Development of an Integrated Model for Chemical-Mechanical Planarization (CMP)

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CMP 2001 Symposium
October 11, 2001

http://www.lma.berkeley.edu

Content

- Background on CMP research at Berkeley
- Modeling work and roadmap
- A Comprehensive Material Removal Model
- Experimental Validation
- Conclusions & Future Work

Acknowledgements

Researchers: Serdar Aksu, Uday Ayyagari, Andrew Chang, Edward Hwang, Sunghoon Lee, Jianfeng Luo, Zhoujie Mao

Research sponsors: UC SMART/SFR, NSF, and NSF/SRC ERC at Univ of Arizona, Applied Materials

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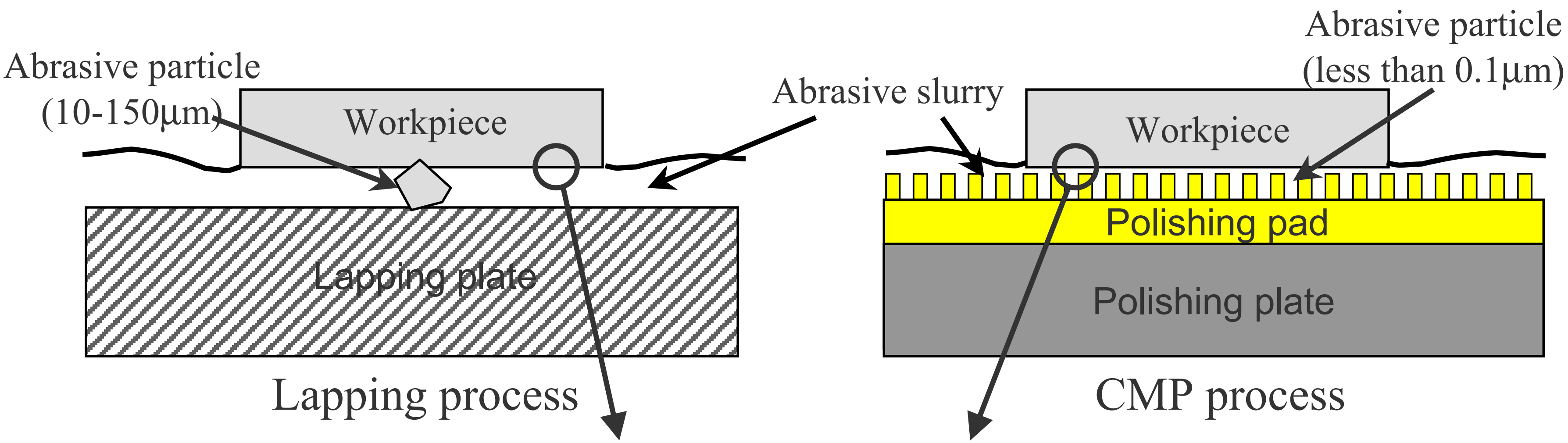
Major Thrusts of Research at Berkeley

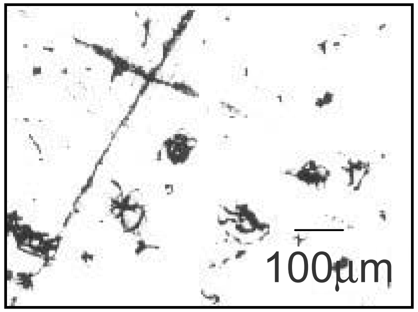
- Integrated model of CMP ✓
  - mechanical elements (abrasive size, shape, dist'n, pad characteristics- hardness and roughness, pressure, velocity, etc.)
  - chemical elements integration
  - validation/software "packaging" for CAD
- AE-based process feedback and optimization
- Consumable/surface design ✓
- Metrology (scatterometry) for profile development
- Environmental modeling

Polishing and CMP

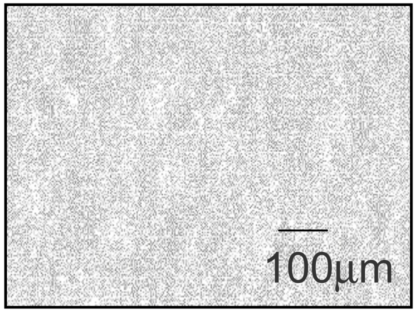


Lapping process

CMP process



Soda lime glass surface
by lapping



Silicon wafer surface
by CMP

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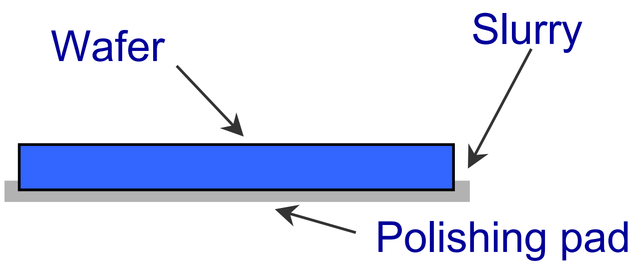
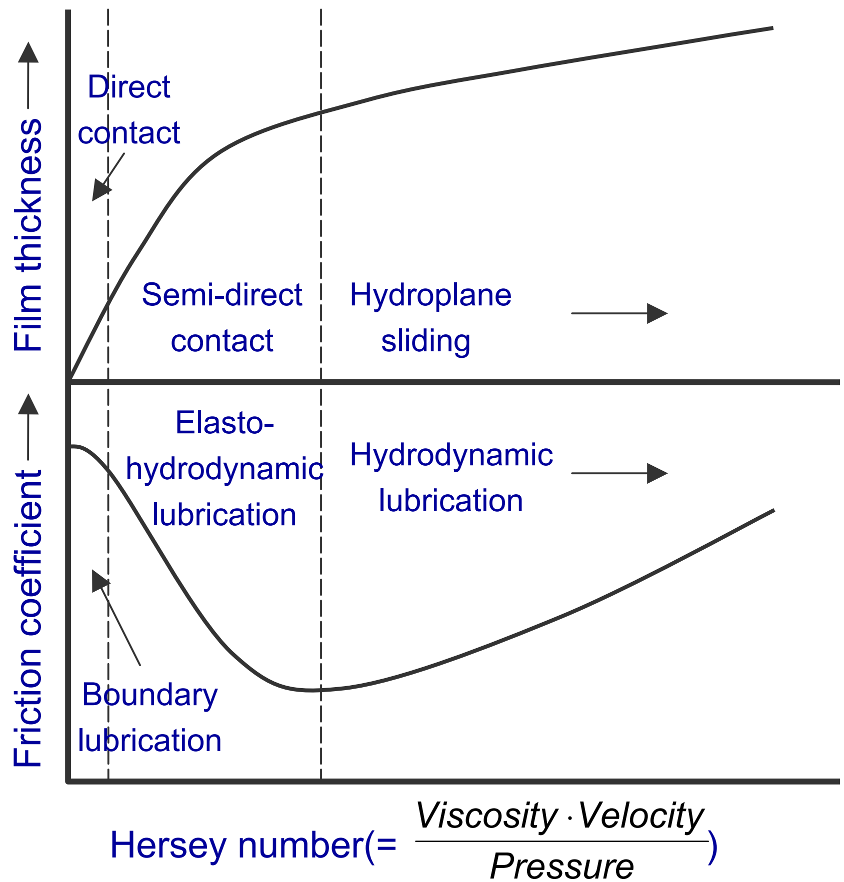
Characteristics of slurry film thickness



Direct contact

Semi-direct contact

Hydroplane sliding



Stribeck curve

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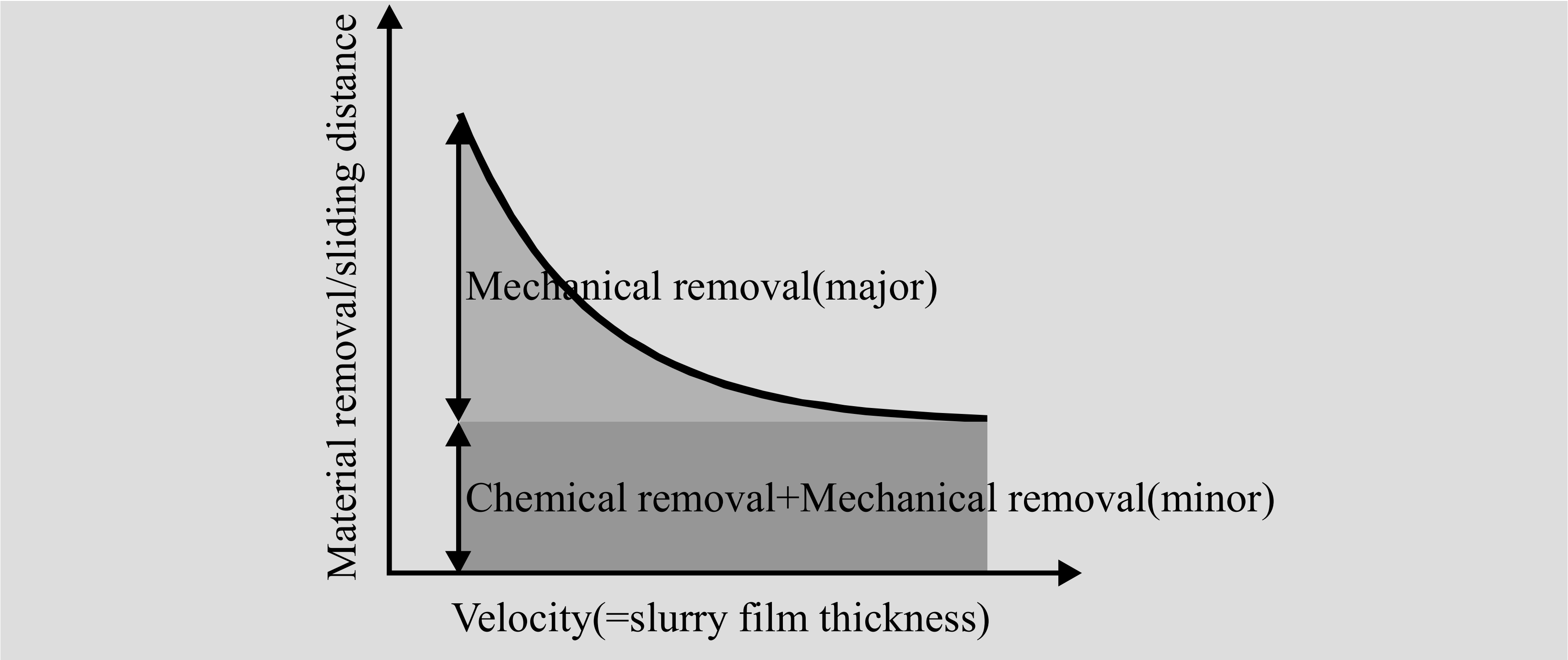
Mechanical and Chemical Material Removal Effects vs Slurry Film Thickness



Source: Yongsik Moon and David A. Dornfeld, "Investigation of Material Removal Mechanism and Process Modeling of Chemical Mechanical Polishing (CMP)," Engineering Systems Research Center (ESRC), Technical Report 97-11, University of California at Berkeley (September 1997)

Effect of gap on CMP - material removal

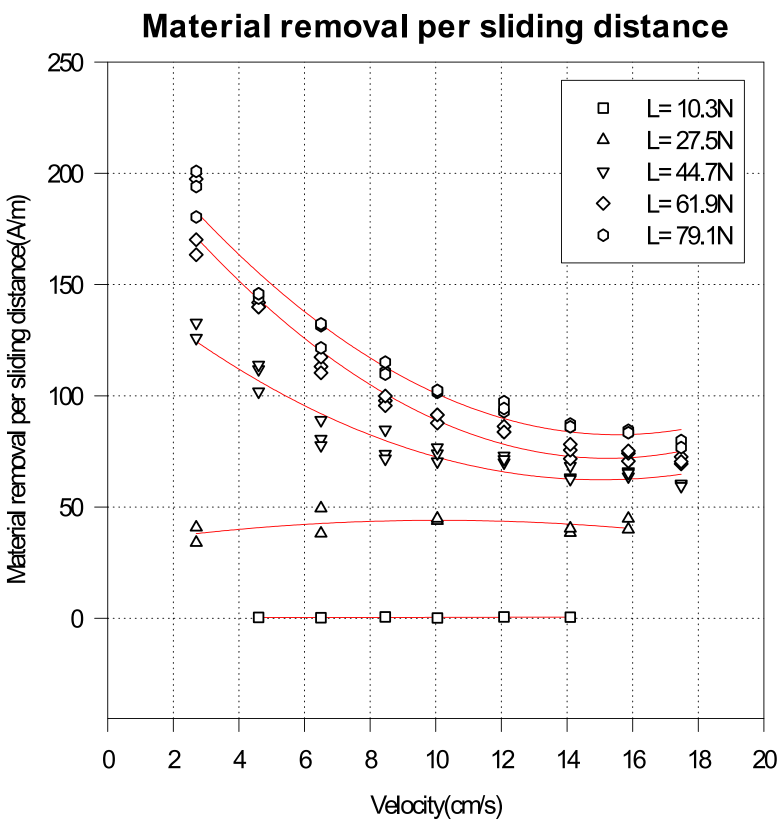
- Material removal per sliding distance

Preston's equation:

$$\frac{\Delta h}{\Delta t} = C \cdot P \cdot V = C \cdot P \cdot \frac{\Delta s}{\Delta t}$$

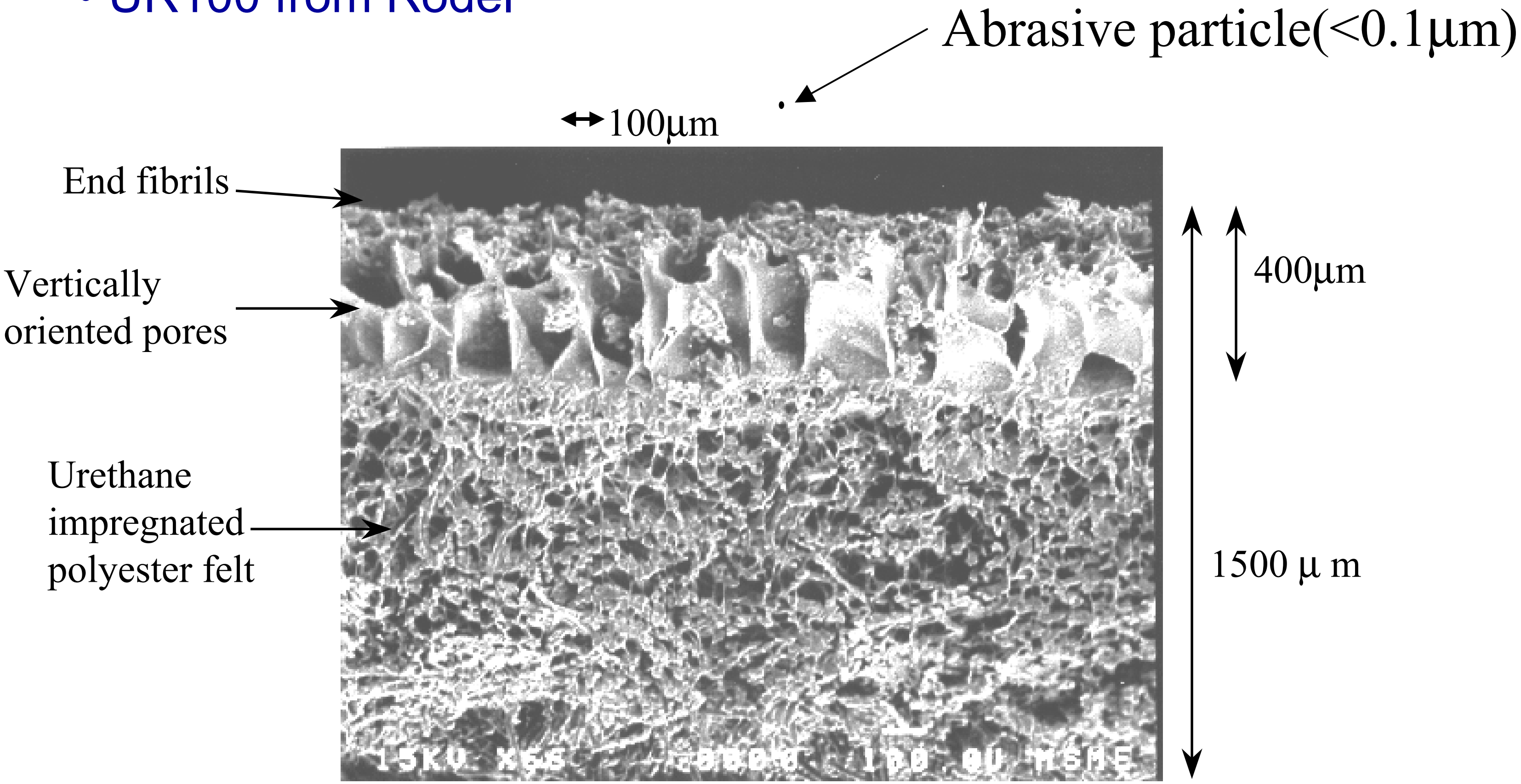
$$\frac{\Delta h}{\Delta s} = C \cdot P$$

(C=Preston's coefficient
P = pressure, V=velocity,
h=removed height, s=sliding distant
t= time)

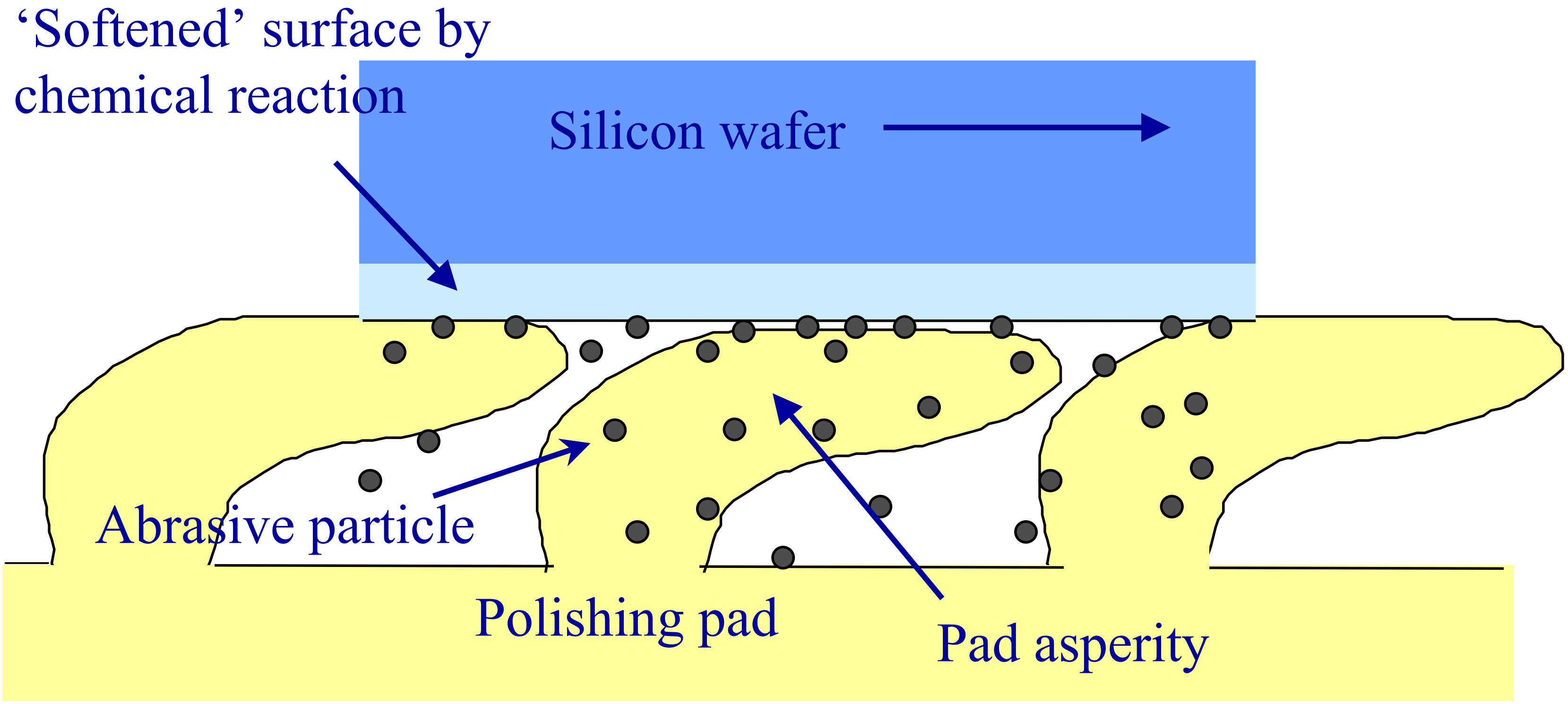


Scale effects – Abrasives/Pad

- UR100 from Rodel



Idealized CMP



Mechanical Aspects of the Material Removal Mechanism in Chemical Mechanical Polishing (CMP)

CMP Parameters

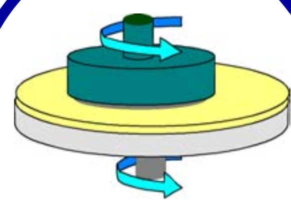
Input Parameters

Pad
Fiber Structure Conditioning
Compressibility Modulus

Slurry
pH Oxidizers
Buffering Agents, Abrasive Concentration
Abrasive Geometry and Size Distribution

Wafer Geometry and Materials

Process
Pressure Velocity
Temperature Slurry Flow
Polish Time



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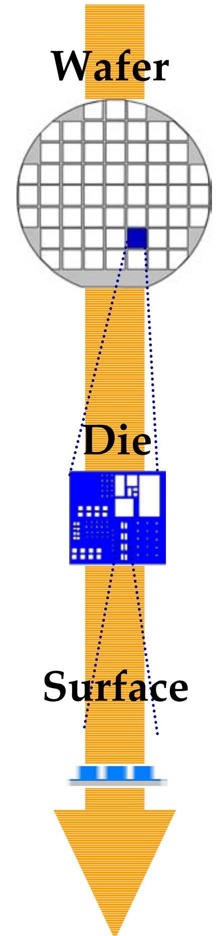
Output Parameters

Material Removal

WIWNU
(Within-Wafer Non-Uniform Material Removal)

WIDNU
(Within-Die Non-Uniform Material Removal)

Surface Quality
Roughness, Scratching



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CMP Modeling Roadmap

Objectives from Industrial Viewpoint - VMIC 2001

- Models are not reliable enough to be used as verification of process
- Usefulness of modeling is the ability to give feedback for “what-if” scenarios (predicting “polishability” of new mask designs) in lieu of time-consuming DOE tests
- Models should give some performance prediction for realistic, heterogeneous pattern effects
- Models should predict not only wafer scale phenomena but also have some capability to capture feature/chip scale interaction

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Roadblocks for Modeling

- Multi-scale (wafer-, die-, feature-level) interactions must be integrated for global CMP modeling to be useful
- Linkage of models to upstream (deposition, etc.) and downstream (lithography,etc.) processes
- Models need to address defectivity
- New materials, consumables (pad, slurry, etc.) modeling and characterization

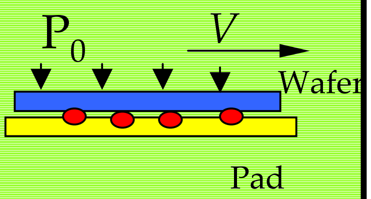
Literature Review of Modeling of CMP

		MRR			Non-uniformity	Slurry/Water usage	Abrasive Concentration	Other Chemical Effluent	Energy	References
		Wafer Level	Feature Level	Die Level						
Empirical Model	Preston	✓			✓				✓	Preston, 1927
	Boning		✓		✓				✓	Boning, *et al*, 1997-1998 (4)
	Others		✓	✓	✓				✓	Various (10) incl. Burke, Runnels, Zhao
Individual Model	Tribology	✓	✓		✓				✓	Various (11)
	Kinematic	✓			✓				✓	Various (2)
	Pad	✓			✓				✓	Various (4)
	Chemical	✓			✓					Various (6)
Integrated Model		✓	✓	✓	✓	✓	✓	✓	✓	

Past 2-D Material Removal Rate (MRR) Models

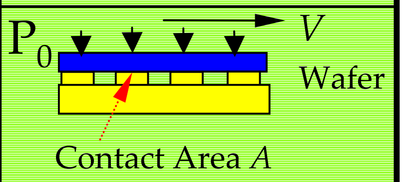
- **Experimental Model [1]: Preston's Equation**

  $MRR = K_e P_0 V + MRR_0$ *where* K_e *an all-purposed coefficient,* MRR_0 *a fitting parameter,* P_0, *Down pressure, and V, the relative Velocity.*



- **Analytical Model Considering Wafer-Pad Contact Area[2]: Zhao's Equation**

  $MRR = K_e (P_0 - P_{th})^{2/3} V$, *where* P_{th} *a fitting parameter.*
  Active *abrasive number is proportional to contact area. Contact area* $\propto P_0^{2/3}$



*All with an all purpose factor K_e to represent the roles and interactions of other input variables except the down pressure and velocity

[1] Preston, 1917, J. of Glass Soc.
[2]. Zhao et. al., 1999, Applied Physics

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Motivations for a Comprehensive Material Removal Model

- Identify the most important input parameters related to Slurry Abrasives, Wafer, and Polishing Pad except the down pressure P_0 and velocity V
- Investigate the interactions between the input parameters
- Develop material removal rate formulation to consider the roles of the input parameters and their interactions
- Model as a basis for process design and optimization (including environmental impacts)

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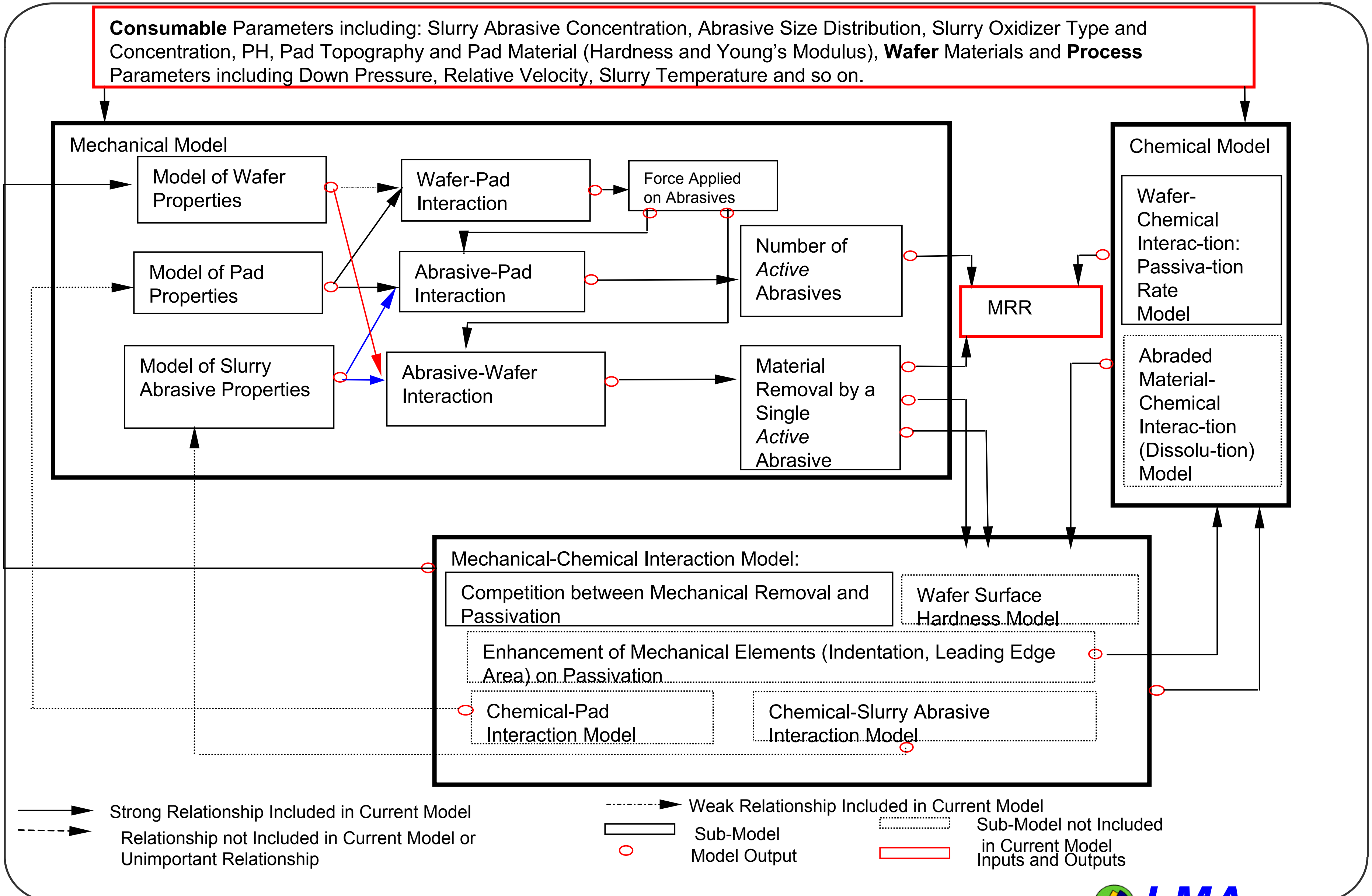
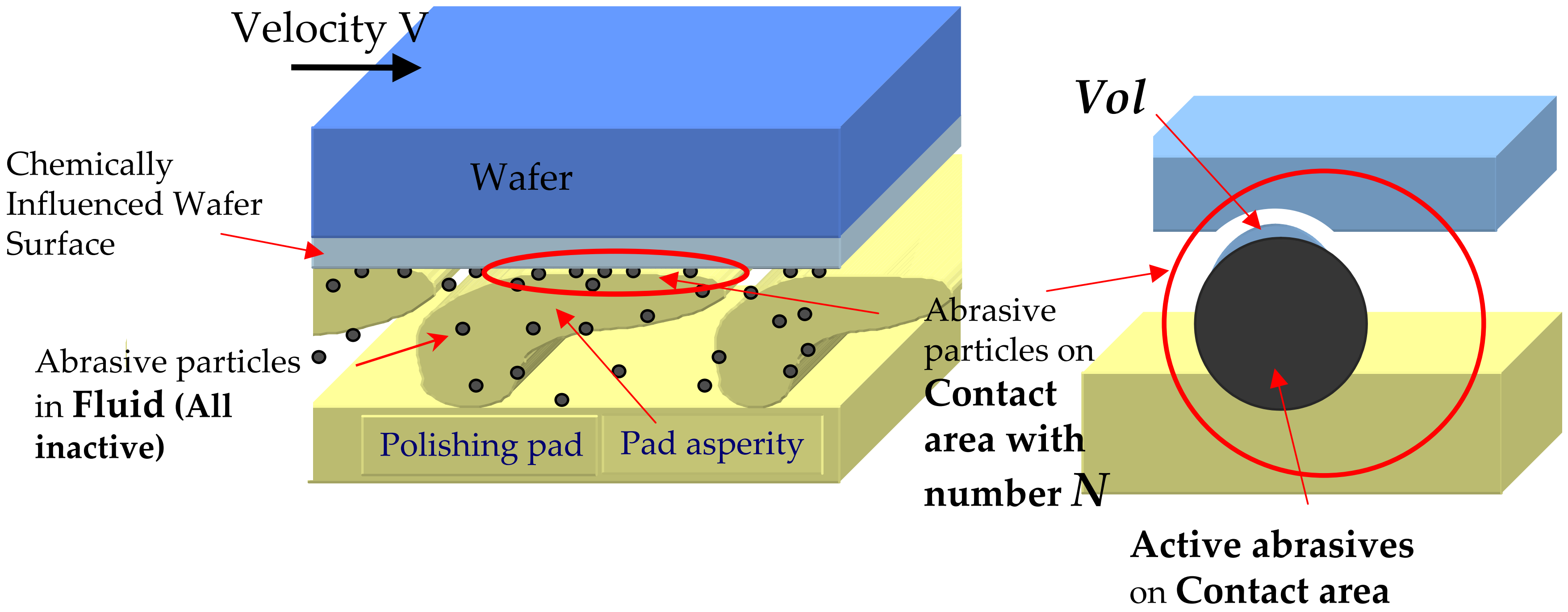

Consumable Parameters including: Slurry Abrasive Concentration, Abrasive Size Distribution, Slurry Oxidizer Type and Concentration, PH, Pad Topography and Pad Material (Hardness and Young's Modulus), **Wafer** Materials and **Process** Parameters including Down Pressure, Relative Velocity, Slurry Temperature and so on.
Mechanical Model
Model of Wafer Properties
Wafer-Pad Interaction
Force Applied on Abrasives
Model of Pad Properties
Abrasive-Pad Interaction
Number of *Active* Abrasives
Model of Slurry Abrasive Properties
Abrasive-Wafer Interaction
Material Removal by a Single *Active* Abrasive
MRR
Chemical Model
Wafer-Chemical Interac-tion: Passiva-tion Rate Model
Abraded Material-Chemical Interac-tion (Dissolu-tion) Model
Mechanical-Chemical Interaction Model:
Competition between Mechanical Removal and Passivation
Wafer Surface Hardness Model
Enhancement of Mechanical Elements (Indentation, Leading Edge Area) on Passivation
Chemical-Pad Interaction Model
Chemical-Slurry Abrasive Interaction Model
Strong Relationship Included in Current Model
Relationship not Included in Current Model or Unimportant Relationship
Weak Relationship Included in Current Model
Sub-Model
Model Output
Sub-Model not Included in Current Model
Inputs and Outputs

Chemical Aspects of CMP

- Chemical and electrochemical reactions between material (metal, glass) and constituents of the slurry (oxidizers, complexing agents, pH)
  - Dissolution and passivation
- Solubility
- Adsorption of dissolved species on the abrasive particles
- Colloidal effects
- Change of mechanical properties by diffusion & reaction of surface

Interactions between Input Variables

Four Interactions: Wafer-Pad Interaction; Pad-Abrasive Interaction; Wafer-Slurry Chemical Interaction; Wafer-Abrasive Interaction



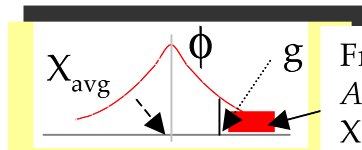
Source: J. Luo and D. Dornfeld, IEEE Trans: Semiconductor Manufacturing,, 2001

Framework Connecting Input Parameters with Material Removal Rate

Basic Equation of Material Removal: $MRR = N \times Vol$

N

- Slurry Abrasive Weight Concentration C
- Average Abrasive Size X_{avg}
- Proportion of *Active* Abrasives



Fraction of *Active* Abrasives X_{avg-a}

Fraction of *Active* Abrasive: $1-\phi((g-X_{avg})/\sigma)$ where g is the minimum size of active abrasives

Vol

- Force F & Velocity
- *Active* Abrasive Size X_{avg-a}
- Wafer Hardness H_w / Slurry Chemicals & Wafer Materials

Pad Topography & Pad Material

Abrasive Size Distribution ϕ

Down Pressure P_0

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Modeling of Pad and Wafer Interaction

Pad Surface :

- Rough and all asperities are in contact with wafer

Wafer Surface

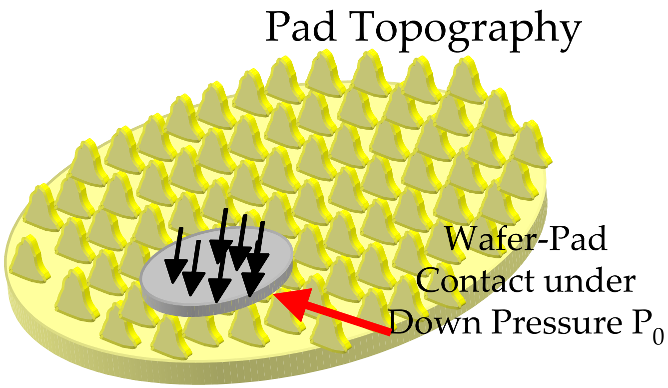
- Smooth in comparison with pad surface

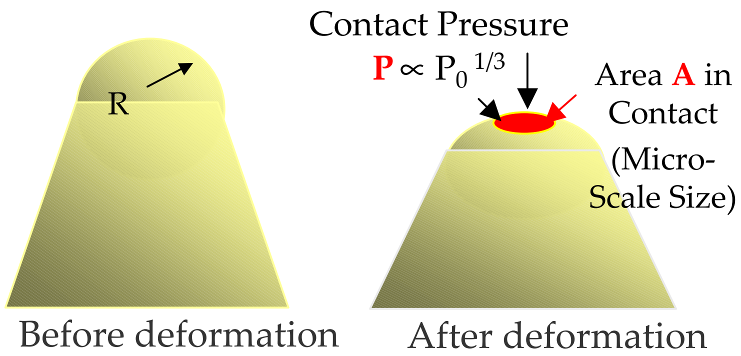
Pad Material:

- Young's Modulus E

Wafer Material

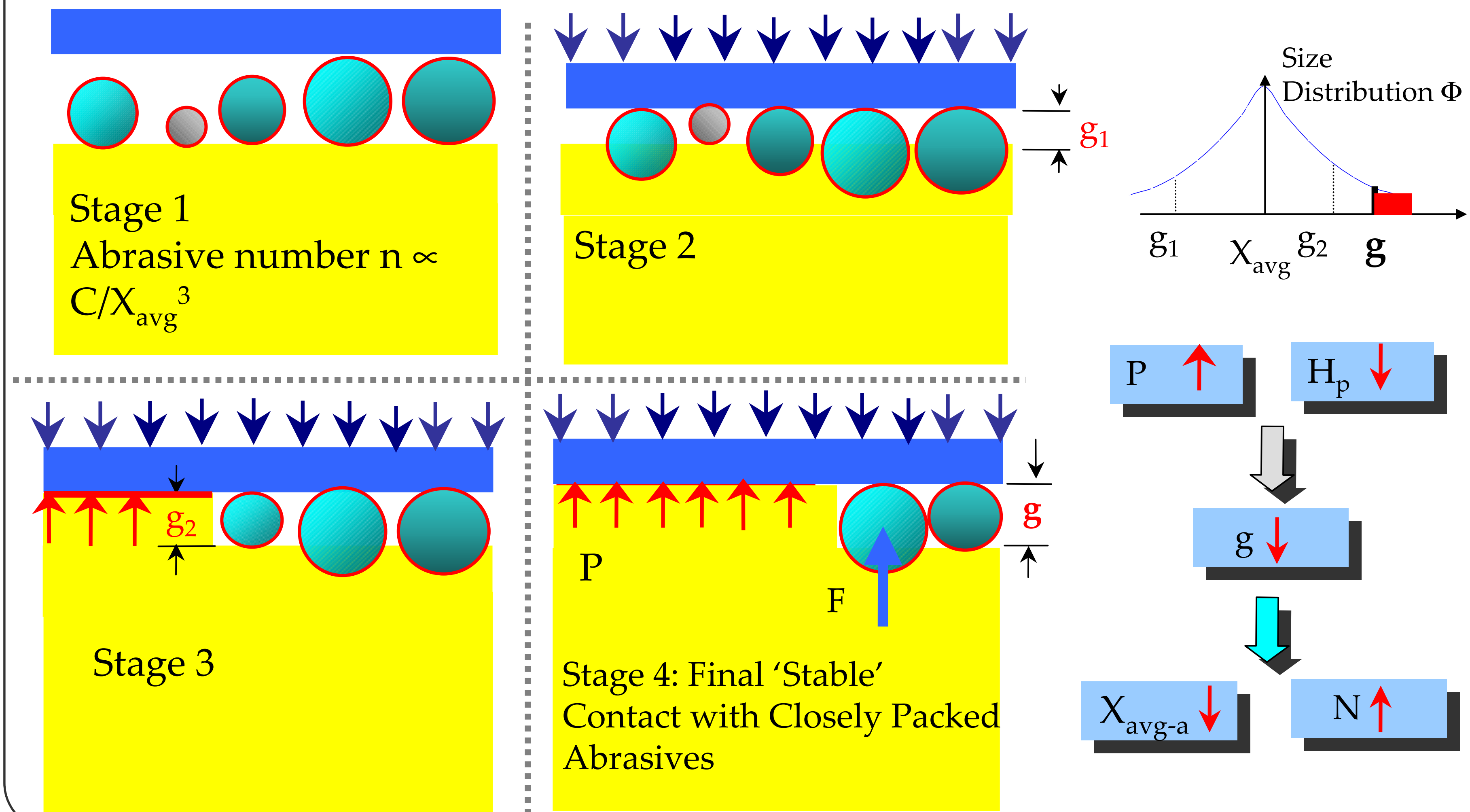
- Rigid-body in comparison with pad





An Asperity with spherical tip under Load

Modeling of Pad-Abrasive Interactions on the Contact Area: Fraction of *Active* Abrasives



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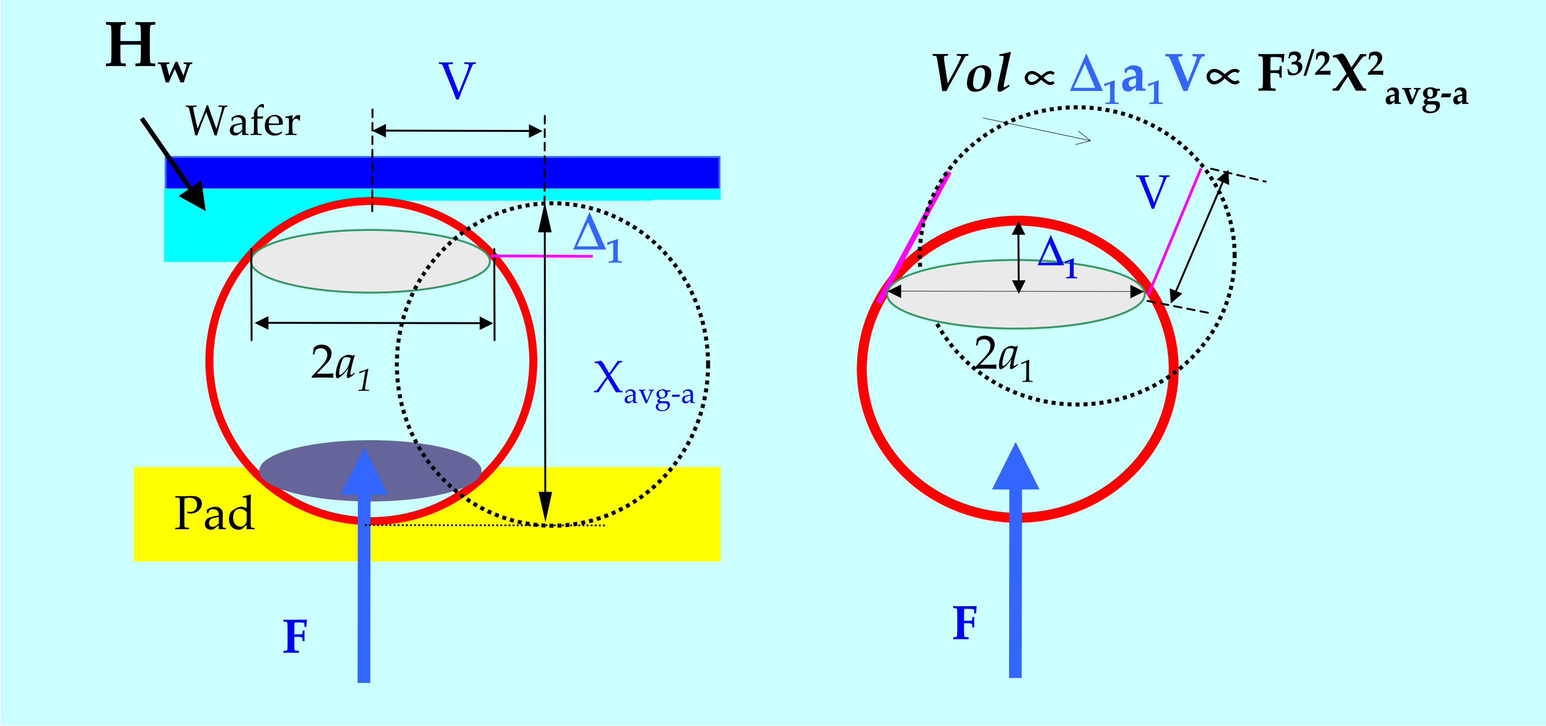
Interaction Between Wafer and Abrasive: Material *VOL* Removed by a Single Abrasive



Model of Material Removed by a Single Abrasive

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Material Removal Rate as Functions of Down Pressure and Abrasive Size Distribution

$$MRR = N \times Vol = K_1 \{1-\phi(1 - K_2 P_0^{1/3})\} P_0^{1/2} V.$$

N

- Slurry Concentration C
- Average Abrasive Size X_{avg}
- Proportion of *Active* Abrasives

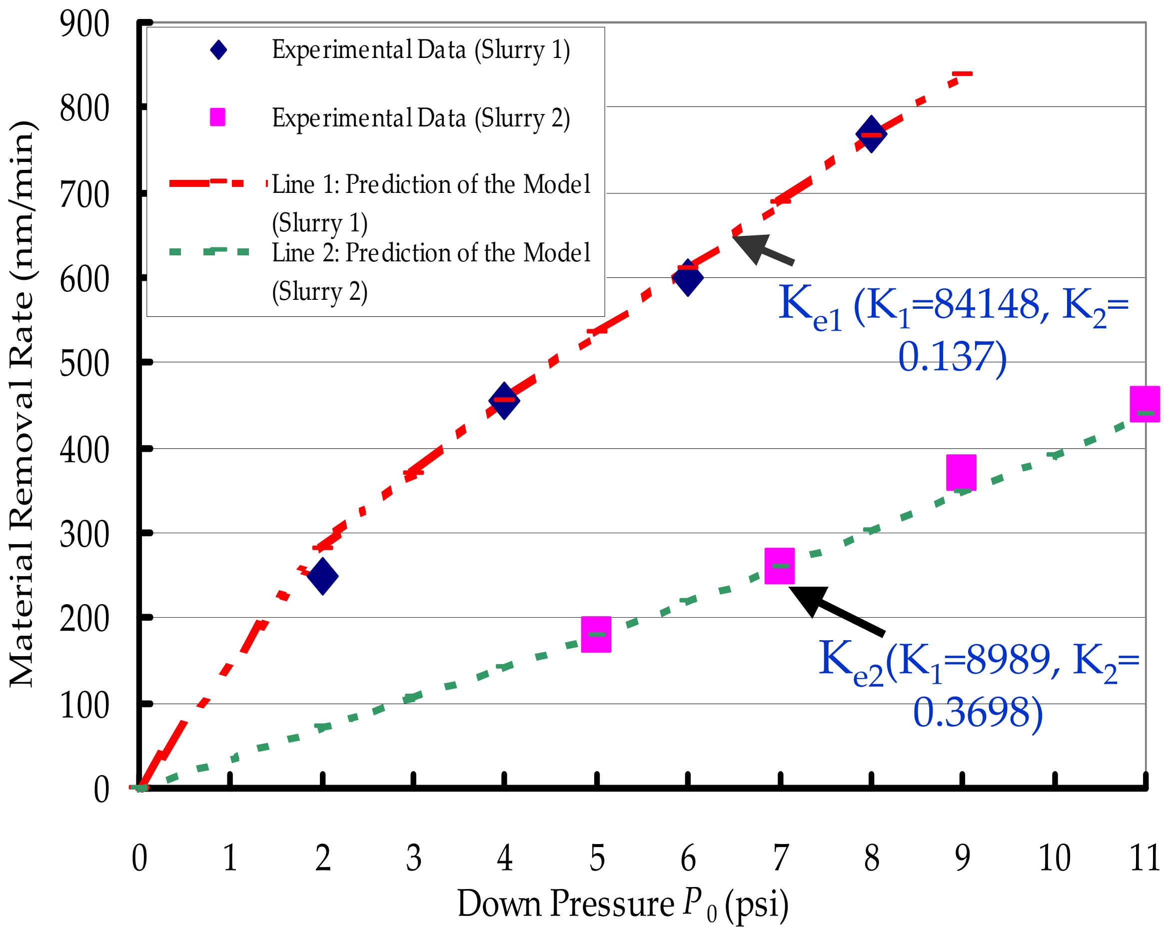
Fraction of *Active* Abrasive: $1-\phi((g-X_{avg})/\sigma)$ where g is the minimum size of active abrasives

Vol

- Force F & Velocity
- *Active* Abrasive Size $X_{avg\text{-}a}$
- Wafer Hardness H_w/ Slurry Chemicals & Wafer Materials

$$MRR = N\, Vol = K_3\, C/X_{avg}^{3}\{1-\phi(X_{avg}-g)/\sigma)\}\ X_{avg\text{-}a}^{2}$$

Experimental Verification of Pressure Dependence of Material Removal Rate (MRR) (I)



$MRR = N\ Vol = K_1 \{1-\phi(1-K_2 P_0^{1/3})\} P_0^{1/2}$.

Advantage over Preston's Eq. $MRR = K_e PV + MRR_0$:

What input variables and how they influence K_e is predicable

SiO_2 CMP Experimental Data from Zhao and Shi, Proceedings of VMIC, 1999

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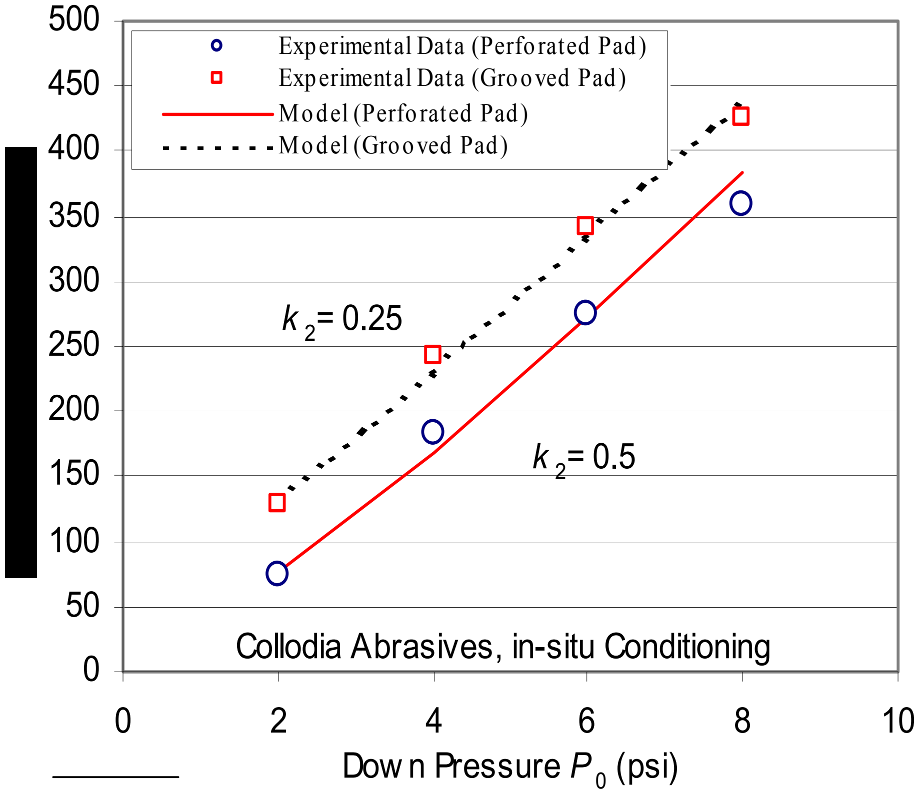
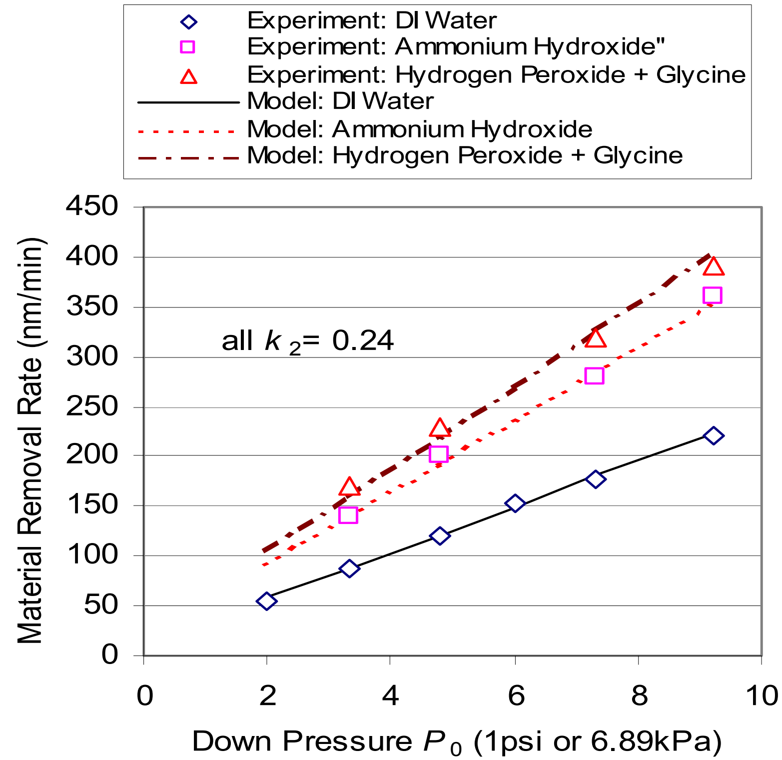
Experimental Verification of Pressure Dependence of Material Removal Rate (MRR)(II)



Experimental data from Clark et. al., CMIC, 1999.



Experimental data from Ramarajan et. al., MRS Proceedings, CMIC, 2000.

k_2 is a function of consumable factors including abrasives and polishing pad but independent of slurry chemicals. This agrees well with the model prediction.

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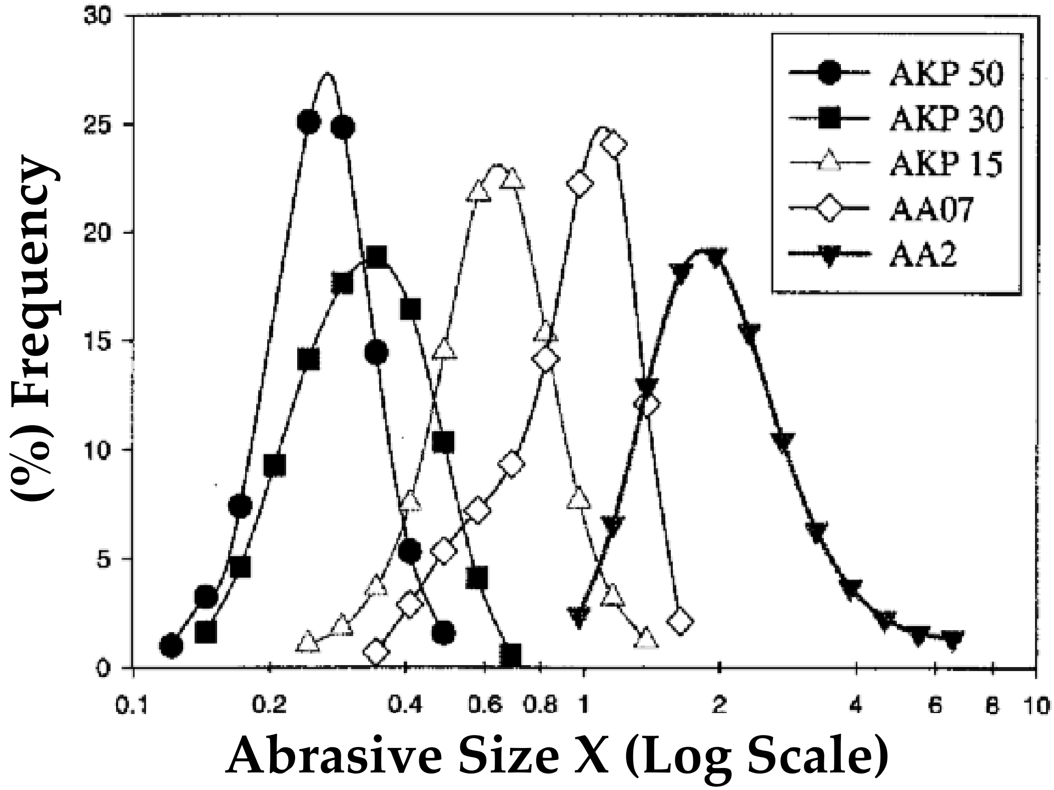
Abrasive Size Distribution Dependence of MRR:

Particle Size Distribution [1]

Five Different Kinds of Abrasive (Alumina) Size Distributions for Tungsten CMP



	Mean Size (μm)	Standard Deviation (μm)
AKP50	0.29	0.070222
AKP30	0.38	0.118959
AKP15	0.60	0.210633
AA07	0.88	0.288768
AA2	2.00	1.056197

[1]. Bielmann et. al., Electrochem. Letter, 1999

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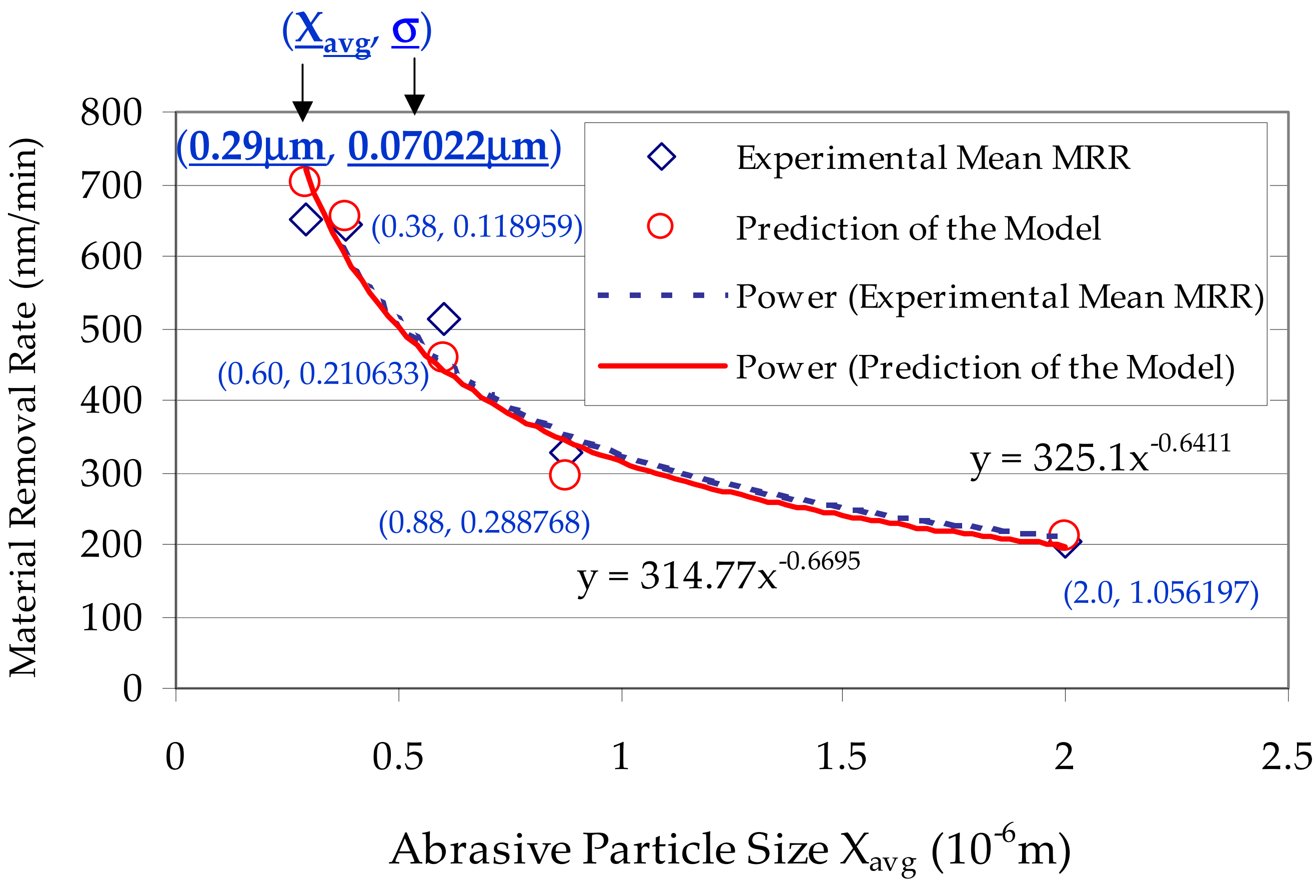
Abrasive Size Distribution Dependence of MRR:

Experiment Results [1] VS. Model Predictions

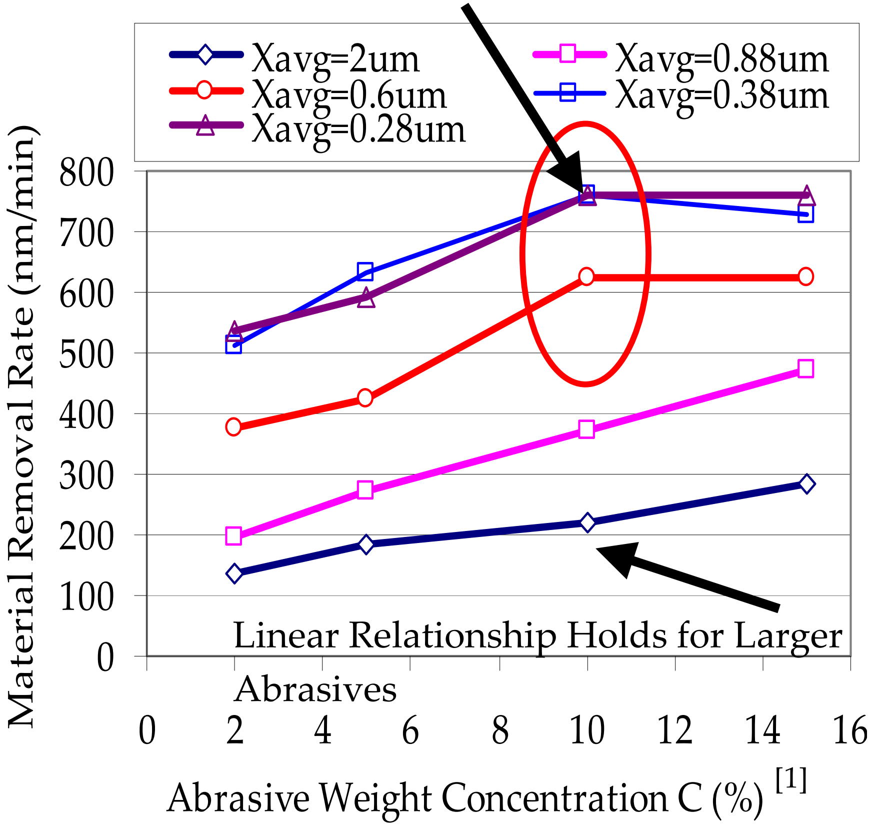


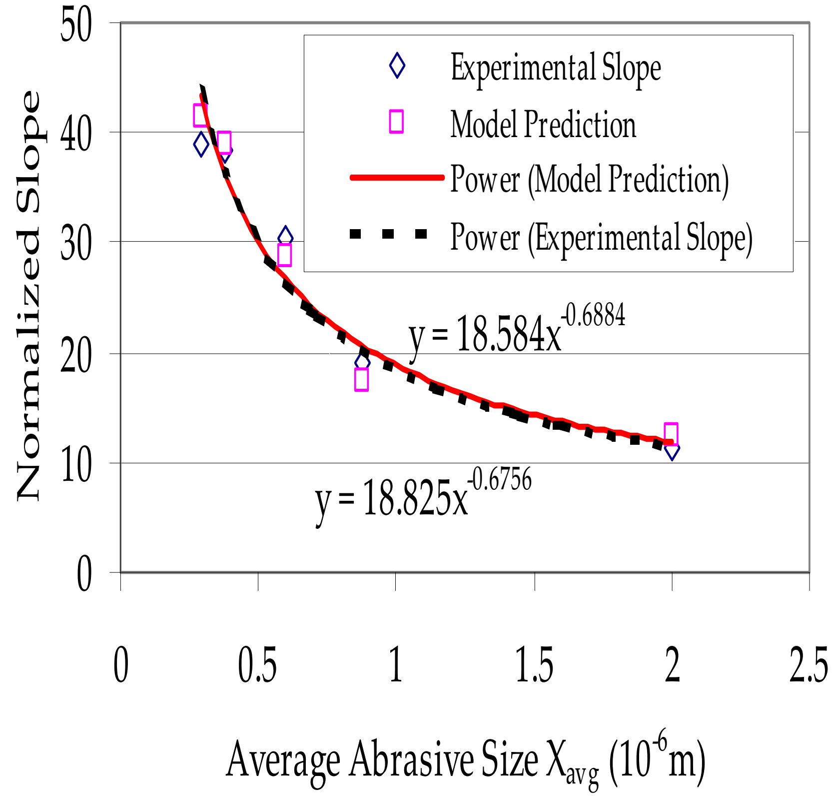
[1]. Bielmann et. al., Electrochem. Letter, 1999

Abrasive Size Distribution Dependence of MRR:

MRR as a Function of Concentration and Abrasive Size Distribution

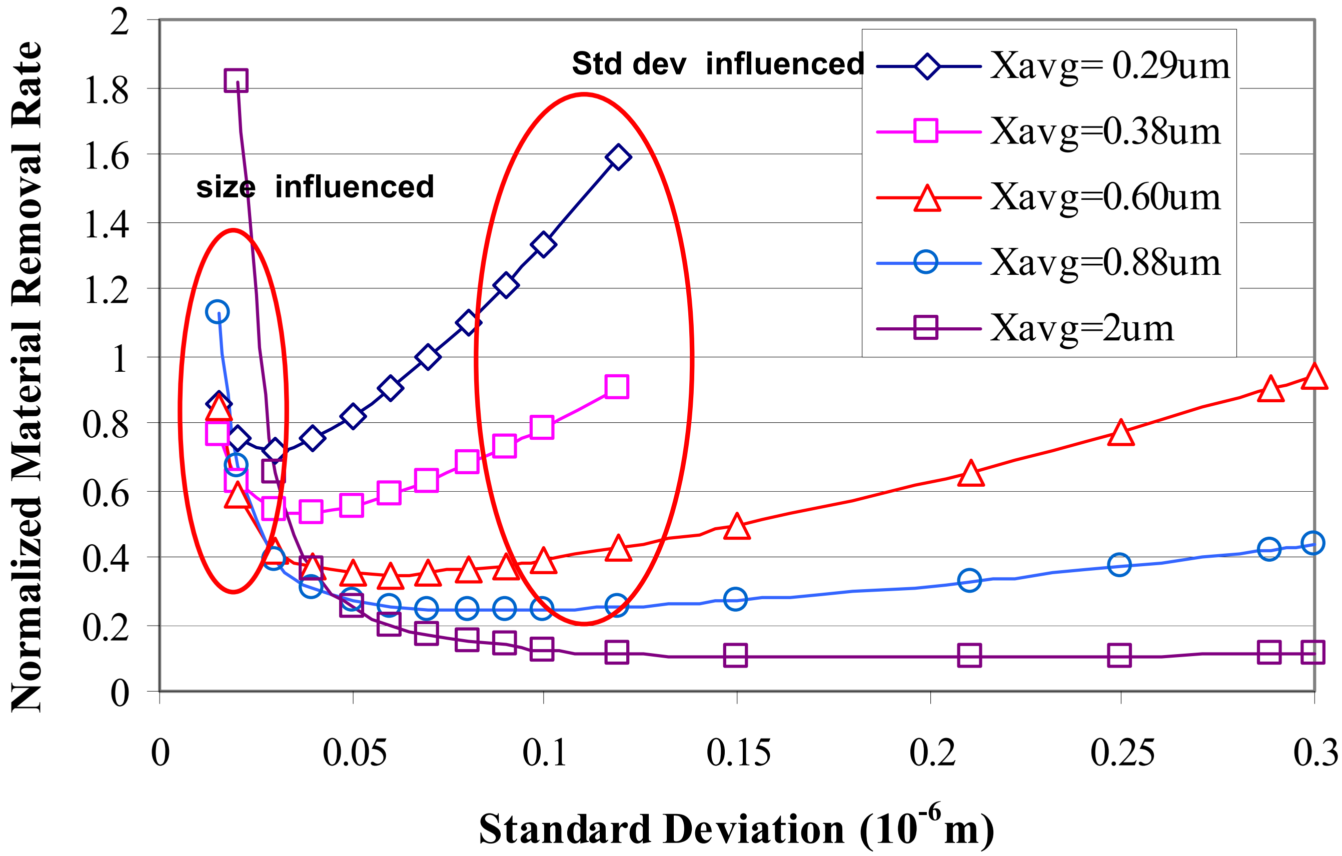
MRR Saturation at Concentration 10% for Smaller Abrasives





[1]. Bielmann et. al.., Electrochem. Letter, 1999

Relationship between Standard Deviation and MRR Based on Model Prediction



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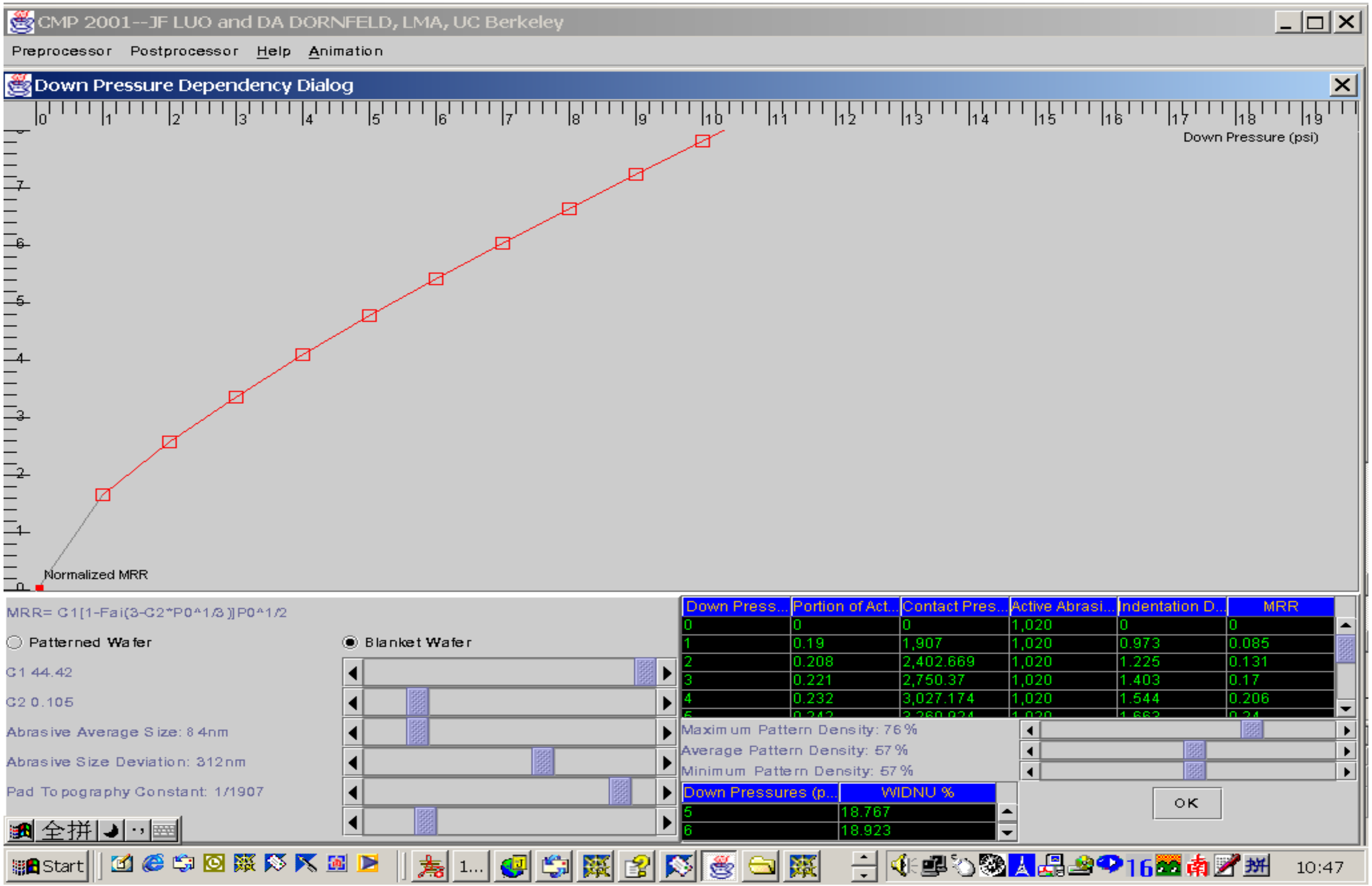
Java Implementation of CMP Optimization Software based on the Material Removal Model



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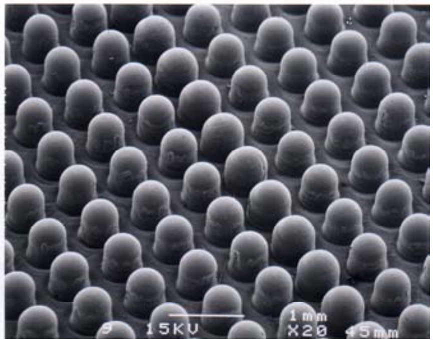
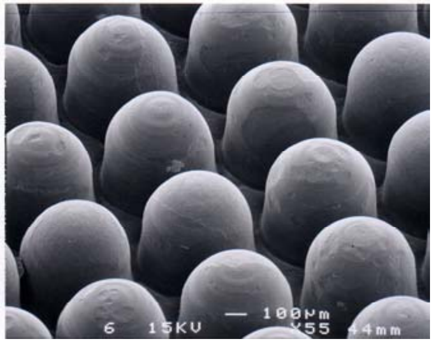
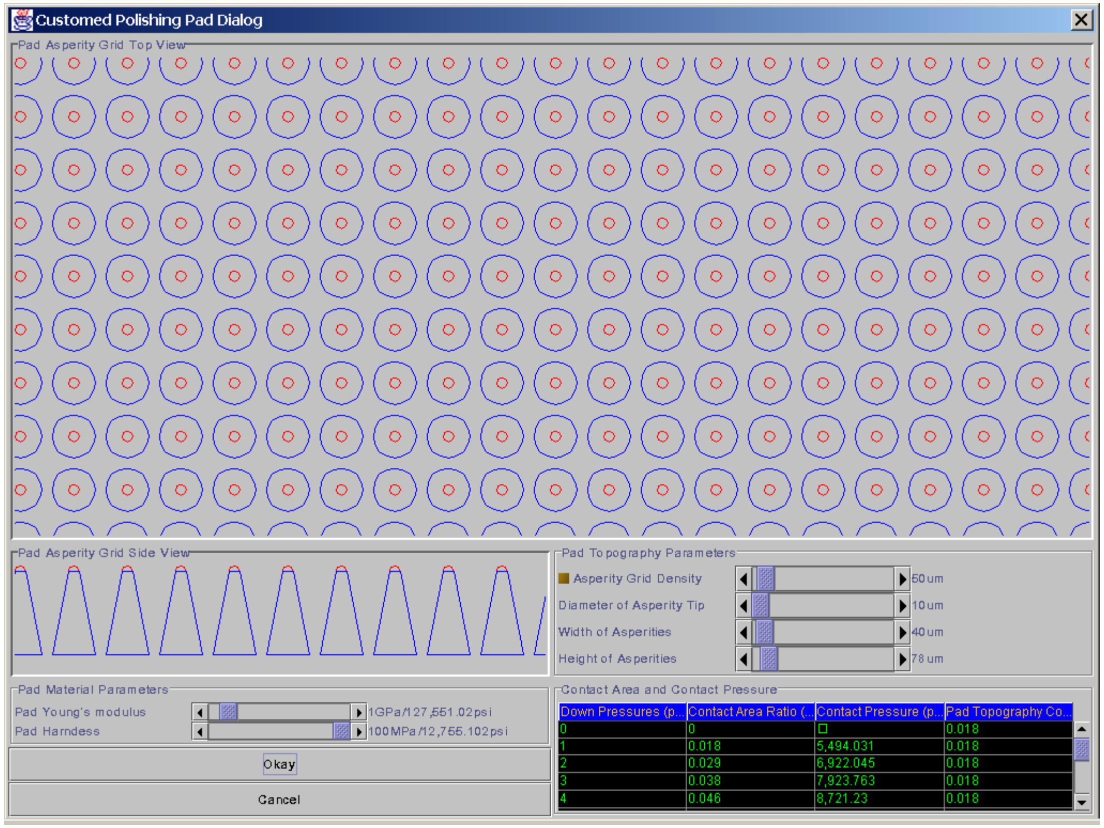
"Design" of consumables - Pad Example



Prototype surface, 20X



Prototype surface, 55X



Design software interface for prototype pad surface; geometry of individual elements, pitch and mechanical properties are Variable, courtesy of J. F. Luo, LMA, 2001

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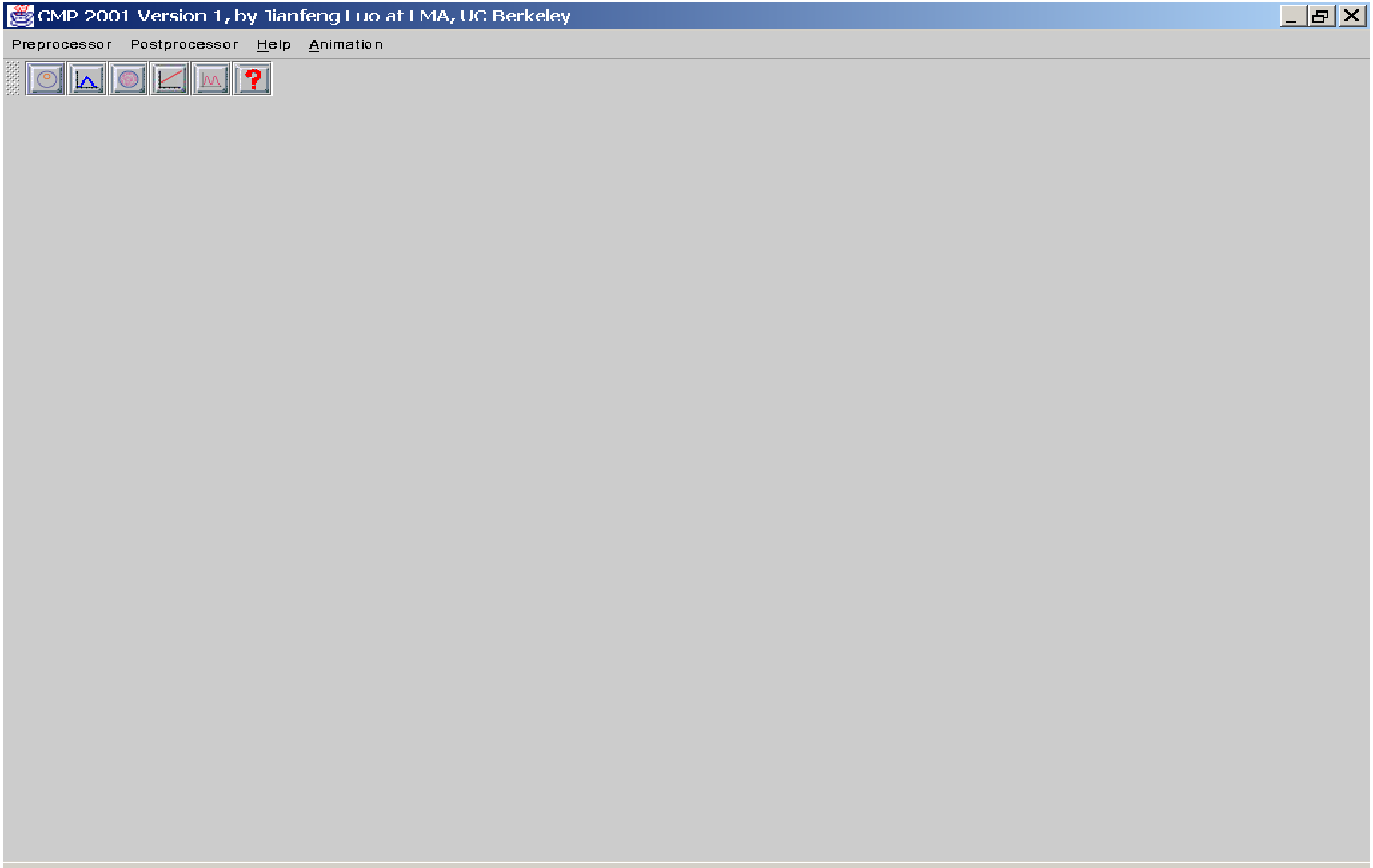
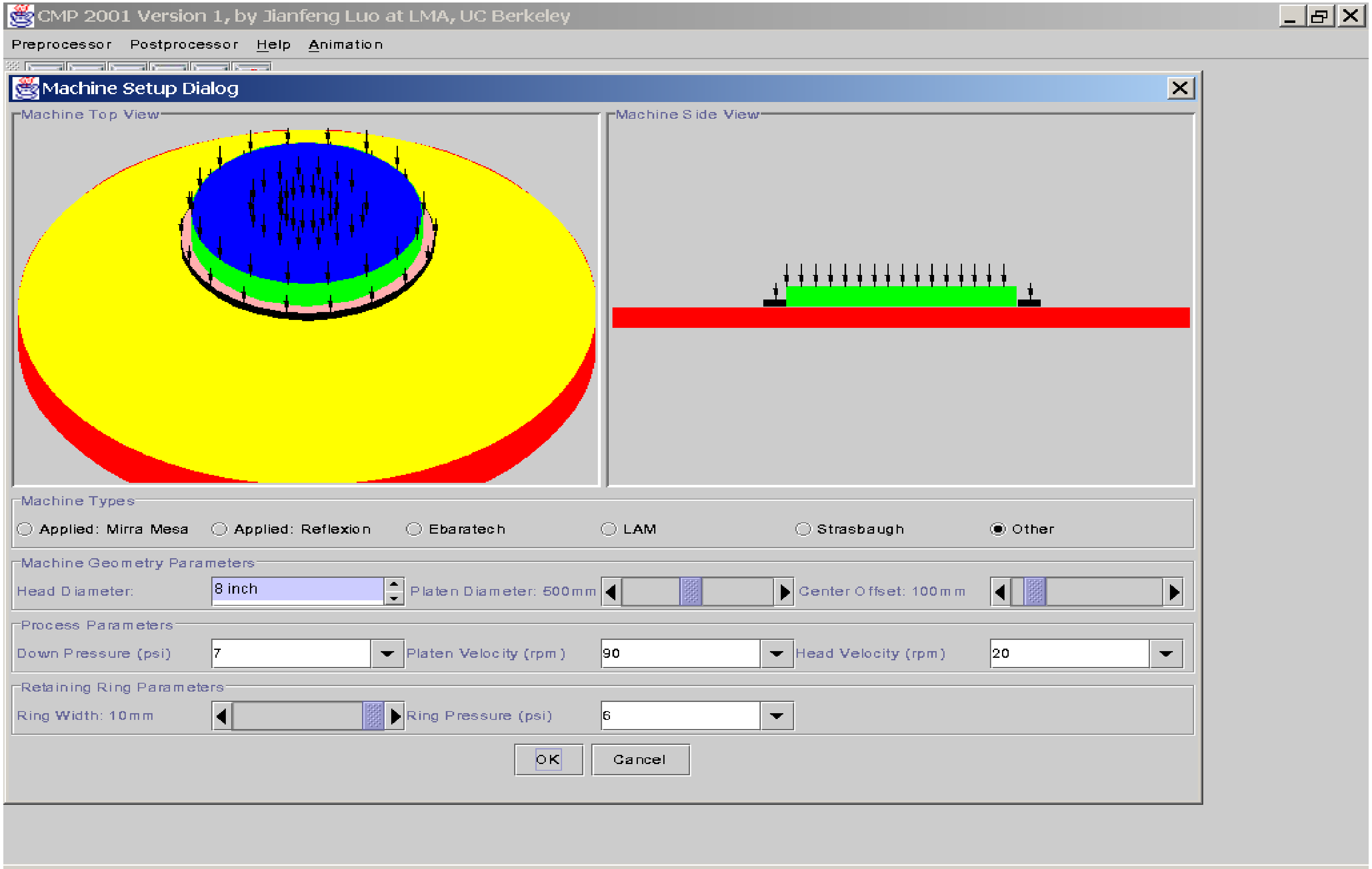
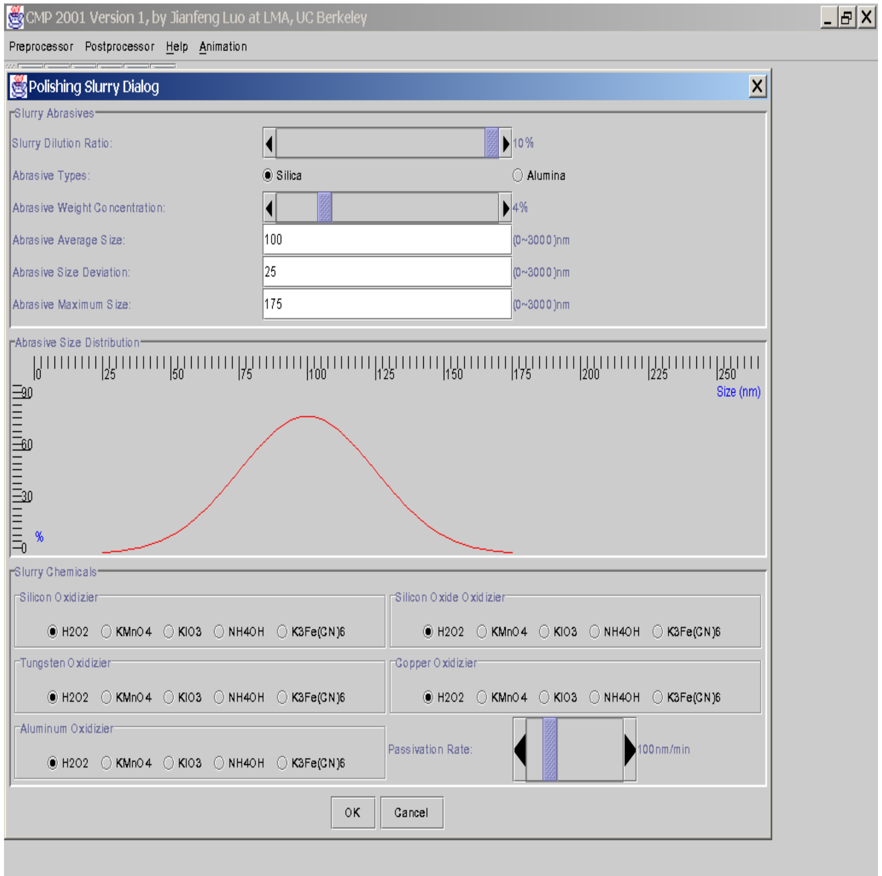
Basic Framework of the CMP Optimization Software



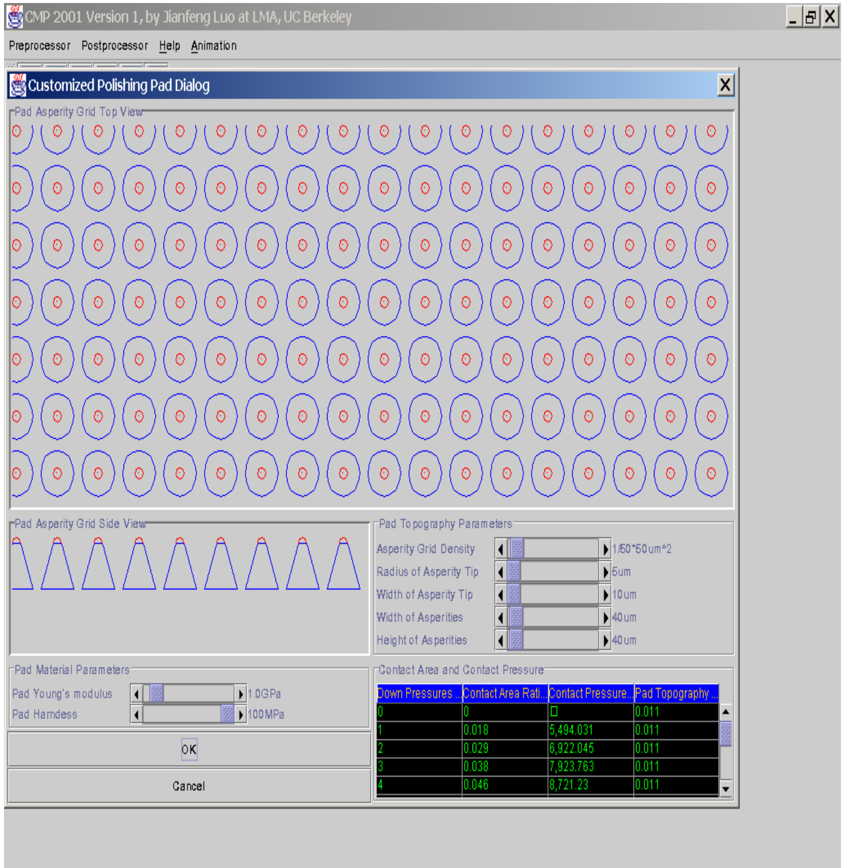
Preprocessor: Machine Setup



Preprocessor: Consumable Setup



Slurry



Pad

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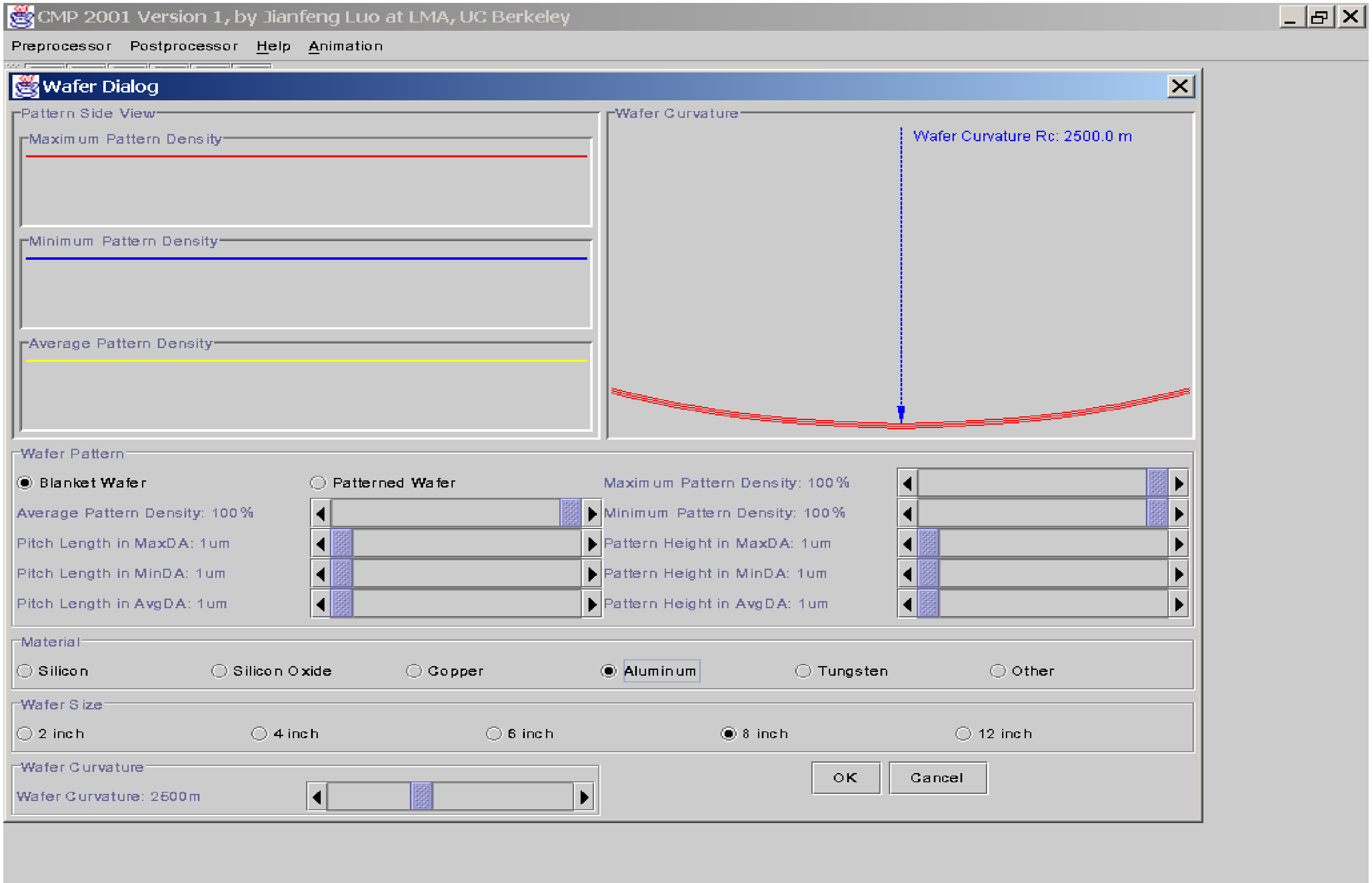
Preprocessor: Wafer Setup



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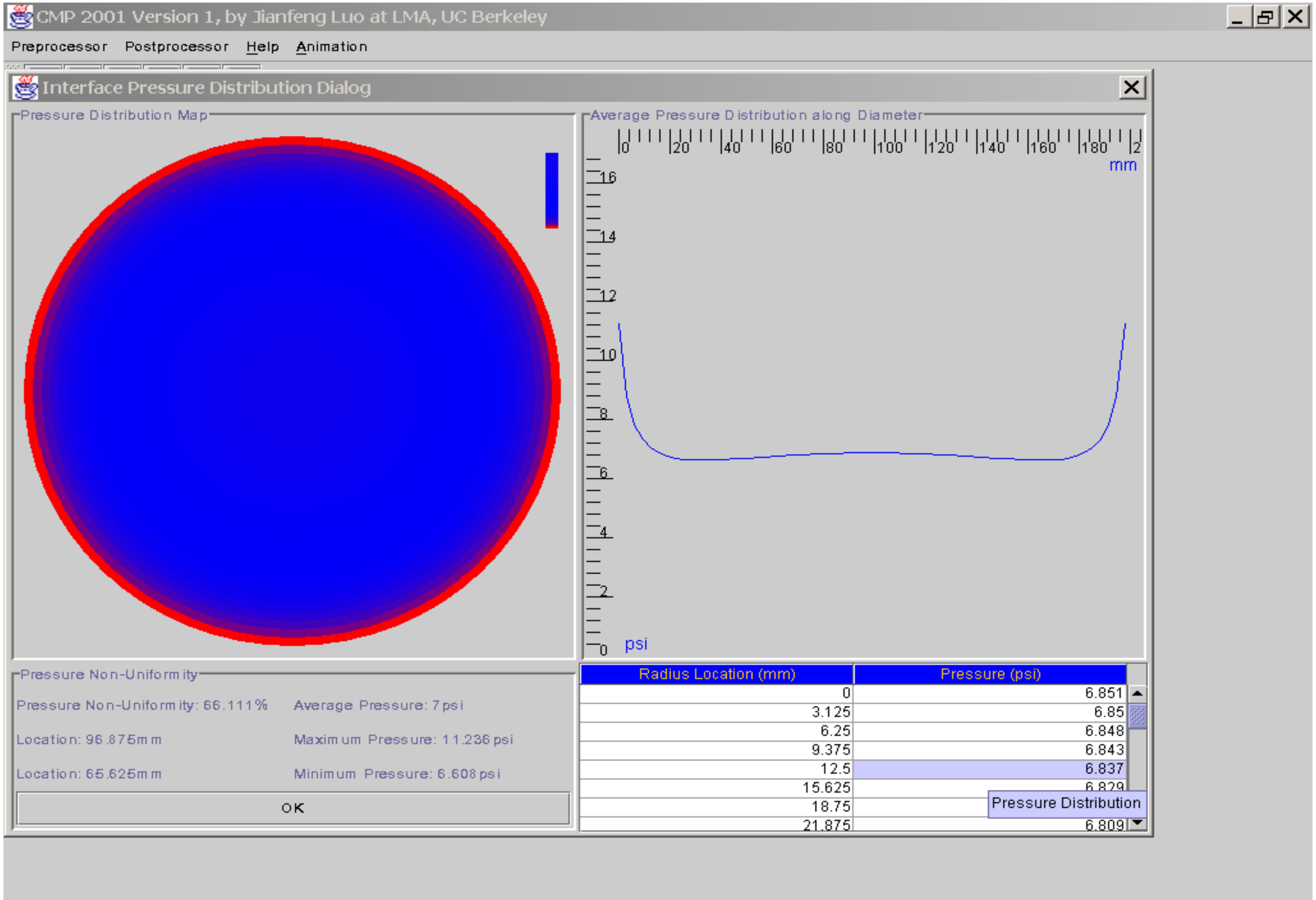
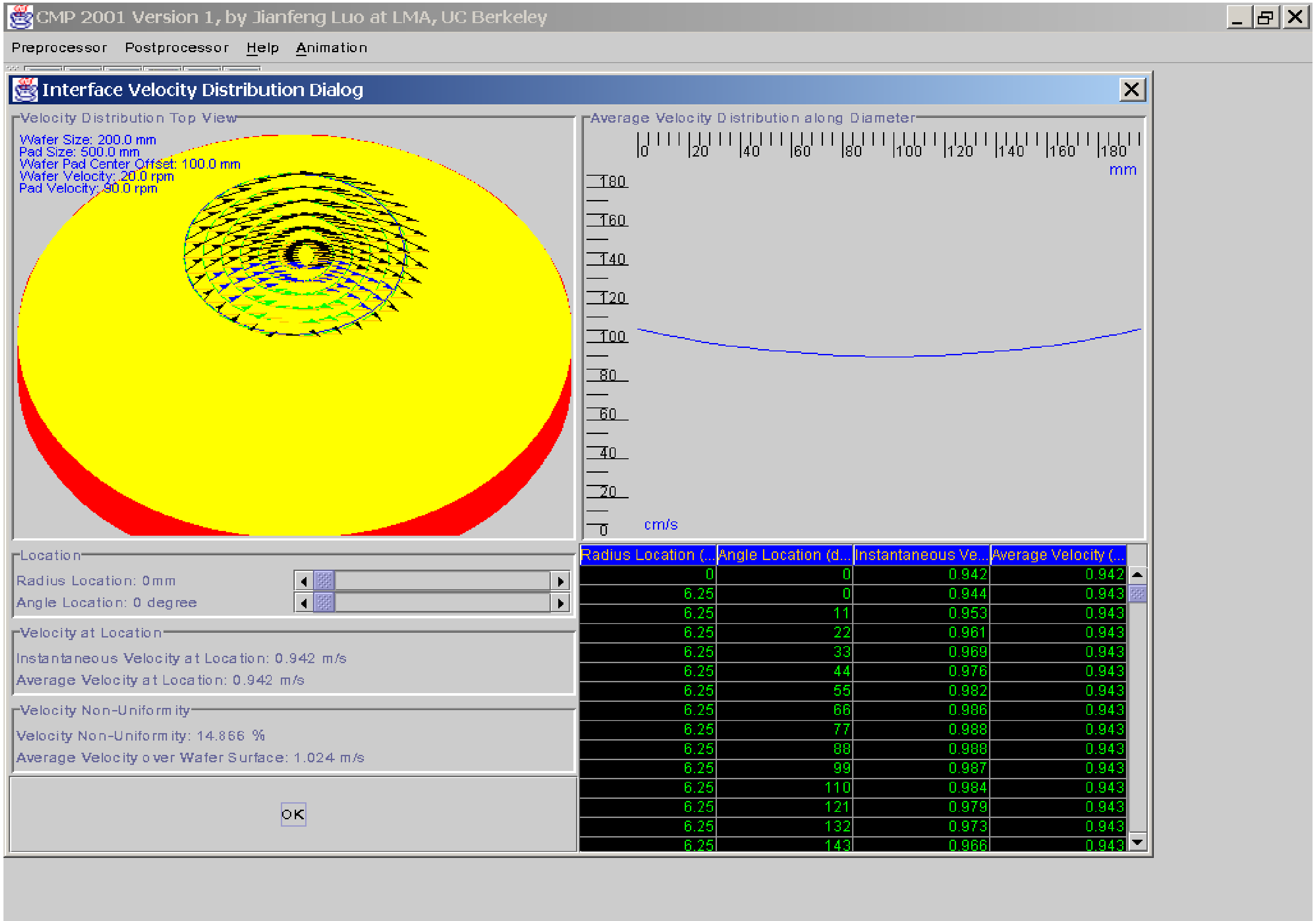
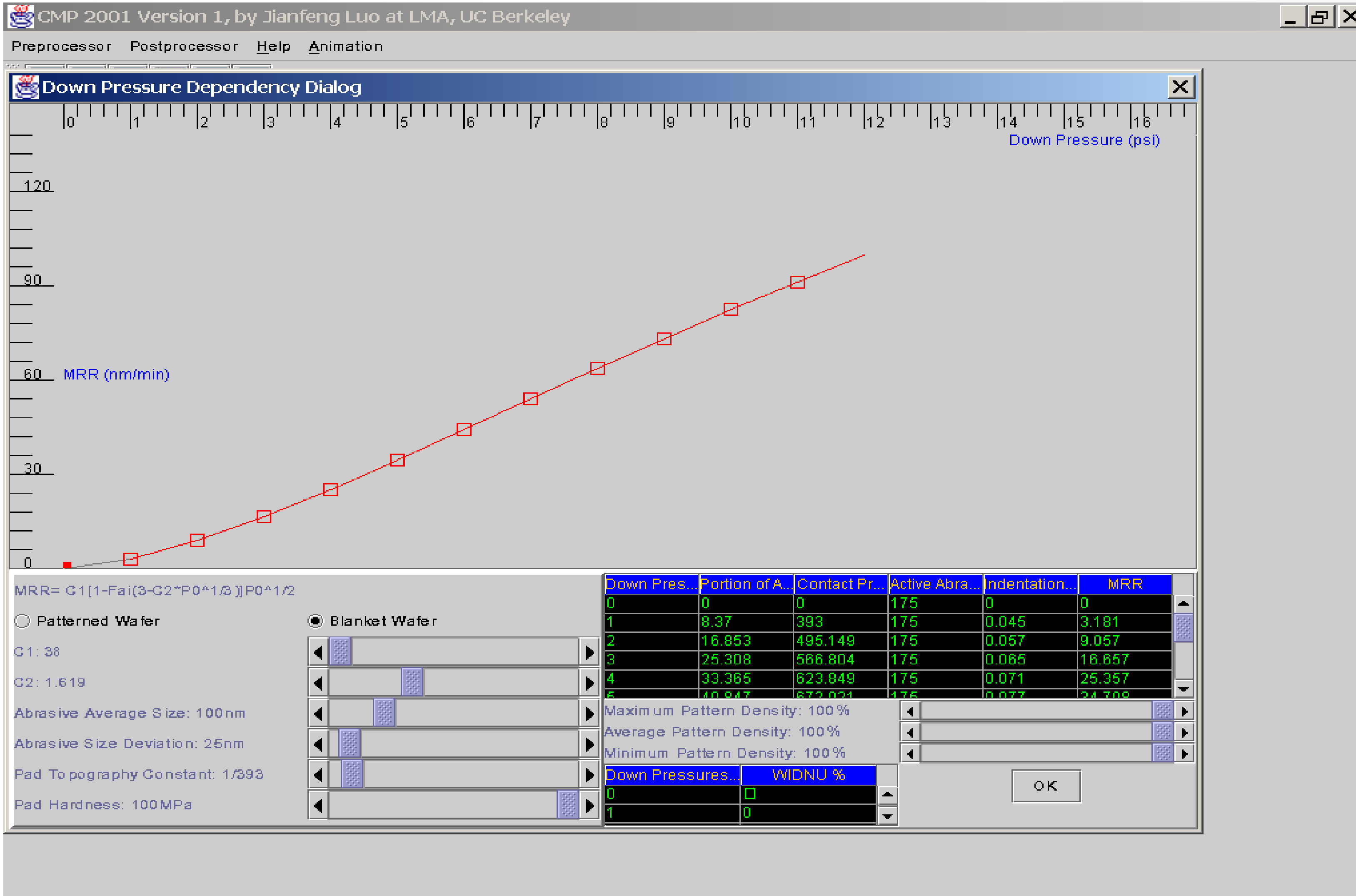
Postprocessor: Interface Pressure Distribution



Postprocessor: Velocity Distribution



Postprocessor: Down Pressure Dependency of MRR



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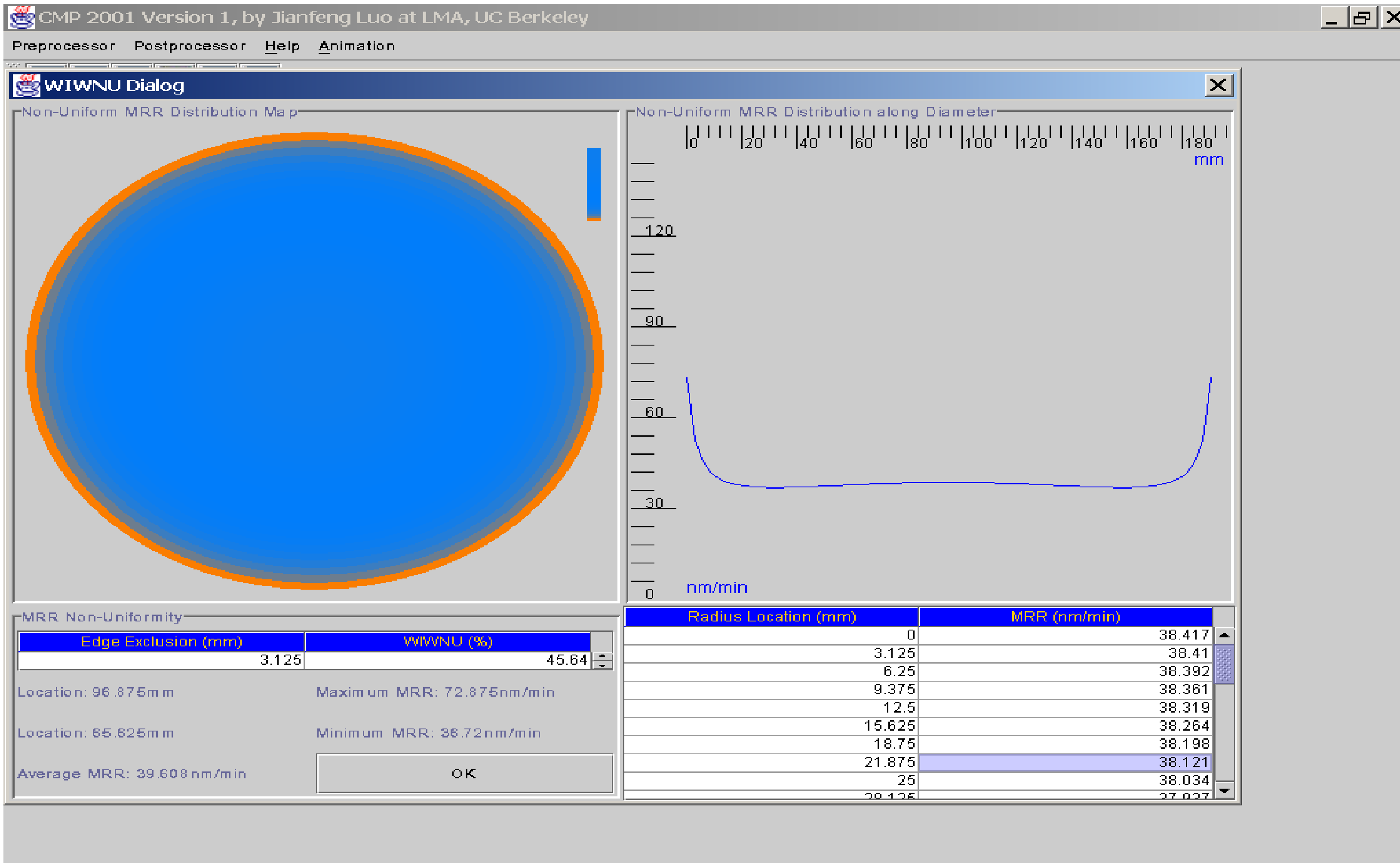
Postprocessor: WIWNU: Function of Pressure Distribution, Velocity Distribution and Pressure Dependency of MRR



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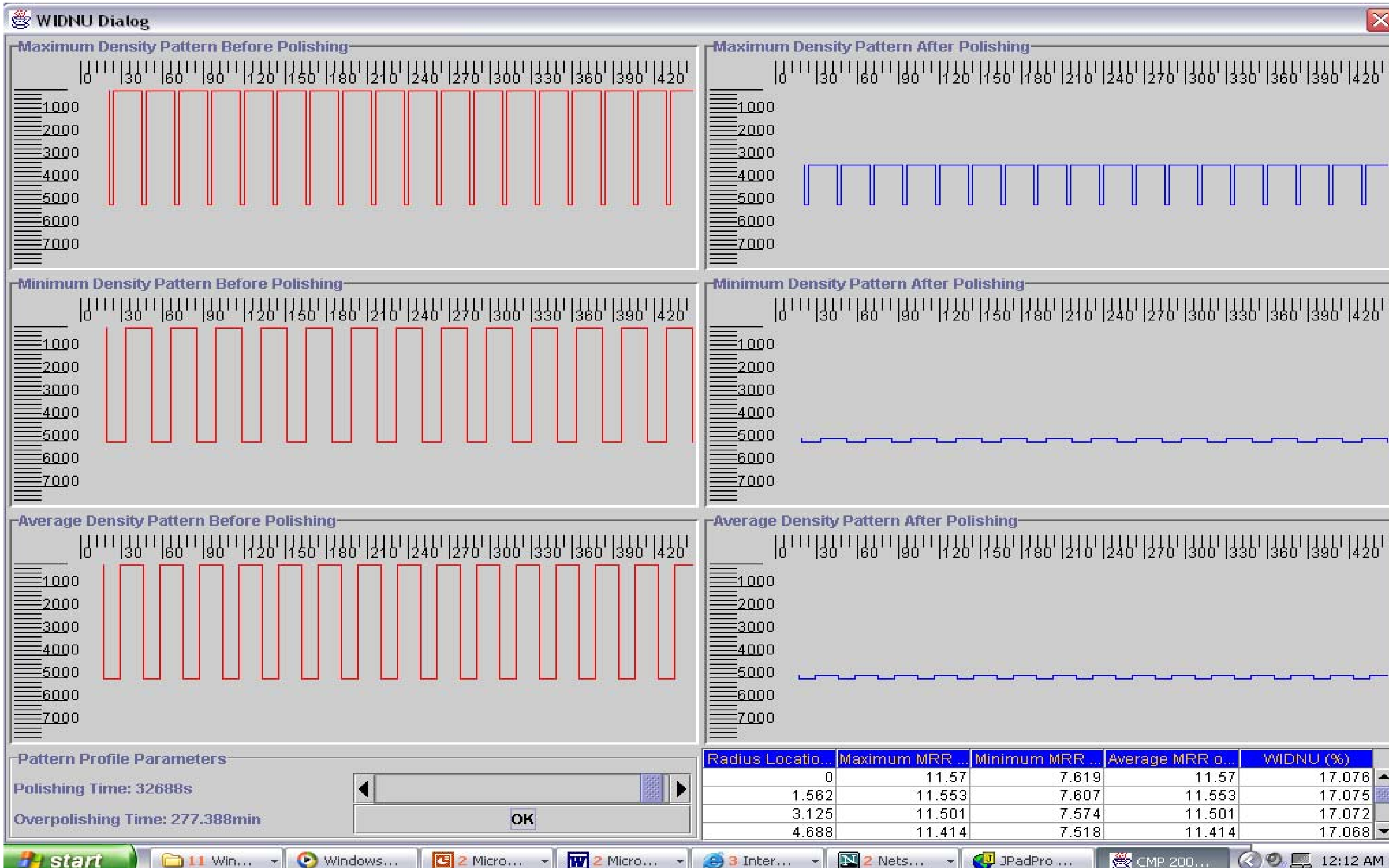
Postprocessor: WIDNU: Function of Pattern Density and Pressure Dependency of MRR



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Conclusions

- A comprehensive model is developed to explain the material removal mechanism in CMP
- The roles and interactions of polishing pad, slurry and wafer are being identified using this comprehensive model
- MRR formulations considering the integrated effects of input variables are developed and verified

Future Work

- Further experimental verification of the model needed
- Model-based process optimization (e. g. using Java)
- Process "design" capabilities (e.g. pad, abrasive, chemistry)