

Copper Removal at Short Times*

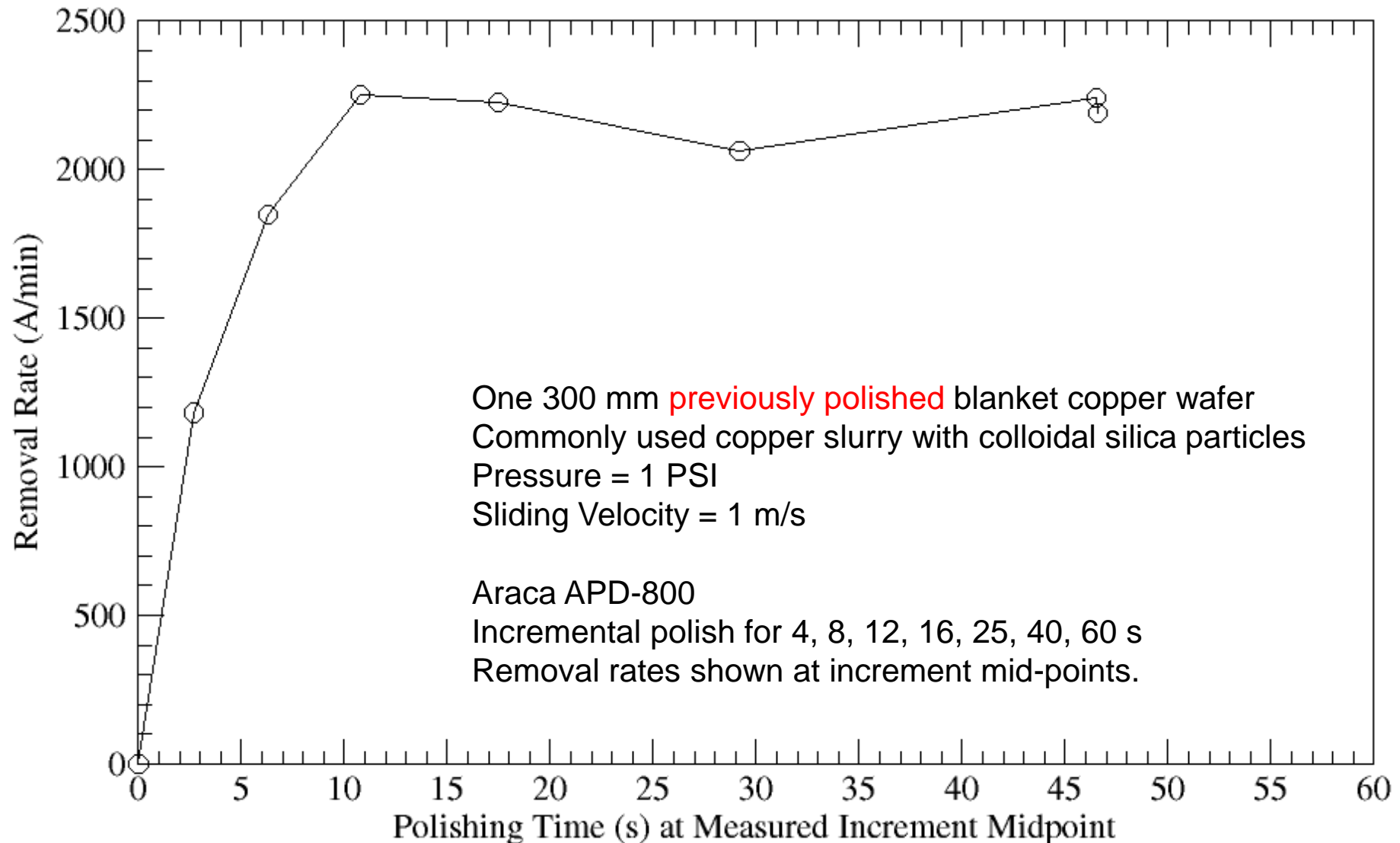
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and Ara Philipossian**

Araca Inc., Tucson Arizona



*The equations in this talk require only a knowledge of fractions

What Caused this Cu Removal Rate Transient?



What Do You Think Caused it?

- The pad surface temperature
- The wafer temperature
- A transient in the COF
- A lag in bringing the head and platen up to speed
- The time required to stabilize the pressure
- Or some other reason?

The APD-800 Polisher and Tribometer

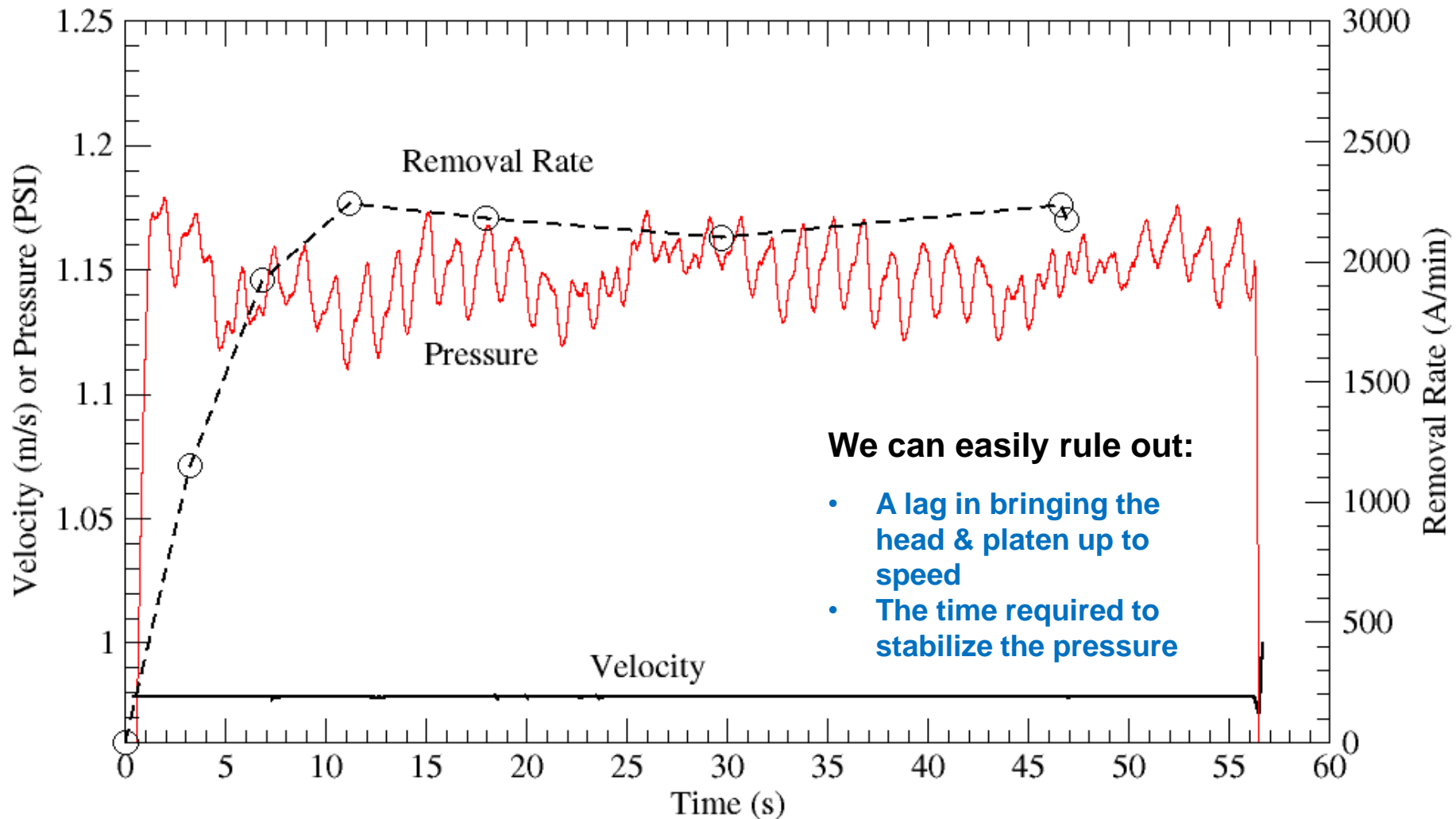
**Among other things,
this tool measures:**

- Normal force on the platen
- Shear force in the pad-slurry-wafer interface
- Pad surface temperature at a spot near the carrier leading edge.
- Platen and carrier speeds.

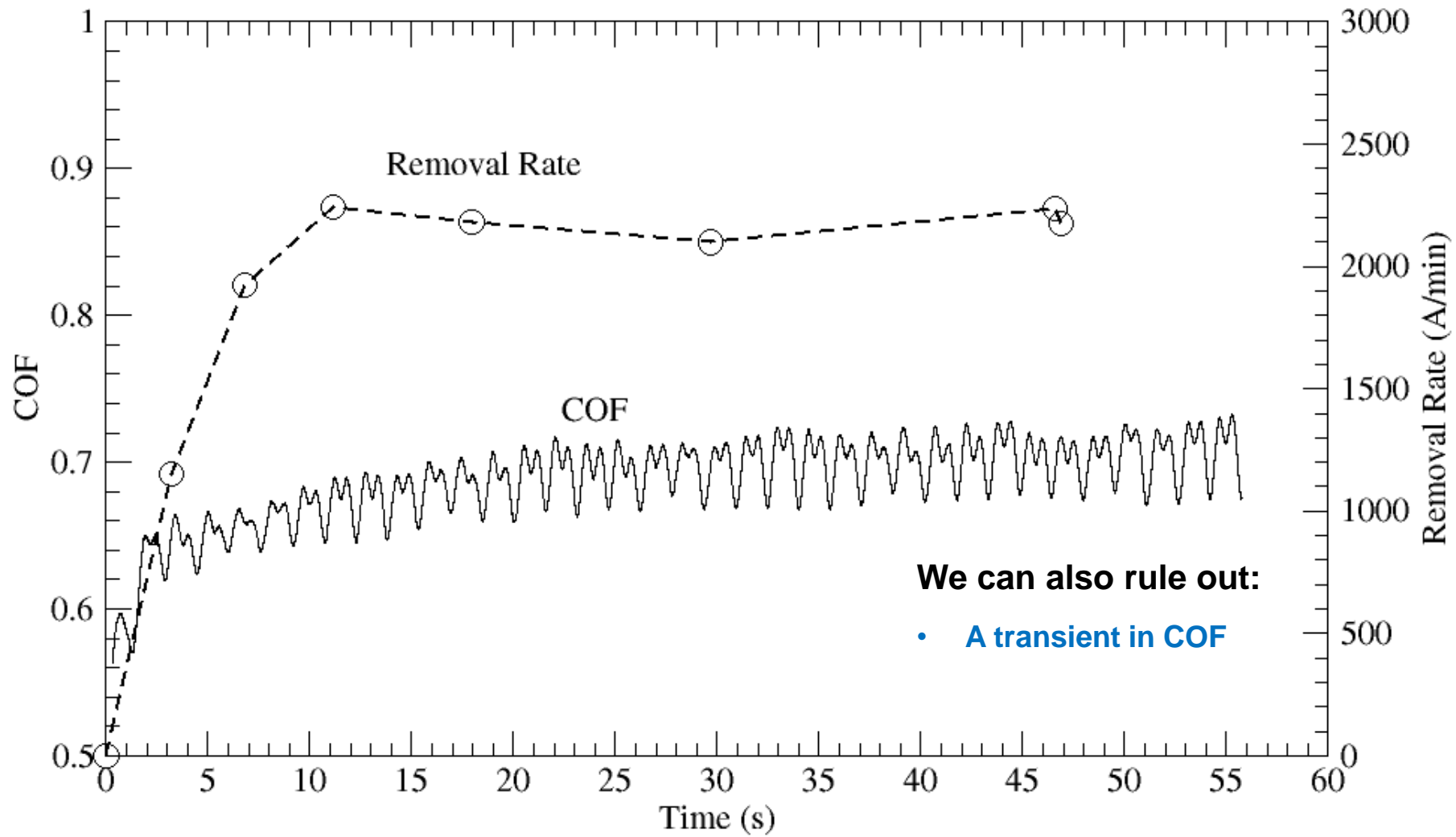
**Acquisition frequency
is 1,000 Hz for all of the
above metrics.**



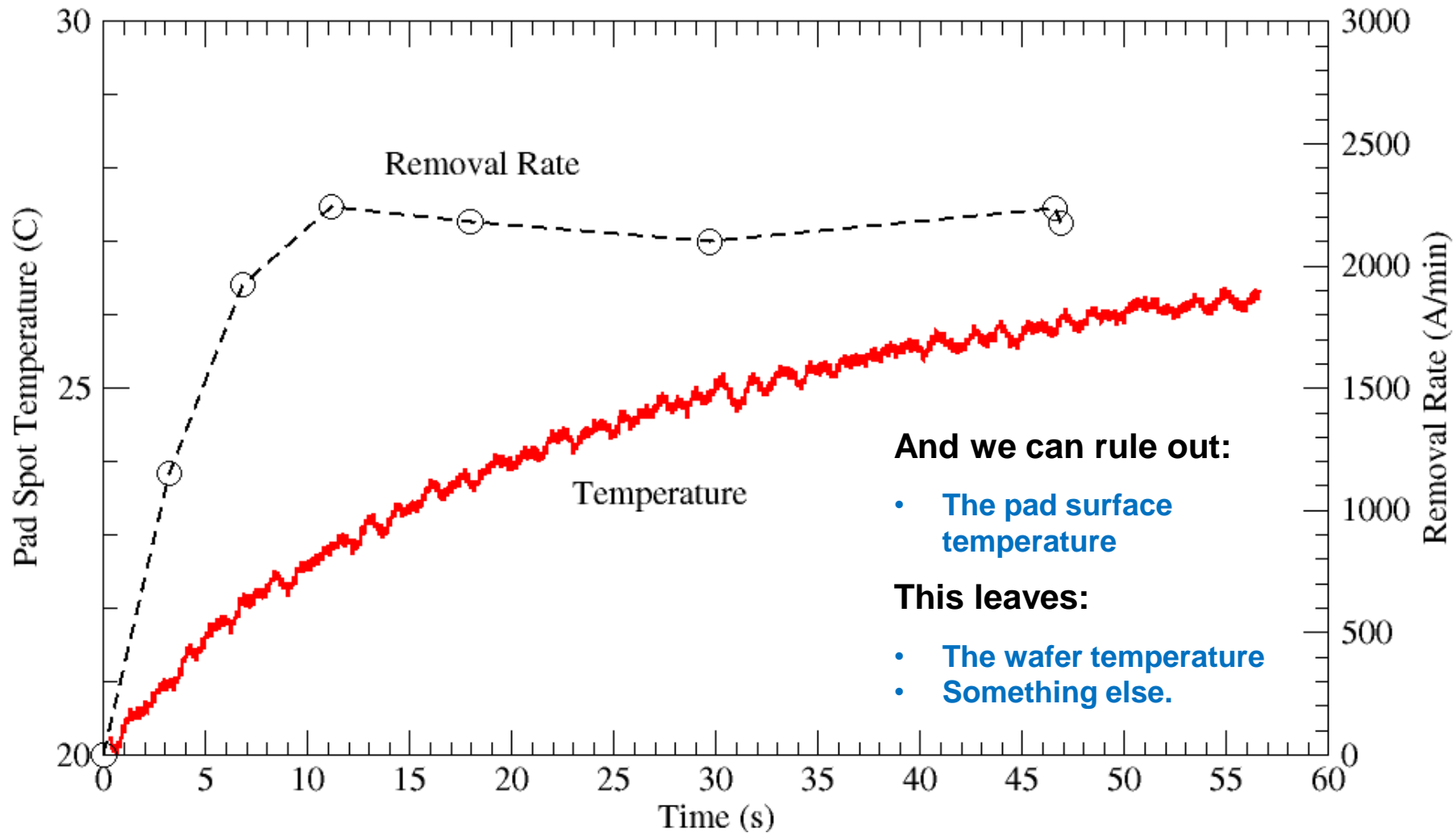
Pressure and Velocity Data from the Polisher



COF Data from the Polisher

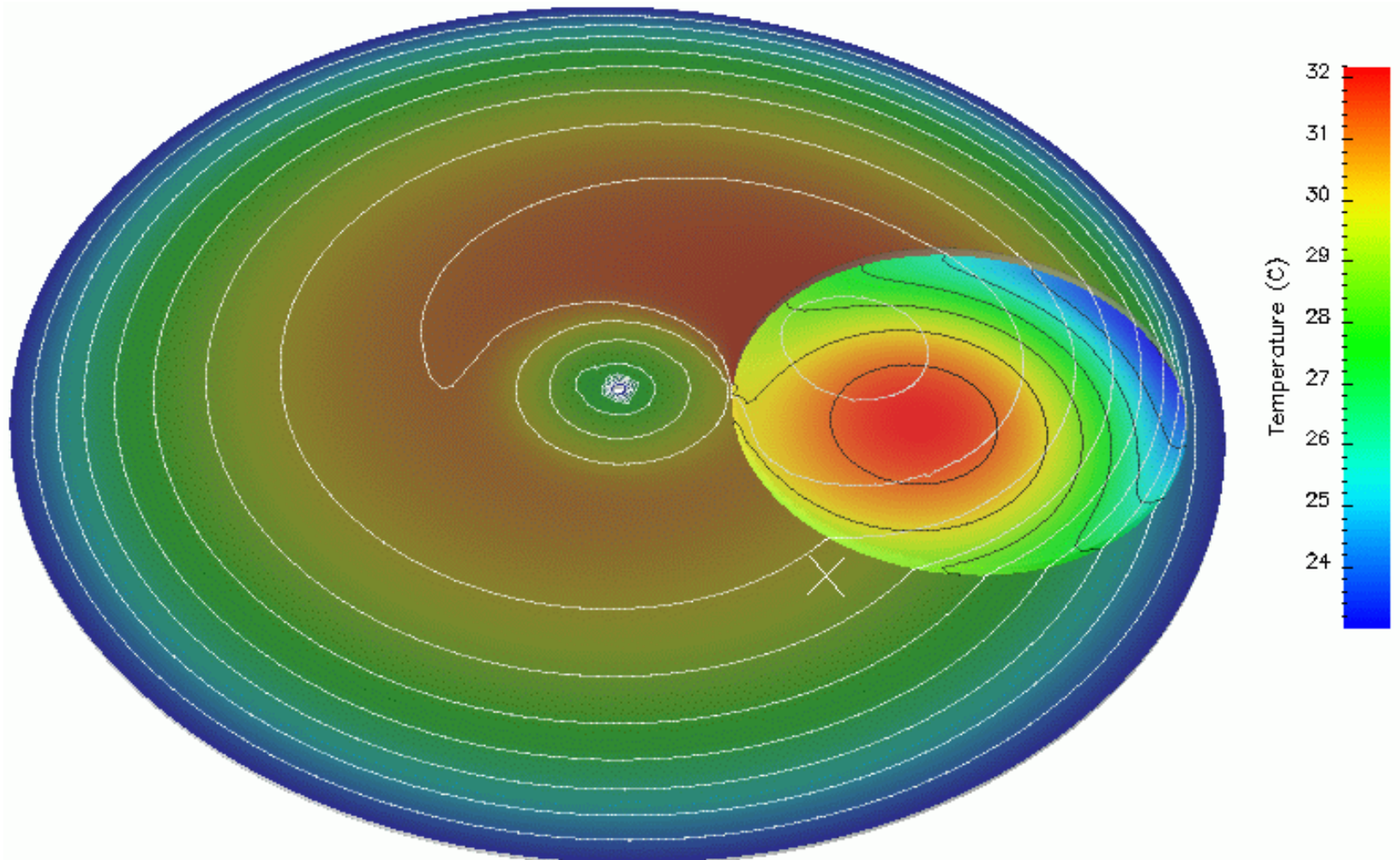


Pad Temperature Data from the Polisher

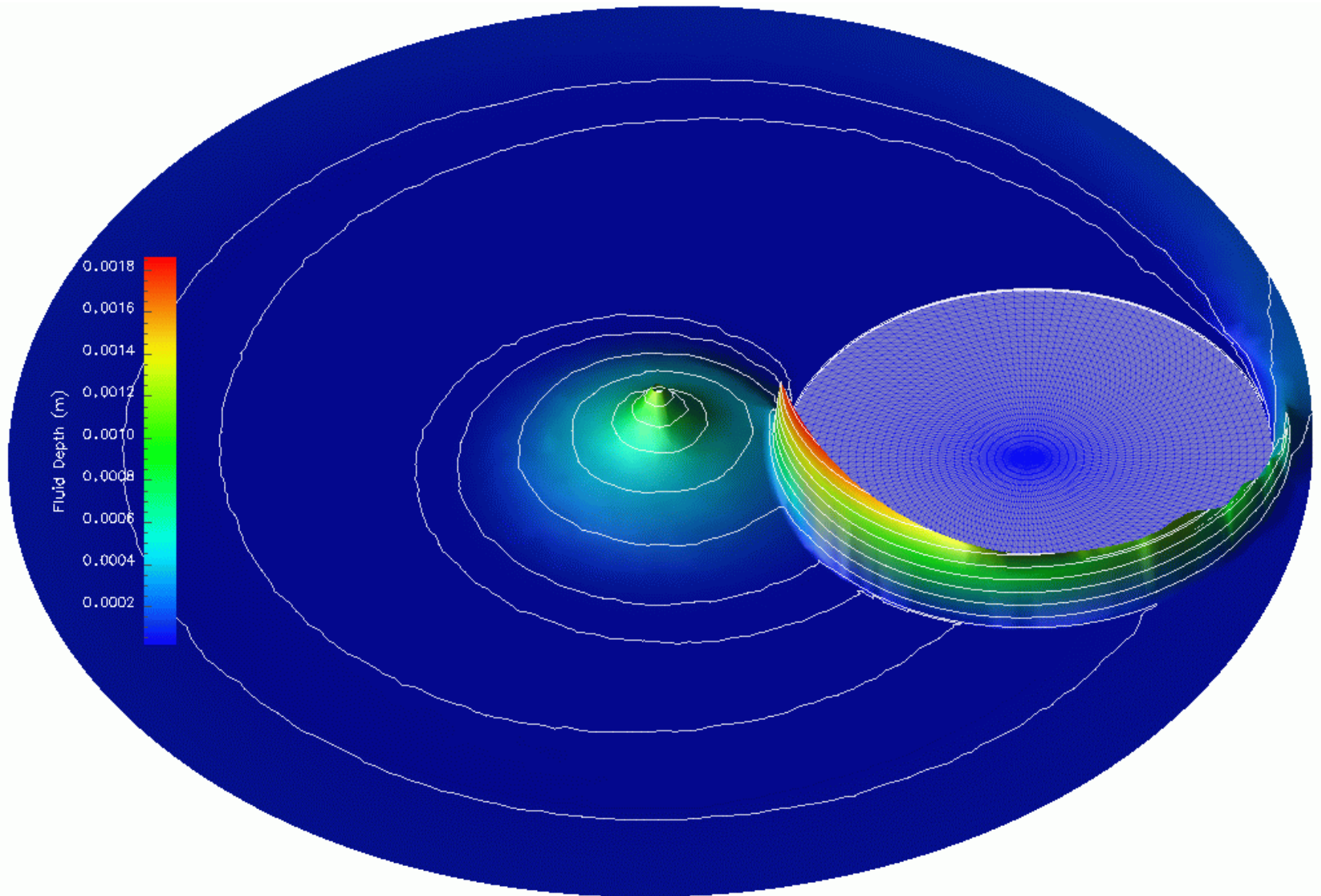


The Wafer Temperature

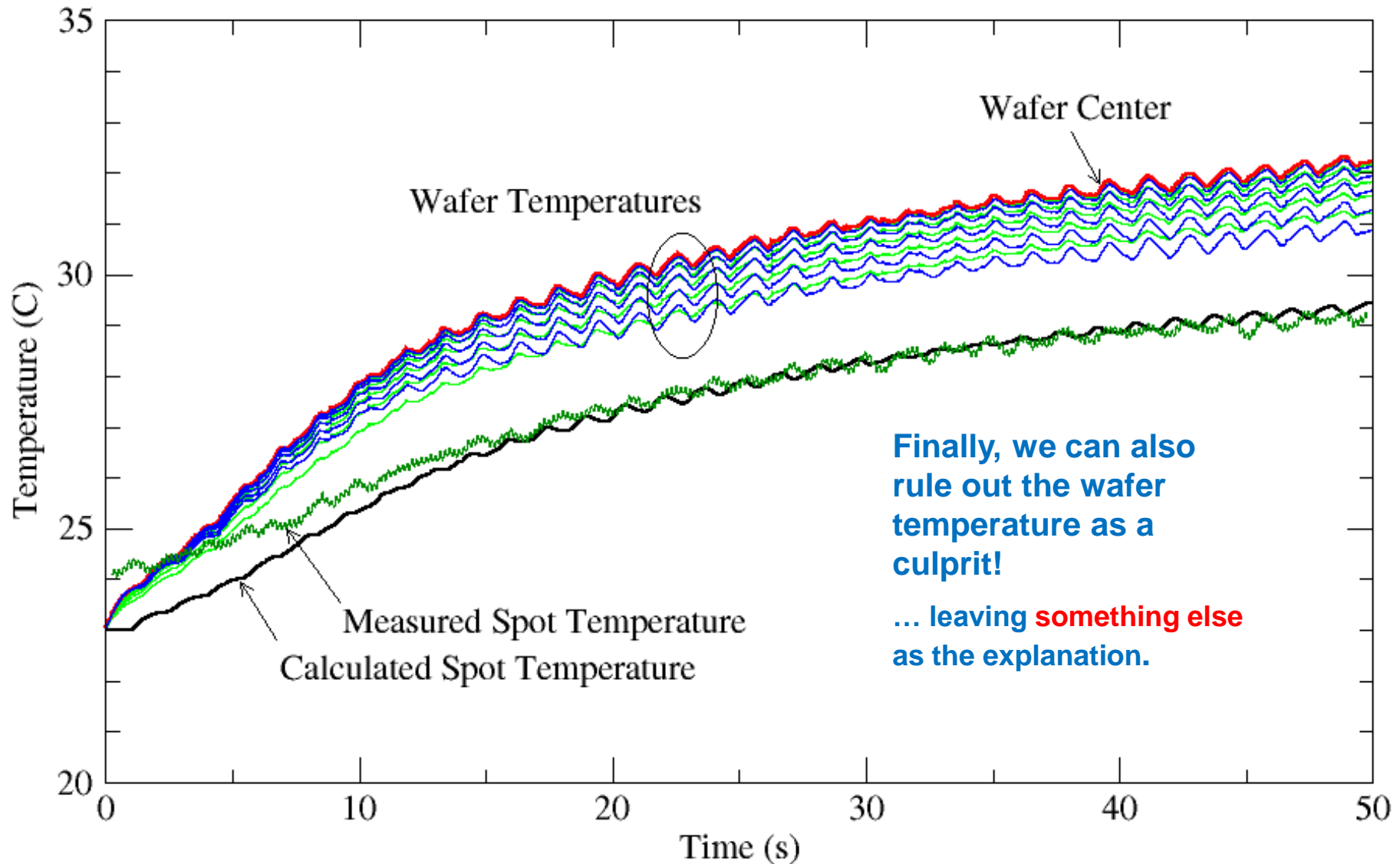
We don't measure the wafer temperature but can estimate it using a 3D tool model that includes most of the basics, including slurry flow, frictional heating and heat transport by the slurry and the rotating pad, wafer and carrier.



Tool Model: Slurry Flow



The Wafer Temperature



What is Causing this RR Change for Short Times?

Like everyone, we rinse the pad with water and prime it before polishing the next wafer. Could the rinse do this?

f_w = fraction of rinse water in the slurry on the pad
 $f_s = 1 - f_w$ = slurry fraction

Then

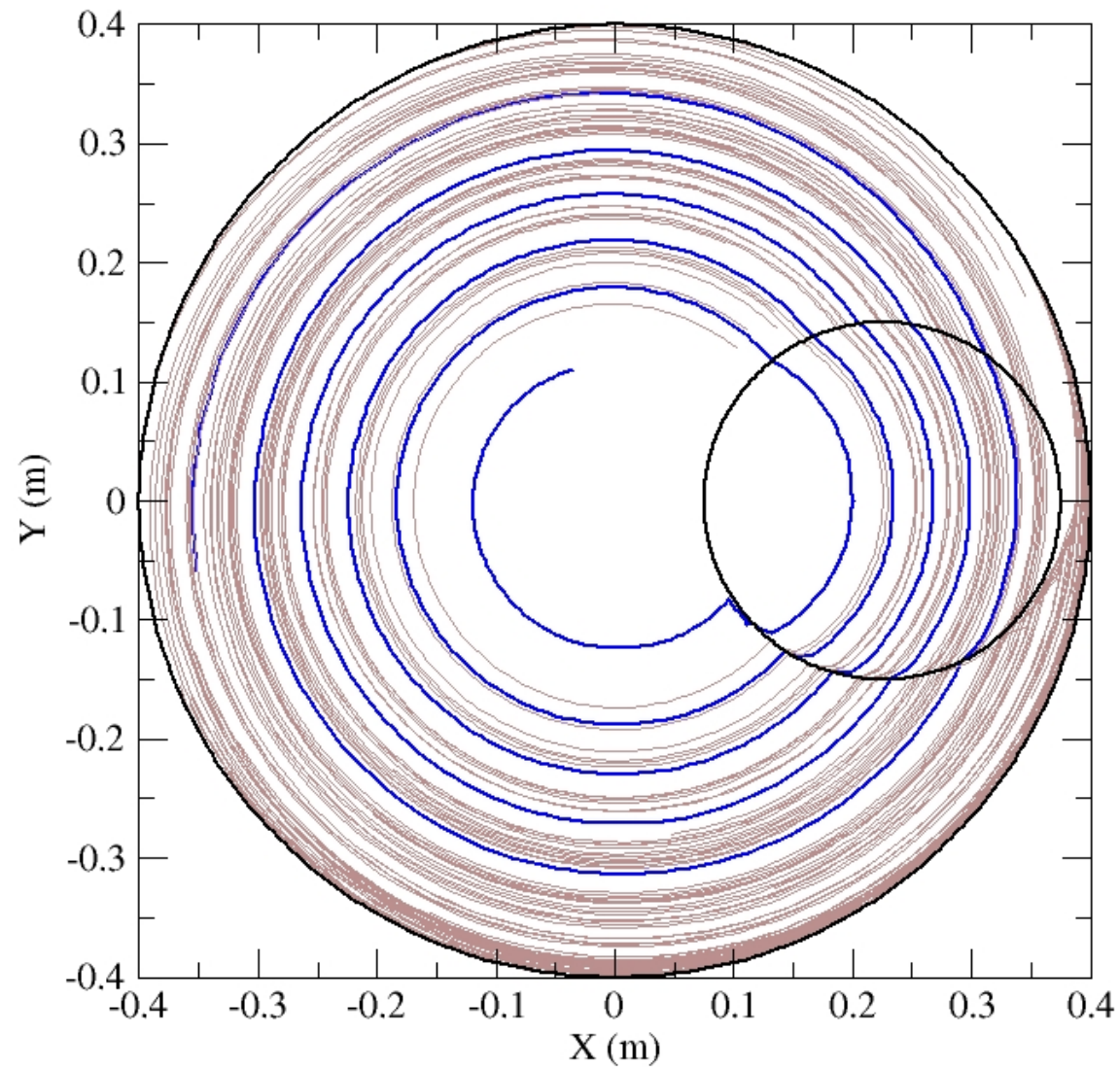
$$\begin{array}{lcl} \text{Chemical rate} & = & f_s k_1 \\ \text{Mechanical rate} & = & f_s k_2 \end{array} \quad \text{Rates without dilution}$$

Using a two-step Langmuir-Hinshelwood model:

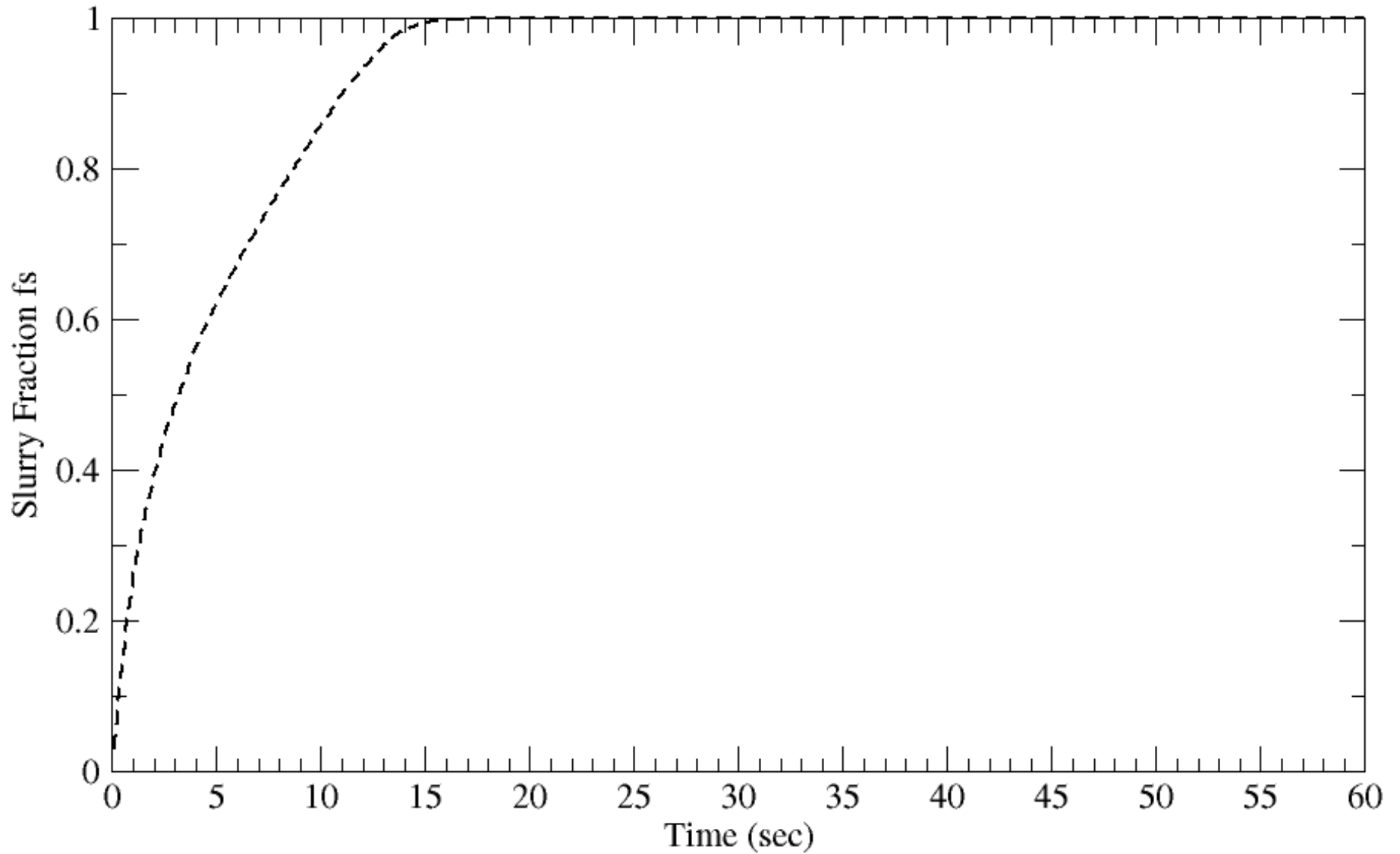
$$\begin{aligned} \text{Removal rate} &= \frac{M_w}{\rho} \frac{\text{Chemical} * \text{Mechanical}}{\text{Chemical} + \text{Mechanical}} = \frac{M_w}{\rho} \frac{(f_s k_1)(f_s k_2)}{(f_s k_1) + (f_s k_2)} \\ &= f_s \text{ RR} \end{aligned}$$

This doesn't hold for slurries for which dilution increases the removal rate or where the effect of dilution on the chemistry is non-linear.

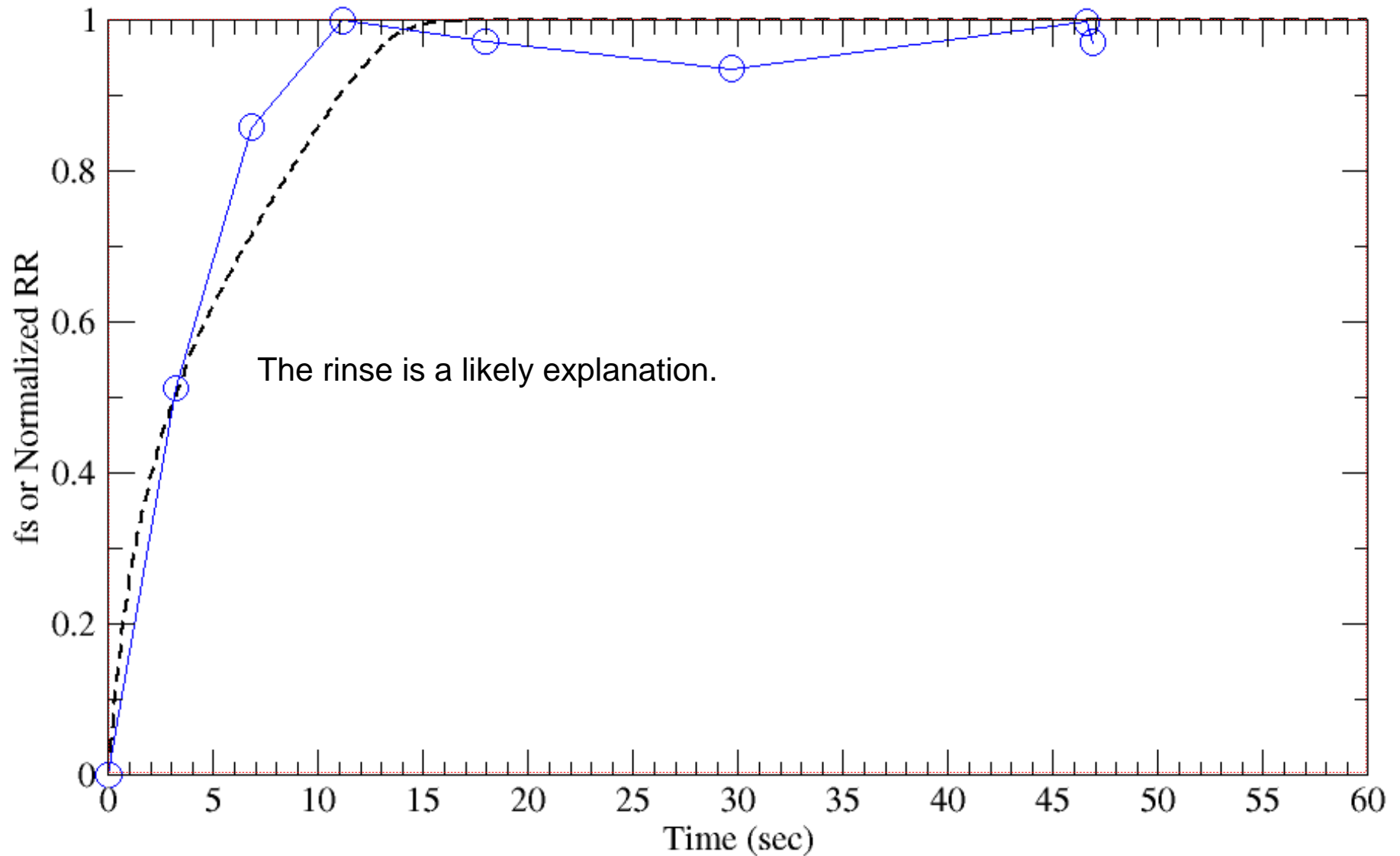
Fate of the Rinse Water



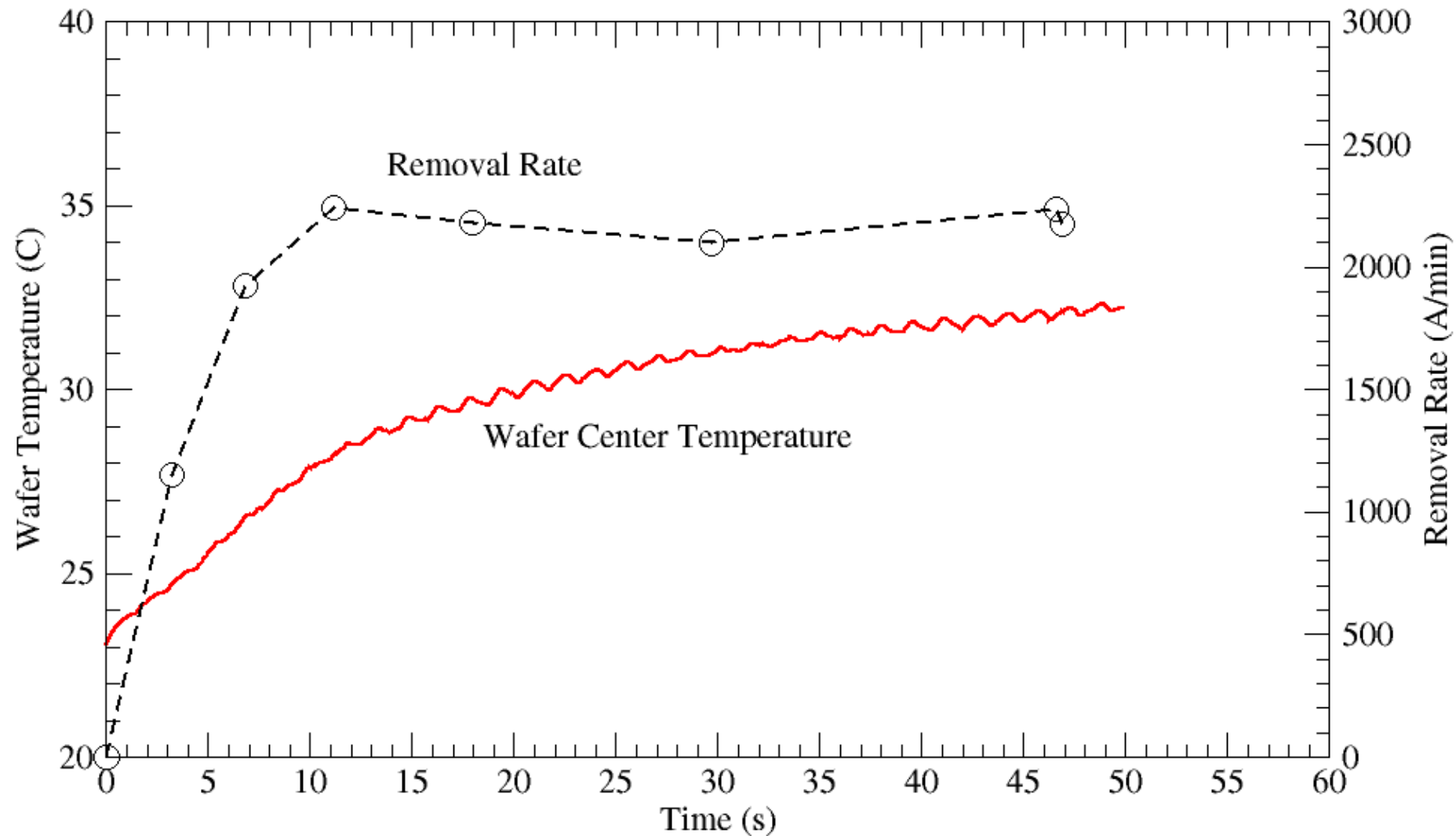
Slurry Fraction vs. Time



Removal Rate Comparison



Why Doesn't the Wafer Temperature Affect the RR?

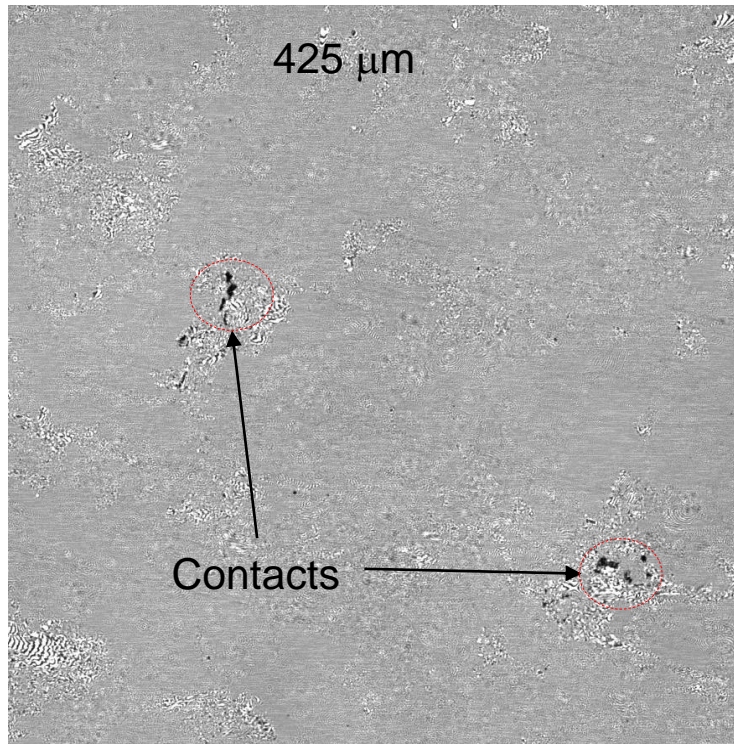


Chemical Reactions in Metal CMP

Basic Questions:

- What are the reactions?
- Where and when do they occur?
- What is the activation energy?
- What is the reaction temperature?

POV: All of the mechanical work and removal chemistry occurs during contact encounters.



For a hard pad, contacts are small, ~ microns.

Actual contact pressures exceed the applied pressure by a factor of 10^2 - 10^4 .

Contact temperatures have to be much higher than the measured pad temperature.

At 1 m/s, a 1 μm contact interacts with a point on the wafer for only 1 μs.

Removal chemistry has to occur within this time scale.

Activation energies have to be low.

Activation Energies

Can be estimated from the reaction product if the reaction temperature is known.

Simple chemical reaction

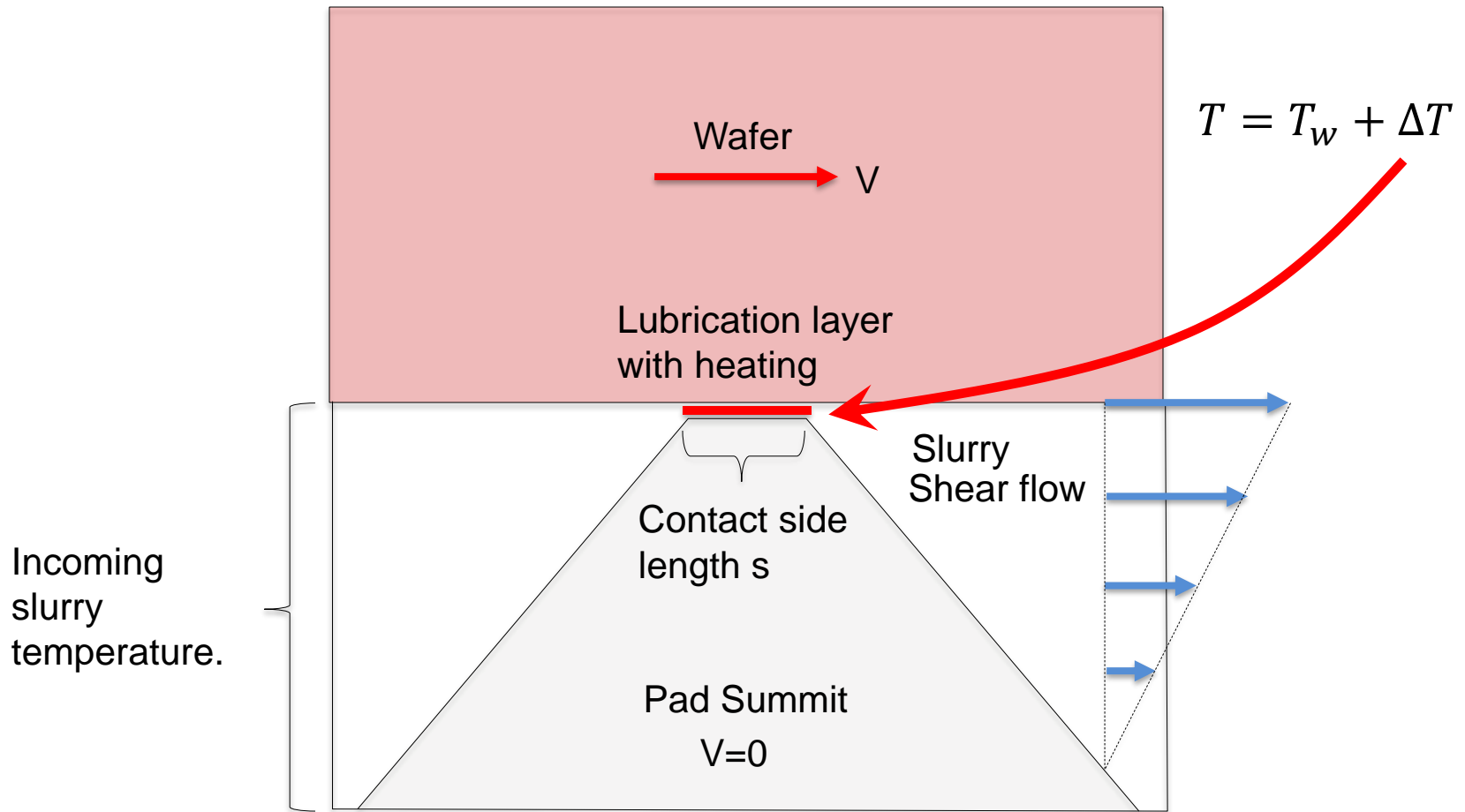
$$k = Ae^{-\frac{E}{kT}}$$

CMP

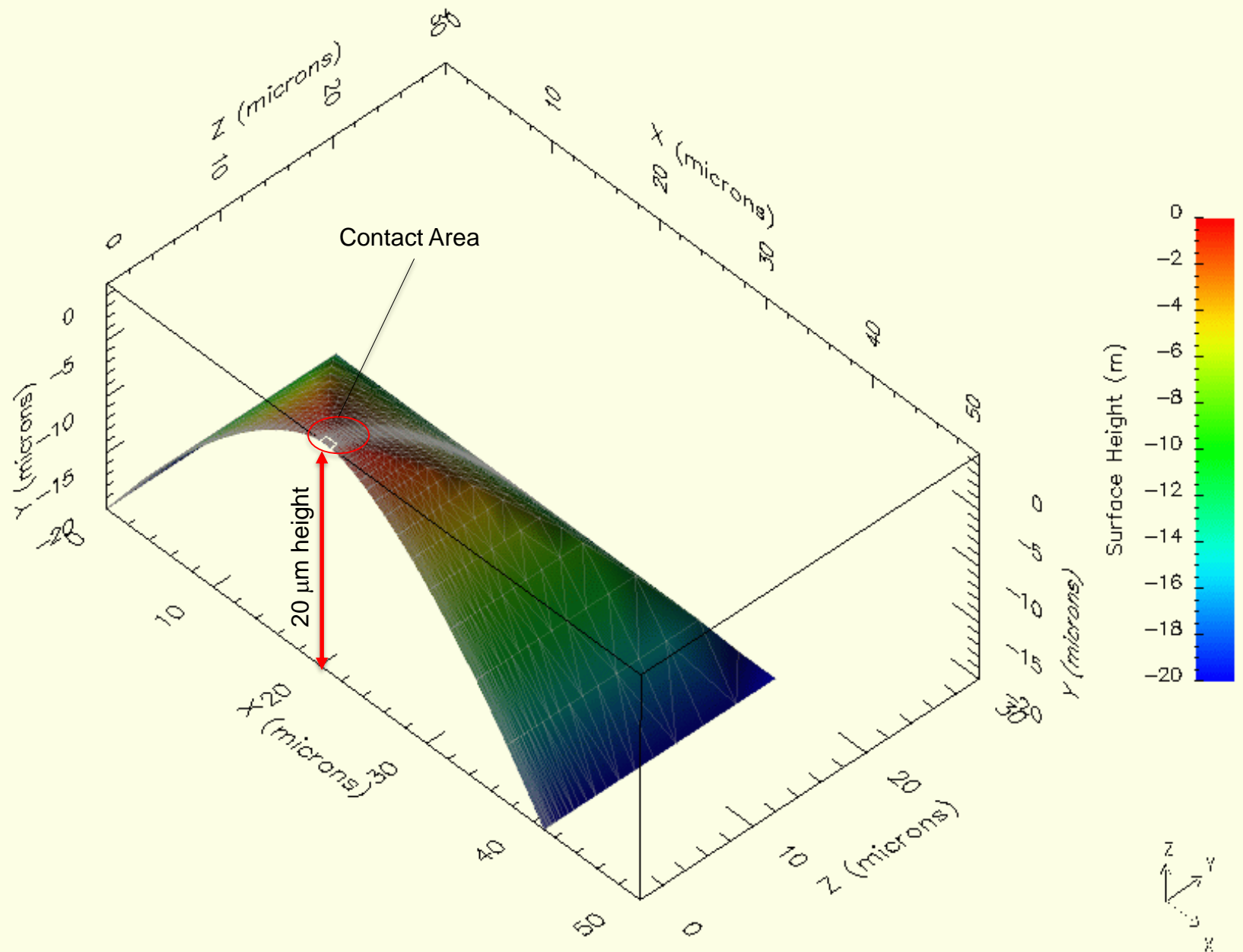
$$RR = \frac{M_w}{\rho} \frac{k_2 Ae^{-\frac{E}{kT}}}{k_2 + Ae^{-\frac{E}{kT}}}$$

Have to separate the chemical and mechanical rates
Easy to estimate E from the removal rate if T is known

Reaction Temperature Model Schematic



Example Pad Summit Model

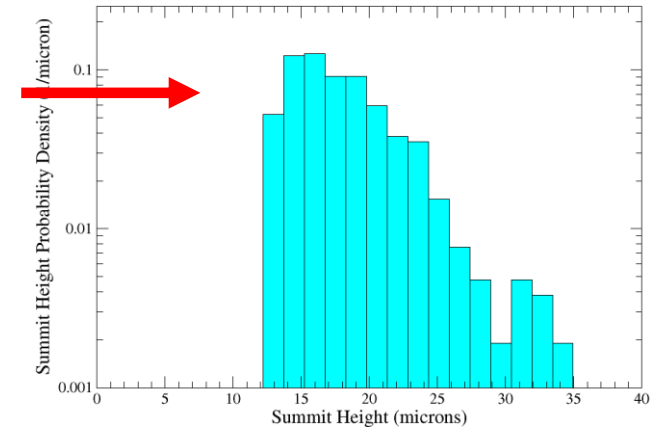


Empirical Basis of Reaction Temperature Estimates

Reaction temperature calculations use:

- Measured pad topography and contact area data
- COF, pressure and velocity data from the polisher
- Well-established material thermal properties
- Rough surface contact mechanics
- Soft elastohydrodynamic lubrication theory.

There are no adjustable parameters.



Calculated reaction temperatures are the *mean or expected value* taking into account all contacting summits and their distribution of heights, curvatures, actual contact pressures, and lubrication layer thicknesses.

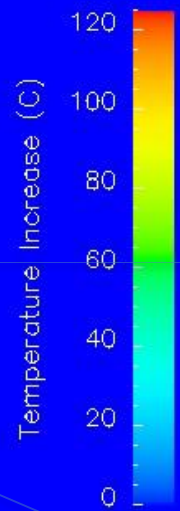
Wafer (Cu)

$p=1.2$ PSI
 $\text{COF}=0.72$
 $V=1.0$ m/s



Slurry

Pad



$t=1$ microseconds

ΔT reaches steady state very quickly, so it is constant over most of the wafer.

Activation Energy

For the slurry used in this talk, calculated reaction temperatures imply that

$$\begin{aligned} E &\approx 0.065 \text{ eV} \\ &\approx 1.5 \text{ kcal/mol} \end{aligned}$$

Verified for two types of hard pads, 7 different conditioners, 70-80 polishing runs

Small activation energy. Supported by several independent lines of reasoning.

Kinetic theory implies that at the calculated temperatures, a first order reaction with this energy goes to > 99% completion in less than 1 μ s.

Why Doesn't the Wafer Temperature Affect the RR?

$$\text{Chemical Rate} = Ae^{-\frac{\overset{\text{Small}}{\overset{\circ}{E}}}{k(T_w + \overset{\circ}{\Delta T})}}$$

Constant $\Delta T > T_w$

$$\approx \text{Constant}$$

Summary

Some transients are easy to explain. The initial transient in the Cu polishing experiment is likely due to the rinse.

A test without rinsing would be required to check this.

Some questions about transients involve some of the hardest topics in CMP.

A paper is in preparation.

BIO

Len Borucki received a Ph.D. in mathematics from RPI in 1978. After teaching at Lafayette College, he had an opportunity to move to the semiconductor industry where he worked for IBM and then for Motorola. It was at Motorola that he became fascinated by CMP. He is currently retired but still collaborates with Araca, Inc.