# Removal Rate Modeling with the Shear Force Law

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# Polisher and Experiment


**Araca APD-800 Polisher and Tribometer**

Measures shear and normal forces on the wafer.

**The Experiment**

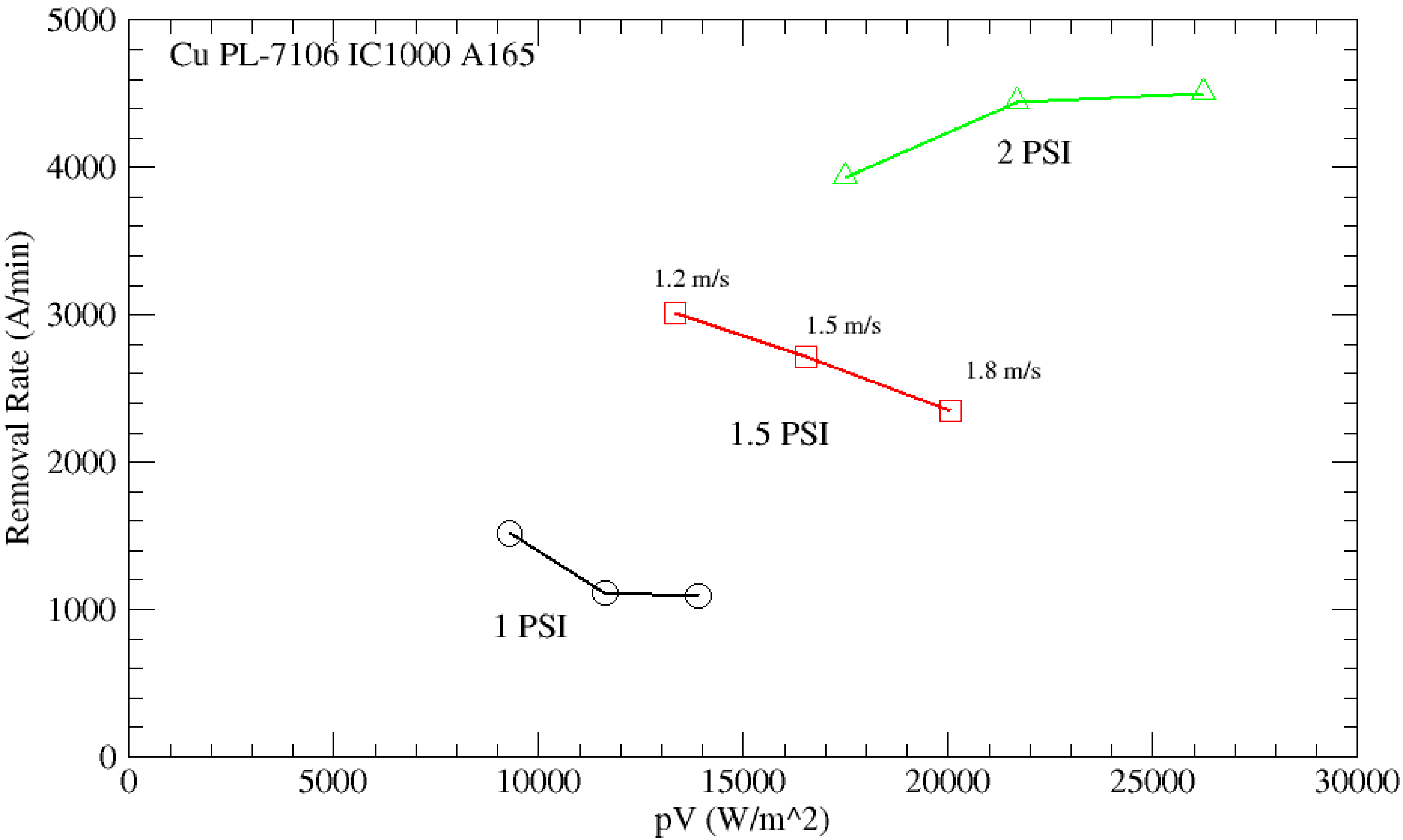
300 mm blanket Cu wafers

3p x 3V:

| | |
|---|---|
| p: | 1, 1.5, 2 PSI |
| V: | 1.2, 1.5, 1.8 m/s |
| Slurry: | PL-7106 w/0.03% $H_2O_2$ @ 250 ml/min |
| Pad: | IC1000 k-groove |
| Dresser: | 3M A165 |
| Time: | 60 sec |

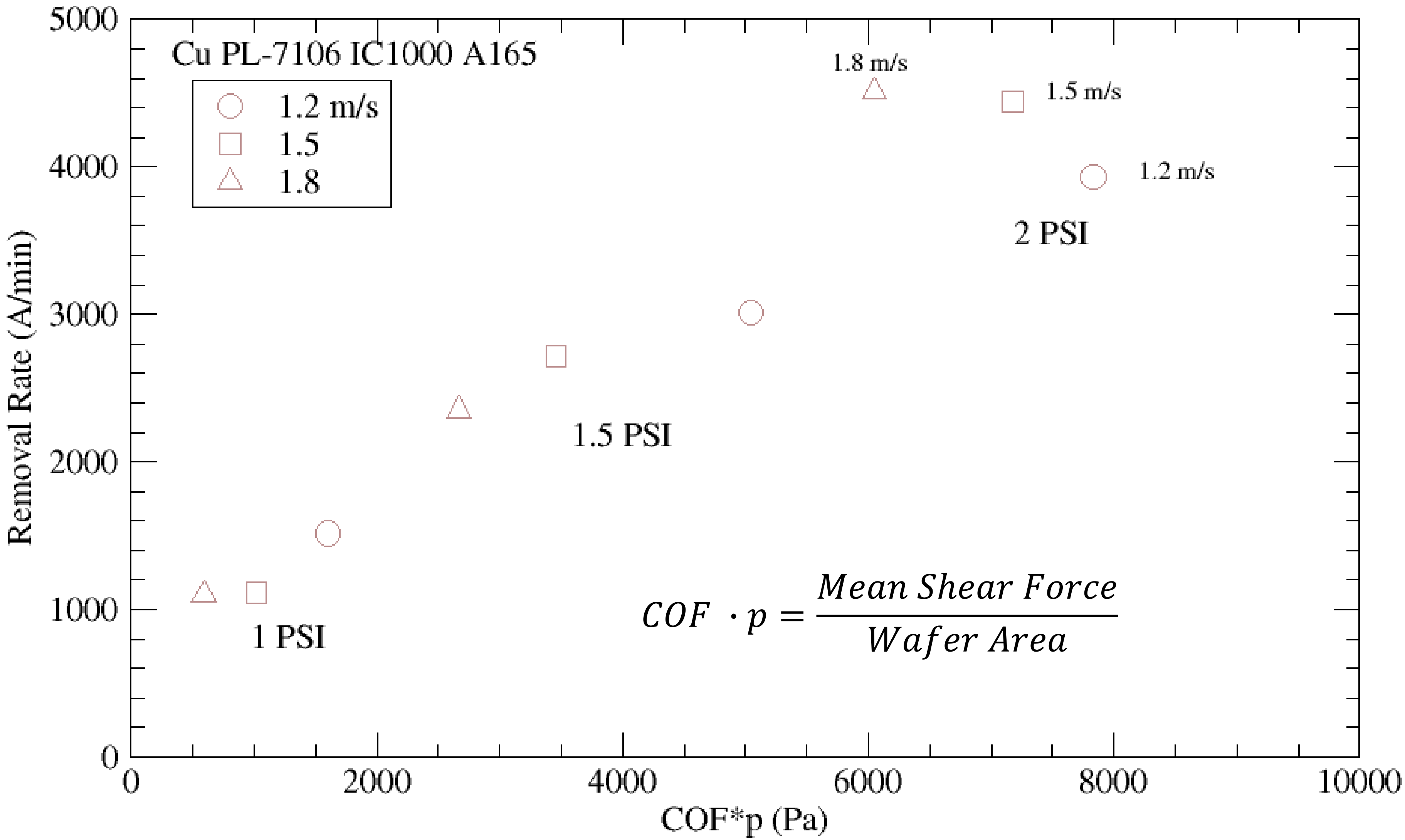
# Preston Plot of the Removal Rate

Mean removal rates in this experiment do not follow Preston's Law: $\boldsymbol{RR = c_p pV}$.
How can we make sense of these measurements?



# Removal Rate vs. Shear Force/Wafer Area

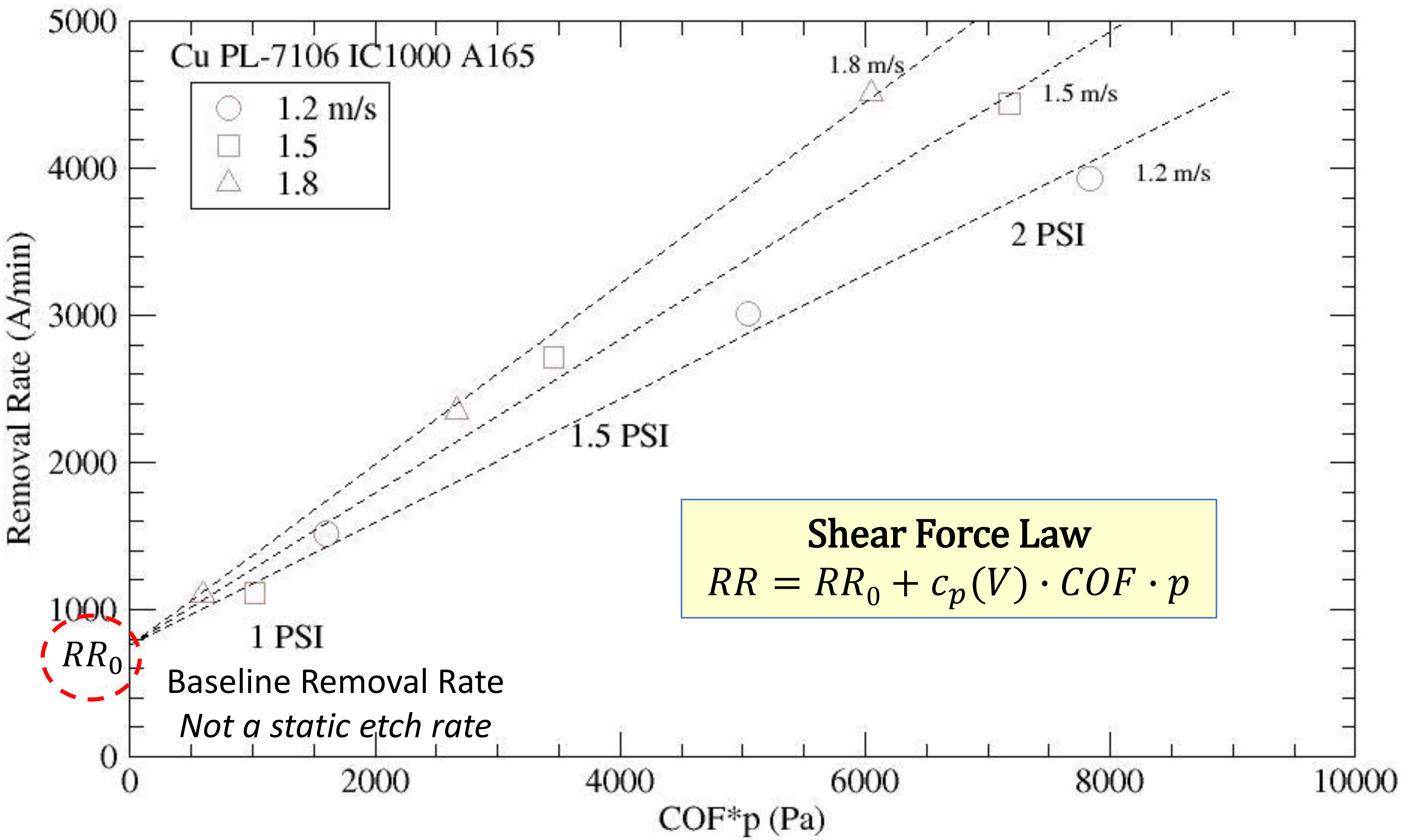
We start with something more basic than Preston's Law: *No CMP tool can remove material mechanically without applying a shear force to the wafer.*




$$COF \cdot p = \frac{Mean\ Shear\ Force}{Wafer\ Area}$$

# Removal Rate vs. Shear Force/Wafer Area

The data fall on/near lines that radiate from a point on the RR axis that are indexed by speed. This is not an accident – it happens in every experiment we have examined.

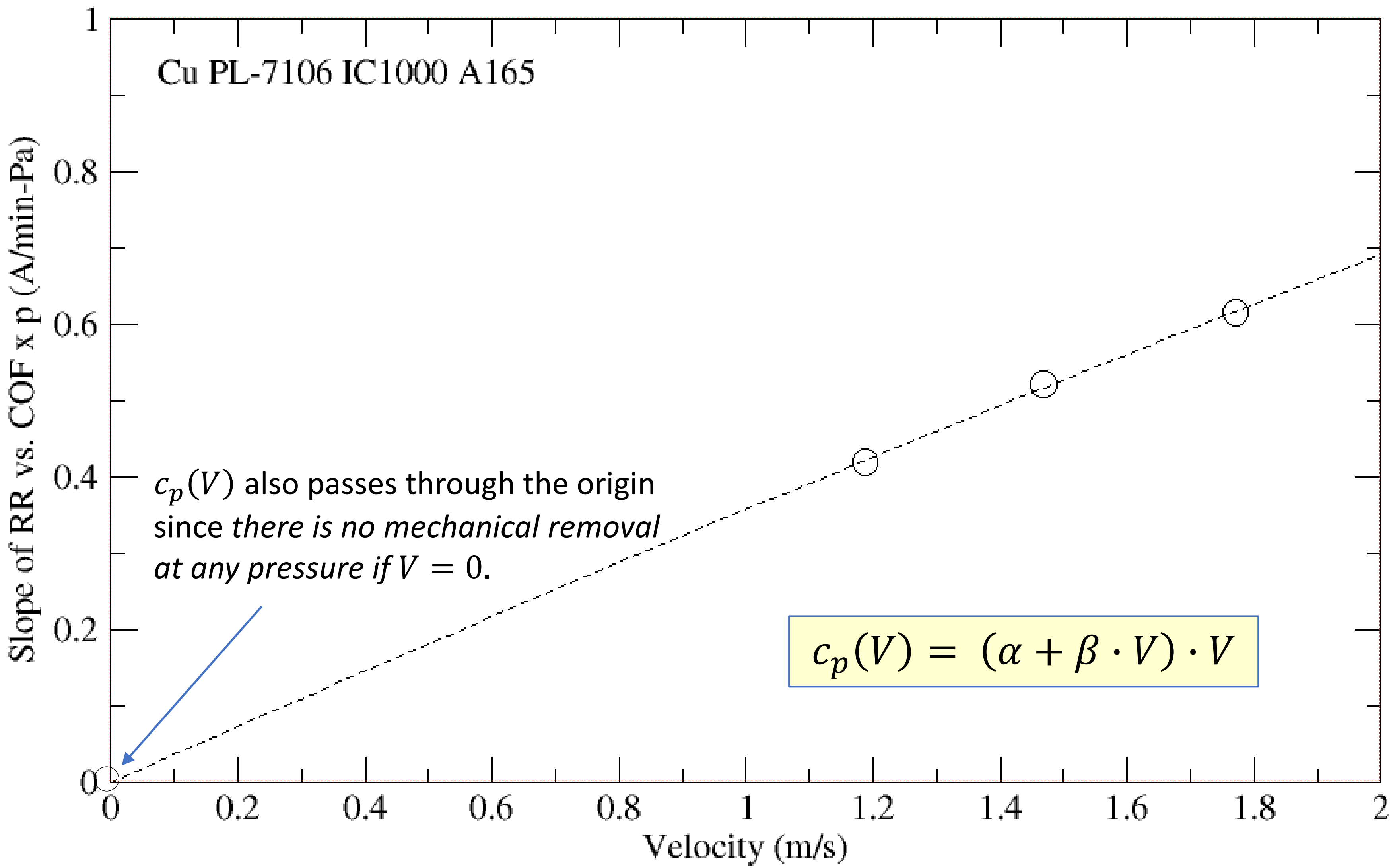



**Shear Force Law**

$$RR = RR_0 + c_p(V) \cdot COF \cdot p$$

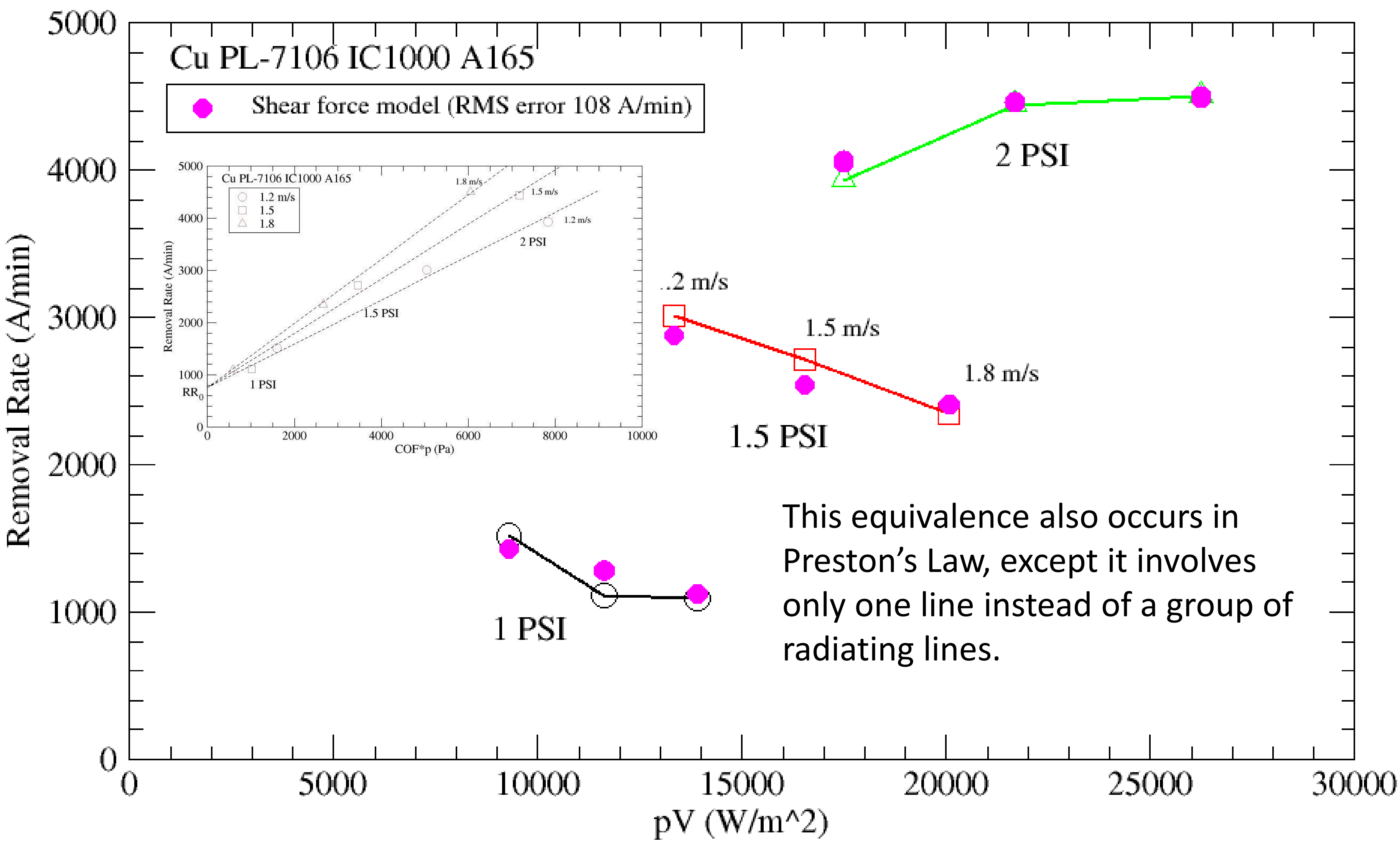
# The Slope Function $c_p(V)$

In addition to the slopes corresponding to the three experimental conditions, we know with certainty that $c_p(V)$ has to pass through the origin. This is insured by the second factor of $V$ below.



# Removal Rate vs. pV

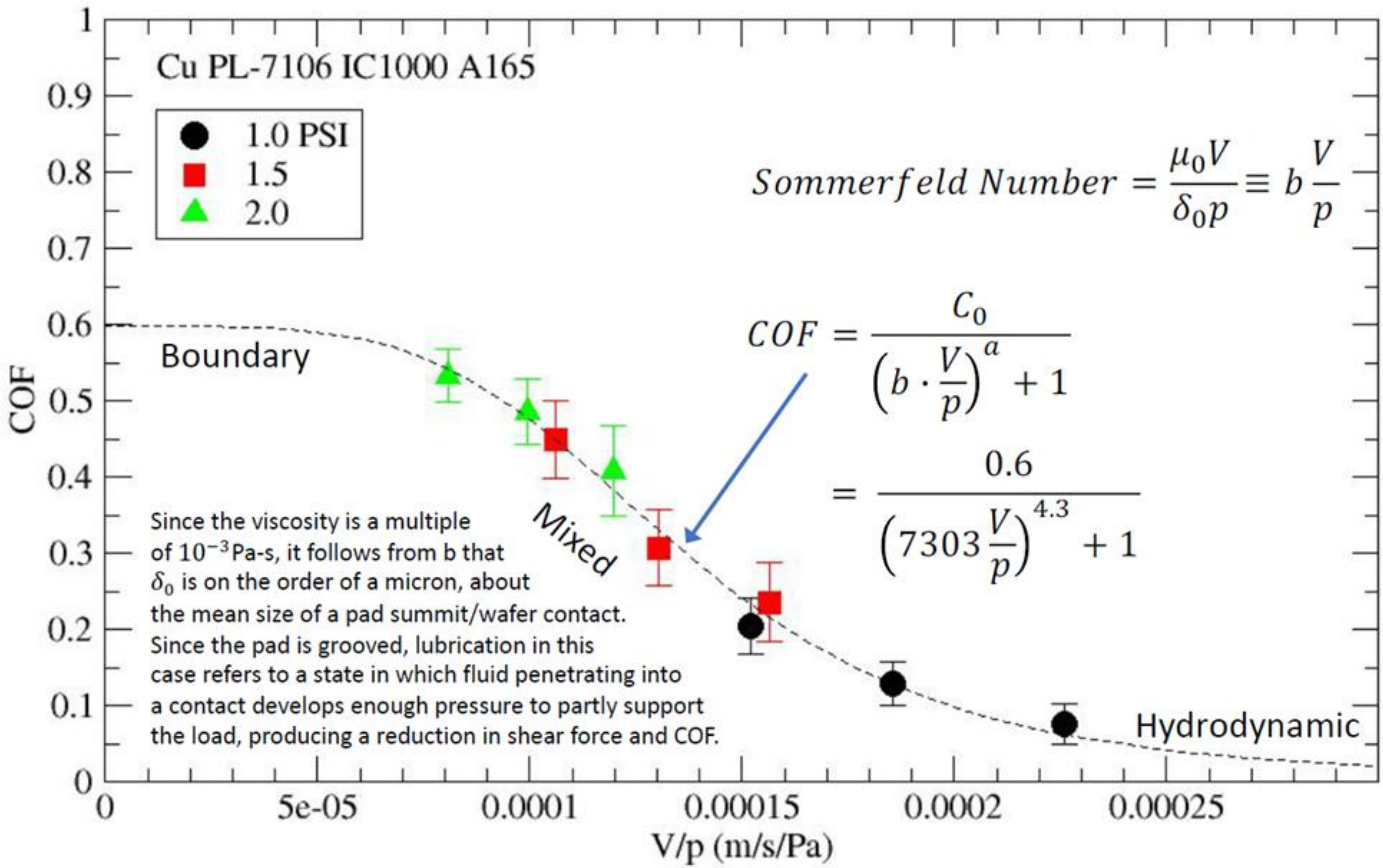
Since the data are close to the radiating lines, the shear force model is close to the data … but, it doesn't provide any more insight into why the data are this way. The key is the COF.




This equivalence also occurs in Preston's Law, except it involves only one line instead of a group of radiating lines.

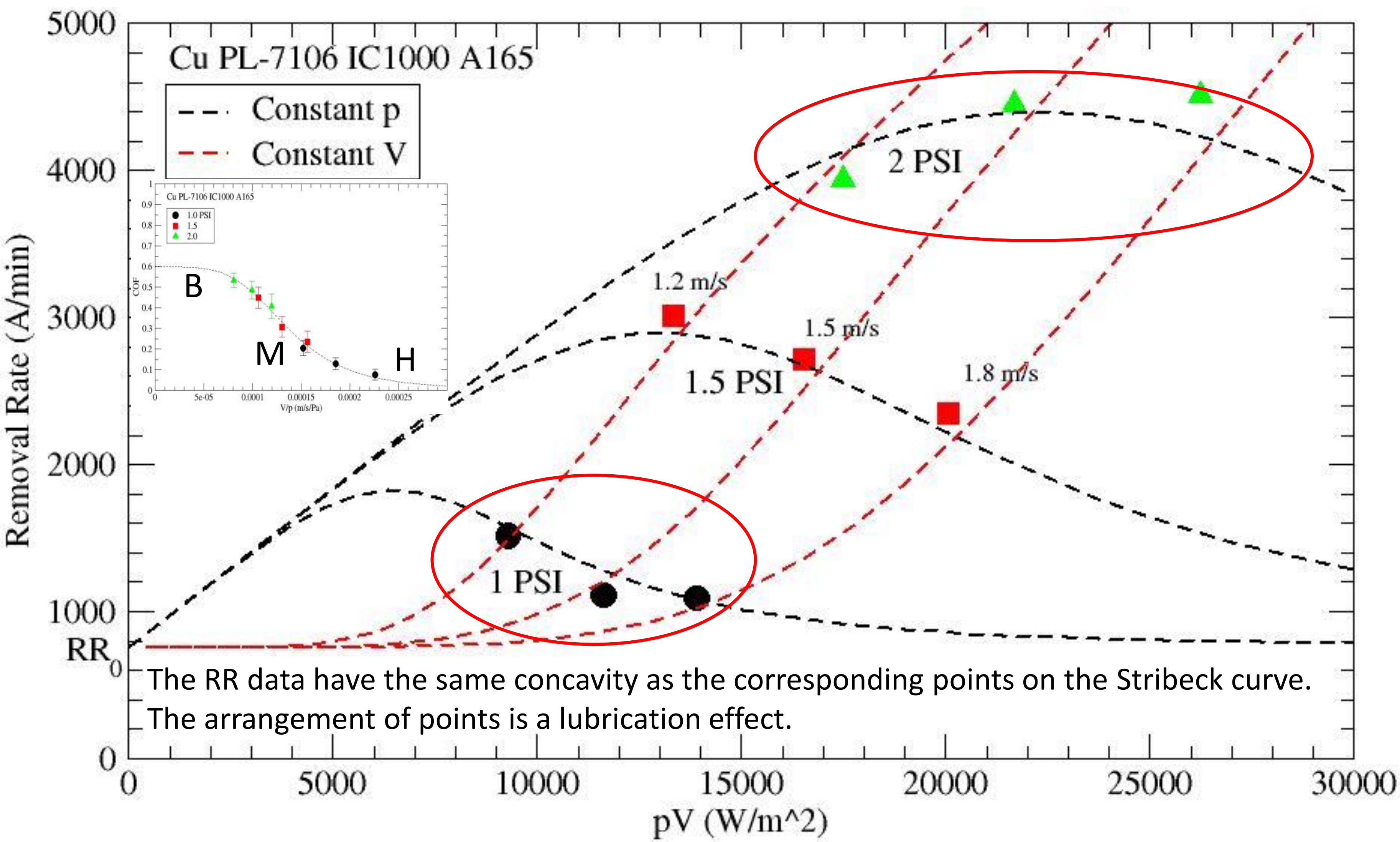
# The Stribeck Curve

The COF, plotted against V/p, follows a Stribeck lubrication curve. V/p is a factor of the Sommerfeld number, which arises by nondimensionalizing the Reynolds equation for fluid flow.



# The Removal Rate Near the Experimental Space

$$RR = RR_0 + c_p(V) \cdot COF(V/p) \cdot p$$

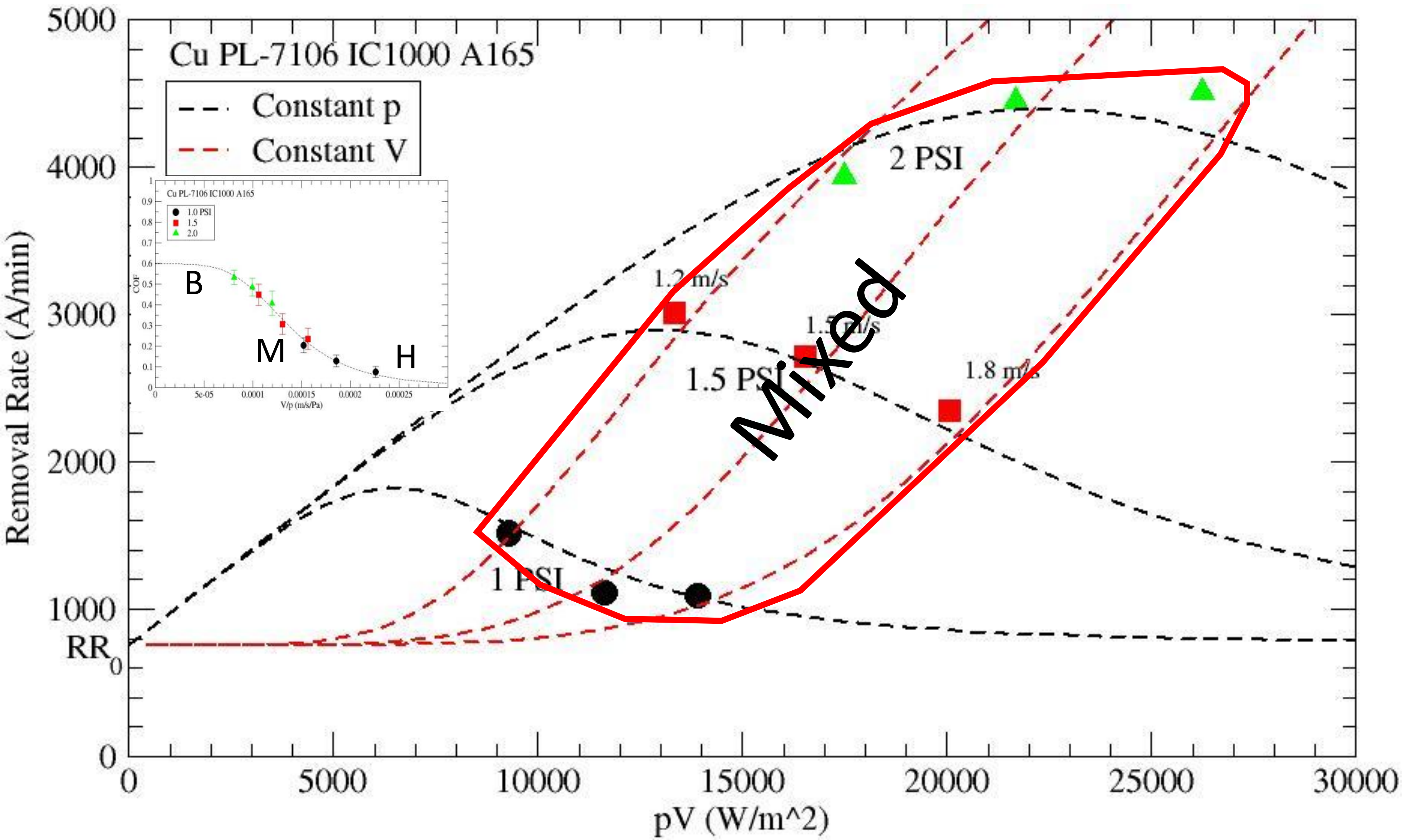



The RR data have the same concavity as the corresponding points on the Stribeck curve.

The arrangement of points is a lubrication effect.

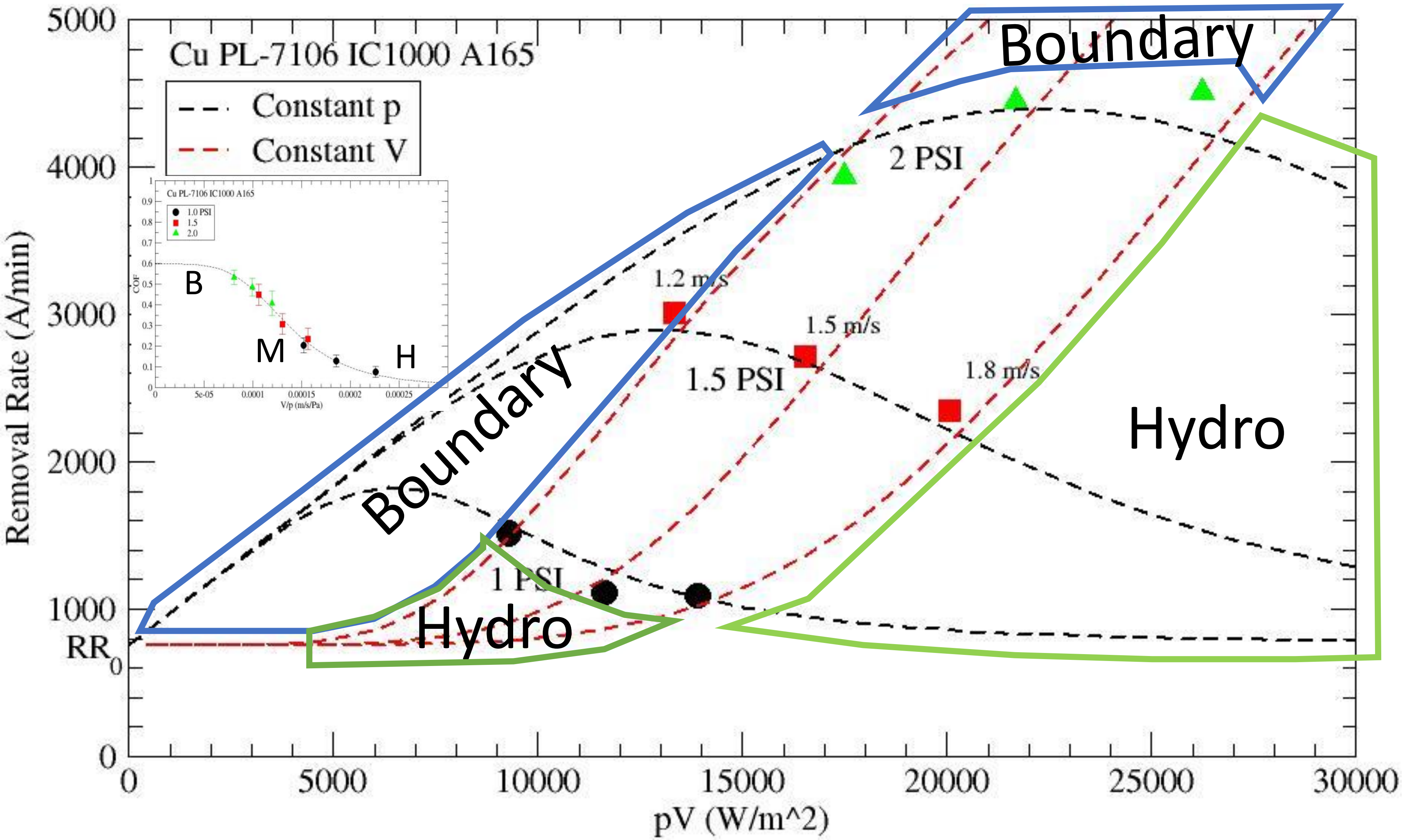
# The Removal Rate Near the Experimental Space

The points in the convex hull of the data all lie in the mixed lubrication part of the Stribeck curve where there is plenty of data. The interpolation in this region is reliable.



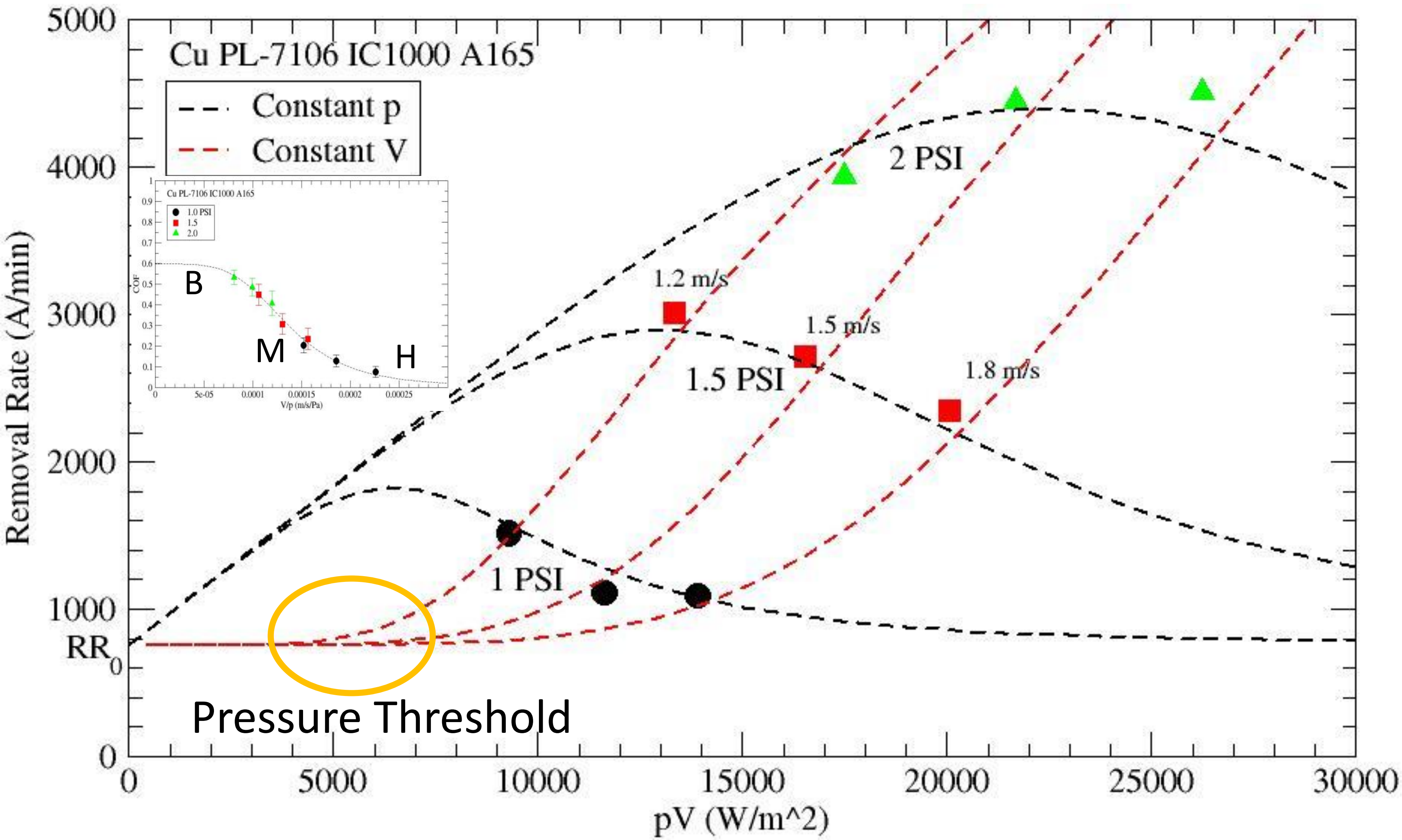
# The Removal Rate Near the Experimental Space

The reliability of the extrapolations in the indicated areas depends on how well the Stribeck model represents the boundary and hydro regions of the curve.



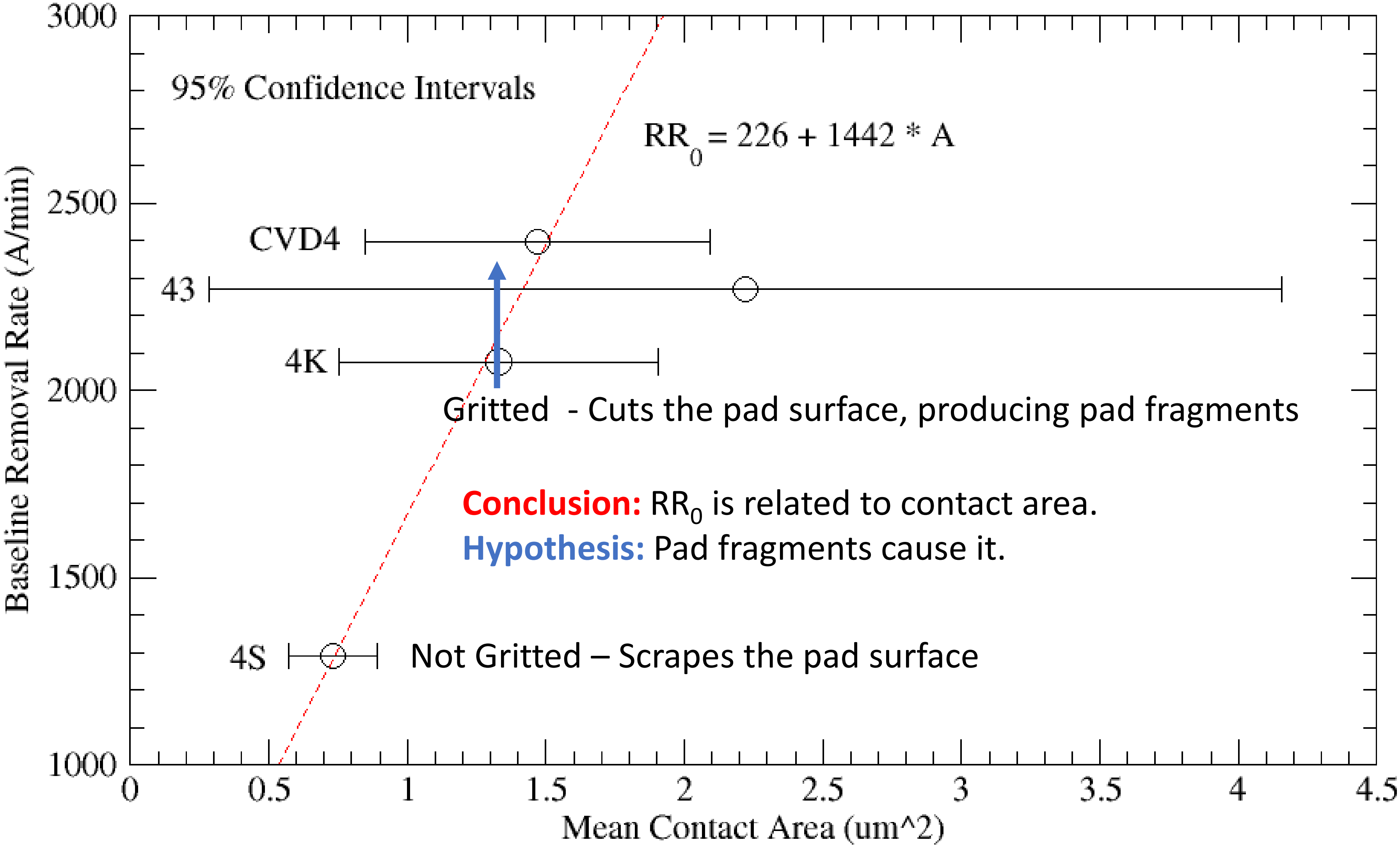
# The Removal Rate Near the Experimental Space

The model predicts a pressure threshold for shear force removal. At the given speeds, this is just the minimum $p$ Needed to overcome summit/wafer)lubrication and begin engaging in solid/solid contact.



# Baseline Removal Rate $RR_0$ and Contact Area

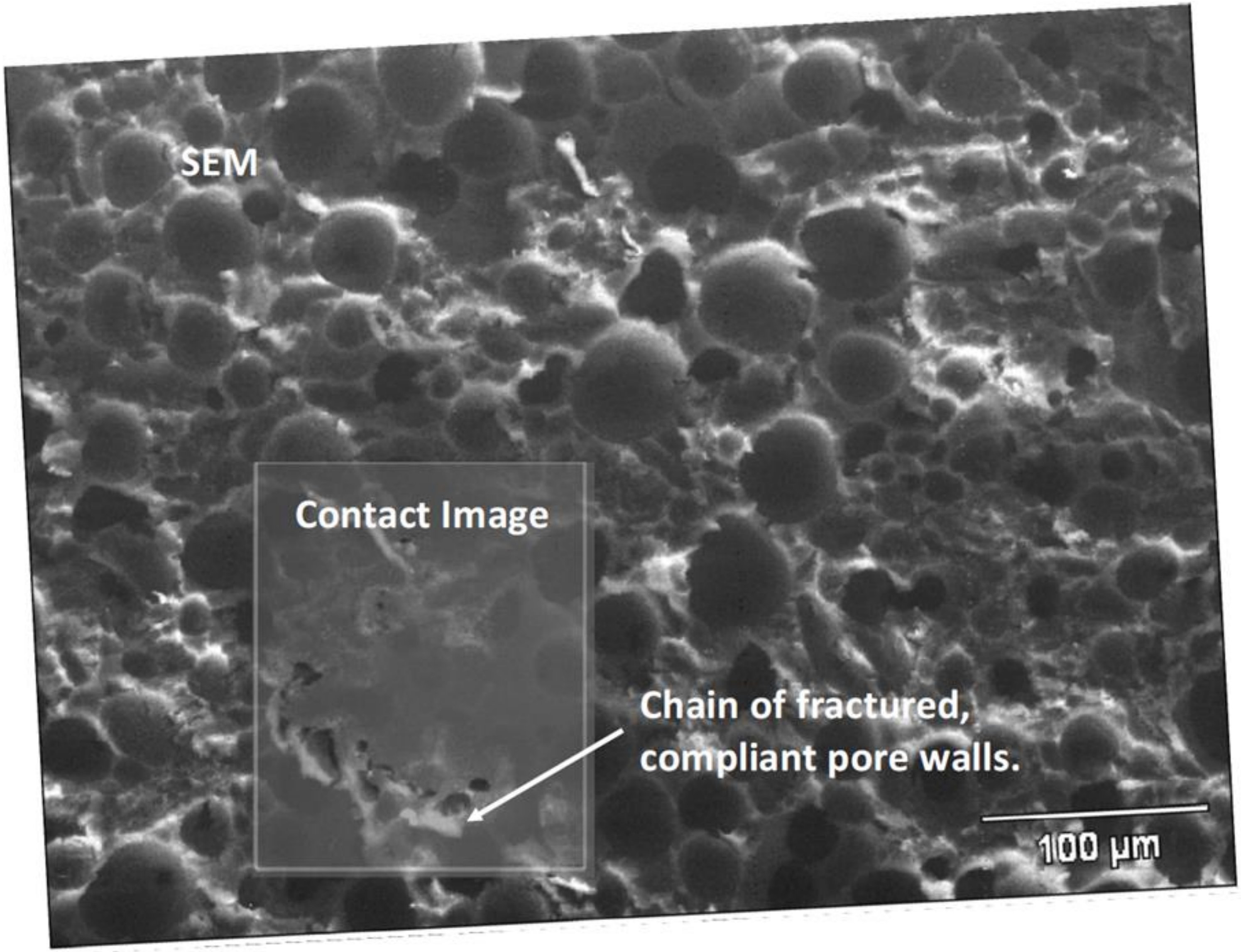
**Archival Experiment:** 300 mm Cu polished on D100 using PL-7106 to test conditioners. Pad samples were taken and contact area measured @ 2 PSI by confocal microscopy.




**Conclusion:** $RR_0$ is related to contact area.
**Hypothesis:** Pad fragments cause it.

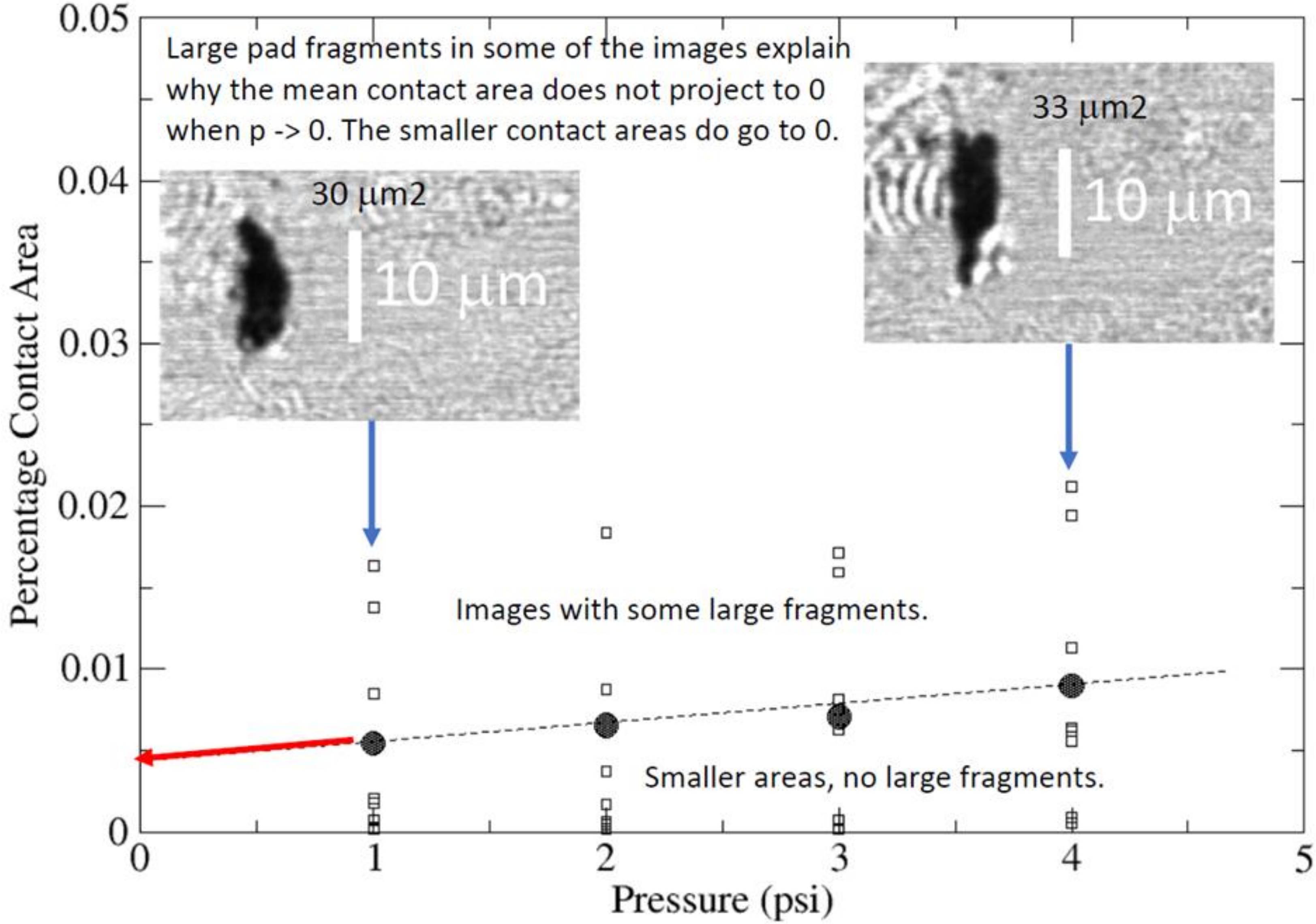
# Large Contact Areas = Compliant Pad Fragments

**Archival Data:** Broken pore walls can produce very large contact areas.

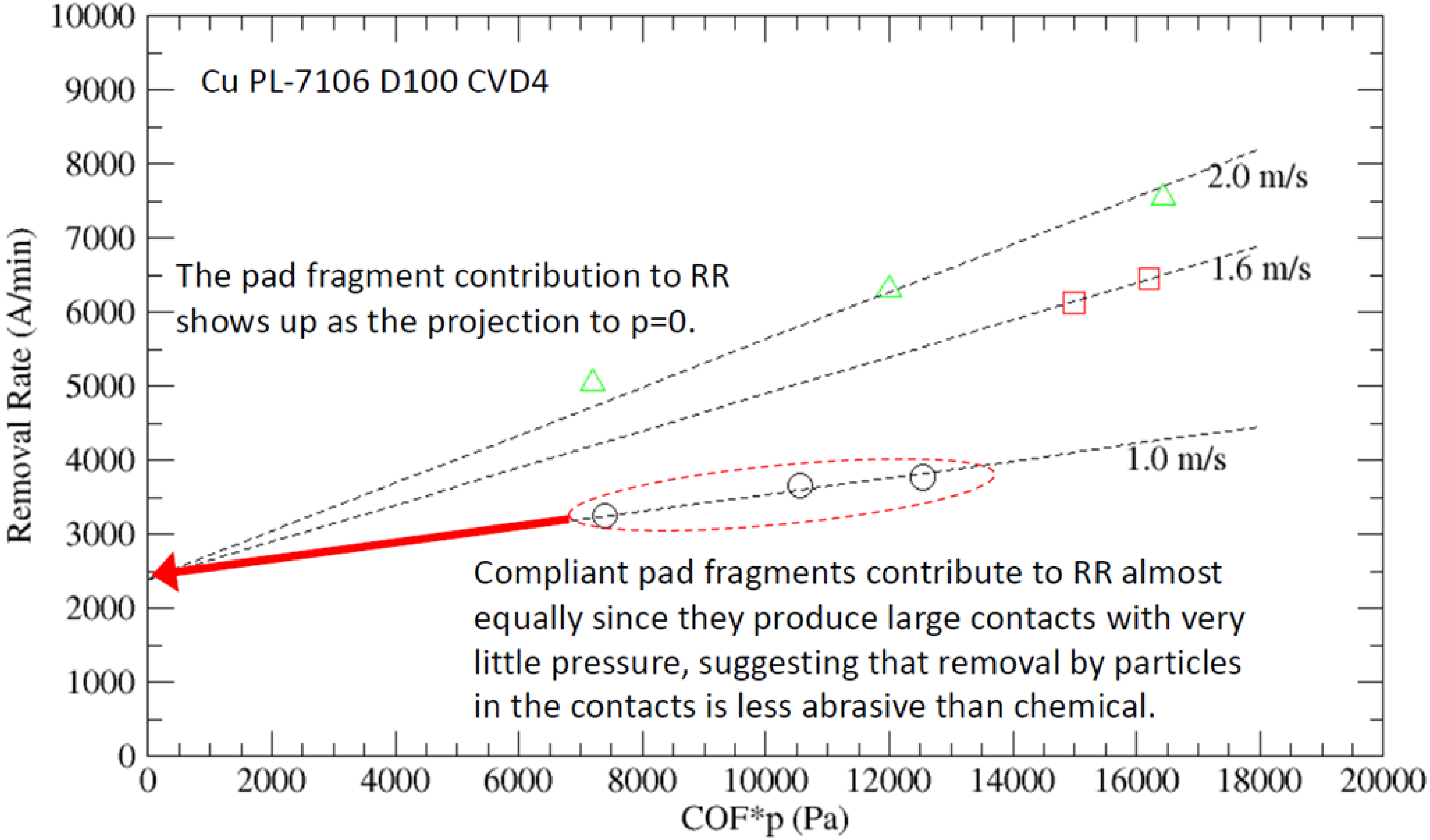


# Compliant Fragments Under Pressure

**Archival Data:** Eight 425x425 $\mu m^2$ contact images, 4 pressures.

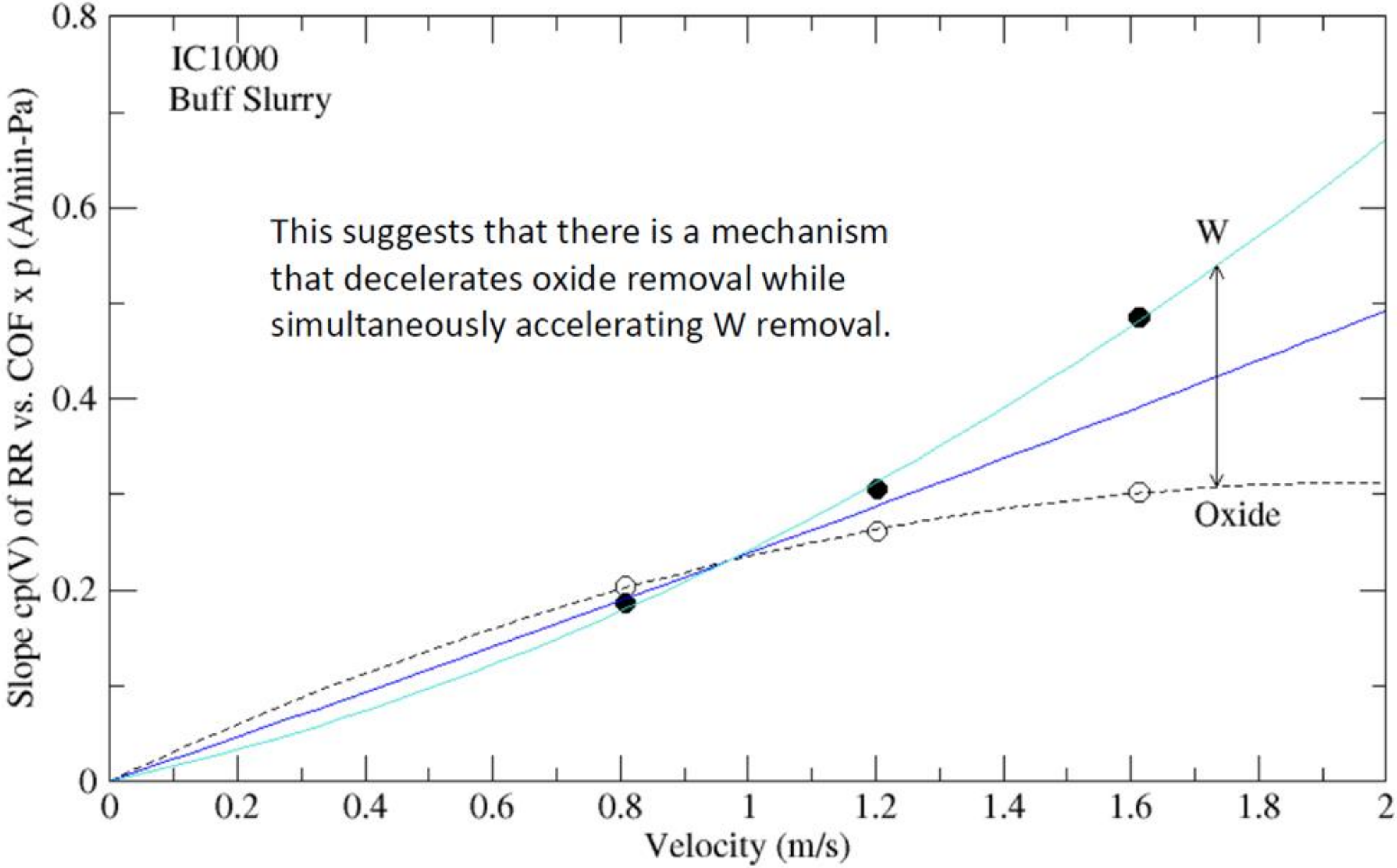


# Removal Rate Projection to 0 Pressure



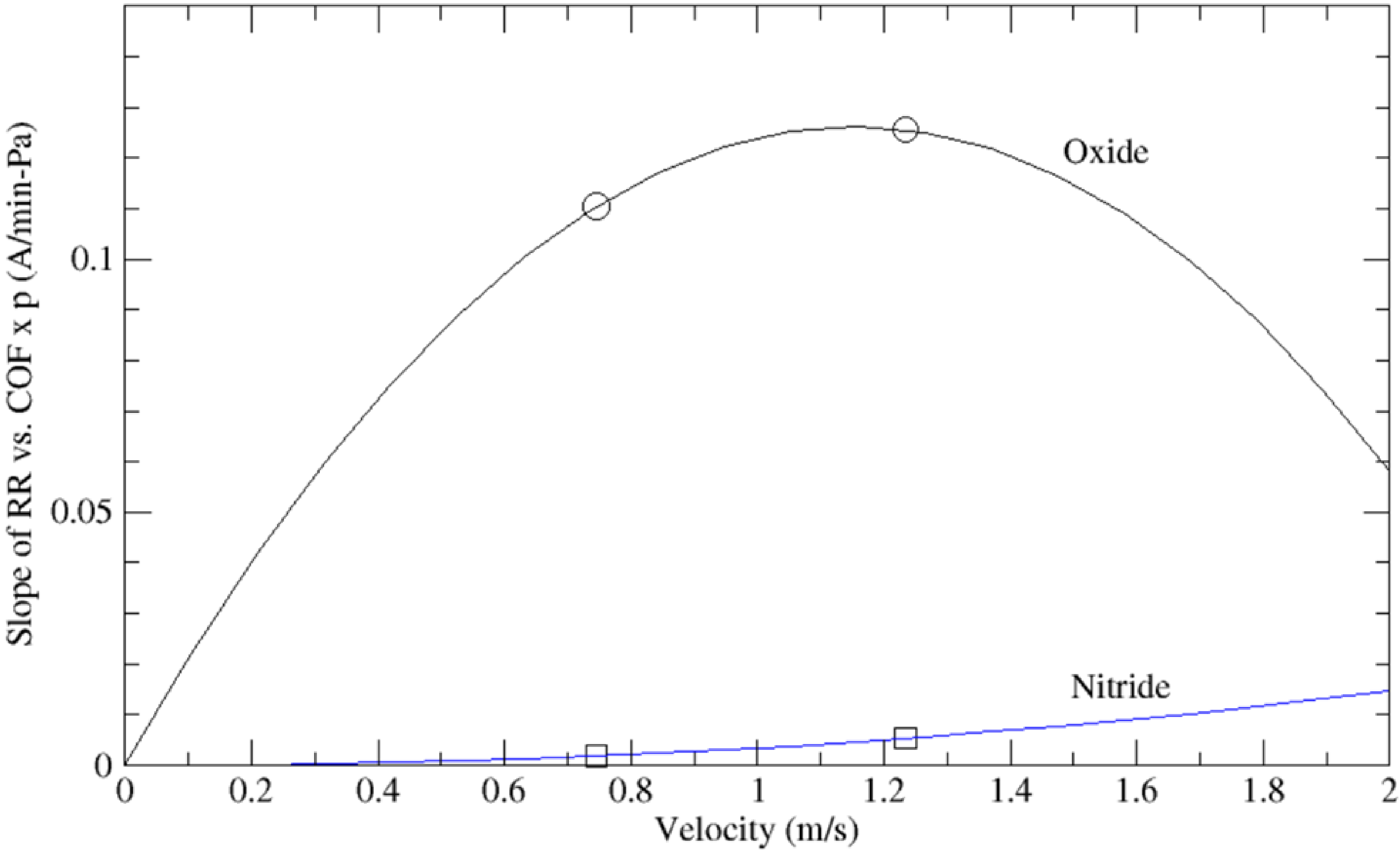
# The Slope Function $c_p(V)$

What, exactly, does it do? For the Cu example, it is linear, but for dual purpose slurries, it has some interesting behaviors. This is a W buff slurry, applied under exactly the same conditions to W and ILD blanket wafers.



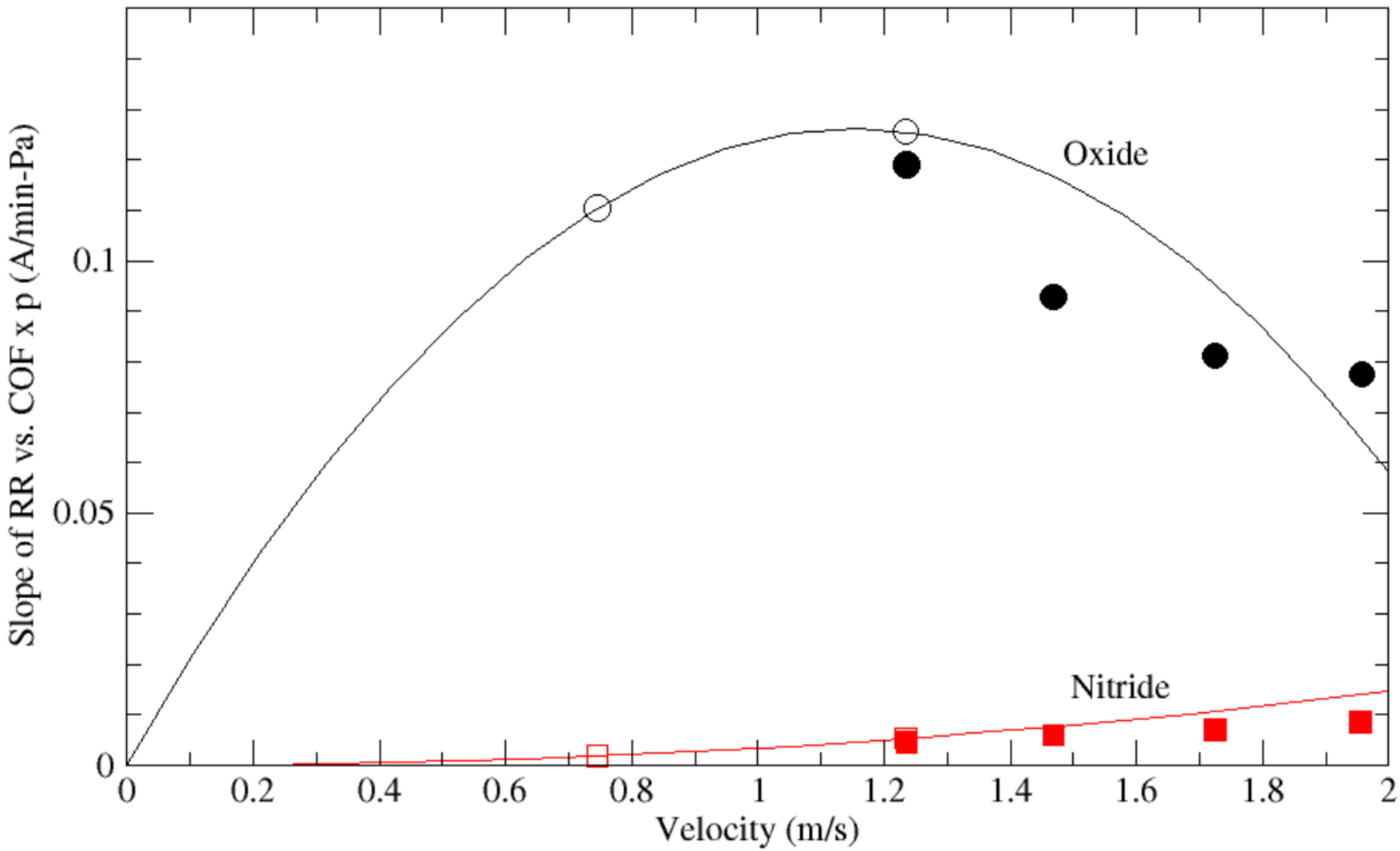
# The Slope Function $c_p(V)$

These functions are from identical experiments using an STI slurry that removes oxide and stops on nitride. The model makes a prediction about what will happen for higher V. Is it real, or is it an artifact of using a quadratic fitting function?



# More on the Slope Function $c_p(V)$

The prediction is qualitatively confirmed by a separate experiment using the same consumables. The trend is not an artifact.



# What is Good about the Shear Force Law?

Generalizes Preston's Law (when the COF is constant and $c_p(V)$ is linear)

Based on simple mechanics (RR $\propto$ shear force) and well-established lubrication theory, which should both be universal.

When it is possible to construct a Stribeck curve, provides clarity about the "why" of some measurements and makes reasonable removal rate predictions.

Useful framework for investigating phenomena and integrating various bits of knowledge:

- Defines a place for pad summit fluid lubrication and contact mechanics in CMP.
- Provides some information about chemistry or slurry particle action.
- Led to an explanation of "static etch rate" ($RR_0$ = compliant pad fragments).
- Elucidates what causes pressure thresholds (one shown – there is another!).

Successfully applied to 28 experiments so far (4 materials, 5 slurries, 3 pad types, many conditioner designs).

More information? Contact lborucki@aracainc.com

# Supplementary Slides

# Shear Force Law Removal Rate Model Summary

$$RR = RR_0 + c_p(V) \cdot COF(V/p) \cdot p$$

$$c_p(V) = (\alpha + \beta \cdot V) \cdot V$$

$$COF(V/p) = \frac{C_0}{\left(b \cdot \frac{V}{p}\right)^a + 1}$$

$\boldsymbol{RR_0}$ is the baseline removal rate, the common intercept in a plot of *RR* vs. $COFp$. When $RR_0 < 0$ , the horizontal axis intercept is a removal rate shear force threshold.

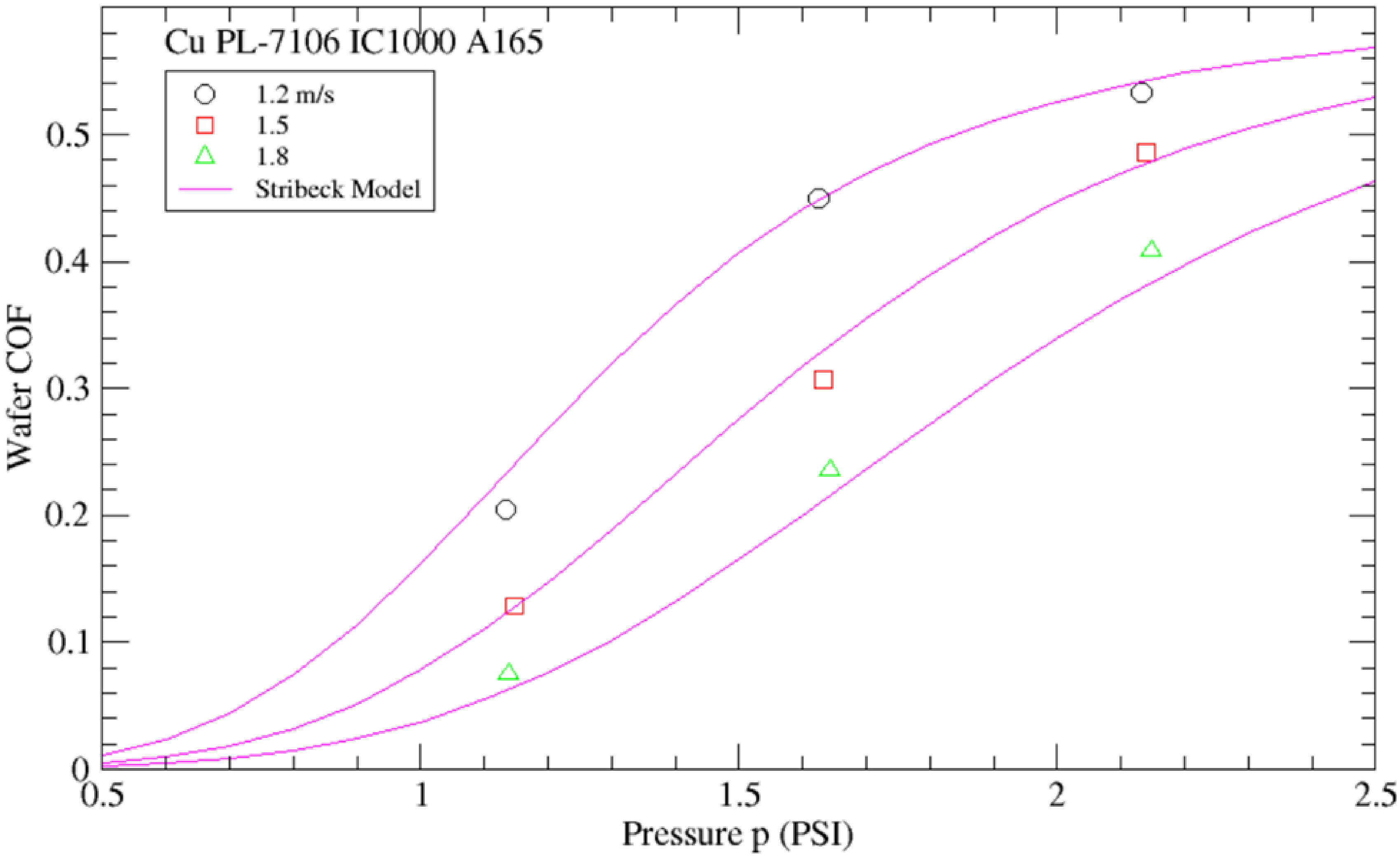
$\boldsymbol{c_p(V)}$ is the slope function, an empirical fit to the slopes of the rays in the *RR* vs. $COFp$ plot that also passes through the origin.

$\boldsymbol{COF(V/p)}$ is an empirical fit to Stribeck data. It describes the balance between solid/solid contact and lubrication in summit/wafer contacts. It is the fluid-dynamic part of the theory.

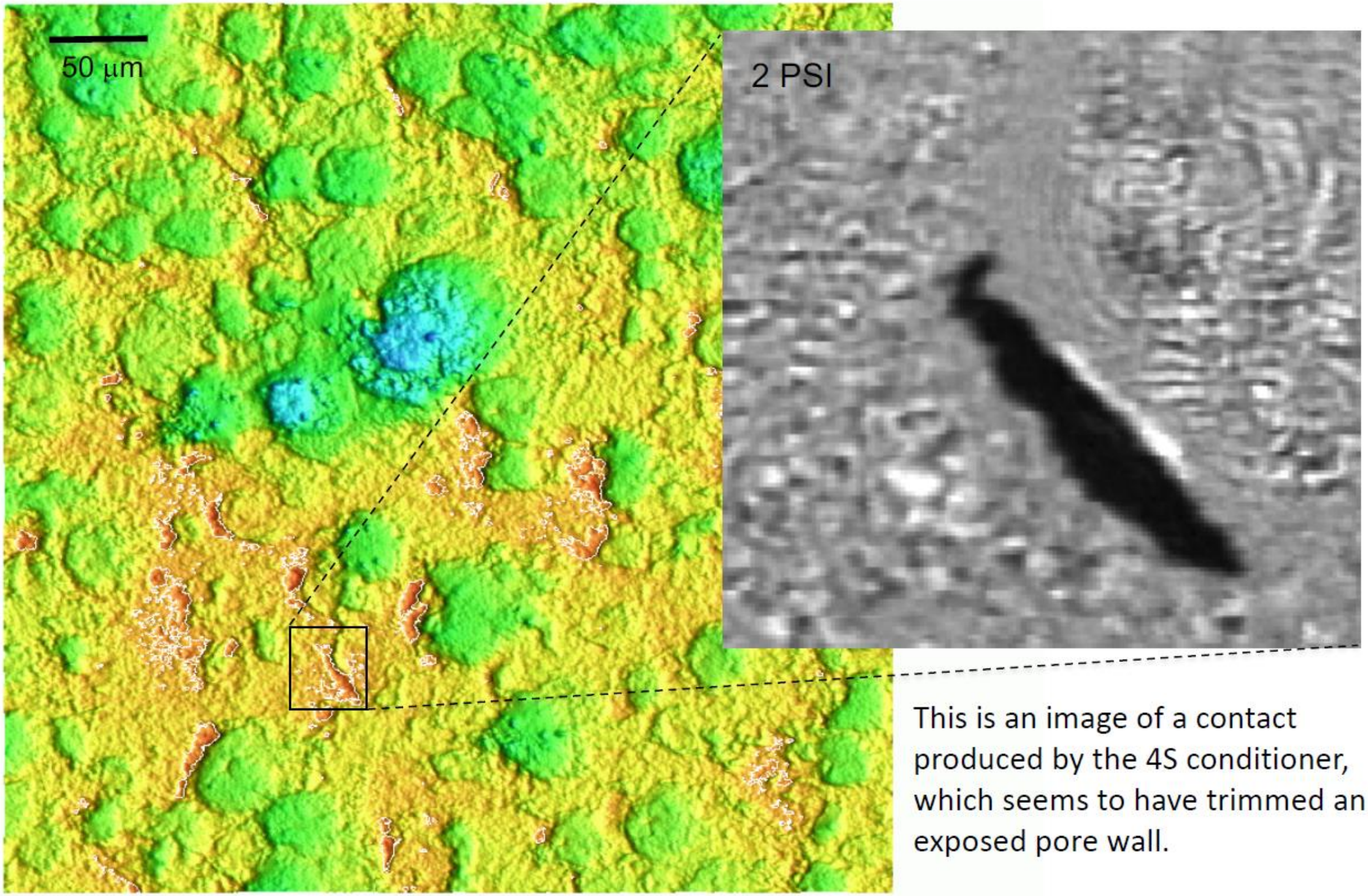
$C_0$ is the limiting COF at very low speed or very high pressure.
$b$ is the ratio of the dynamic viscosity to a length scale, $\mu_0/\delta_0$.
$a$ is related to the slope at the solid vs. lubricated balance point: $slope = -abC_0/4$.

# The Mean Wafer COF

The COF has some interesting behavior in the example. It increases with pressure and decreases with speed as you might expect. But the COF is also *low* (0.075) at 1.14 PSI and 1.8 m/s and has a 7x range. This graph is a good way to understand it but not the best way to model it.

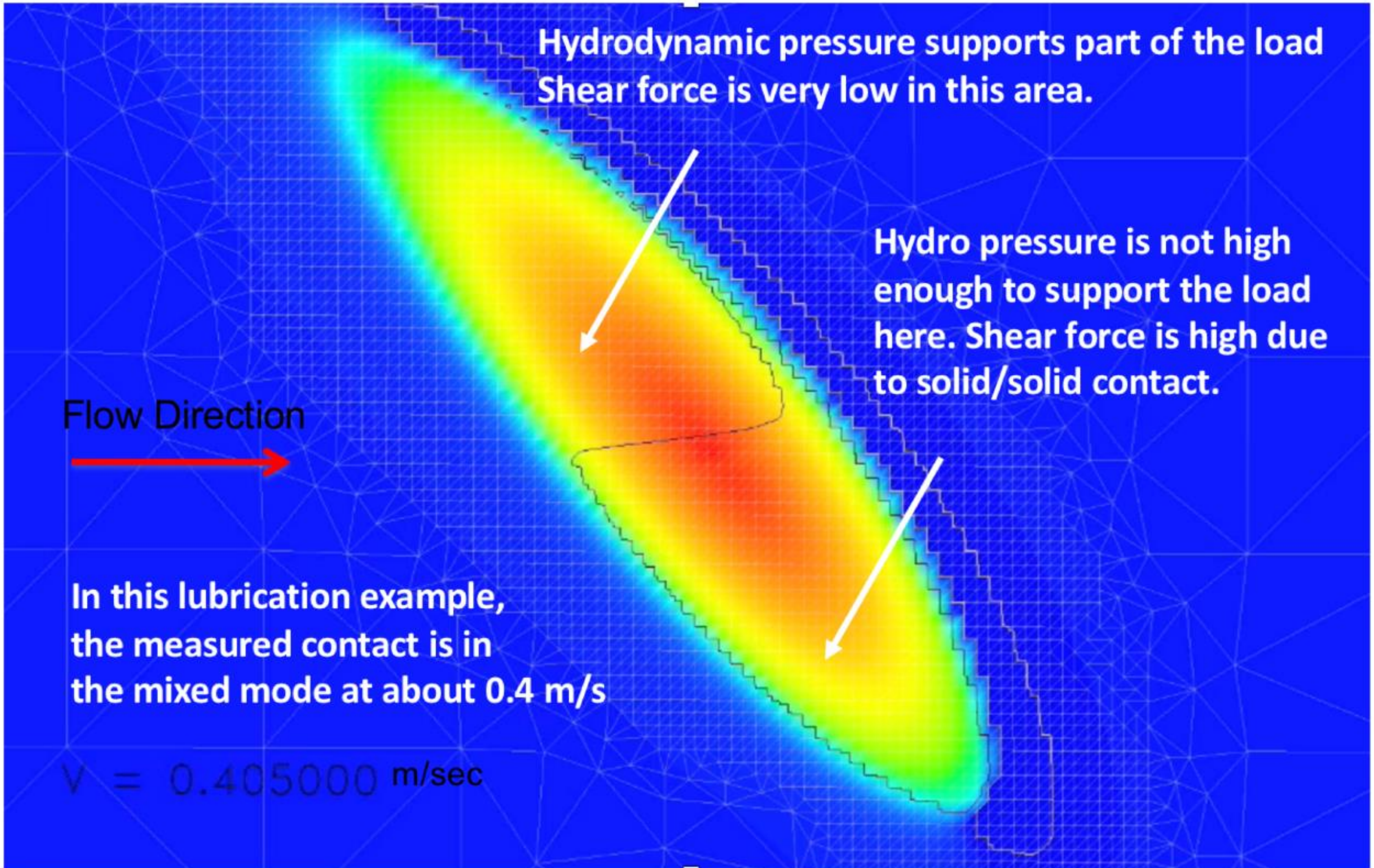


# Lubrication of a Real Contact



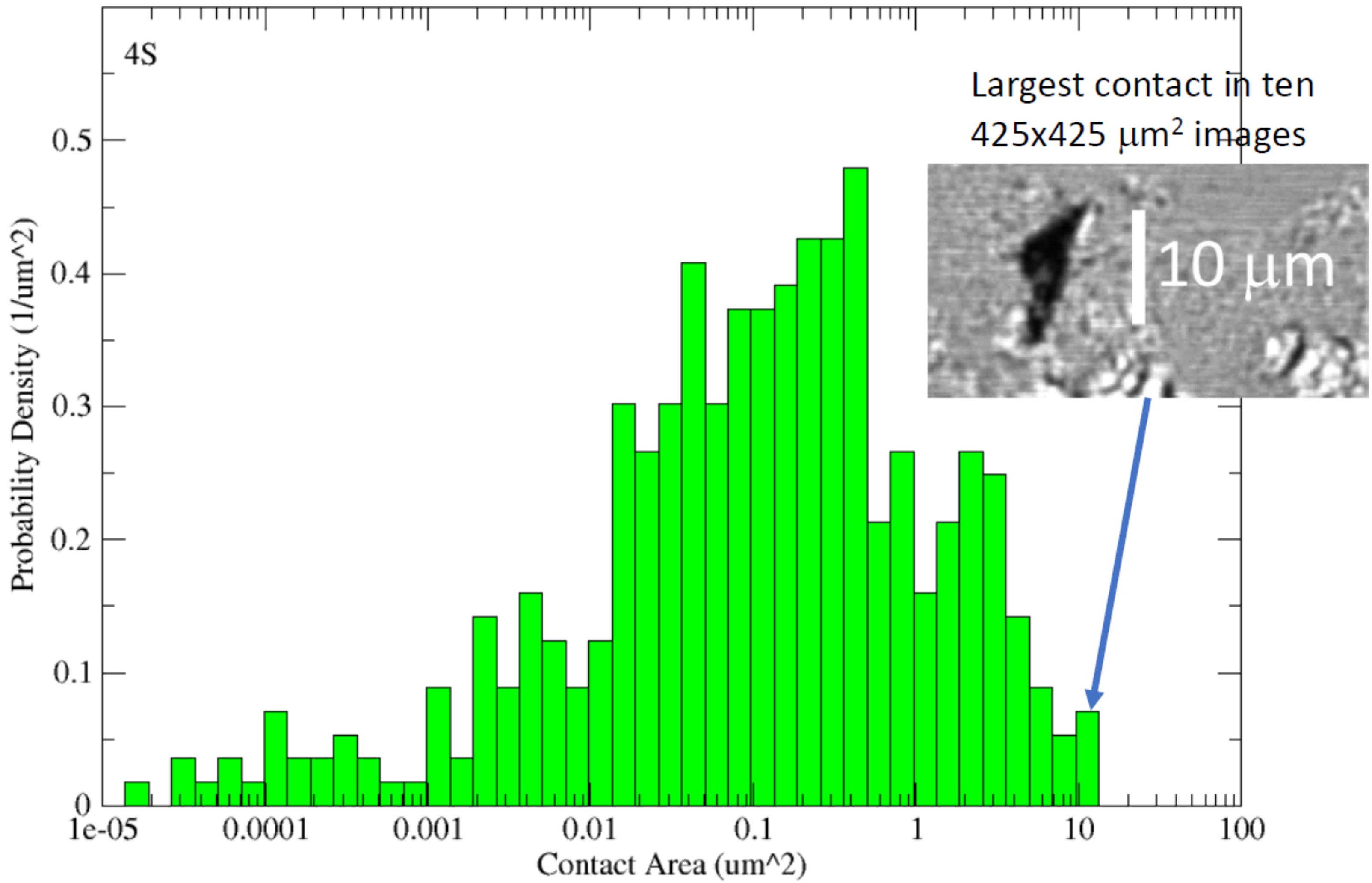

This is an image of a contact produced by the 4S conditioner, which seems to have trimmed an exposed pore wall.

# Lubrication of a Real Contact

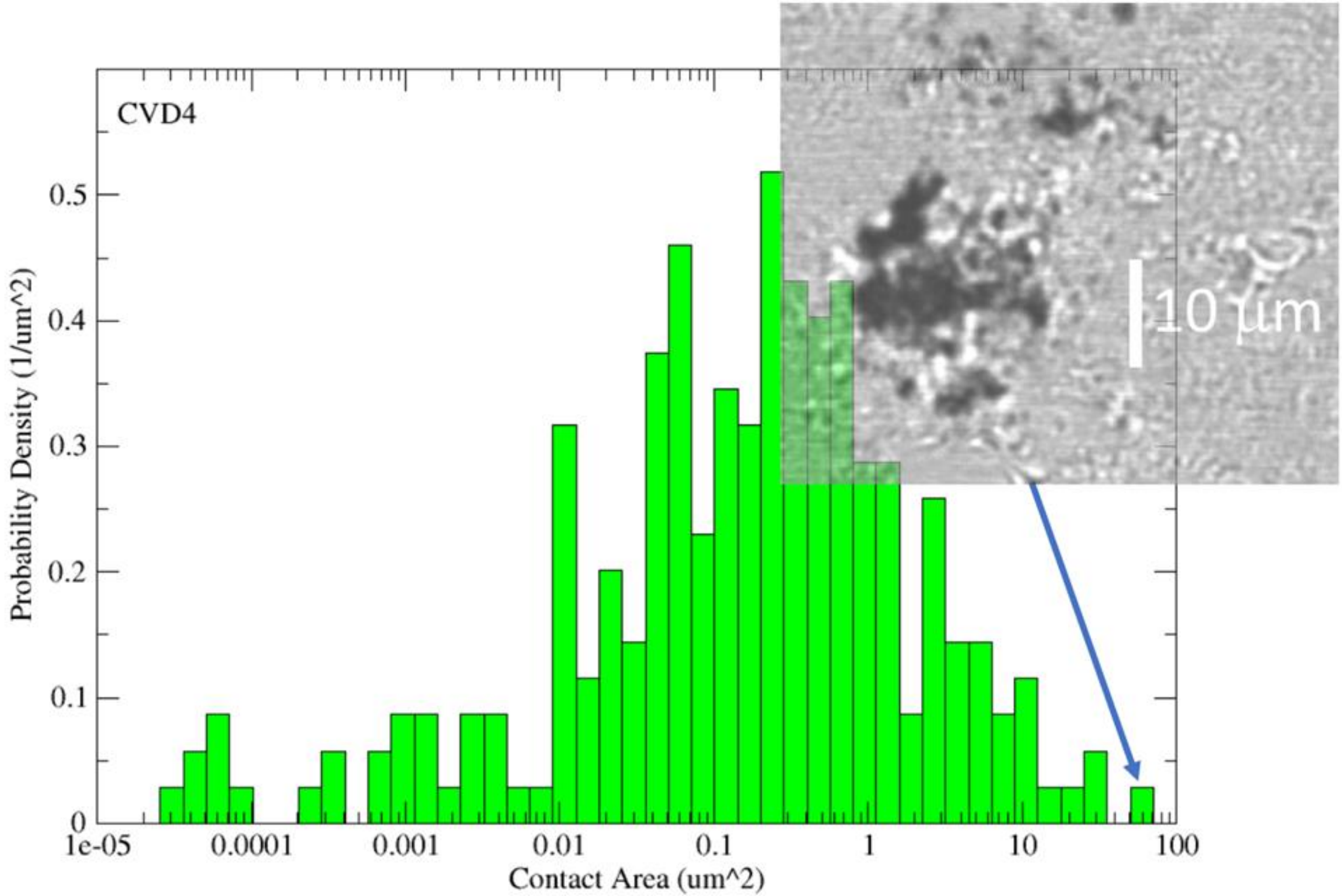


# Contact Area Comparison: 4S vs. CVD4

Compared with 4S, CVD4 has fewer small contact areas and more large contact areas, as can be seen from the shift to the right in the histograms on this slide and the next. The contact area axis is logarithmic, so there is much more area in this direction.



# Contact Area Comparison: 4S vs. CVD4



# Confocal Microscope Contact Area Measurement Fixture