Role of the Head Disk Interface in HDD Reliability

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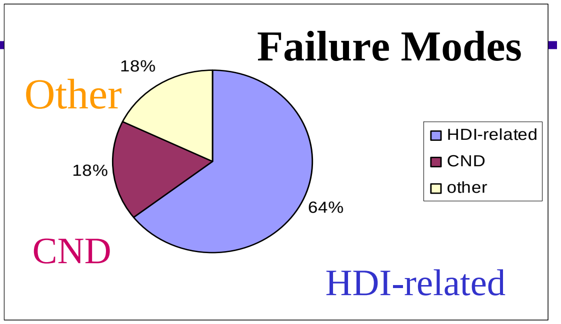
Introduction

- ❑ **Motivation:** Designing a reliable HDD requires a rigorous understanding of the most prevalent failure modes/mechanisms, and a means to predict their impact on end-user failure rates.
- ❑ HDD reliability information can be obtained from a variety of sources
  - **End user** – Reliability information from customers can be the hardest to obtain, is often times the most ambiguous, and can be difficult to feedback into product design.
  - **Customer qualification** – Reliability Demonstration Test (RDT) on well controlled sample distribution to determine intrinsic reliability of product (AFR% / MTBF) . Sample size can be limited.
  - **Internal qualification** – Highly Accelerated Stress Testing (HAST) during product development to investigate design margins. Drives may not be sufficiently mature, but a substantial number are available.
  - **Subsystem testing** – component-level testing (H/M, platform, firmware, channel) to evaluate product feasibility and uncover design limitations
  - **Fundamental studies** – Research and development into the scientific underpinnings of current technology, and evaluation of new technologies / alternative designs to meet future product specifications
- ❒ Failure rates from drive-level testing (end-user, customer qualification, and internal qualification) are used to identify the predominant failure mechanisms
- ❒ **Failure of the head-disk interface is found to be the dominant factor impacting HDD reliability**
- ❒ A course-grained model for HDD reliability is developed to address the head-disk interface and the influence of a few vital parameters.
- ❑ Results of drive level testing are presented to vailidate the model
- ❑ Model Refinement – results from component level and fundamental studies

Failure Modes Summary



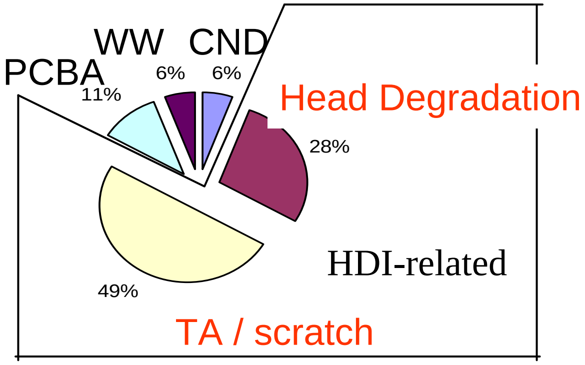
❐ Highly Accelerated Stress testing results

- ➢ Conducted during product development (>10,000 HDD's)
- ➢ **Dominant failure modes (64%) are HDI – related**

❑ RDT testing results (~100 HDD's)

Product	Failure modes	AFR (%)	MTBF (hrs)
80GB/platter (3.5")	1F - PCBA 2F - Disk Scratch 1F - Head Degradation	0.79%	1.11 M
	1F - CND 2F - Disk Scratch 1F - Head Degradation	1.03%	848K
	2F - Disk defects 1F - Weak write 1F - Head Degradation	1.14%	767K

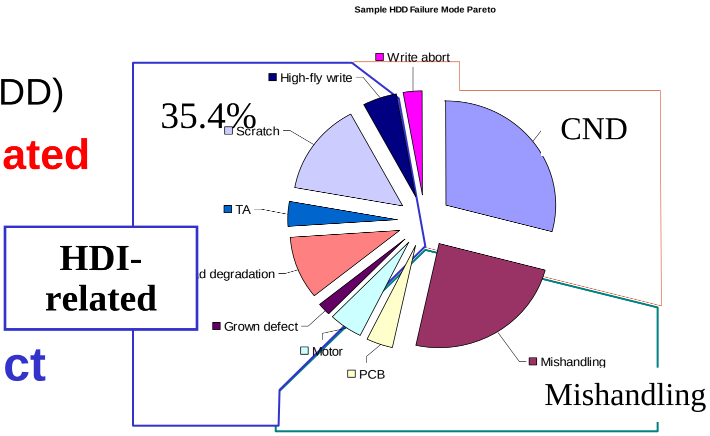
- ➢ **Majority of failures (75%) are HDI – related**



❑ Field Returns – Generic failure pareto (1000's HDD)

- ❑ **Large fraction of "real" HDD failures are HDI-related**

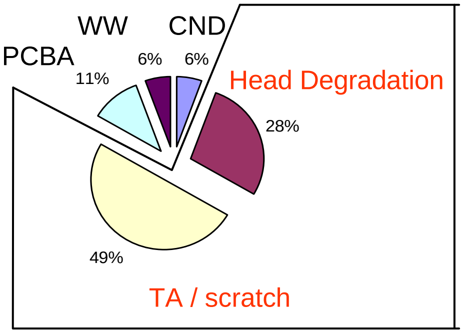
❑ All results point to the head-disk interface as the dominant contributor to HDD reliability



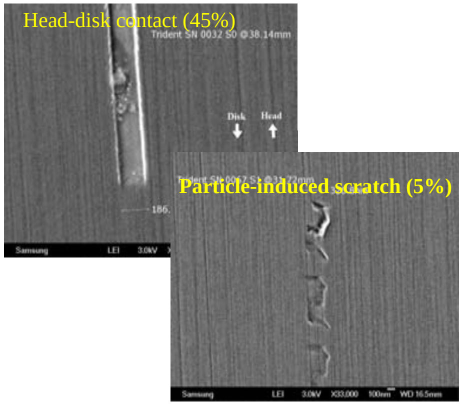
❑ Can we develop a deterministic model to predict these failures?

Failure Analysis – HDI Failures

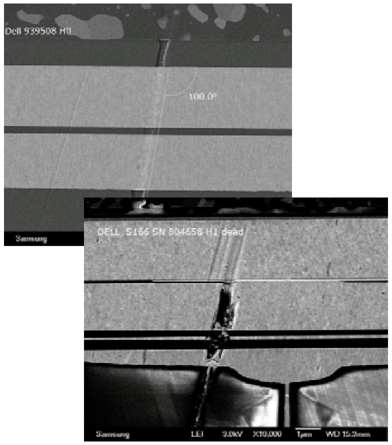
- ☐ Dominant HDI-related failure mechanisms and approximate failure rates



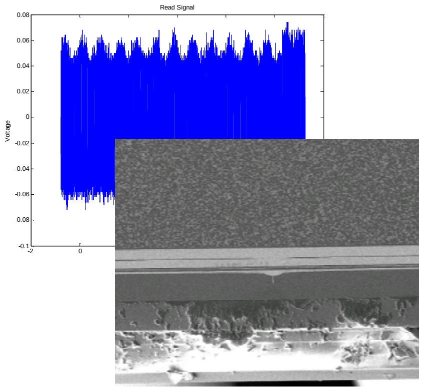
Scratch (50%)



Head degradation (30%)



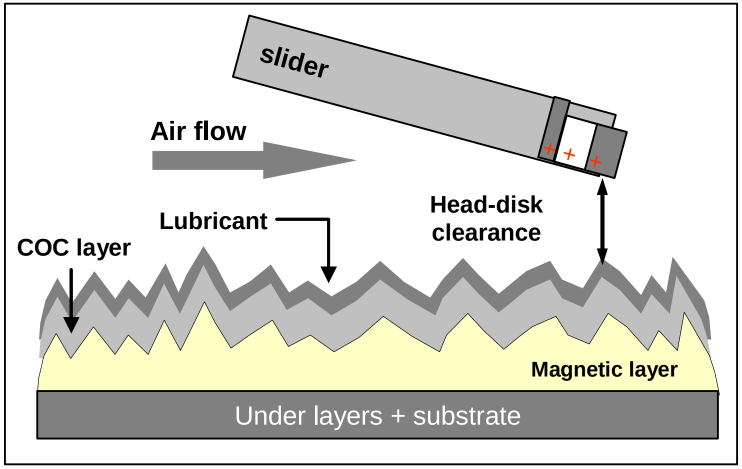
Weak write / modulation (15%)



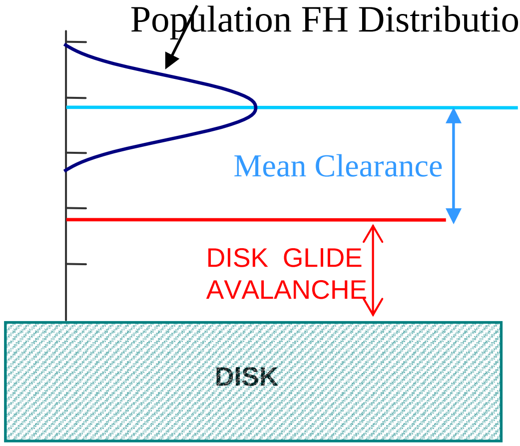
- ➢ 90 – 95% of scratching results from direct contact between flying head and disk
- ➢ Majority of head degradation failures result from head-disk contacts
- ➢ 100% of all modulation failures result from flying too low - “near”contact

- ❑ Majority of HDI-related failures result from the head and disk coming into contact, or near contact

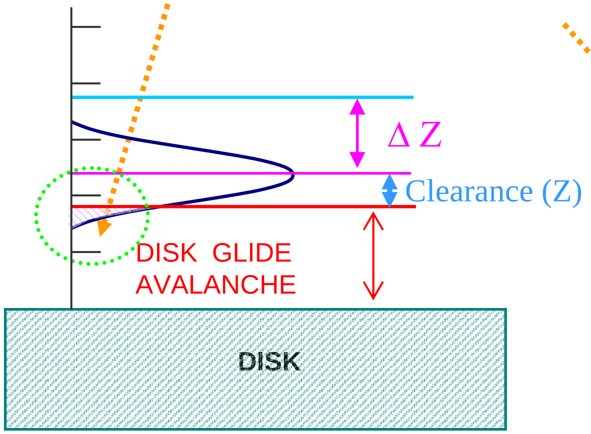
Clearance is key to HDI Reliability



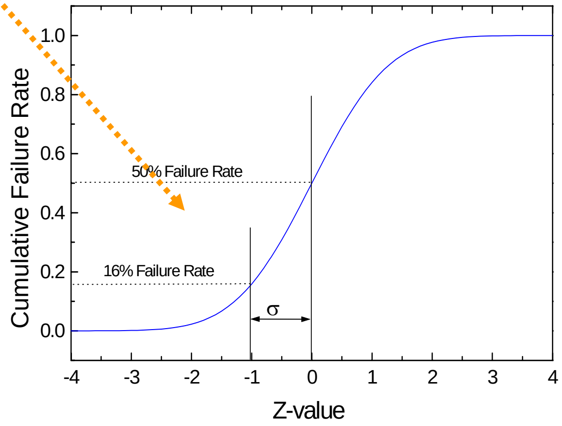
- ❒ Clearance, space between the slider and disk, is the primary factor for HDI reliability.
- ❒ Small clearance results in an increased risk of head-disk contact
- ❒ Zero or negative clearance results in eventual **failure** due to **scratch or head degradation**
- ❒ Failure rates increase exponentially with decreasing clearance



No head-disk contact



Head-disk interference



Reduced HDI failure rate requires minimizing head-disk contacts by maximizing clearance

HDI reliability model

- ❒ **Objective: Provide reliability design criteria by modeling clearance, and predicting failure rates, under any given set of operating conditions.**

- ❒ **Assumptions**
  - ➢ Finite clearance → 0% failure rate
  - ➢ Zero clearance → 100% failure rate
  - ➢ Not a dynamic model, i.e. no explicit time dependence is incorporated into model

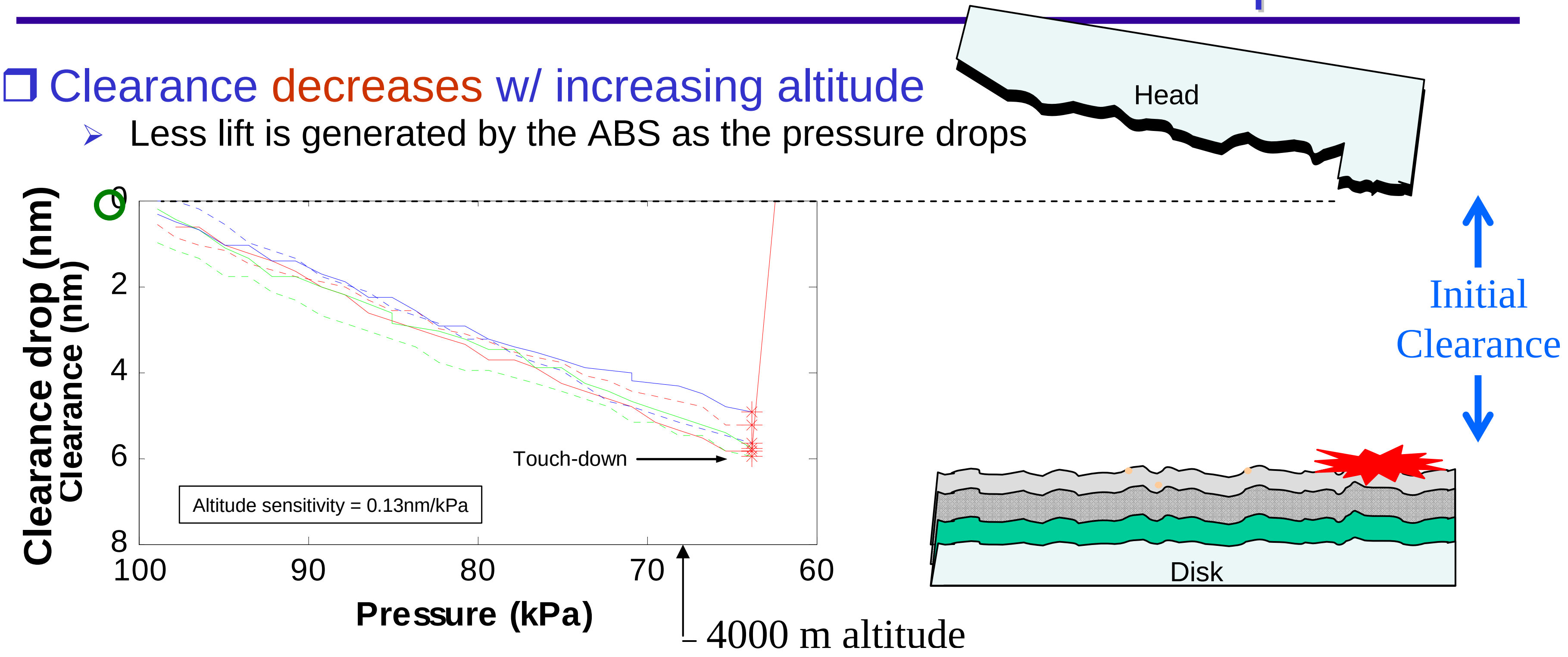
- ❒ **Parameters identified as affecting drive clearance (z) include:**
  - ➢ Incoming clearance distribution (z_o)
  - ➢ Temperature
  - ➢ Altitude
  - ➢ Humidity
  - ➢ Duty cycle: Clearance loss during seek (not covered)

- ❒ **Sensitivity of clearance on each parameter measured independently**

Head-Disk Clearance vs. Altitude and Temperature

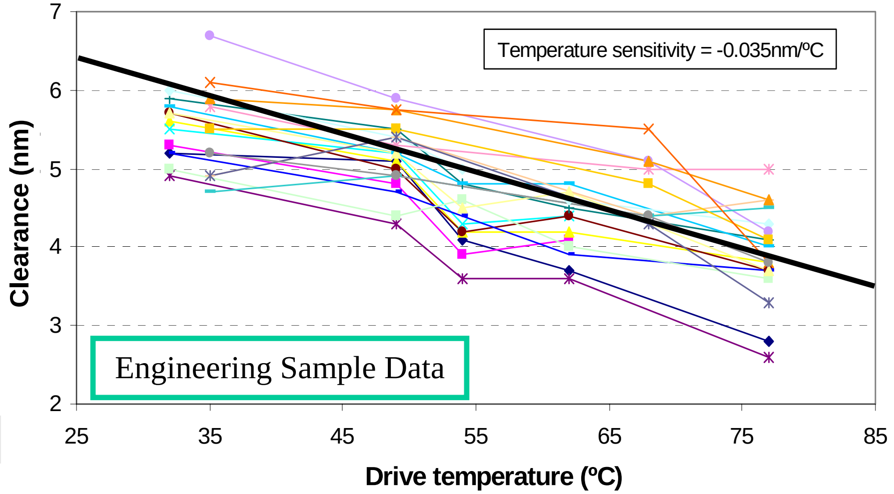
❒ Clearance decreases w/ increasing altitude

- ➢ Less lift is generated by the ABS as the pressure drops



❒ Clearance also decreases with increasing temperature

- ➢ Consistent with temperature derating discussed above.

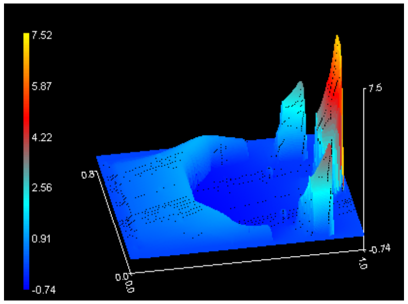


Clearance is Sensitive to Humidity

❒Theoretical model developed to describe the effect of humidity on clearance

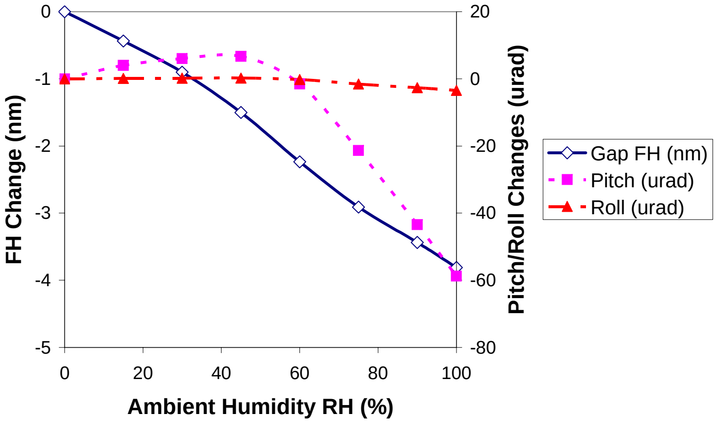
- ➢Compression under ABS can result in local supersaturation of water vapor
- ➢Supersaturated water vapor is incapable of supporting ABS
- ➢Effective ABS lift drops – fly height decreases

ABS Compression

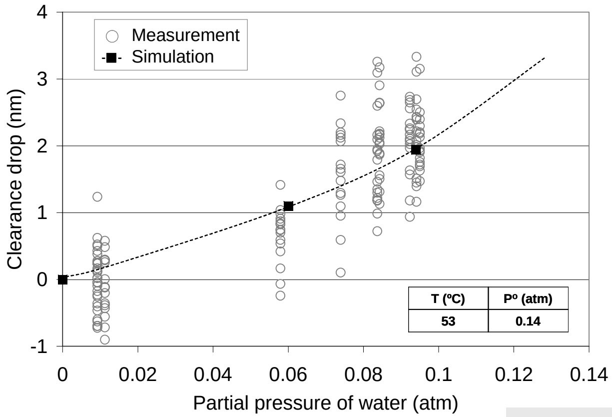


Supersaturation

Fly height drop



❒ The head-disk clearance decreases with drive humidity



T (°C)	P° (atm)
53	0.14

➢ For this HDI design, clearance **decreases with water vapor pressure as – 0.2 nm/kPa** (comparable to altitude effect)

➢ For example, clearance at 60 C drops by **3. 5 nm** when the humidity is increased from 0 → 90%RH

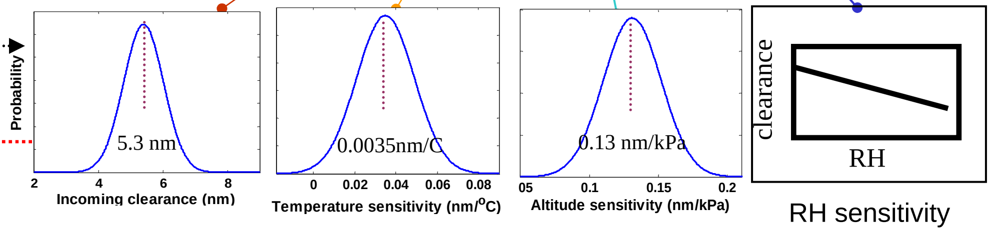
(Strom et al., IEEE Trans. Magn. (2007), 43, 3301)

Reliability / failure rate model

Model structure

- Factors impacting failure rates:
  - Initial clearance
  - Temperature sensitivity
  - Altitude sensitivity
  - Humidity sensitivity

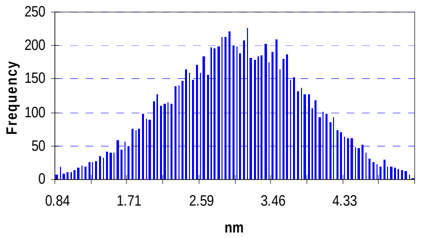
$$z(nm) = z_0 - a\Delta T - b\Delta P - f(RH)$$



- Data input into Monte Carlo simulations

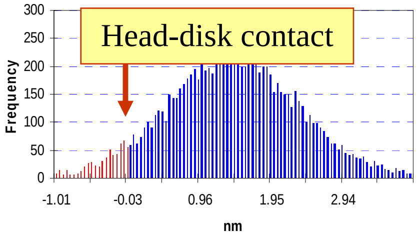
Model Output

T=65ºC, RH=30% (Altitude=sea level)



No failure

T=65ºC, RH=80%



6.2% failure rate

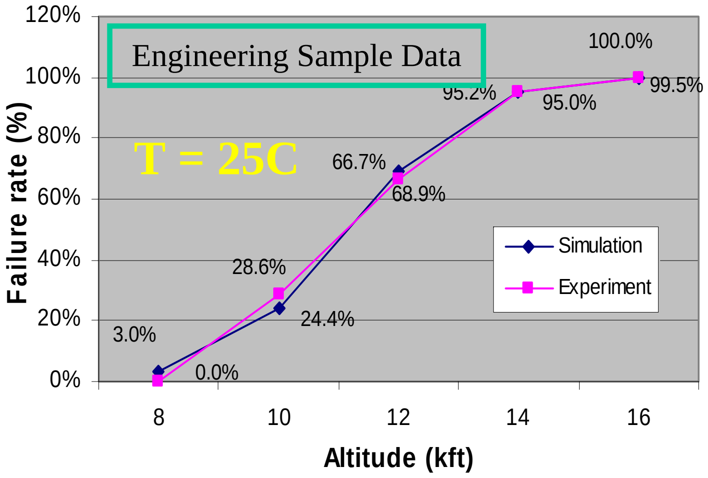
- The failure predictions were then compared directly with results obtained from standard HDD reliability testing conducted under the specified temperature / altitude / humidity conditions

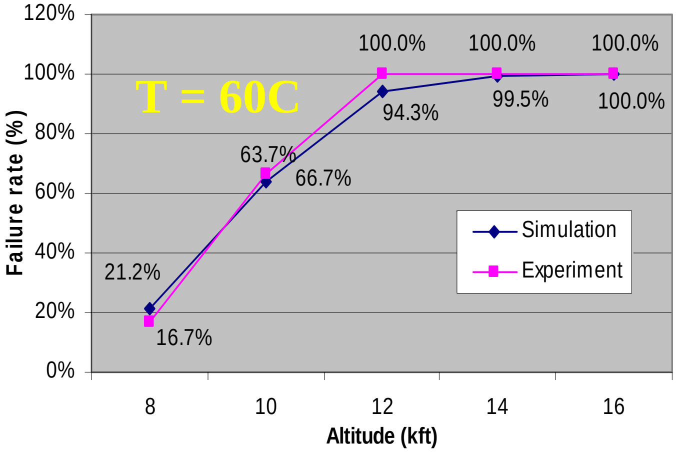
Model Verification – Failure rate vs Altitude and Temperature

❑ **Conditions: Variable altitude test conducted at two temperatures**

$$Clearance \quad (nm) = z_0 - a\Delta T - b\Delta P - f(RH)$$

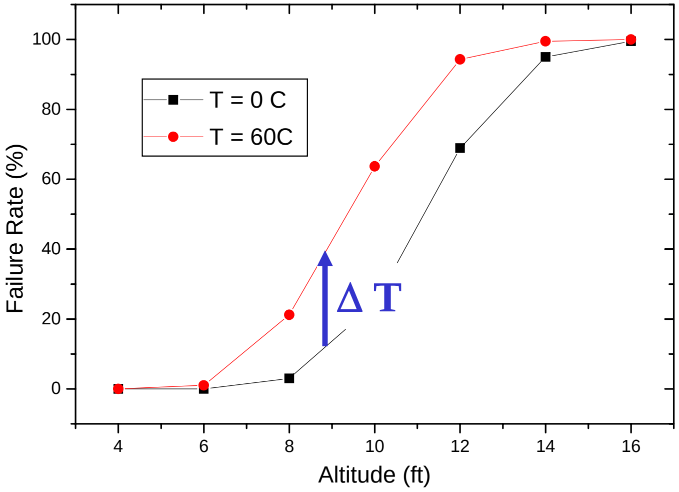
❑ **Experimental vs Model results**





❑ Quantitative agreement found between model and experiment

- ➢ **Failure rate increases with increasing temp**
- ➢ **Failure rate increases with increased altitude**



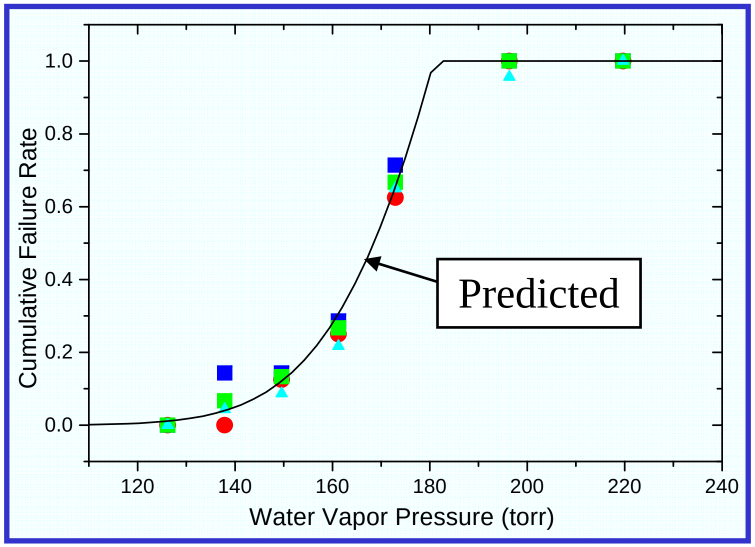
Humidity impact on drive reliability

- **Conditions: Fixed Temperature (T = 70ºC) / variable humidity (5 – 95%)**

$$Clearance\quad (nm) = z_0 - a\Delta T - b\Delta P - \boxed{f(RH)}$$

- **Model failure rate predictions vs Experimental Data**

Relative Humidity	Predicted Failure Rate	Experiment data
60	**0.0%**	**0.0%**
65	**6.3%**	**3.9%**
70	**12.2%**	**12.0%**
75	**25.5%**	**30.6%**
80	**66.4%**	**65.8%**
90	**99.0%**	**100.0%**



- **Excellent agreement observed**
  - **Indicates validity of approach for clearance / humidity dependence**

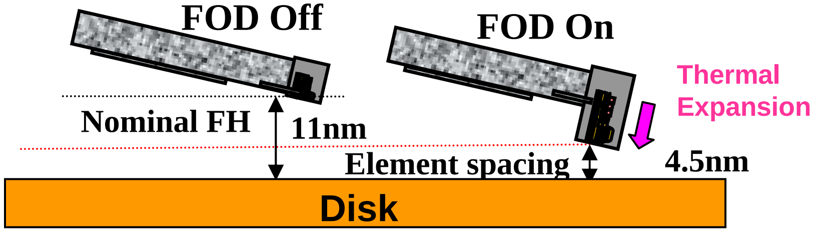
Summary of clearance-based reliability model

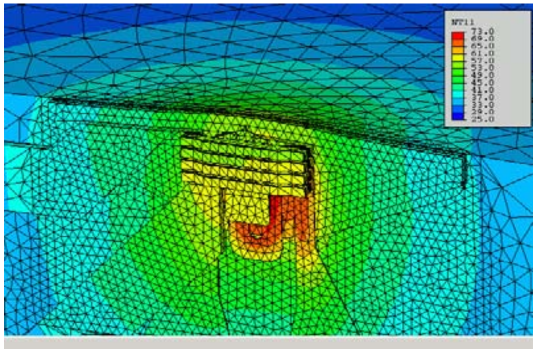
- A clearance-based reliability model was developed and successfully tested.
- The following parameters affecting clearance have been measured and incorporated in the model:
  - Initial clearance distribution
  - Operating temperature
  - Altitude
  - Internal drive humidity (Developed theoretical model of humidity affect on clearance)
- On the basis of the excellent correlation with experiment we conclude that. slider-disk clearance should be treated as a critical parameter by which to design a mechanically reliable magnetic hard disk drive.
- Cautionary note: The impact of humidity and temperature on drive failure rates in the field cannot be attributed exclusively to the clearance effects discussed above.

Head-disk Spacing Control

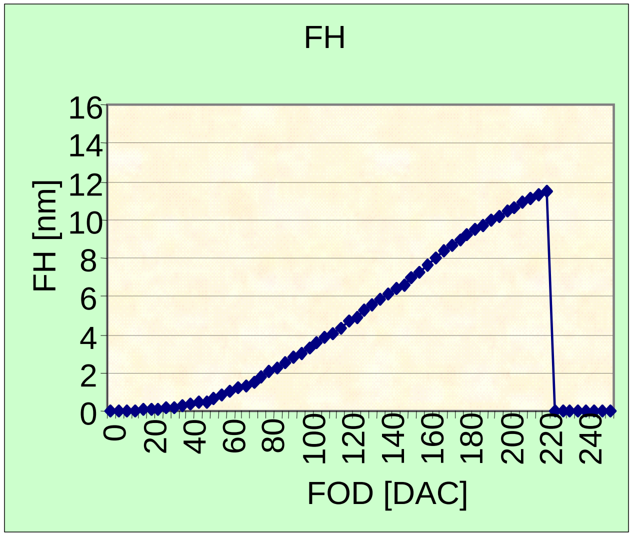
❑ "Fly-height On Demand" (FOD) concept

- ➢ Head-disk spacing is controlled by resistive heating of the pole tip region of the head





- ➢ Thermal actuation is only performed during read and write operations
- ➢ Since head – disk occur only during FOD actuation, the "effective" duty cycle, and AFR are reduced
- ➢Clearance measured by magnetic signal change via the Wallace spacing loss equation
- ➢ FOD allows for a fourfold decrease in the std. deviation of the clearance.



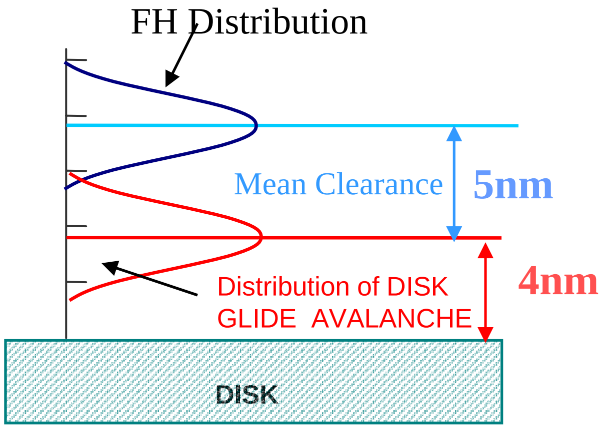
❑ Current FOD systems actively compensate for changes in drive temp, altitude, and humidity

❑ Future designs promise to supply real time feedback on spacing fluctuations (analogous to position error signal)

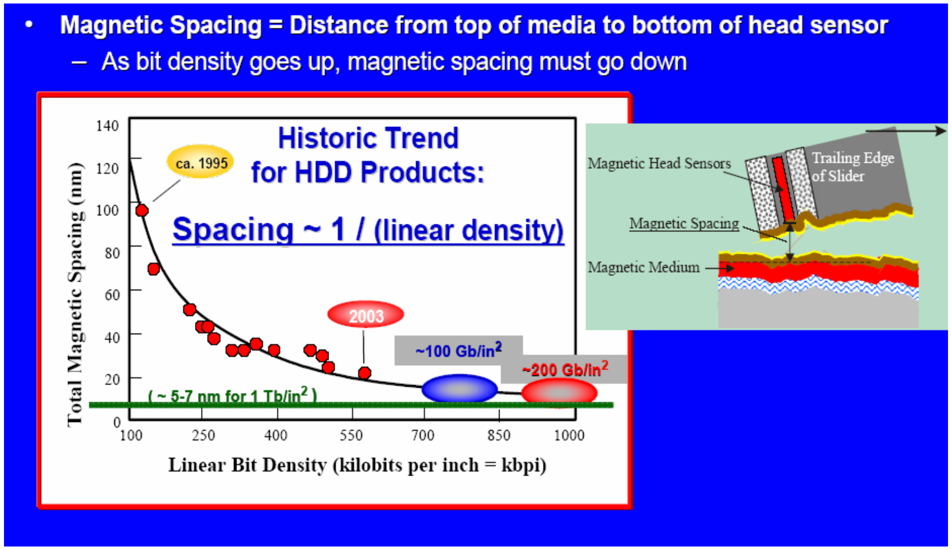
Does FH control solve all our problems?

❒ Finer Details – Glide Avalanche

- Physico-chemical properties of disk lubricant
- Long-term effects of temperature
- Other adverse impacts of high humidity



❒ The Future Challenge

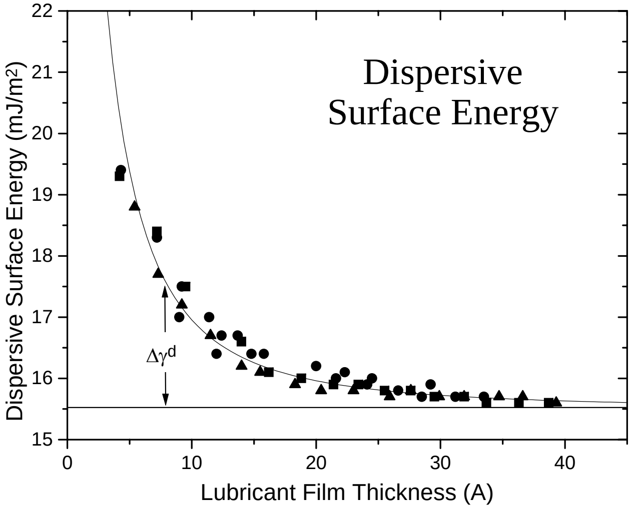


- **Magnetic Spacing = Distance from top of media to bottom of head sensor**
  - As bit density goes up, magnetic spacing must go down

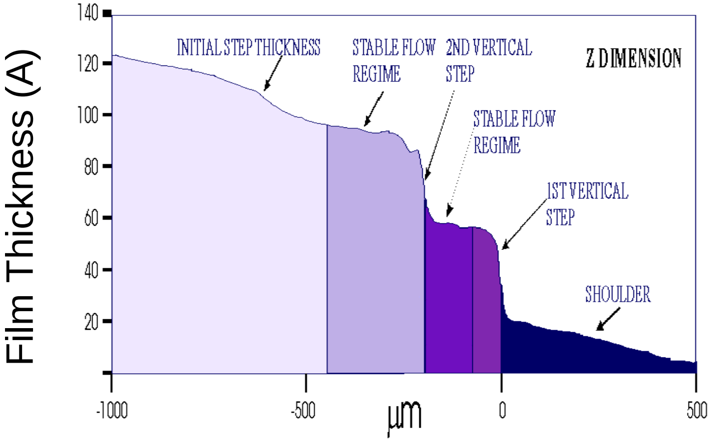
- The effect of intermolecular forces when macroscopic objects are separated by nanoscopic distances – **van der Waals interaction forces**

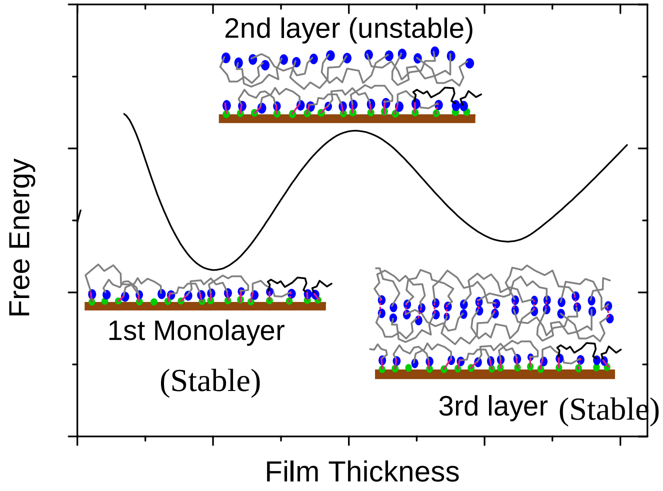
Molecularly -Thin PFPE Lubricant Films

- Energetics of molecularly thin PFPE films are dependent on the amount of material present
  - Surface-induced confinement results in properties that deviate substantially from bulk material.
  - Anomalous materials properties – presence of disjoining pressure unique to molecularly-thin films
  - Tthickness dependent film properties
    - Lubricant displacement by flying head
    - diffusion coefficients (effective viscosity),
    - Adhesive forces
    - Friction forces



- Oscillatory polar surface energy of PFPE films indicates layering phenomenon
  - Thermodynamic instabilities develop
  - Readily apparent in terraced spreading

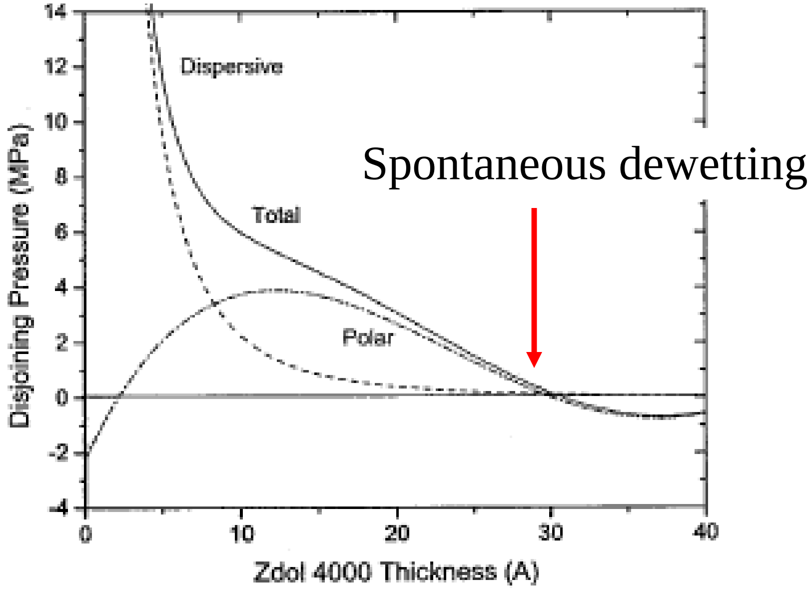




Lubricant Stability – Autophobic dewetting

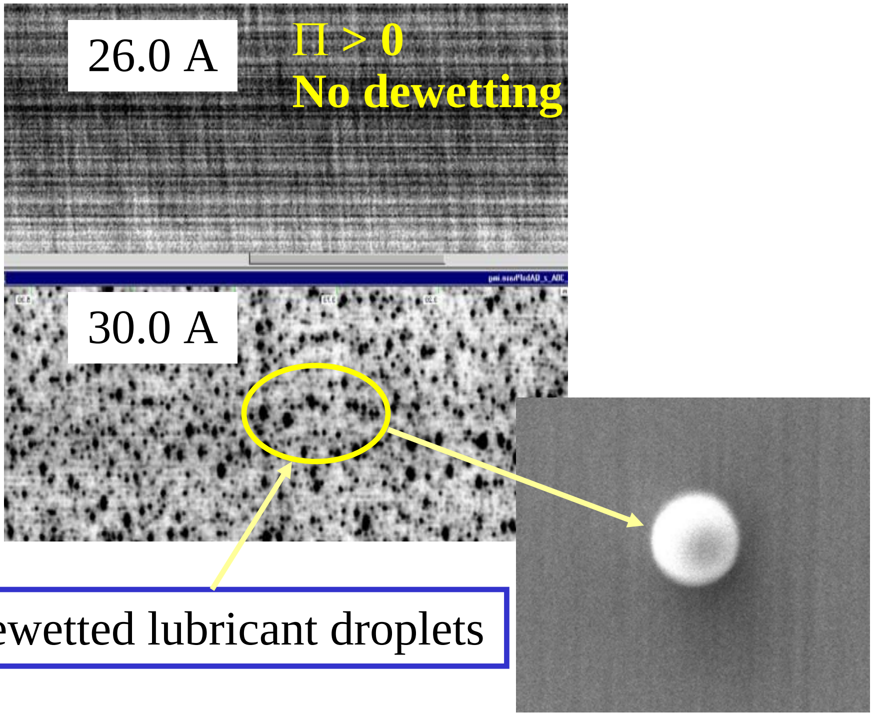
- ❐ Oscillatory polar surface energy, χ^p results in a disjoining pressure ($\Pi = -d\chi/dh$) that changes sign as a function of film thickness
- ❐ Thermodynamic stability requires that $\Pi > 0$
- ❐ When $\Pi < 0$, film is unstable and will spontaneously dewet.

Disjoining Pressure Zdol (MW =4000)



Waltman, Khurshudov, Tyndall
Trib. Lett. (2002), 12, 163.

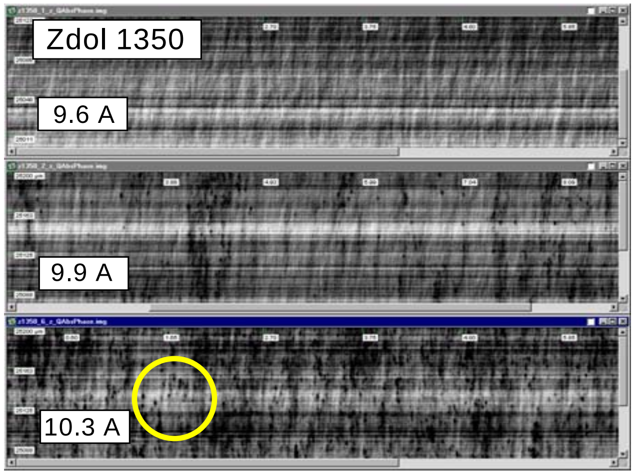
OSA Images



$\Pi < 0$: Dewetted lubricant droplets

Impact of dewetting

❑ Lubricant dewetting produces “soft particles” that can interact with the flying slider

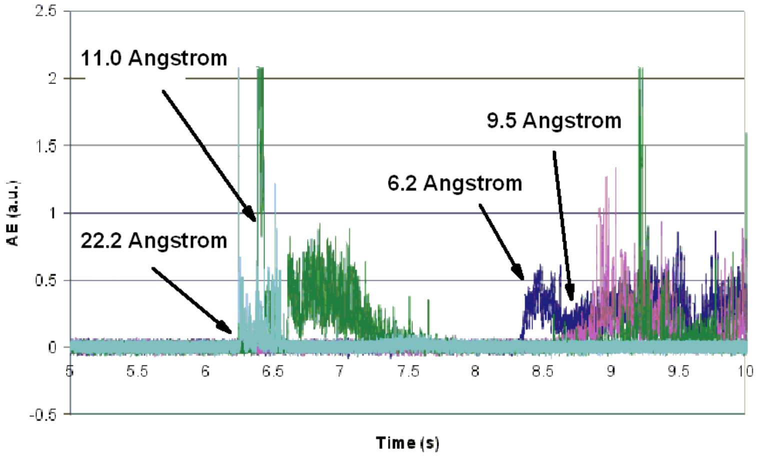


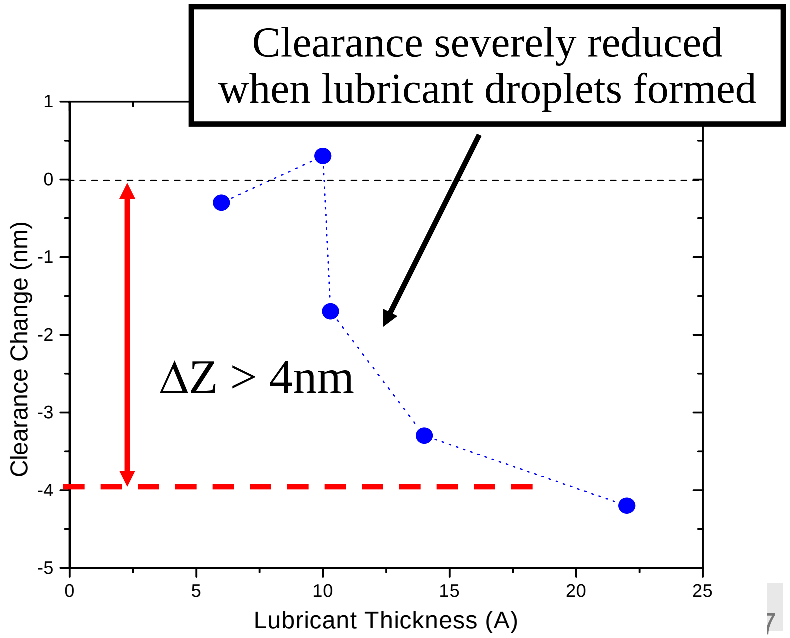
❑ Dewetting of Zdol (MW = 1350)

- Homogenous films observed when film thickness, h, < 10 Å
- Lubricant dewetting occurs at h > 10Å

❑ Clearance measurements

- Acoustic emission results

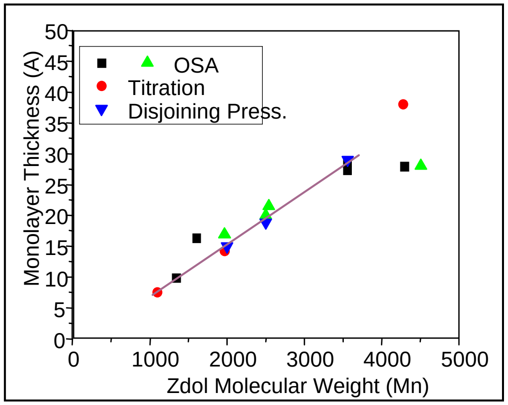



Clearance severely reduced when lubricant droplets formed

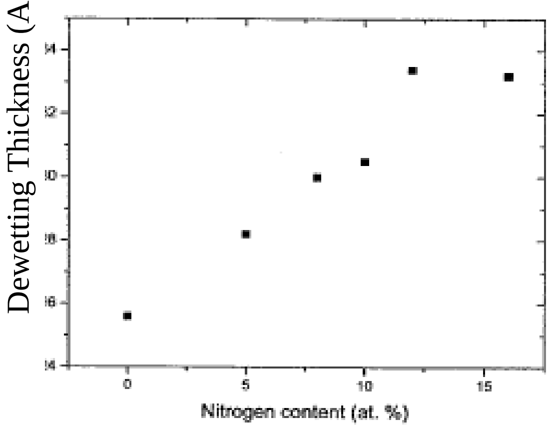
Lubricant Stability - Dewetting

- ❐ PFPE lubricant layering on surfaces is ubiquitous

Impact of PFPE Molecular Weight

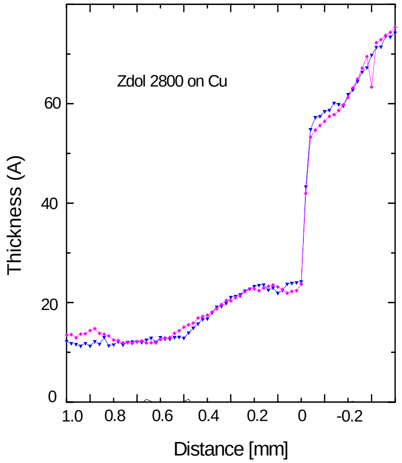


Effect of carbon composition

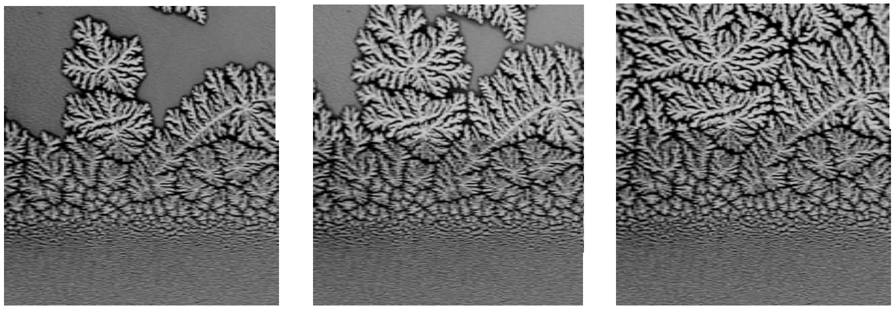


- ❐ Other surfaces

Terraced Spreading on Cu

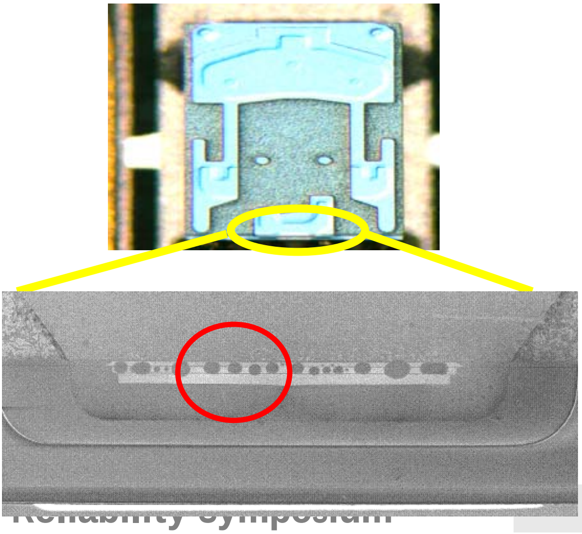


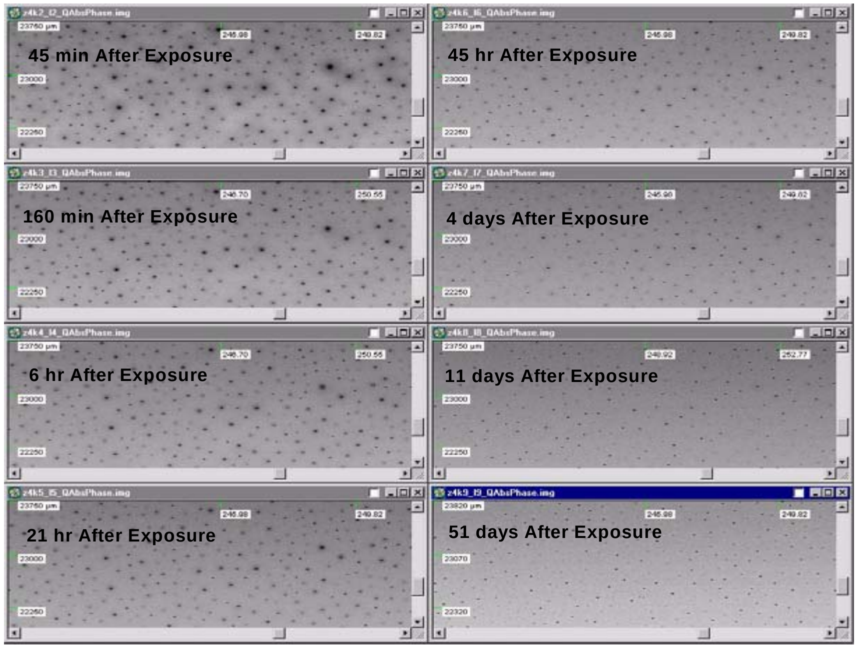
Fractal dewetting on Si



Moisture –related failures modes

- ❒ High moisture levels inside drive interior can adversely impact reliability
- ❒ Failure mechanism #1: Corrosion (well-known phenomenon)
- ❒ Failure mechanism #2: Clearance loss due to supersaturation under flying head (included in failure model discussed above)
- ❒ **Failure mechanism #3: Condensation of long-lived water microdroplets on both heads and disks**
  - ➢ Droplets are abnormally long-lived
  - ➢ Droplets reduce clearance / increase head-disk interaction
  - ➢ Decreased reliability

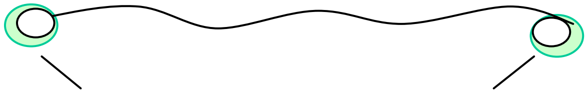




Schematics of Lubricant Bonding

- ❑ PFPE lubricants are available with a variety of backbone structures, molecular weights and functional end-groups.

Z-DOL

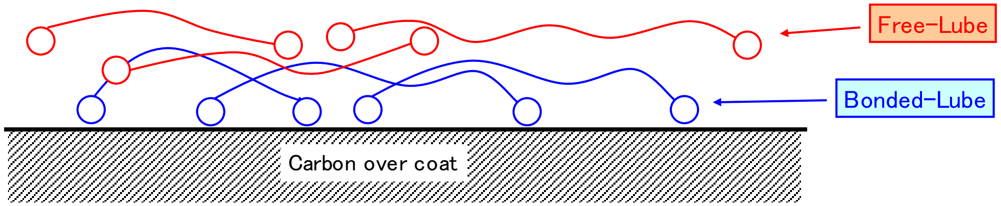


-OH functionality = Lower affinity for disk

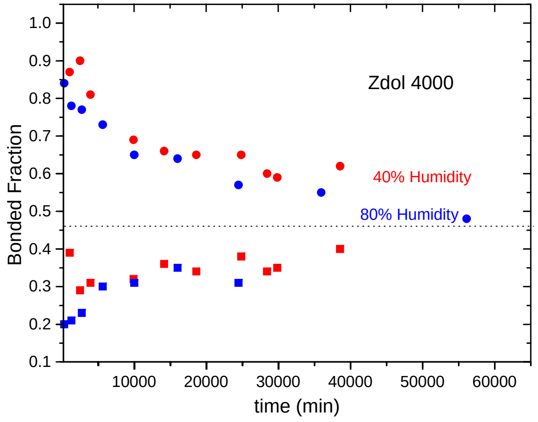
Z-Tetraol

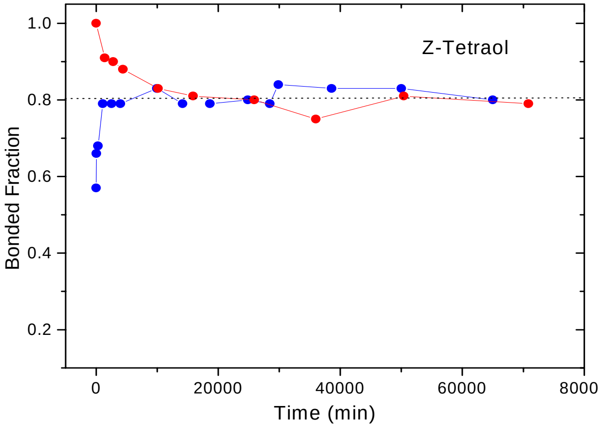
Di-hydroxyl = Higher affinity for disk

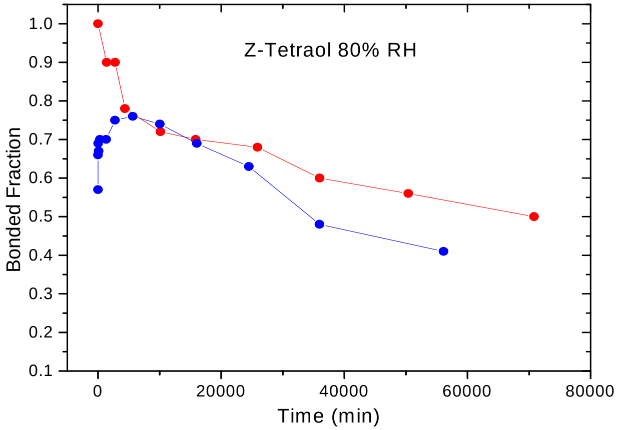
- ❑ Lubricants with functionalized end-groups will spontaneously bond to the disk.



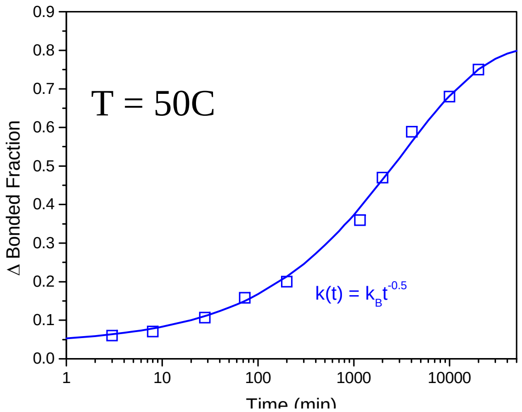
- ❑ Extent of lubricant bonding is dictated by the lube, the temperature and RH.



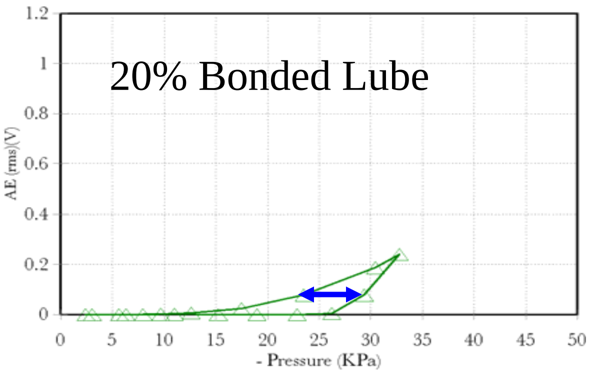


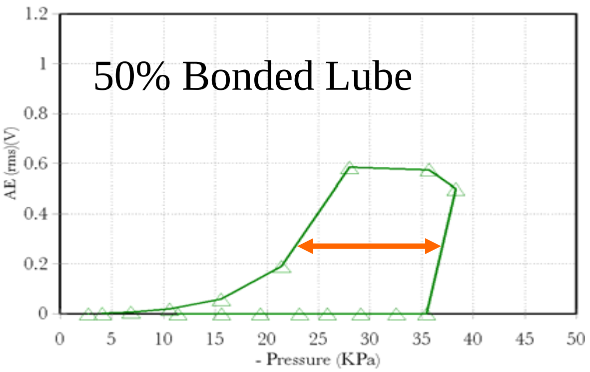


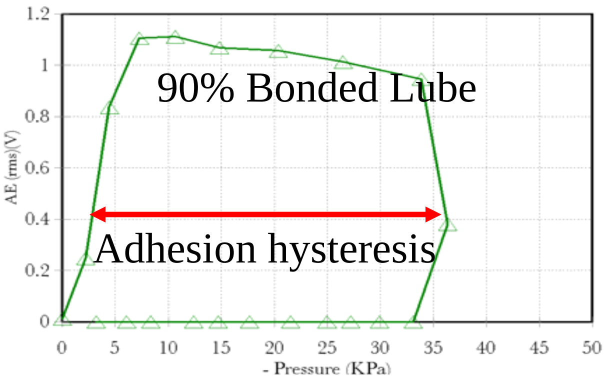
Lubricant bonding



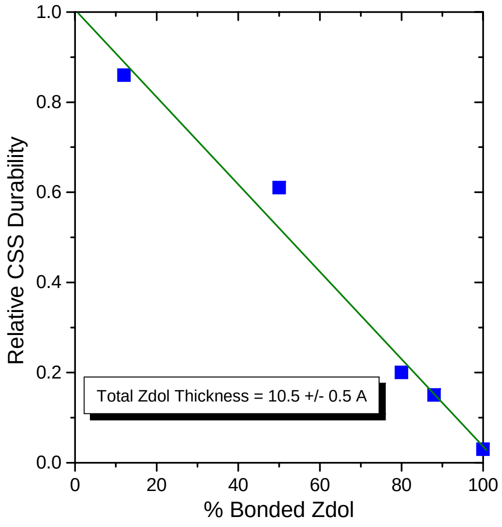
- ❒ Exposure to elevated temperature induces a (reversible) bonding of the lubricant to the disk.
- ❒ Bonding adversely impacts lubricant mobility and contact forces





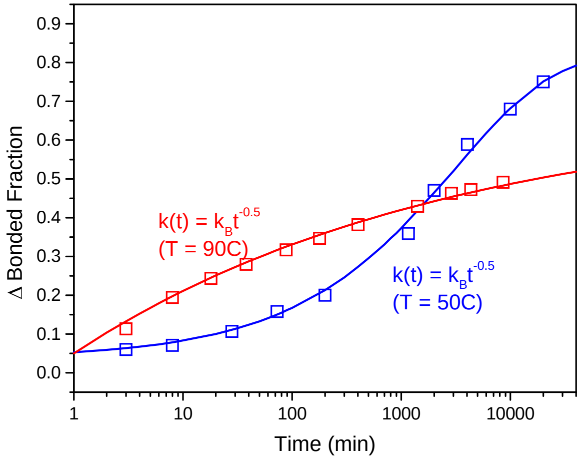


- ❑ Adhesion hysteresis increases with bonded fraction
  - Force required to separate the head and disk surfaces increases as the lube bonding ratio increases.
  - ***Severity of contact*** (time in contact) increases as bonded fraction increases
  - HDI failure rate will scale with the adhesion hysteresis

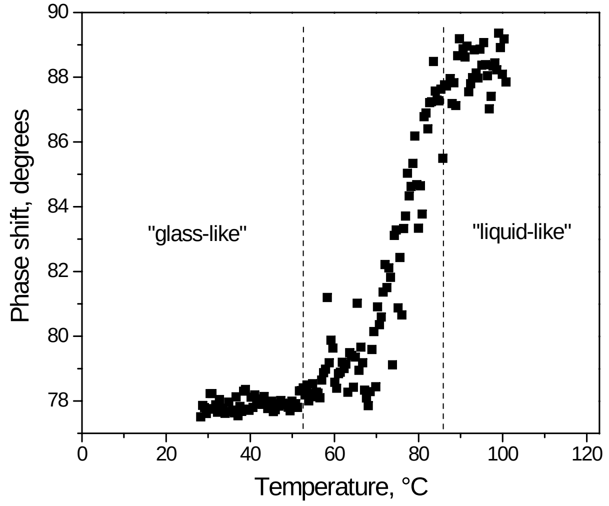


Phase transitions in PFPE lubricants

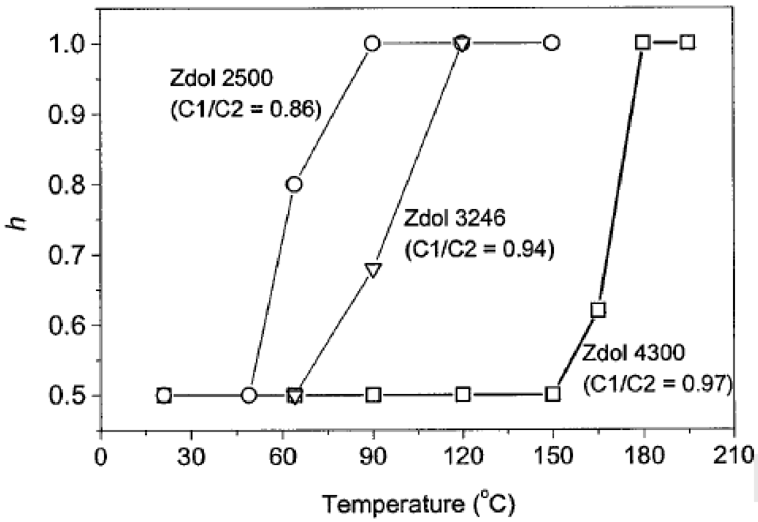
- ❑ PPFE bonding kinetics are non-classical
  - ➢ Time dependent rate coefficients
  - ➢ 1D diffusion – limited reaction
  - ➢ Functional form of rate coefficients can change as a function of temperature
  - ➢ Results indicative of a phase transition



- ❑ Shear modulated AFM measurements confirm a transition from solid-like to liquid-like behavior



- ❑ Transition temperature is dependent on the lubricant molecular weight, PFPE structure and nature of carbon surface



- ❑ Impact of this change in lubricant mobility on HDI reliability has not been addressed

Future (current) Challenge - Intermolecular Forces

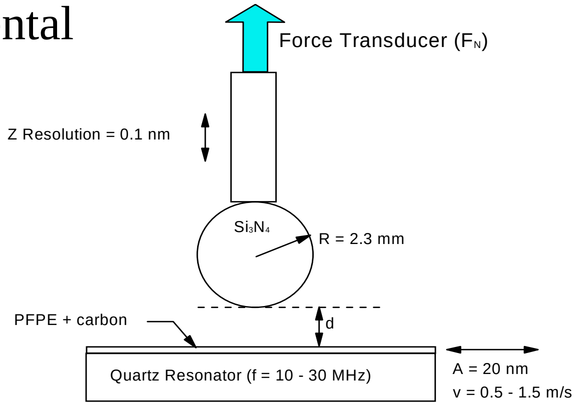
- ☐ It is well known that attractive, intermolecular forces are generated when macroscopic bodies are separated by nanoscopic distances (d < 10 – 20nm).
- ☐ For van der Waals forces, the attractive force is dependent on three factors:

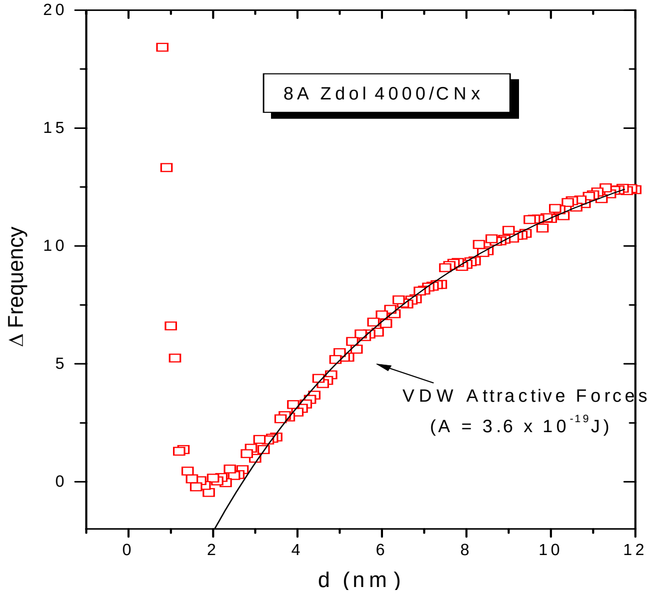
$$F \propto \frac{gA}{d^2}$$

  - ➢ g = **Geometric factor defining the ‘effective’ interaction area**
  - ➢ **A = defines interaction strength between materials on the two surfaces**

- ☐ We operate the head-disk interface in a regime where these forces are not insignificant, and will only get more prominent in future products

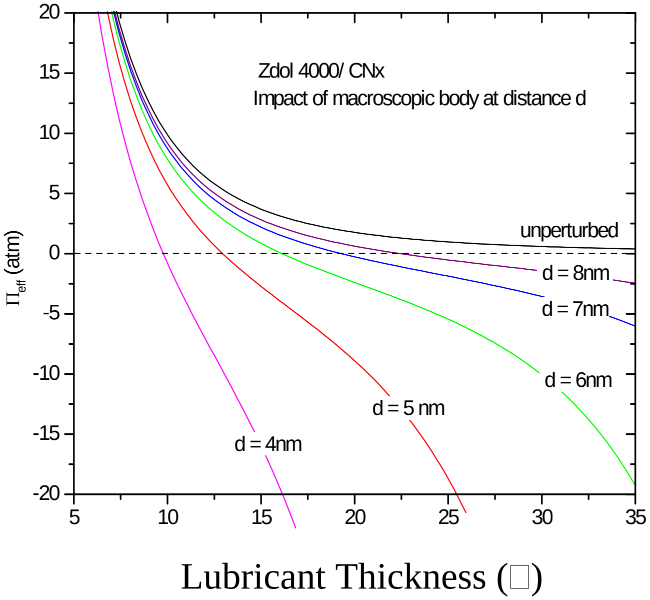
Experimental

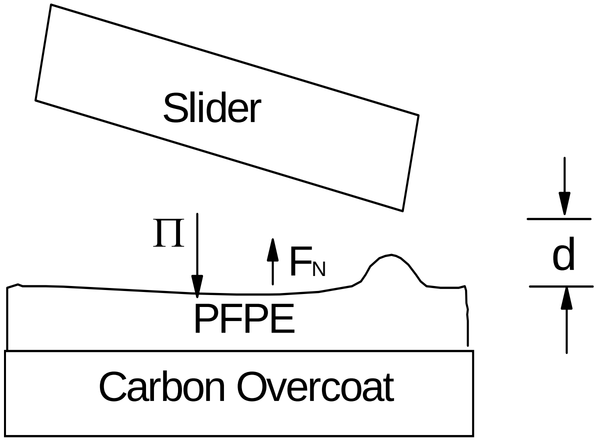




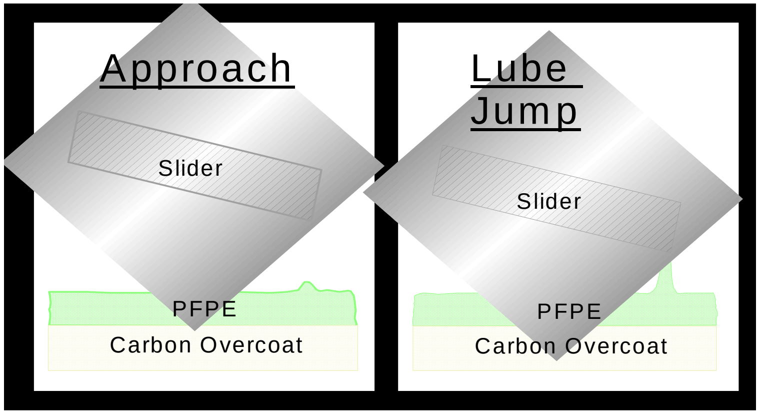
Impact of VDW forces at the head-disk interface

- The attractive VDW forces that develop at the HDI reduces the magnitude of the disjoining pressure resulting in a vertical expansion of the lubricant film





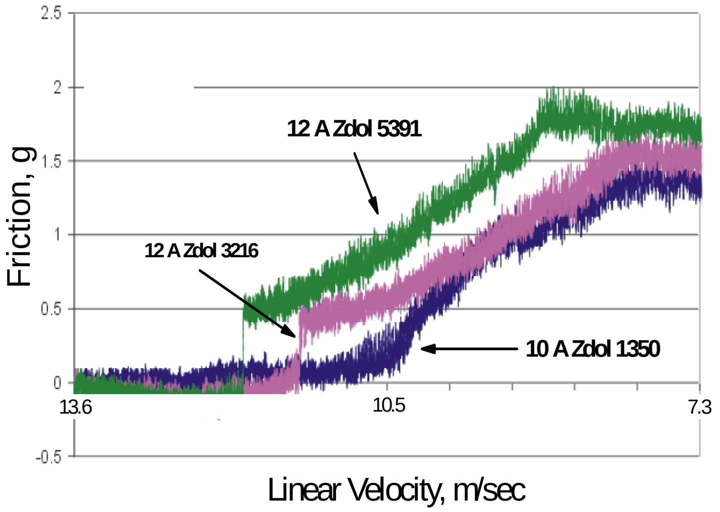
- At sufficiently close distances, the lube will “jump” from the disk to the head.
- This phenomenon will limit the minimum separation distance, and thereby contribute to the glide avalanche.



Effect of Molecular Weight on Glide Avalanche

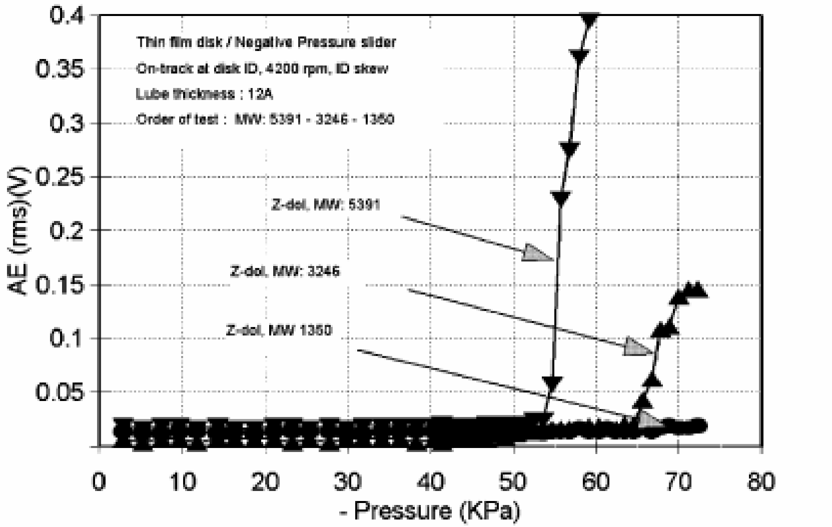
- ☐ Clearance Measurements vs Lubricant Molecular Weight

A) Reduced rotational velocity

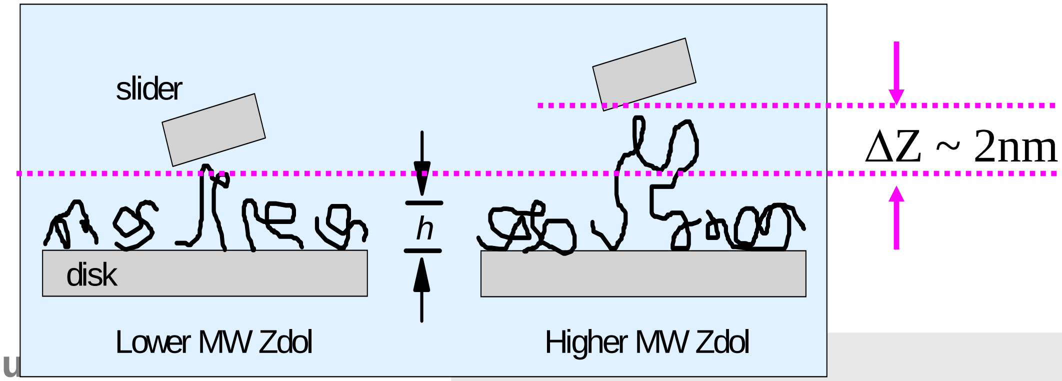


(Khurshudov and Waltman, Trib. Lett. (2001), 11, 143)

B) Reduced pressure



- ☐ Both techniques show clearance decreases with increasing PFPE molecular weight

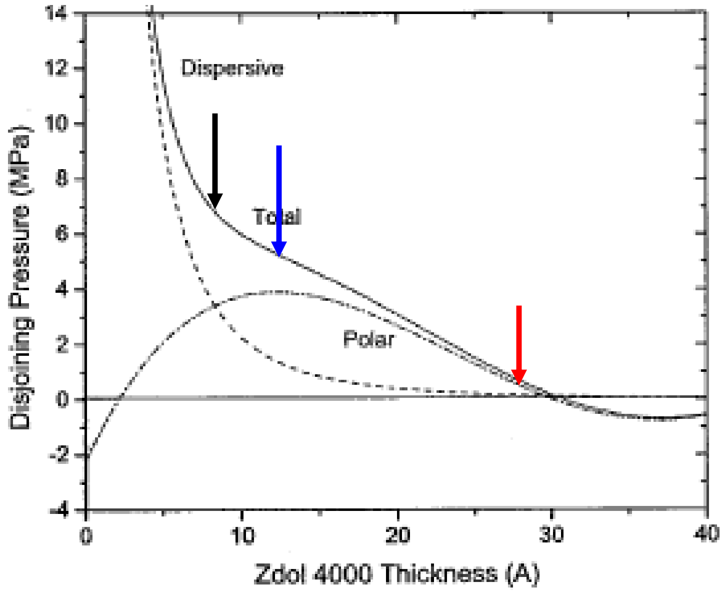


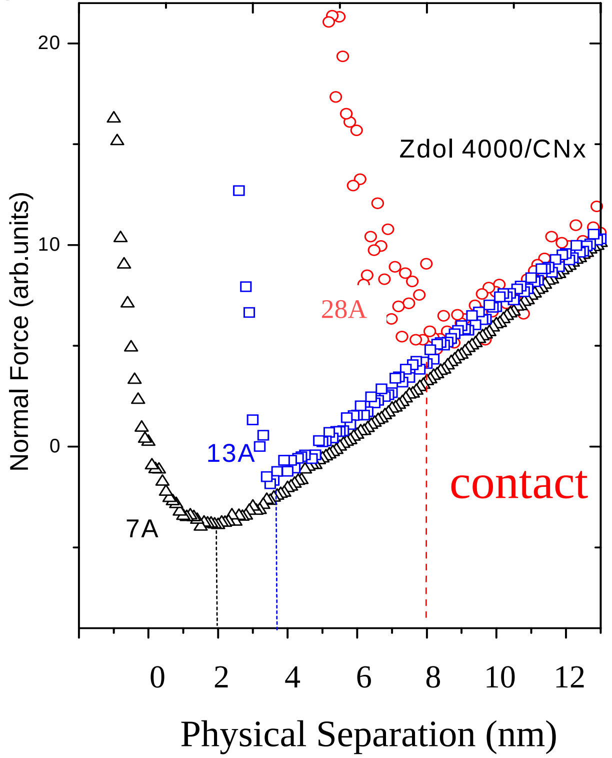
Effect of film thickness on Slider disk interactions

❑ Disjoining pressure characterizing film adhesion decreases rapidly with increasing film thickness

  ➢ Thicker films should jump to contact sooner than thinner films

➢Experimental results confirm this expectation

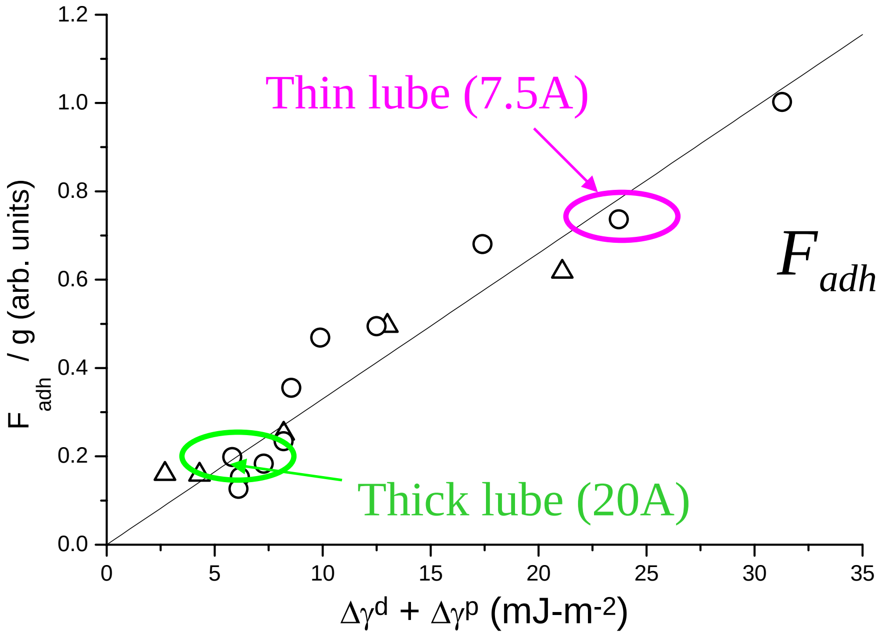




❑ These results also indicate that Intermolecular forces are currently limiting glide avalanche.

Intermolecular Forces: Adhesion

- Previous results suggest that decreased lubricant film thickness would be beneficial from a clearance perspective
- The Adhesive Force generated between the disk and slider (stickiness of interface), increases with decreasing film thickness, however



Thin lube (7.5A)

Thick lube (20A)

$$F_{adh} = 4\pi R \Delta\gamma(h)$$

- Increased adhesive (and frictional) force at low film thickness will increase the severity of any head-disk contact

Pre-contact Frictional Forces

- Pre – contact Frictional forces are generated at low clearances in films of thicknesses used at the HDI

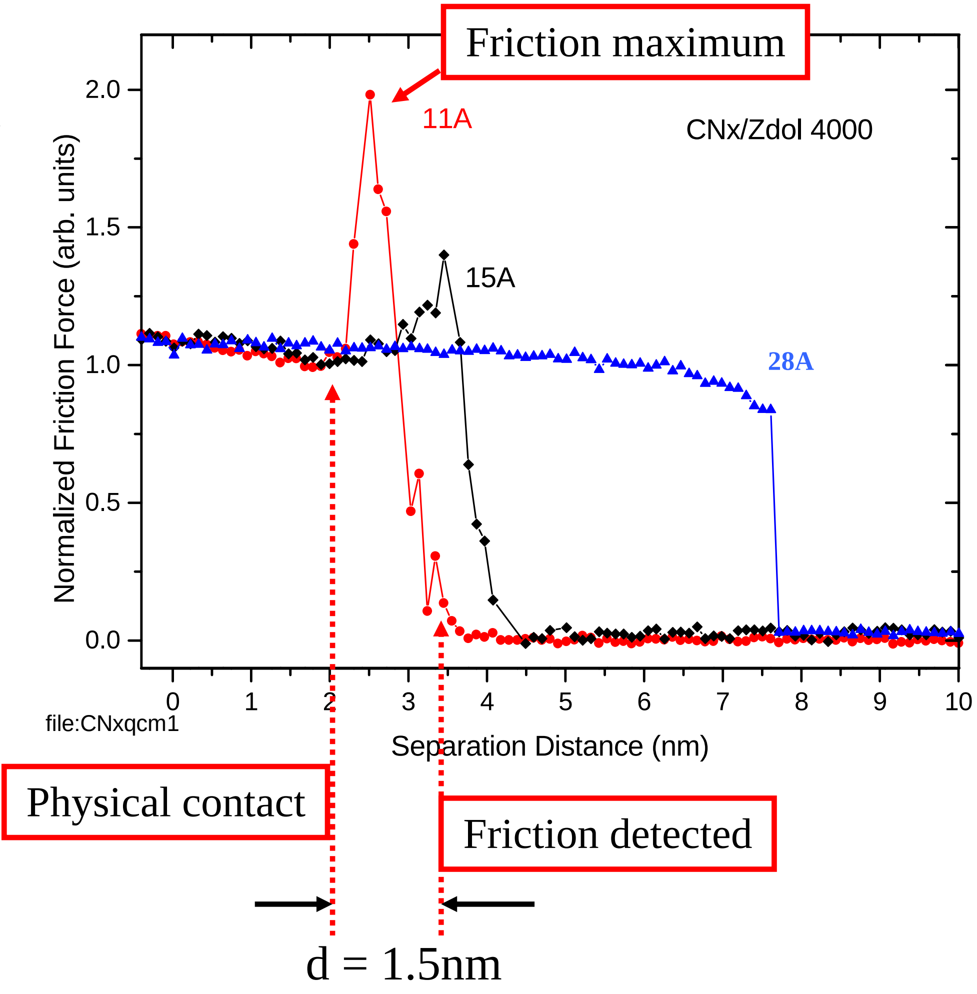
- Friction starts at nominally 1.5nm prior to establishment of physical contact

- Friction signal shows displays a maximum value prior to contact

- Magnitude of friction maximum scales inversely with film thickness

- The origin of these phenomenon are not well understood

- This could also contribute to defining our minimum separation distance.



Friction maximum

Physical contact

Friction detected

d = 1.5nm

Summary

- HDD failure rates can be dominated by the HDI
- HDI failure rates depend strongly on clearance
  - Mean clearance
  - Std. deviation of clearance
  - Sensitivity to environmental parameters
- Interface materials (lube + carbon) dictate HDI performance and can impact clearance
  - Lube thickness, type and molecular weight
  - Carbon type and thickness
  - Temperature and humidity
- Physics underlying many of the interface materials properties is still not understood completely
- Intermolecular forces (both adhesive and friction) will fundamentally limit the lowest head-disk clearance that can be obtained (2 – 3nm)