rate Interaction	2.80	x
Groove Depth- Groove Depth Interaction	x	**6.49**
Platen Speed-Groove Depth-Groove Depth	x	**9.23**
Platen Speed- Platen Speed – Groove Depth	x	-4.41
Platen Speed – Down Force Interaction	-5.38	x
Correlation Coefficient	**0.80**	**0.82**

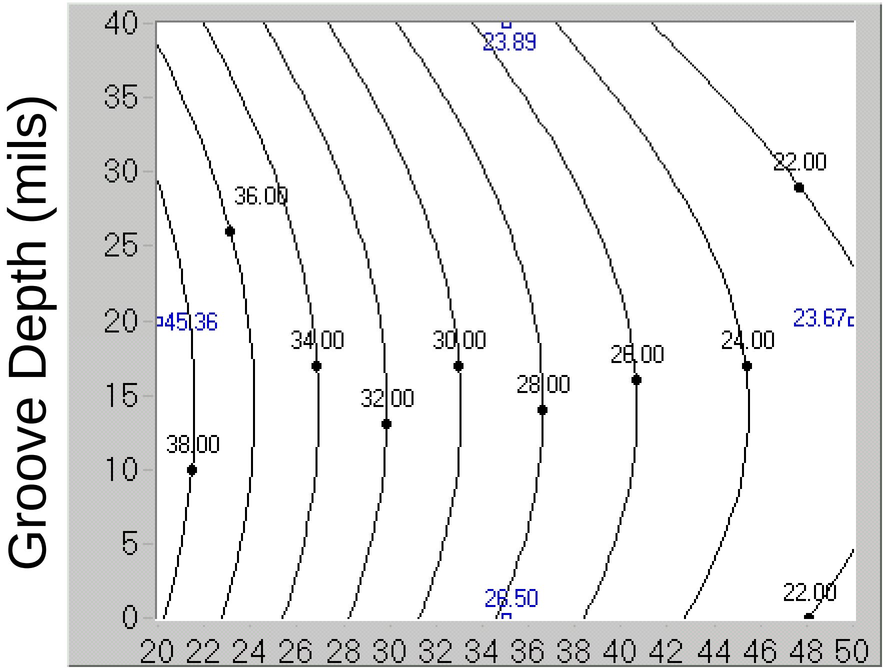
Mean Residence Time Contour Plots

20 mil Groove Depth



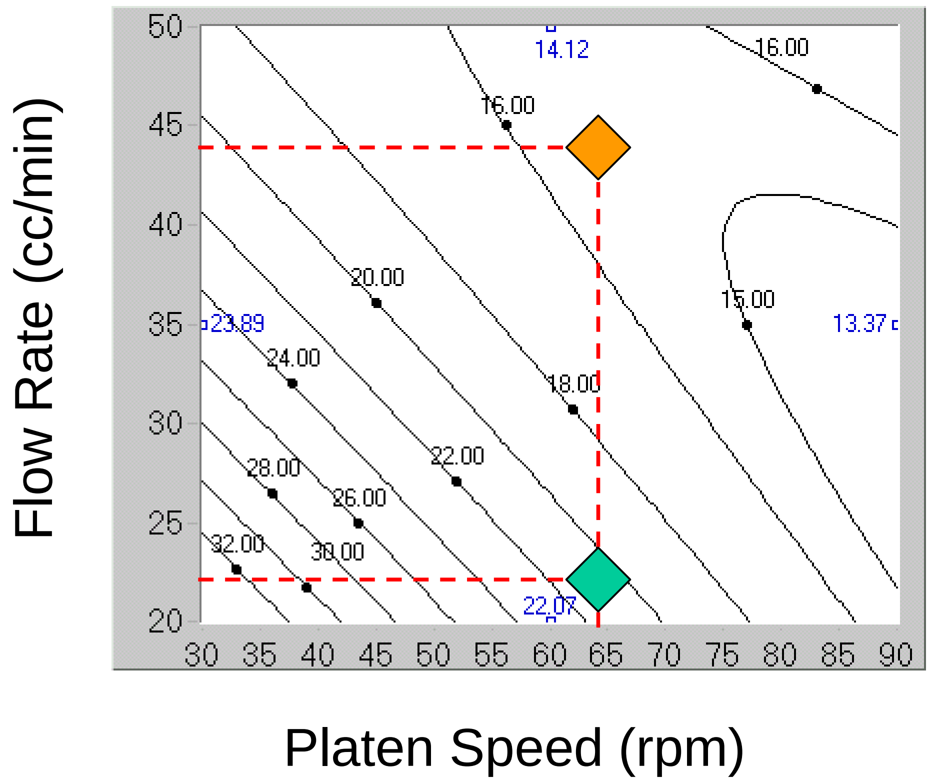
Platen Speed (rpm)

30 rpm Platen Speed



Flow Rate (cc/min)

How Much of the Fresh Slurry Supplied to the Pad Enters the Wafer-Pad Gap ?



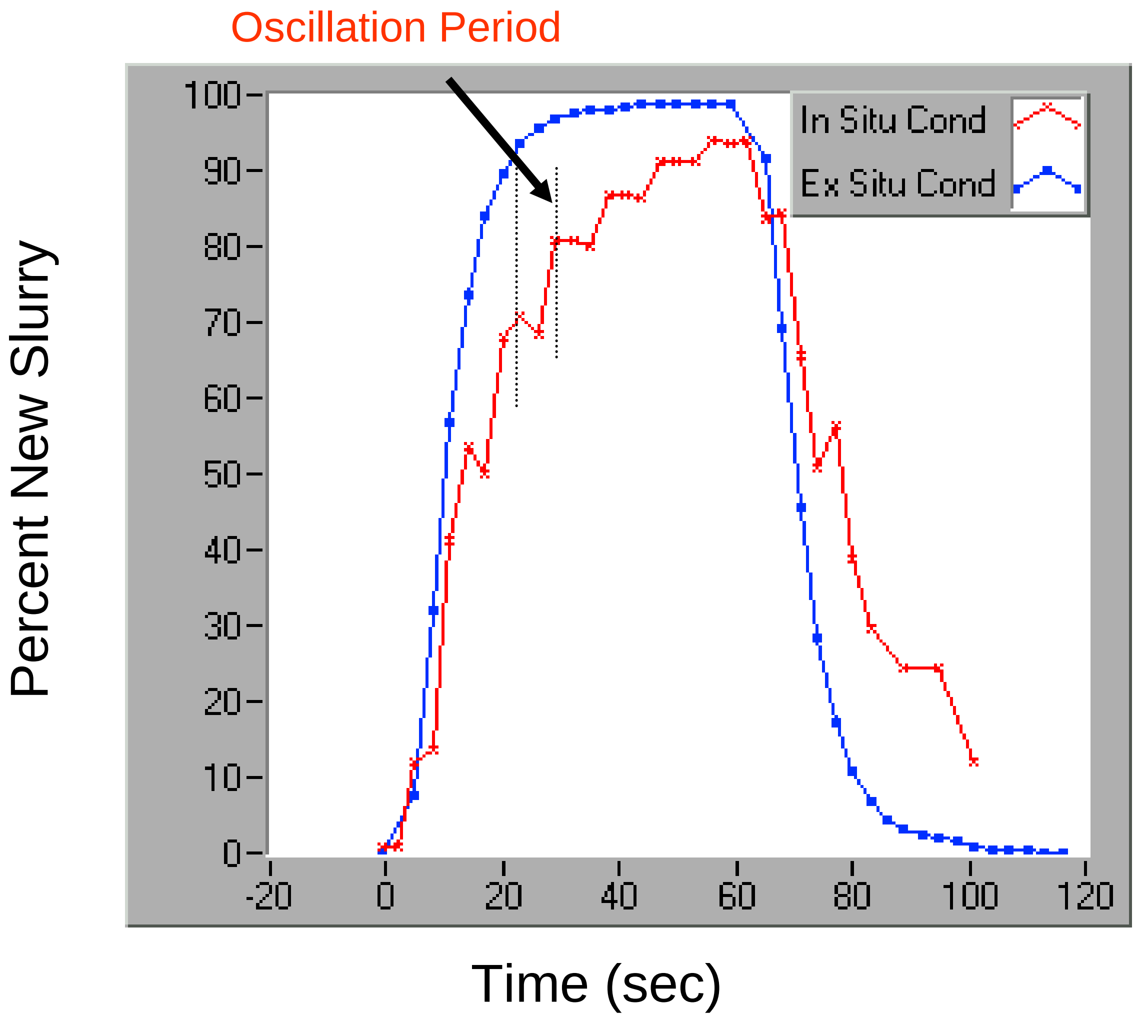
2X increase in flow rate (i.e. from 22 to 44 cc/min) does not reduce Mean Residence Time by 2X !

It reduces MRT from 21 sec to only 16 sec !

Therefore only ~ 45% of fresh slurry supplied to the pad enters the wafer-pad gap region !

~ 55% gets totally wasted !

In-Situ Conditioning



Mean Residence Time =

20 vs 11 sec

(there is tremendous potential to decrease flow rate during in-situ conditioning)

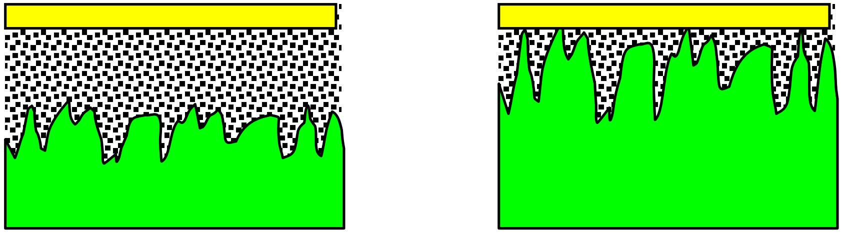
Data Analysis

Variance Significant Factors

Factor	*In Situ Conditioning*	*Ex Situ Conditioning*
Constant	**0.476**	**0.242**
Platen Speed	**-0.143**	x
Flow Rate	**-0.120**	x
Groove Depth	x	**-0.057**
Platen Speed- Platen Speed Interaction	**0.102**	0.042
Flow Rate-Flow Rate Interaction	**0.072**	**0.086**
Groove Depth - Groove Depth Interaction	x	**0.058**
Flow Rate-Groove Depth Interaction	-0.086	x
Flow Rate-Groove Depth-Groove Depth Interaction	0.094	x
Correlation Coefficient	0.67	0.44

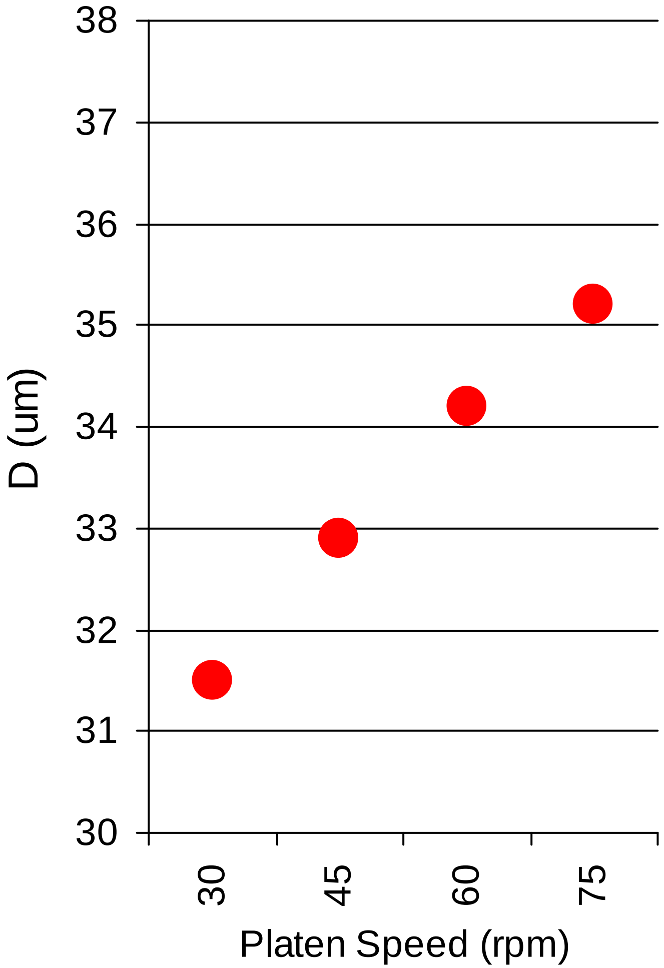
Depth (D)

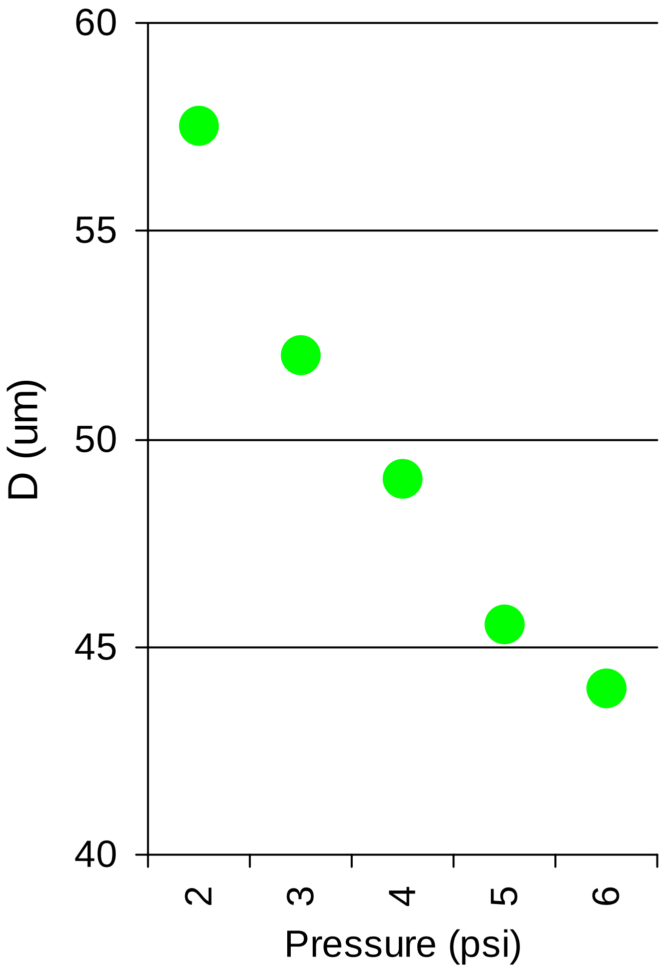
- Does CMP occur via hydrodynamic lubrication, asperity contact or a combination of both ?



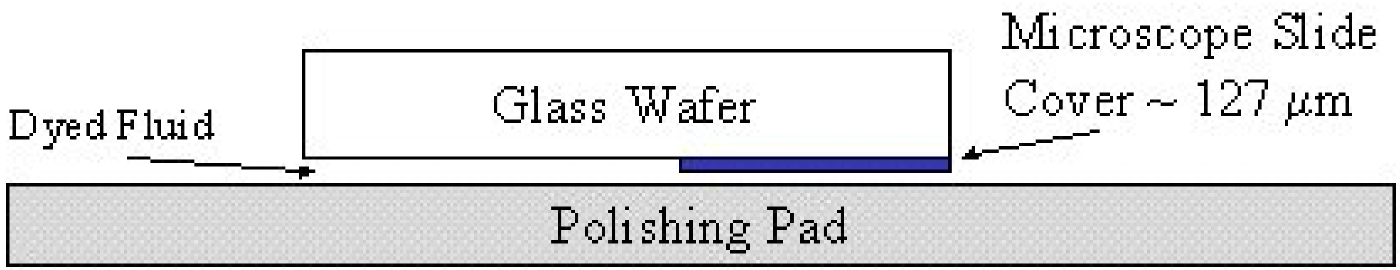
- How do process parameters such as down-force, platen speed, carrier speed, flow rate and type of wafer or film being polished affect ‘D’ ?
- How do polisher parameters such as conditioning methods and carrier designs affect ‘D’ ?
- Can d(D)/d(t) act as a predictor of pad life ?
- How do consumable parameters such as slurry type, solids content, pH, pad type, groove pitch-depth-width-shape affect ‘D’ ?
- How do pads bend locally & globally during the CMP process ?

Effect of Platen Speed & Pressure on ‘D’ (fluid = water)



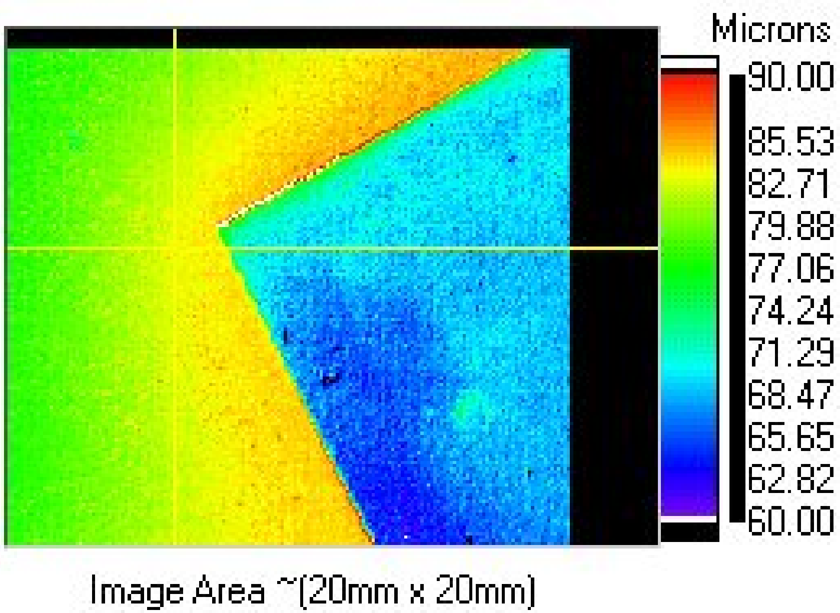


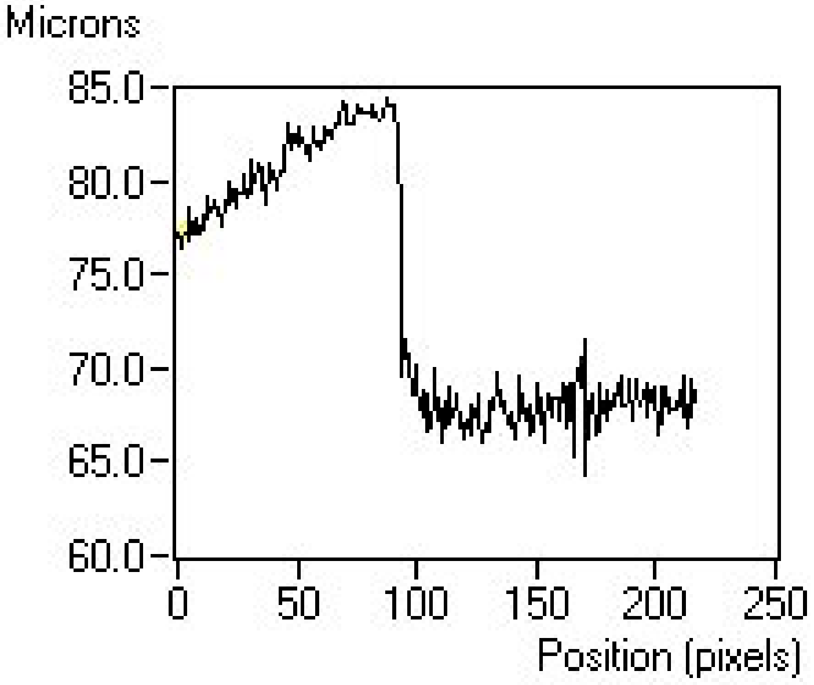
Local & Global Pad Bending



Thickness Profile Underneath Wafer and

Microscope Slide Cover

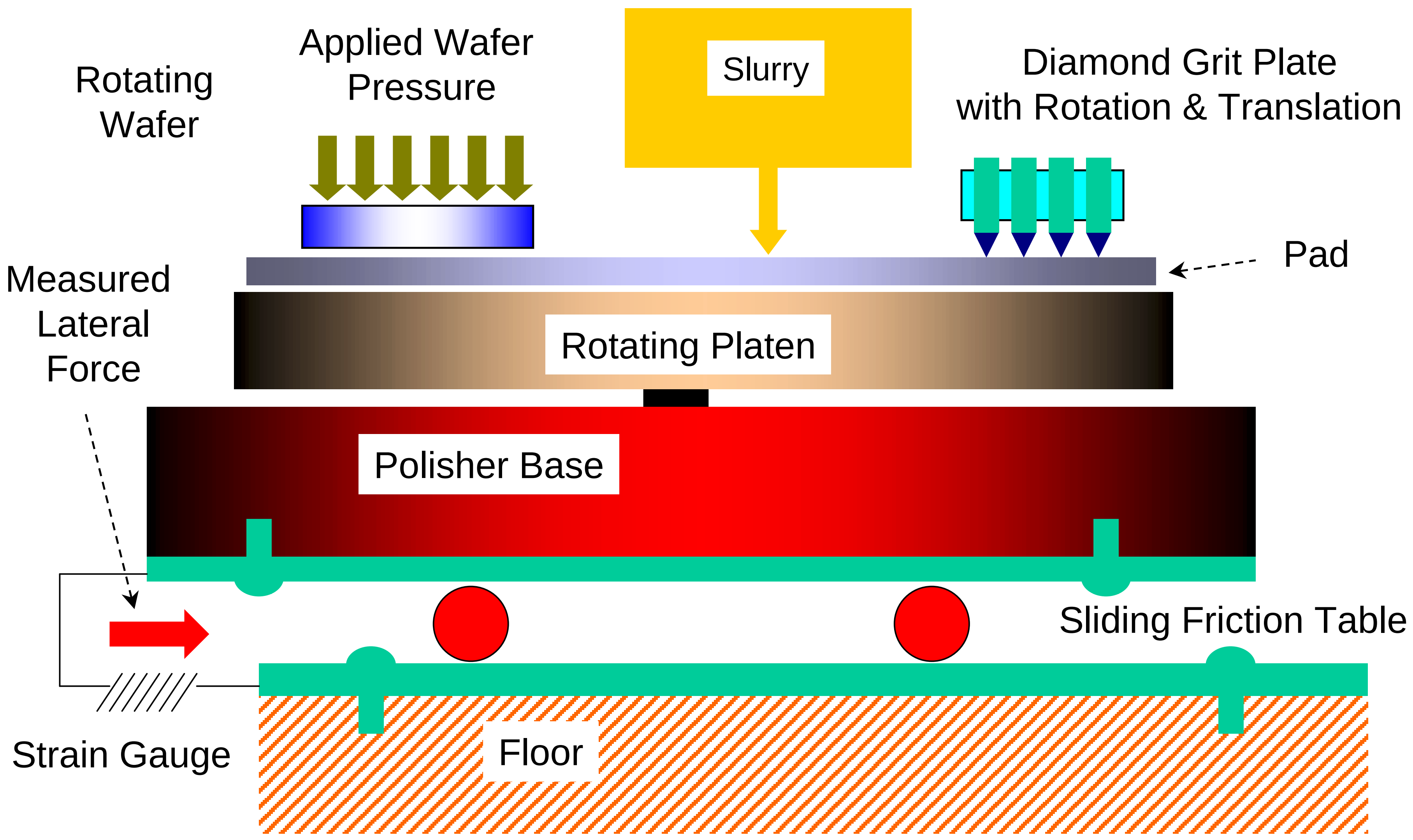




Friction Force (FF)

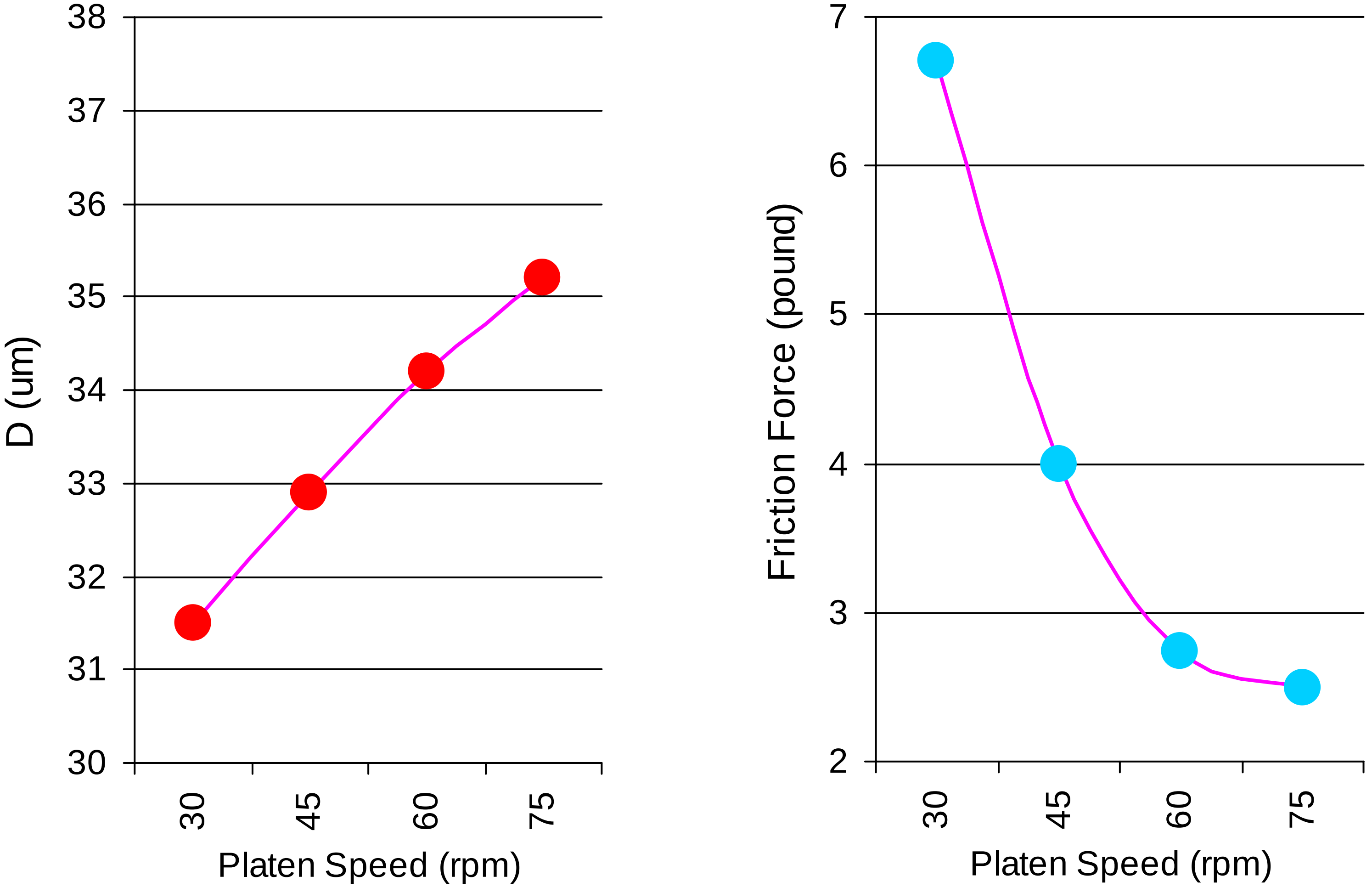
- What is the magnitude of frictional forces acting on the pad-wafer system ?
- How do process parameters such as down-force, platen speed, carrier speed, flow rate and type of wafer or film being polished affect ‘FF’ ?
- How do polisher parameters such as wafer cooling and conditioning methods affect ‘FF’ ?
- Can d(FF)/d(t) act as a predictor of pad life ?
- How do consumable parameters such as slurry type, solids content, pH and pad type affect ‘FF’ ?
- How much ‘FF’ can organic VLK, ELK or ULK materials tolerate without getting de-laminated during CMP ?

Measuring Coefficient of Friction



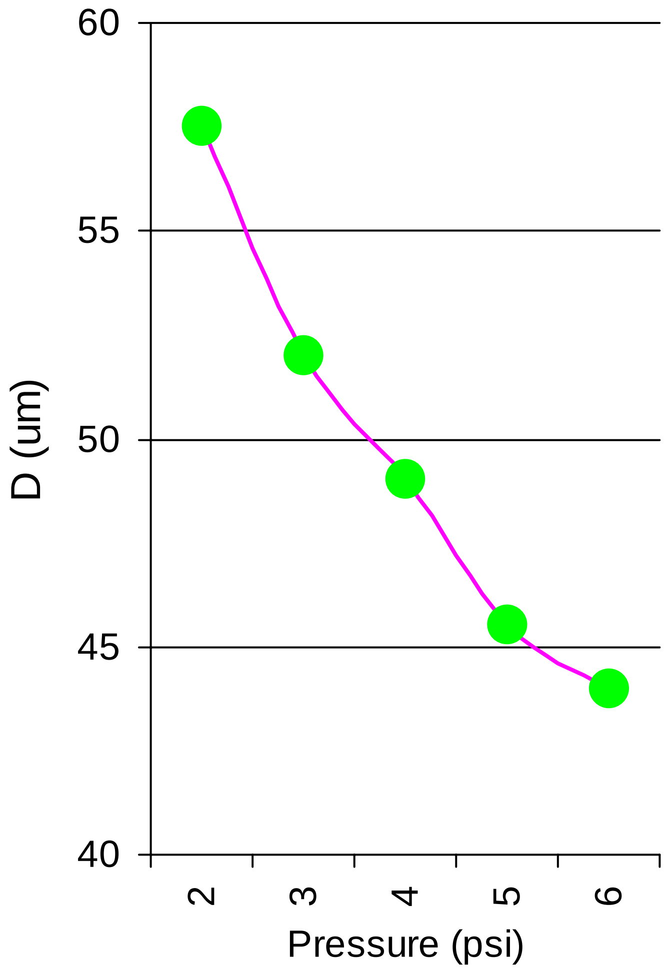
Effect of Platen Speed on 'D' & 'FF'

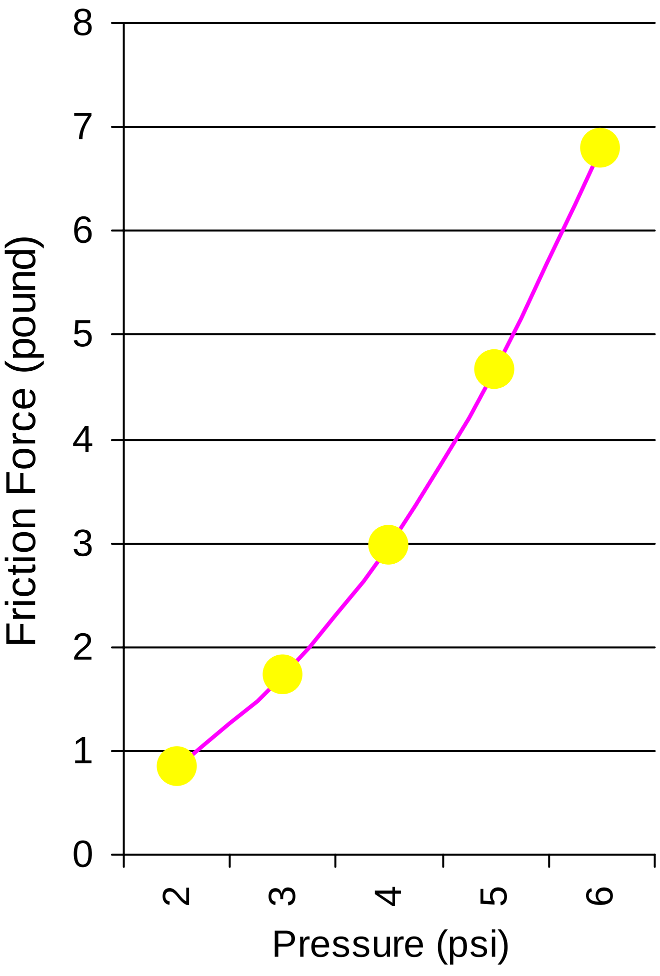
(Fluid = H_2O)



Effect of Wafer Pressure on 'D' and 'FF'

(Fluid = H2O)

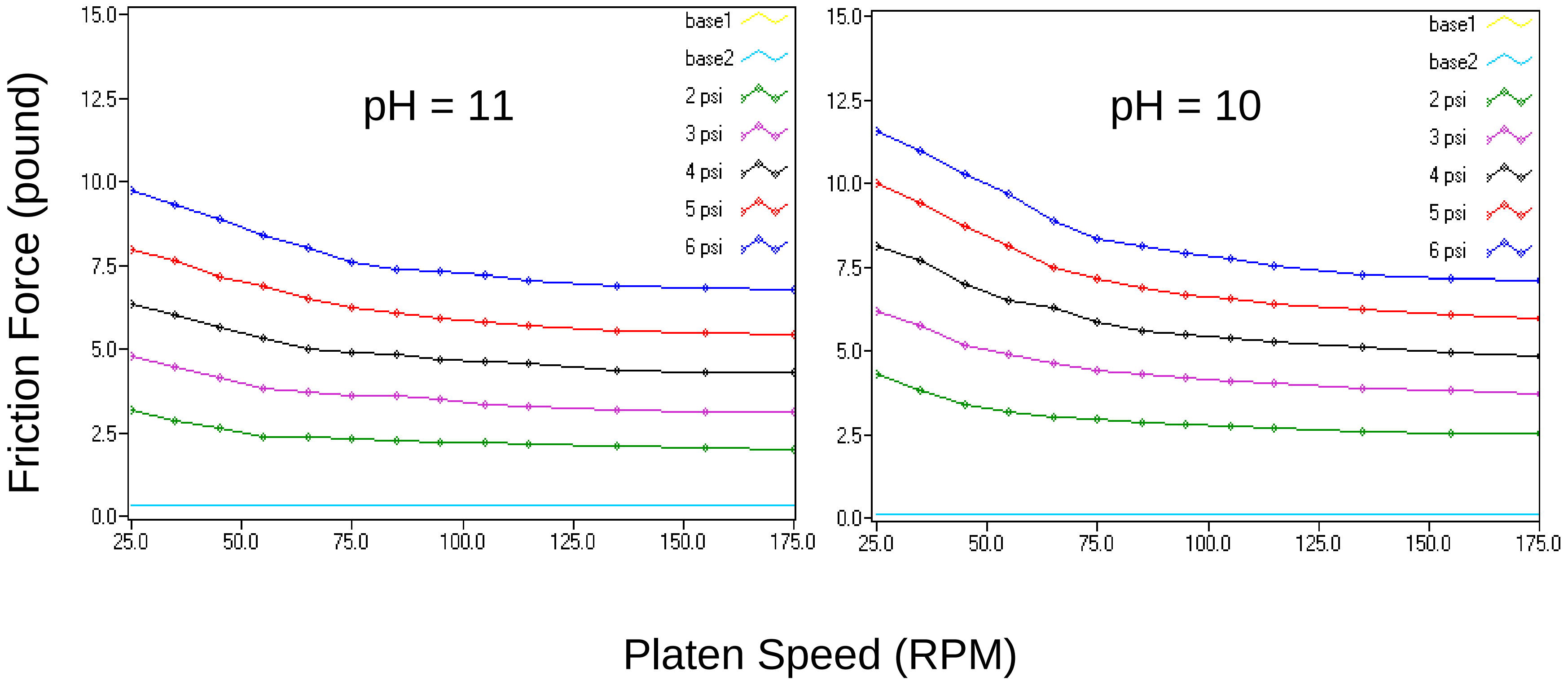




‘FF’ for Various Wafer Pressures

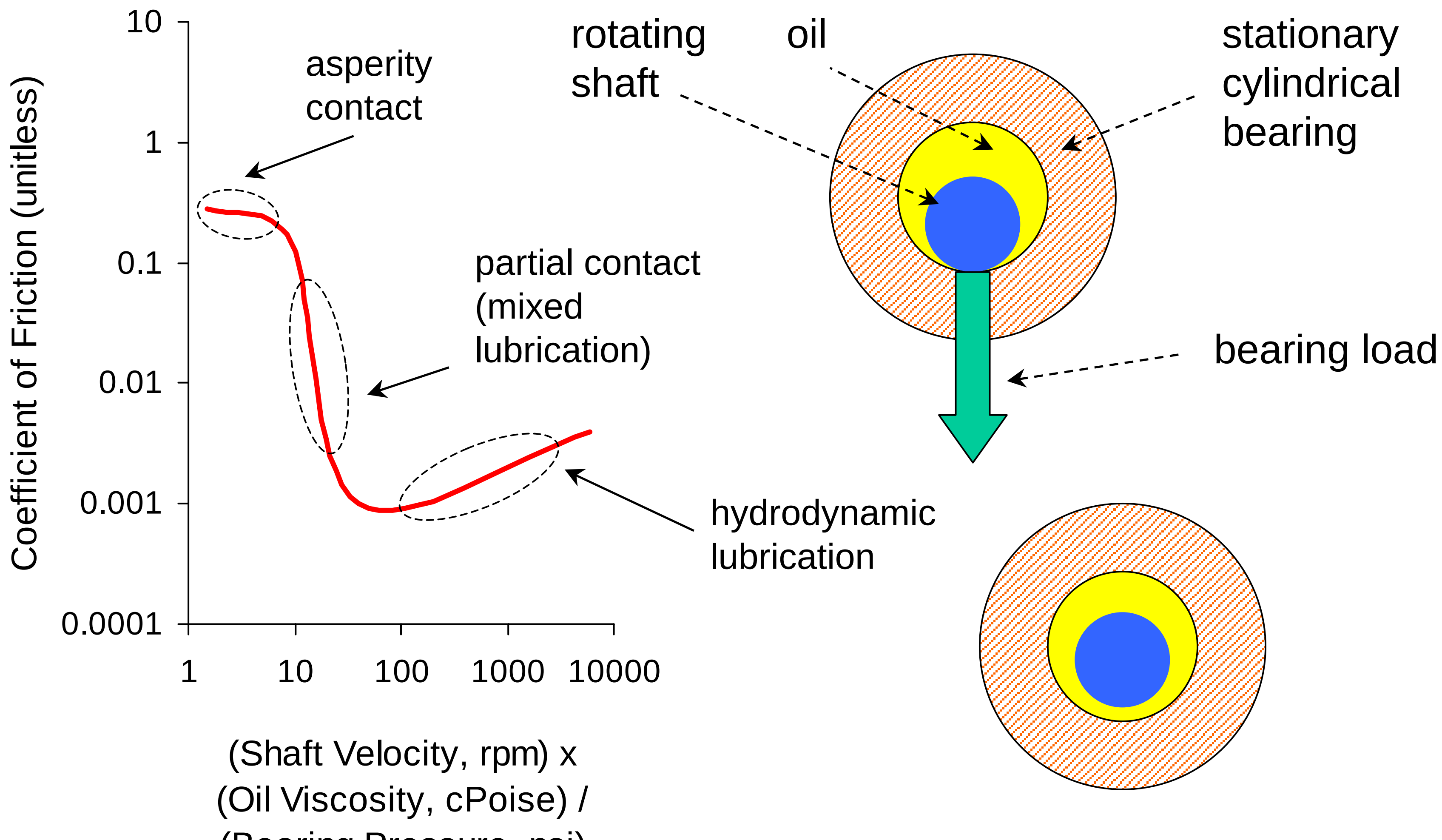
Platen Speeds & pH values

(Fluid = H_2O with In-Situ Conditioning)



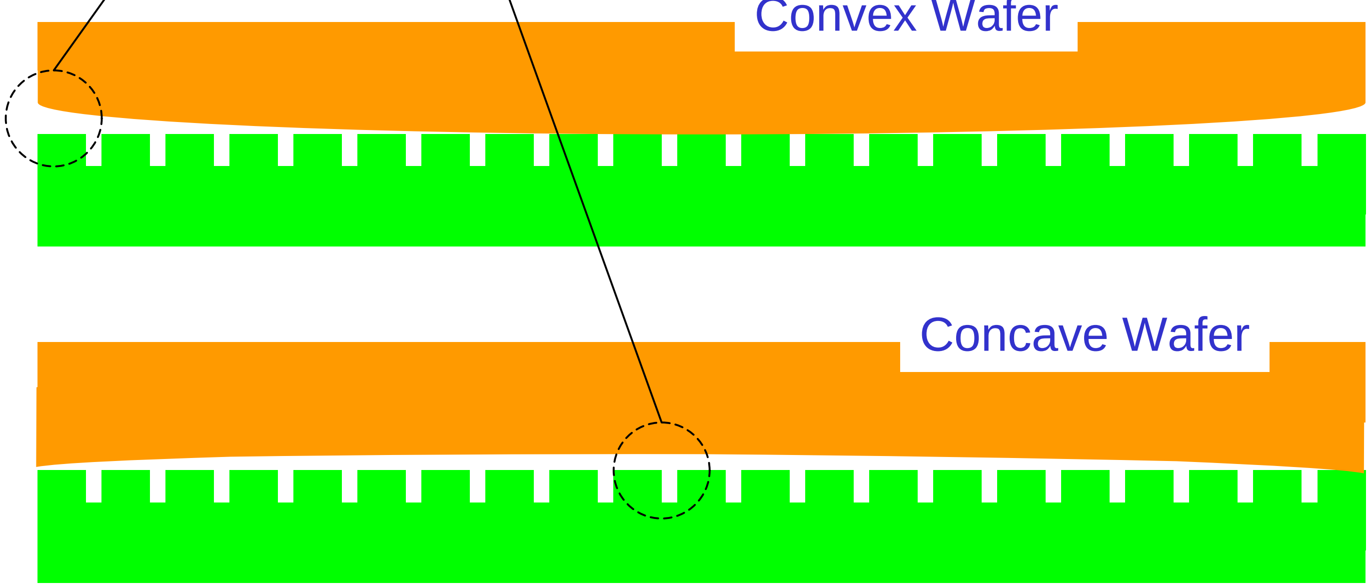
Lubrication in Journal Bearings … Stribeck Curve

Marks' Standard Handbook for Mechanical Engineers, Edited by Avallone & Baumeister, Tenth Edition, McGraw-Hill (1995)



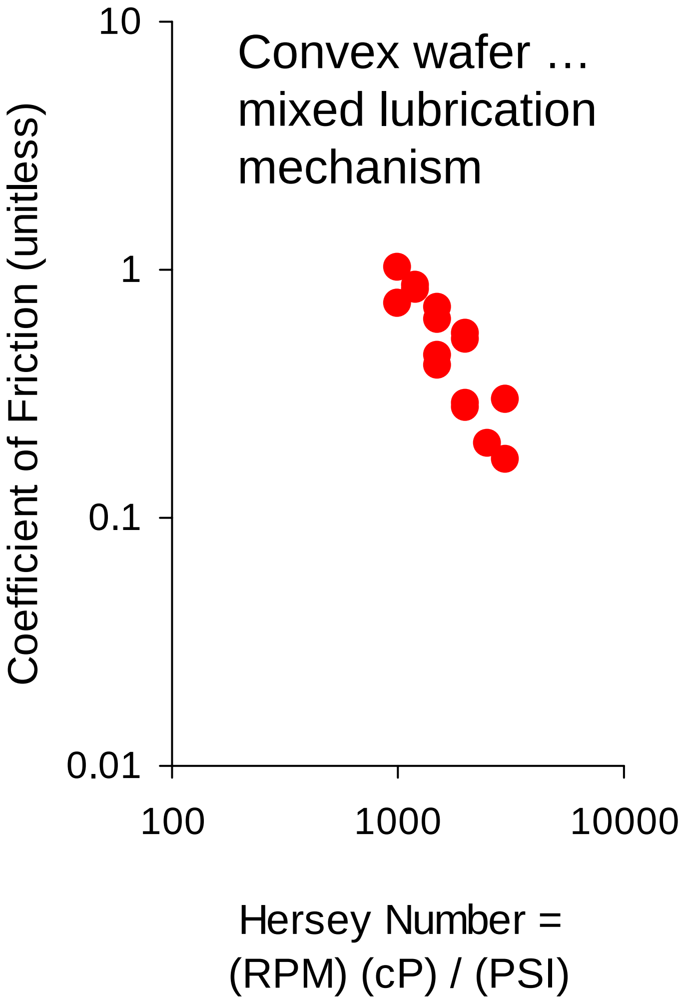
Wafer Shape Effects

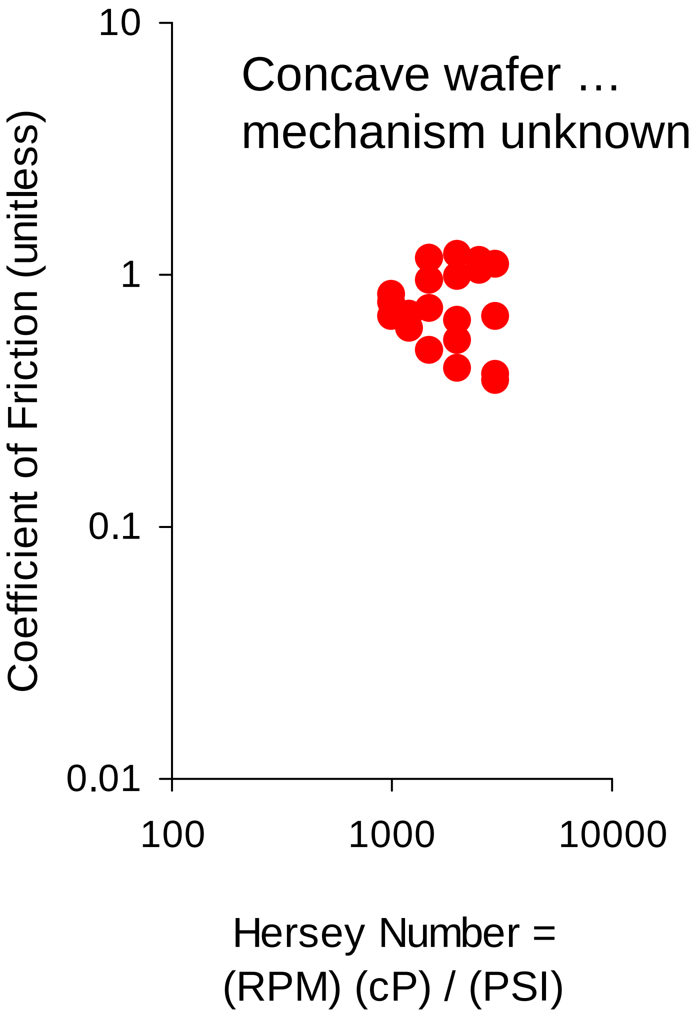
In both cases, the amplitude is ~ 5 micron



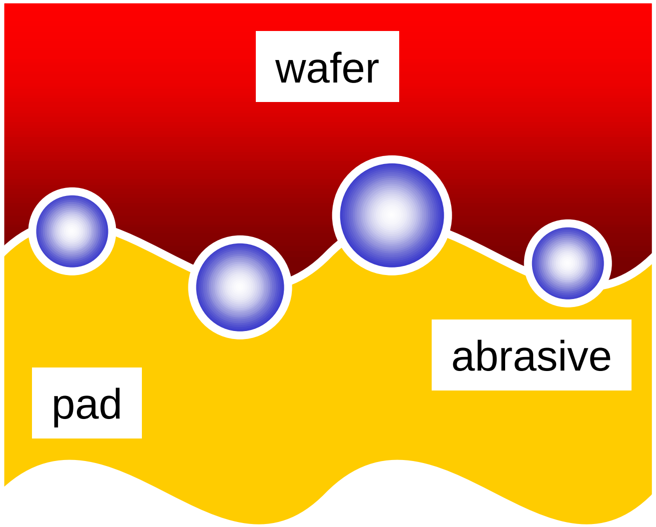
Coefficient of Friction and the Stribeck Curve

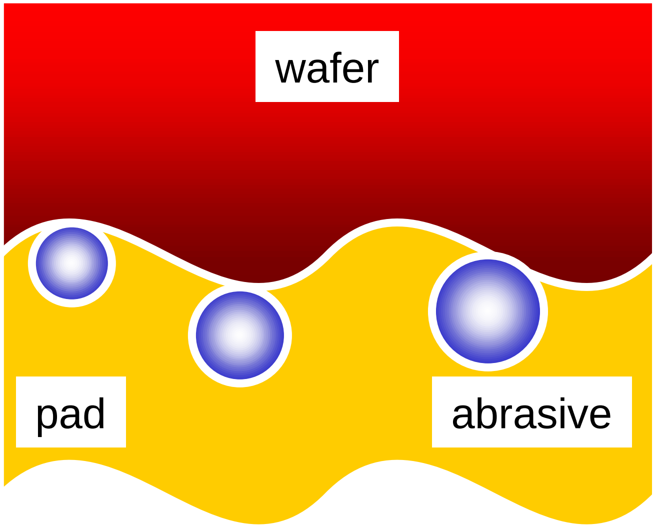
Determination of the Tribological Mechanism





Possible Asperity Contact Models





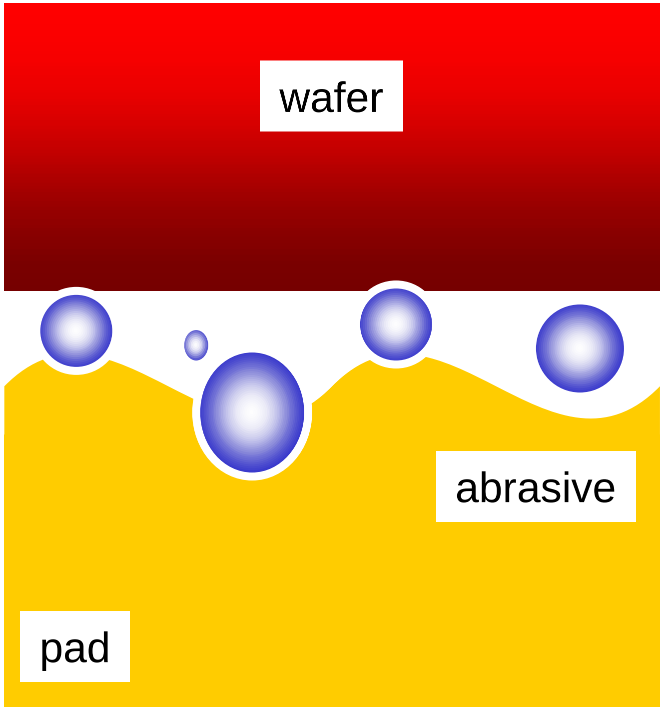
MODEL - I

3-body asperity contact model

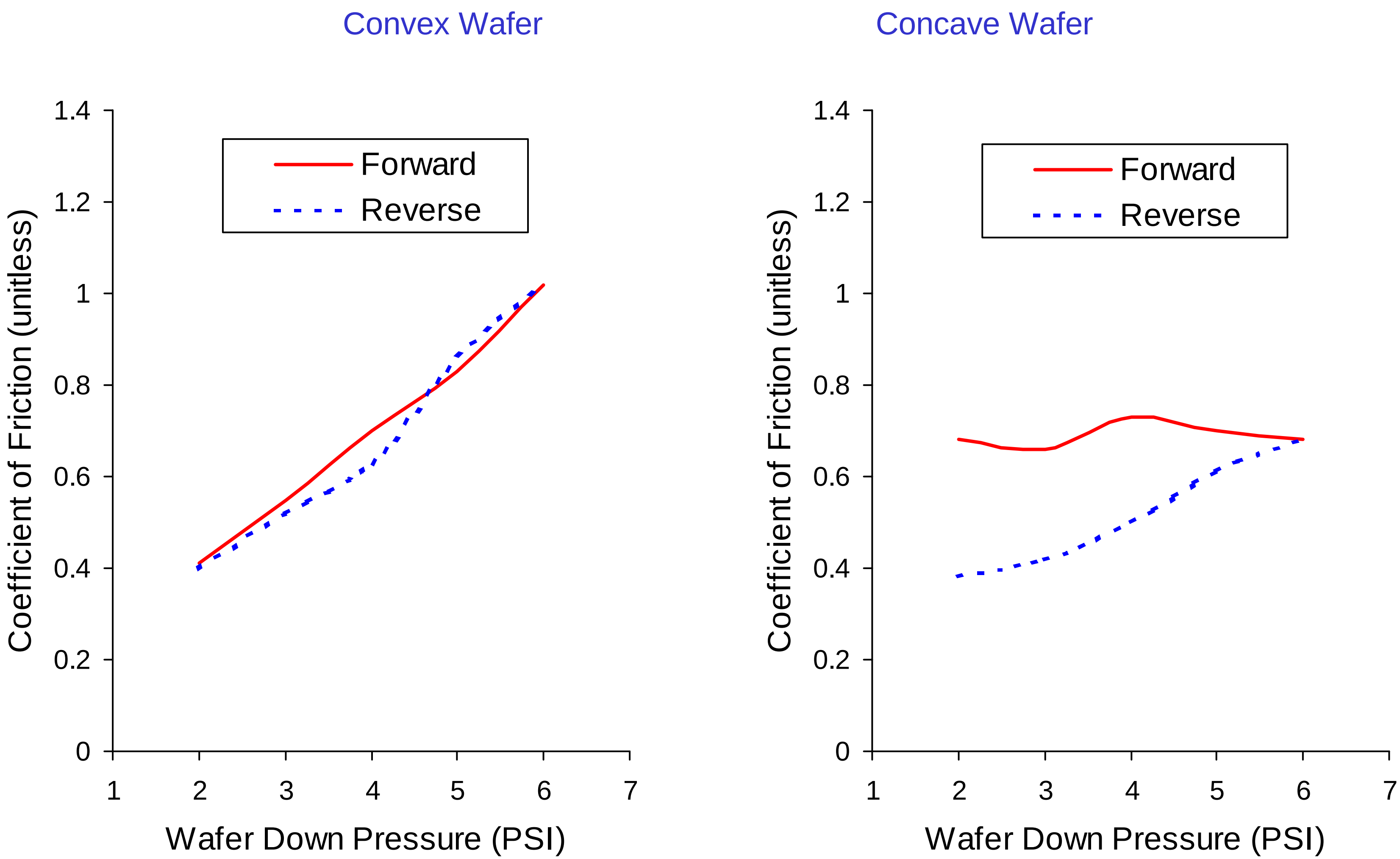
MODEL - II

2-body asperity contact model

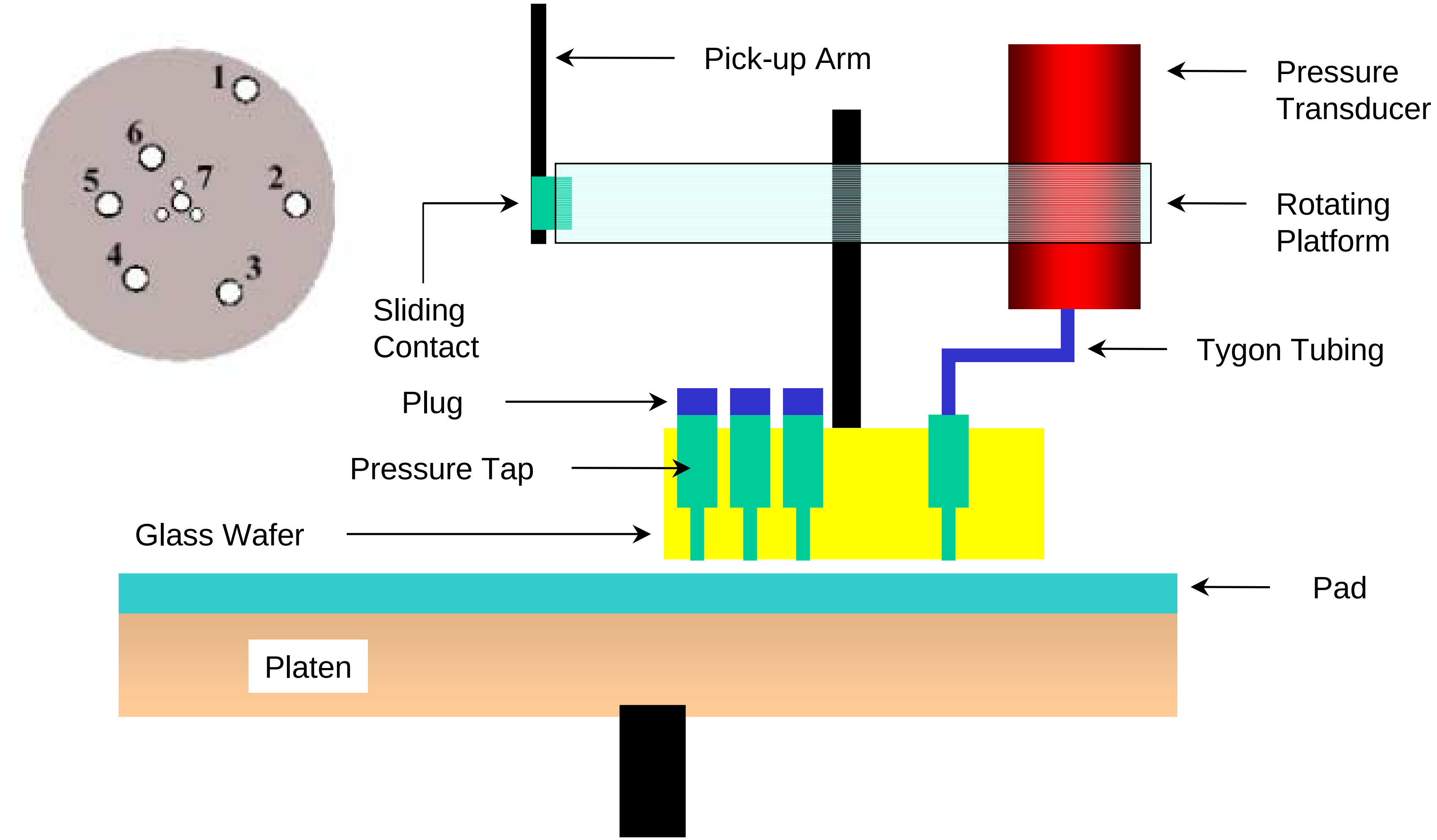
Partial Contact (Mixed Lubrication) Model



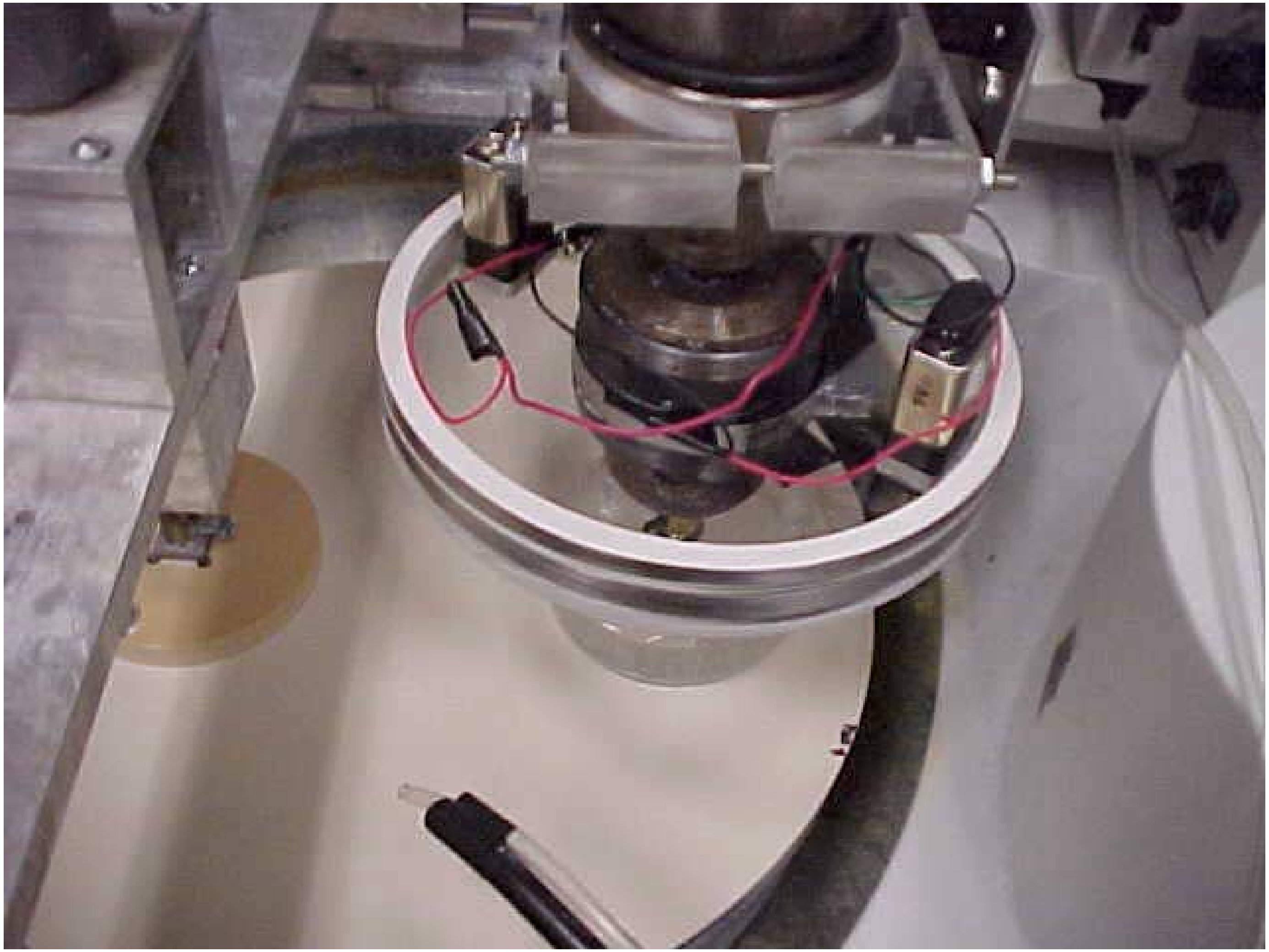
Coefficient of Friction vs. Wafer Down Pressure



Pressure Measurement Apparatus & Location of Pressure Taps on the Wafer



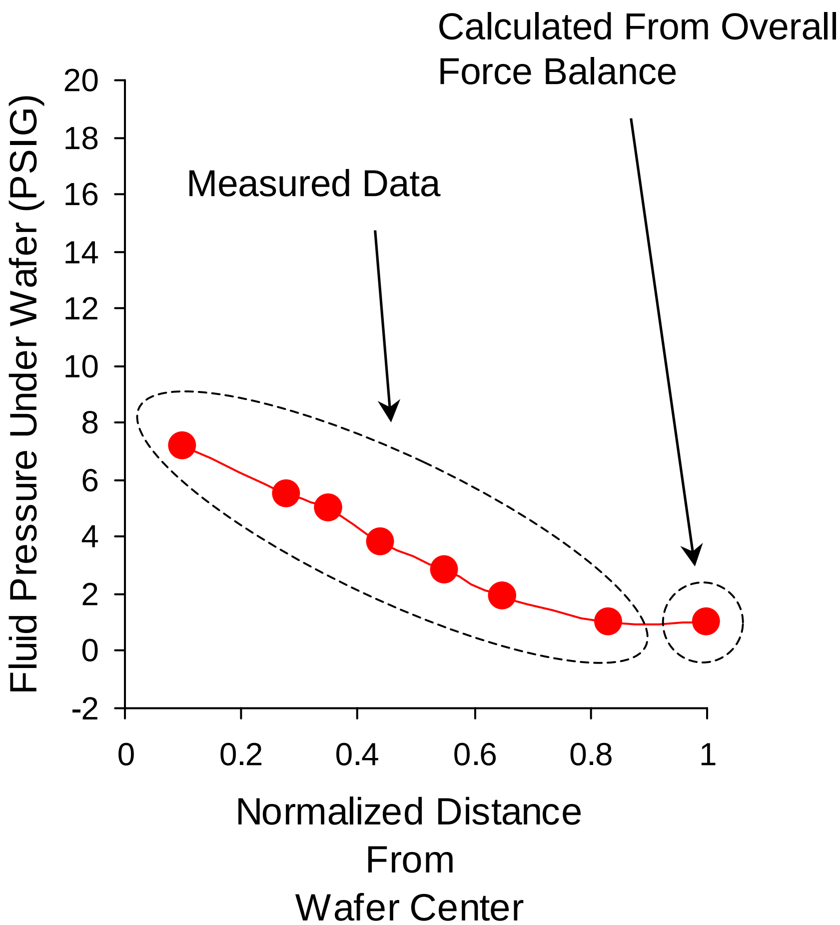
Pressure Measurement Apparatus



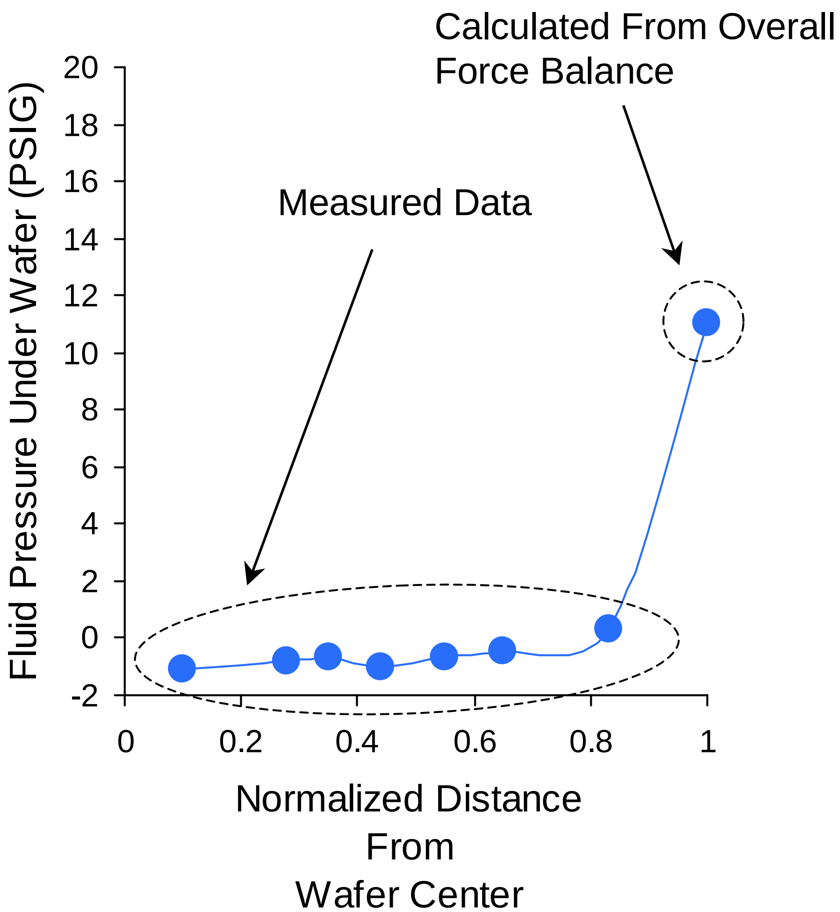
Average Fluid Pressure vs. Wafer Radius

Platen Speed = 60 RPM ; Wafer Pressure = 3 PSI

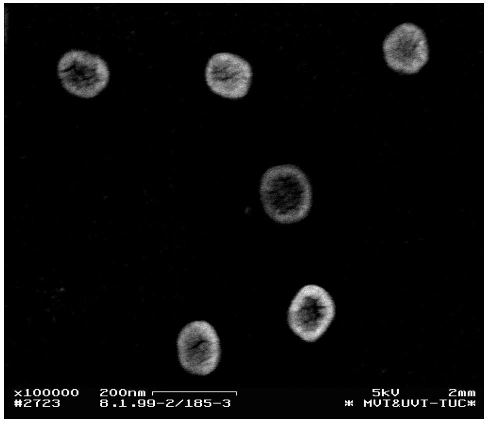
Convex Wafer



Concave Wafer



Varieties of Fumed Silica Slurry



Courtesy of
Degussa-Huls AG