Hard Disk Drive - Reliability Overview

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Outline

1 **State of affairs in HDD Field Reliability**

- **a** HDD complexity leads to a myriad of possible failure modes
- **b** Macroscopic objects at molecular dimensions: **Head-disk Interface**
- **c** Critical Parameters: **Clearance and Workload**

2 **HDD reliability modeling**

- **a** Historical model: derivation and limitations
- **b** Importance of workload and temperature
- **c** Drive parametric measurements: **Virtual Failures**

3 **Data Center Fleet Management: In-field Health Monitor**

Core problem in HDD reliability

1. Try to avoid something analogous to a 'BP' moment (Deepwater Horizon oil spill of 2010) - **Avoid an un-manageable catastrophe midway (or beyond) through a product's warranty life**
   Referred to as 'wear-out' mode in reliability → unbounded Failure Rate at large times

2. For the drives out in the field, develop a predictive analysis for failures

QUESTIONS

- ❑ How do we define a product's "lifetime"?
- ❑ How do we get visibility into what happens during this lifetime?
- ❑ Can we help our customers perform effective Fleet Management in real time?

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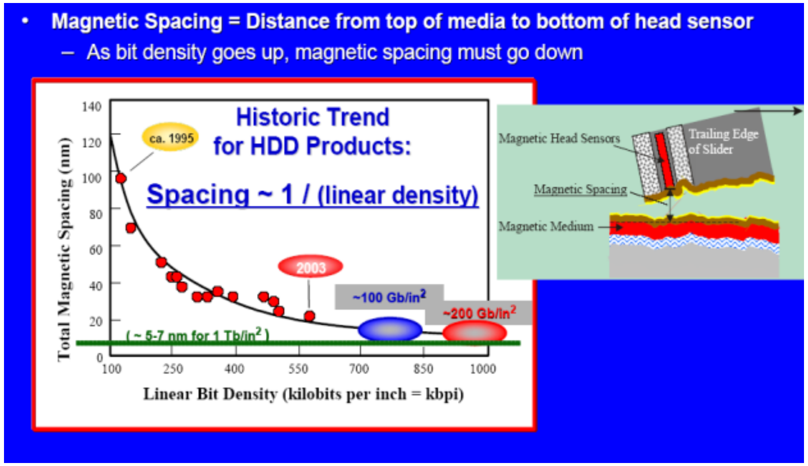
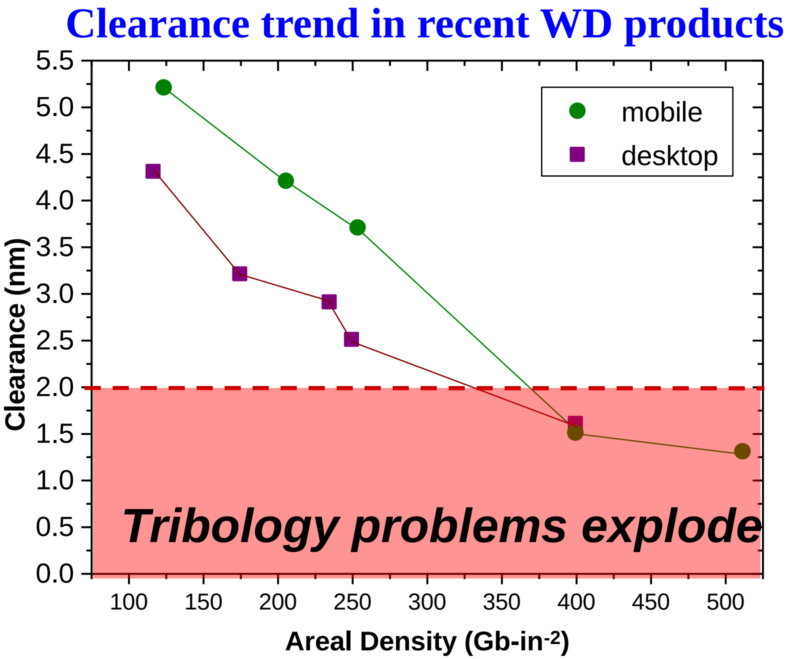
Current HDD Reliability Landscape

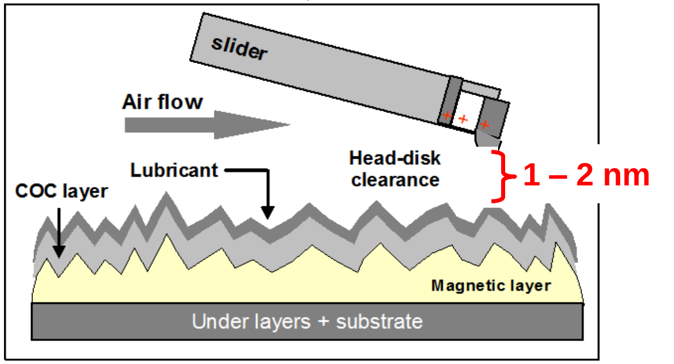
- Increases in areal density have largely come by decreasing the head-disk spacing
  - The Magnetics vs Tribology dilemma
- Current head-media spacings are at molecular dimensions: 1 – 2nm
  - Operating at these clearances can impact the HDD failure rates, and the failure pareto
  - As much as 70% of the failure pareto is attributable to low-clearance operation
- Operation at ever-decreasing spacings requires special attention be paid to:
  - Anamolous physical phenomenon in ultrathin films
  - Non-linear response functions, e.g. Adhesive and frictional forces
  - Mechanical tolerances
  - etc





Head-Media Interface Failures: A Conceptual Model

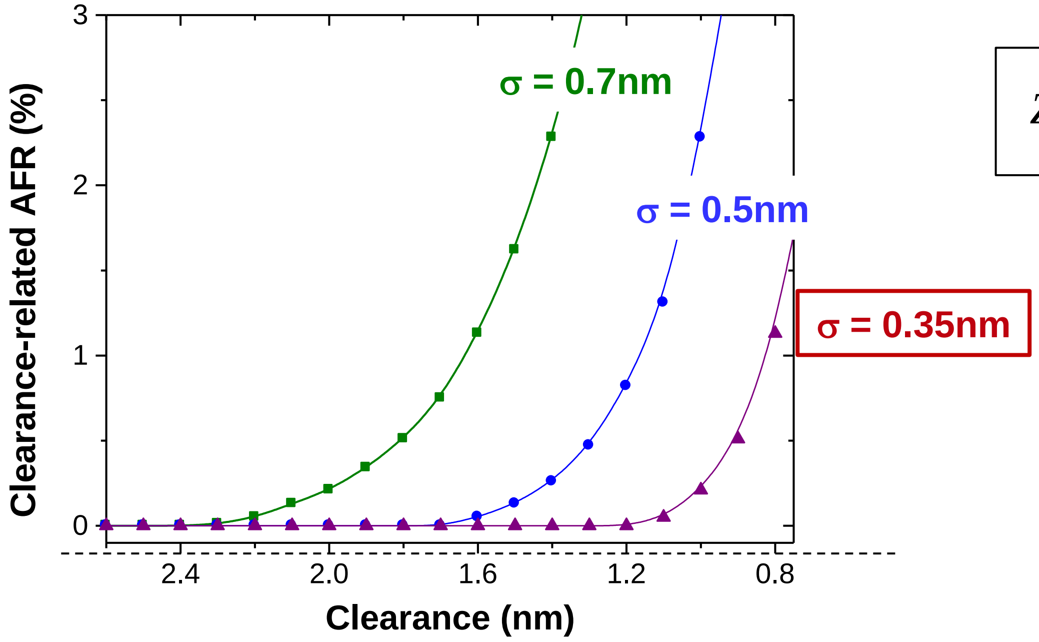
- The **clearance** between slider and disk is a dominant factor dictating **HDI reliability** (~ 70% of all failures).
- **Insufficient clearance results in an increased probability of head-disk interaction** and eventual failure due to HFW, modulation, or head degradation



Model

Influence of Clearance Mean / Sigma

- **HDDs require control of macro-scale mechanics to atomic dimensions!**
- **<u>Toy model</u>**: Failure rates as a function of both the mean clearance and the required standard deviation in clearance are shown below



Design Criteria

$$Z = \frac{\mu}{\sigma} = const. > 3$$

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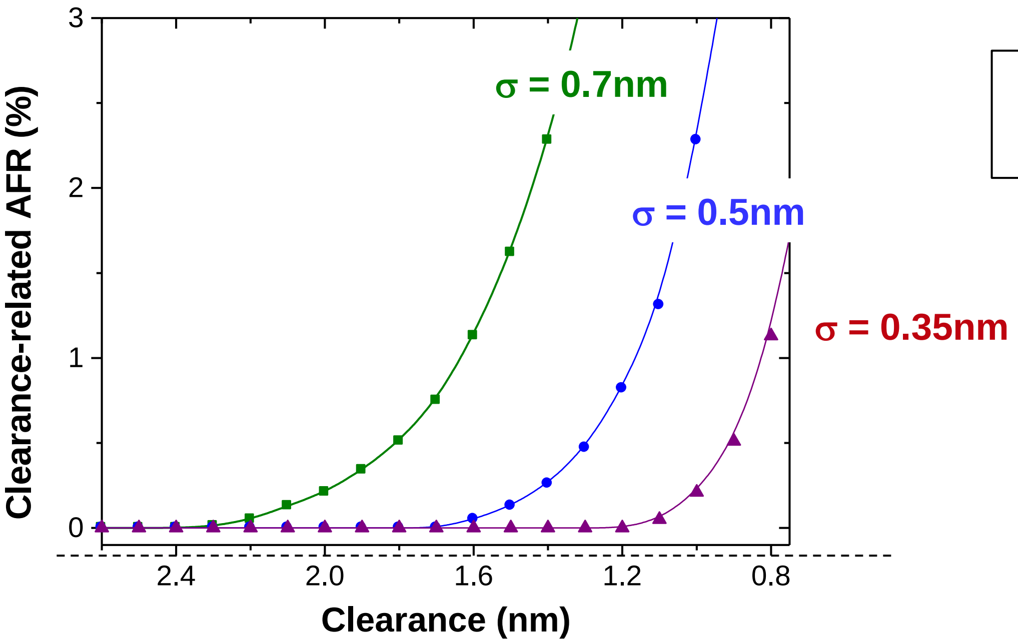

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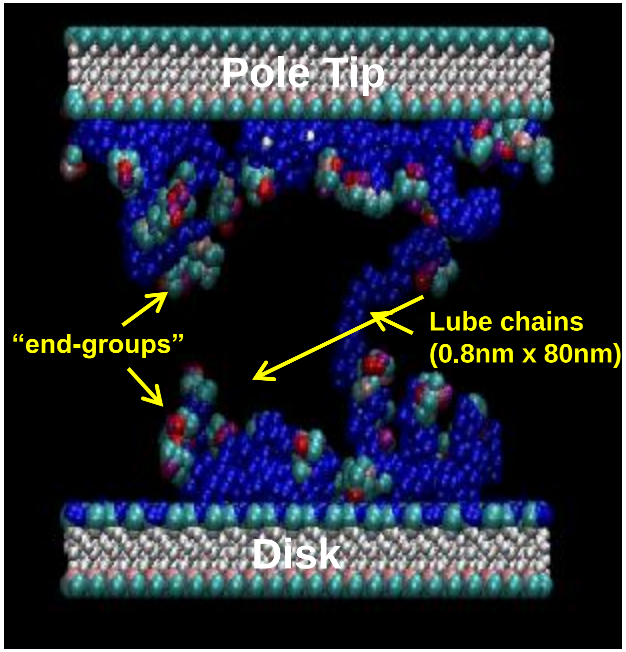
- WD produces 200 million drives per year, with each having multiple heads……. …..something on the order of **1 billion head-disk interfaces / year**
- The Std dev in clearance for these interfaces must all be held to within the Van der Waals **diameter of a single carbon atom = 0.34nm**

HDI: Head-Disk Interface a major challenge area

- ❑ HDD are complex devices that push the envelope of our physics understanding in a number of areas
- ❑ A monolayer of lubricant is used on disk surface to reduce adhesion / friction between slider and disk
- ❑ Lubricant pick-up by the slider is normal



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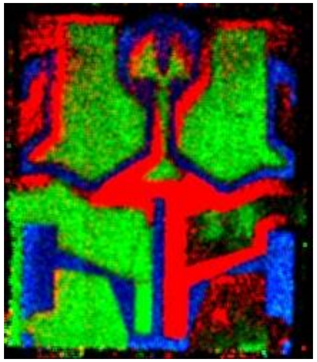
- Lubricant pick-up by the slider is normal, **but lubricant pick-up in excess of one layer can pose a serious reliability risk**
  - HFW, OTW, modulation, and head degradation

Optical image

Chemical image



Red = excess lube

Interface: at the edge of classical thermodynamics

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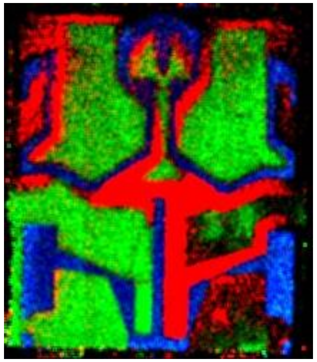

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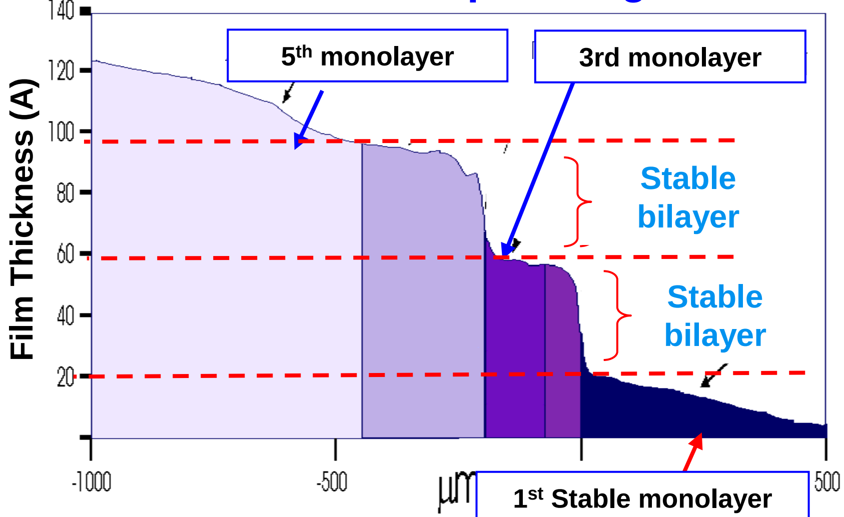
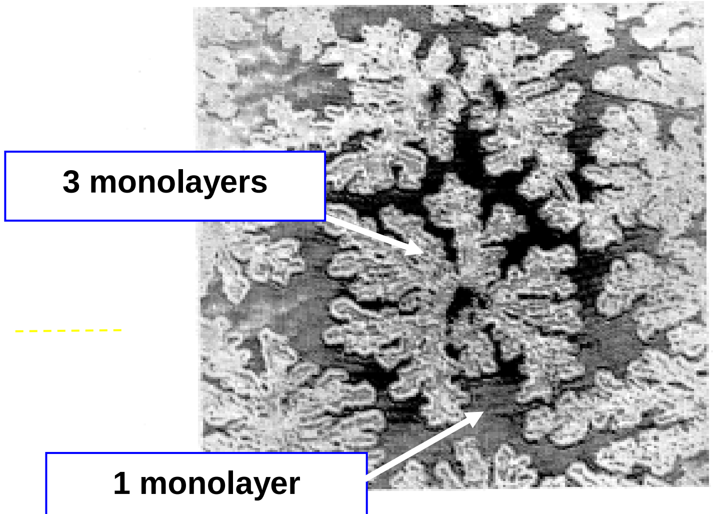
- ❑ Monomolecular films can show anamolous behavior
  - ➢ Non-classical thermodynamics: physical properties are dependent on the amount of material present

Terraced Spreading

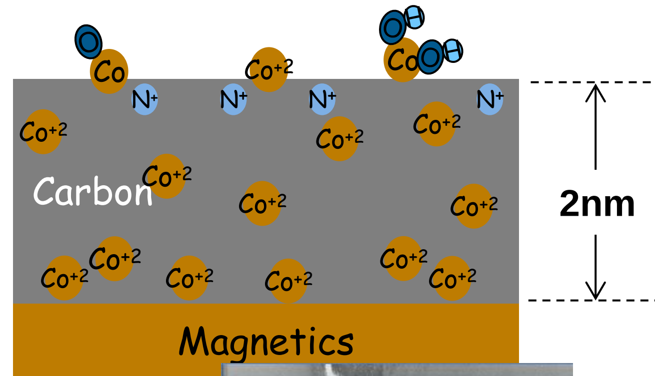


Lube Fractals

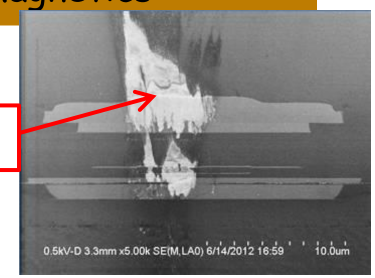


…..with some Chemistry and Materials Science

- **Protective diamond-like carbon (DLC) overcoats are used on both the head and disk surfaces**
  - Constant pressure to thin these overcoats for the purpose of decreasing the magnetic separation distance …..and thereby improving magnetic signal / areal density
  - Current DLC thicknesses on the order of 2nm
  - As these thicknesses are reduced, various reliability risks can arise

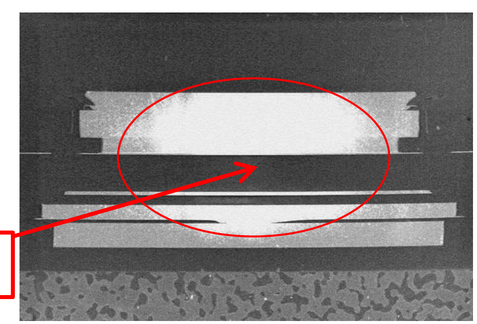


- **Disk example: migration of magnetic material to head-disk interface**
  - Corrective action required modification to carbon deposition energetics / process



Co smear

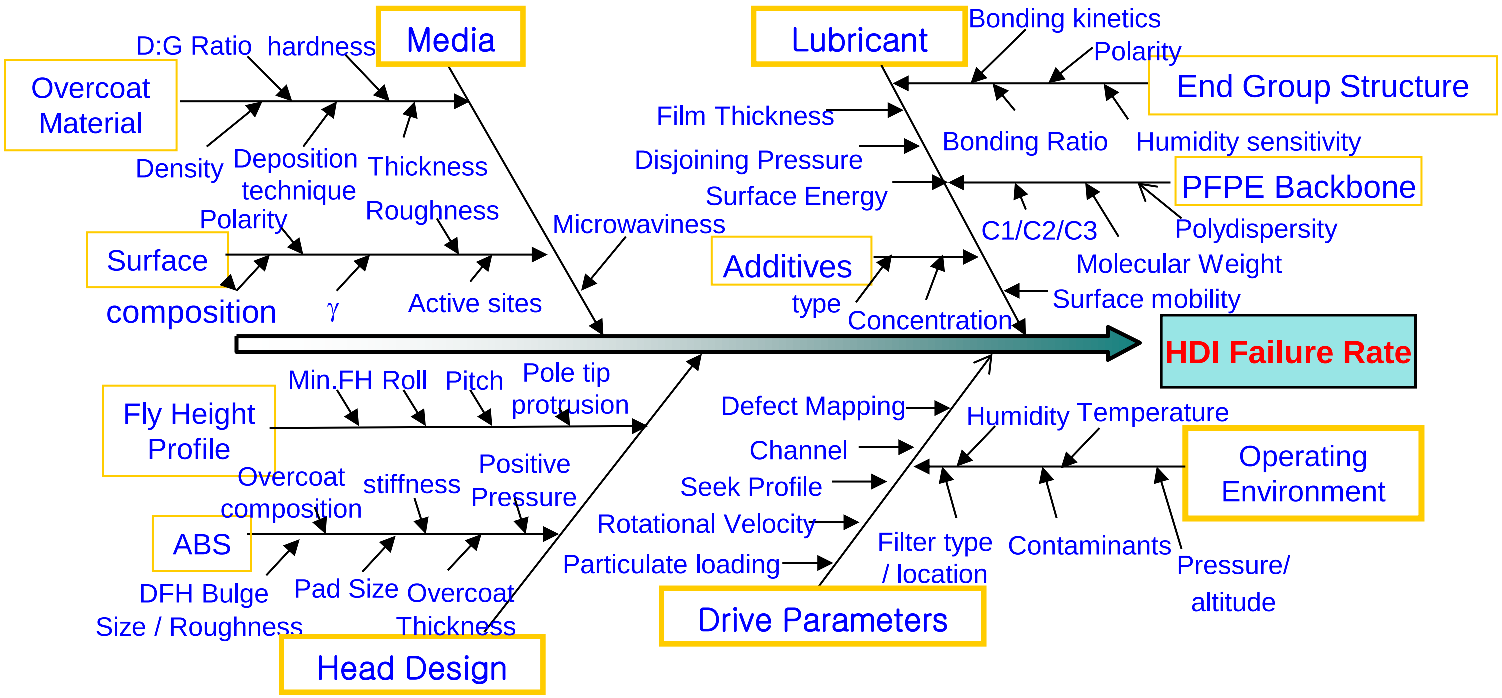
- **Head example: contact stress can result in wear of the pole tip**
  - Corrective action required stricter process control measures
  - Process optimization of sp^3 / sp^2



Carbon wear

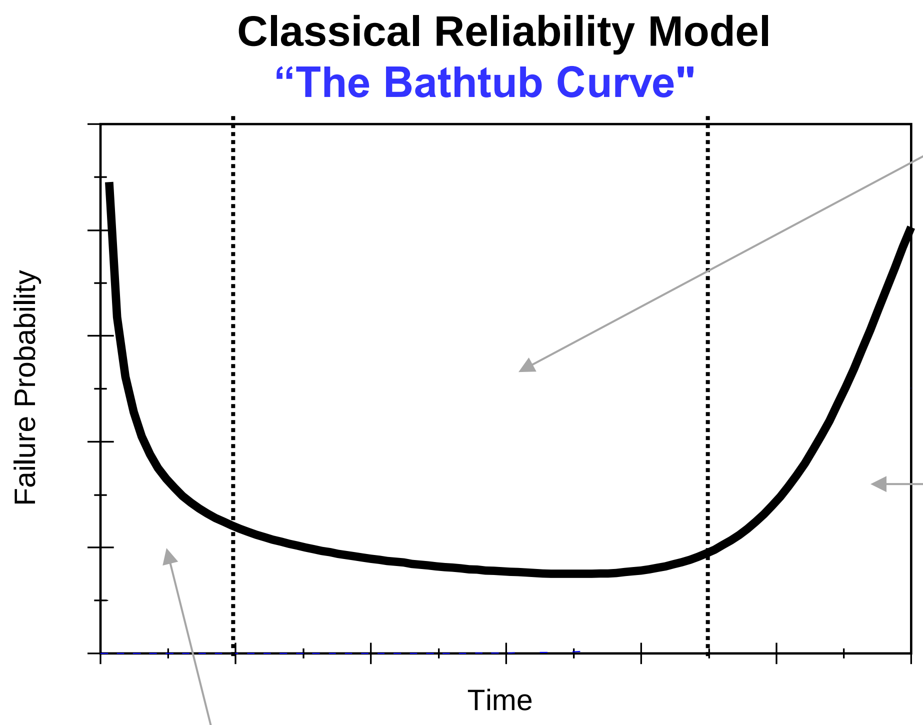
HDI failure rates: critical component attributes

- Maintaining sufficient clearance, and hence ensuring interface reliability is a multi-dimensional problem.



- **HDD reliability is certainly not boring**
  - New issues seem to accompany development of each new product generation
  - Since HDD complexity complicates reliability modeling, must focus on most likely failure modes
- Any simple reliability model is bound to have some weaknesses given this complexity

Time to Failure: The "Bathtub" Reliability Model



- **Steady State region**
  - After the weak drives are removed from the population, the failure rate reaches a fixed value for the service life of the drive
- **Wear-out Region**
  - At long times, one enters the wear-out region where normal wear and tear of the system components results in an increasing failure rate with time
- **Infant mortality region**
  - Failure rate decreases with increasing time
  - Result of defects etiher designed into, or inadvertently built into a product
    - Indicative of quality "escapes"
    - Marginal materials
    - Drives with the least margin for some critical design tolerance.
    - Manufacturing anomaly

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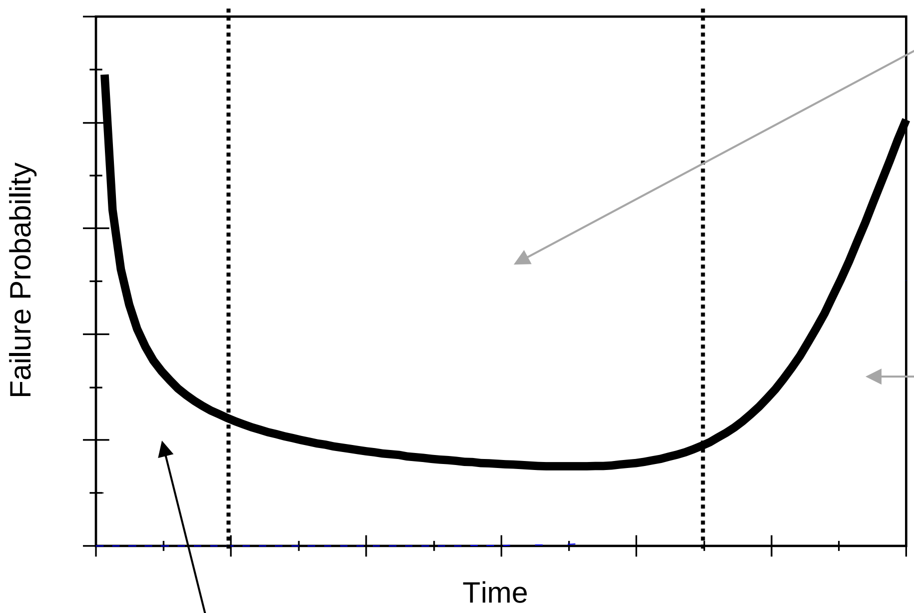
Time to Failure: The “Bathtub” Reliability Model

Classical Reliability Model
“The Bathtub Curve"



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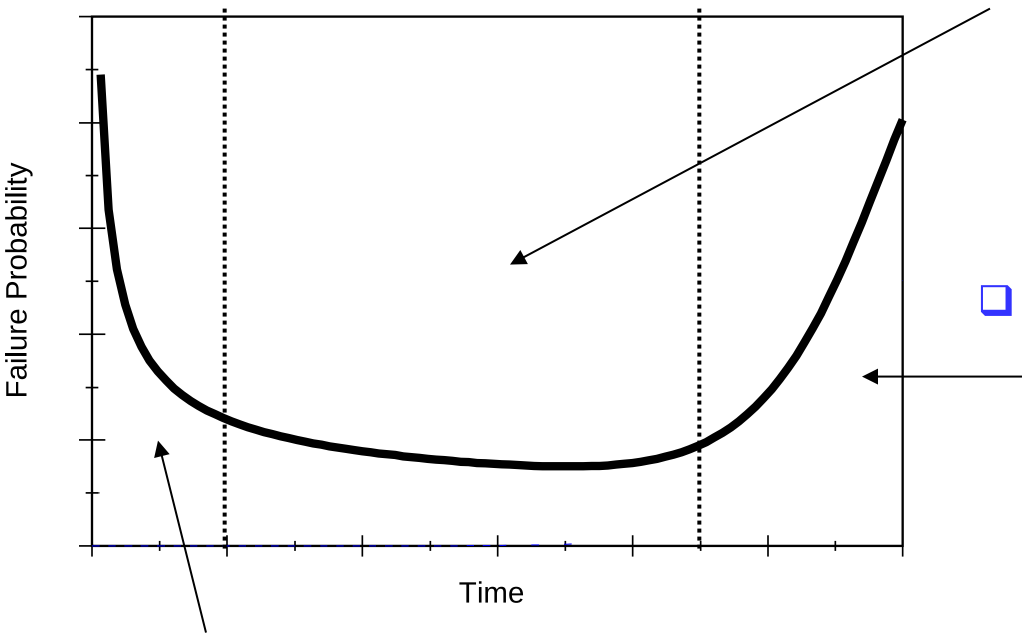

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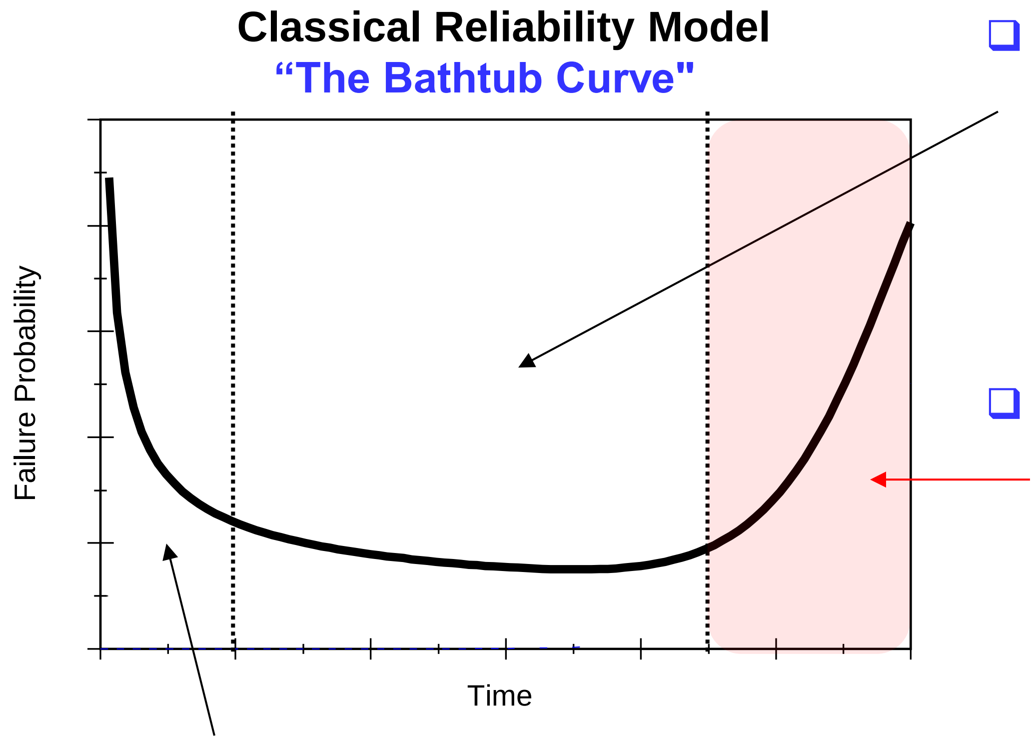

- **Steady State region**
  - After the weak drives are removed from the population, the failure rate reaches a fixed value for the service life of the drive

- **Wear-out Region**
  - At long times, normal wear and tear of the system components results in an **increasing failure rate with time**
  - This type of behavior results in costly excursions to both WD and our customers
  - **This regime must be avoided at all costs**

- **Infant mortality region**
  - Failure rate decreases with increasing time
  - Result of defects either designed into, or inadvertently built into a product
    - Indicative of quality “escapes”
    - Marginal materials
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Classical reliability theory – time dependence

- Standard Weibull Treatment
  - Gives time dependence of unreliability, F(t)
  - Where: t = time
    η = time constant
    β = shape parameter

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$$

- In the limit of small failure rates (<10%) the failure rate vs time simplifies to a power function of time:
  - POH = power-on hrs

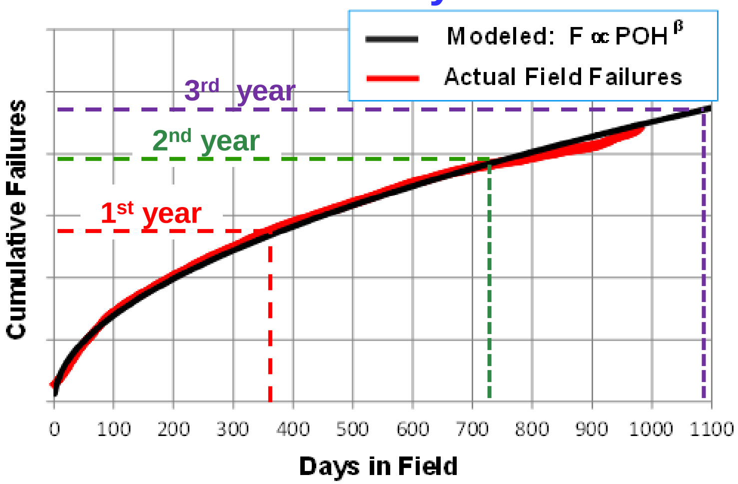
$$F(t) = \left(\frac{t}{\eta}\right)^{\beta} \propto POH^{\beta}$$

- Since failure rate assumed to depend on time alone, **MTTF has been used to quantify the intrinsic reliability of HDD's**
  - MTTF defined by the time required for 63.2% of all drives in a given population to fail

- **But…..use of MTTF alone is meaningless**

- **Reason behind the workload specs introduced by all HDD manufacturers**

Field Reliability vs Time



β < 1: Failure rate decreases with time

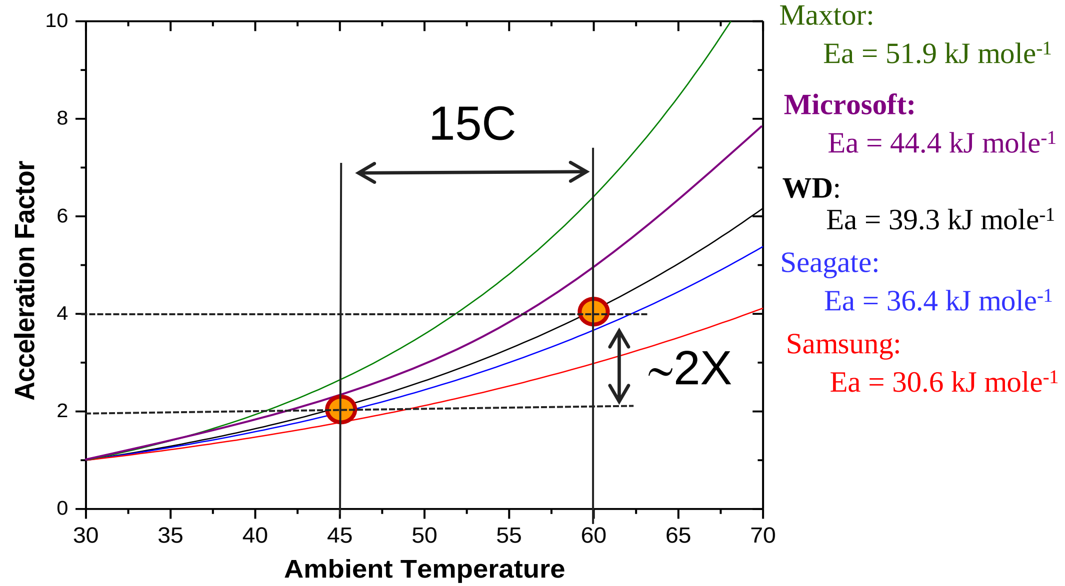
Historical reliability model – impact of temp

- Numerous studies conducted on HDD failure rates at elevated temperature
- Consistent reports of HDD failure rates increasing exponentially with increasing temperature

  - Arhenius equation:

$$F(T) = Ae^{\left[-\frac{Ea}{RT}\right]}$$

  - E_a = activation energy
  - A, R = constants
  - T = Temperature (kelvin)



- Rule of thumb:
  - **Failure rate doubles for approximately 15 C increase in temp**
  - Note: We make use of this acceleration by testing all products at the upper temp spec limit

Historical reliability model – duty cycle

- **A duty cycle term is typically added to general reliability expression**
  - Qualitatively accounts for the intuitive notion that HDD reliability should scale with how much the drive does
  - Usually defined as a power law

- Combination of all three effects, i.e. POH, DC and Temp, yields the classic reliability model
  - This model has been used in the HDD industry for decades

Usage Term

Thermal Term

$$F(t,T) \propto \mathrm{DC}^{x} \,\mathrm{x}\, \mathrm{POH}^{\beta} \times \exp\left[-\frac{E_A}{kT}\right]$$

- **How good is this at describing reality?**

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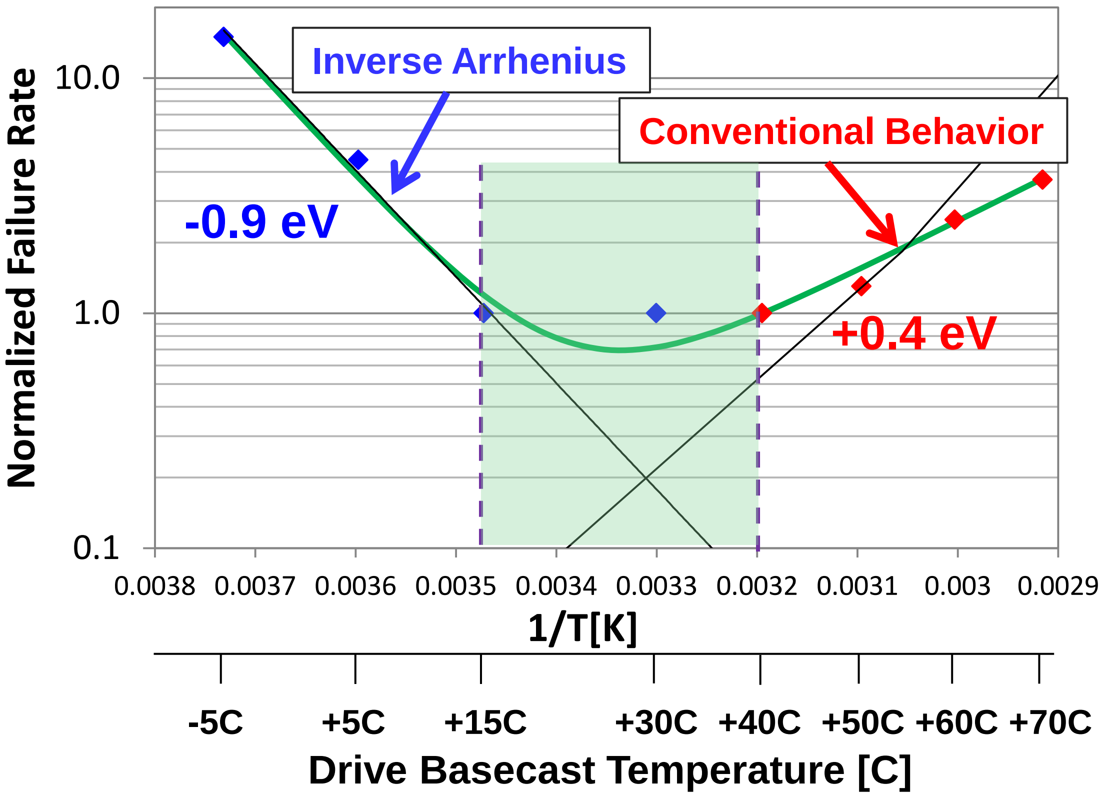
Failure Rate vs Expanded Temp Range

- **Failure rate dependence at cold shows inverse Arrhenius behavior**
  - Magnetic challenges due to higher media coercivity
  - Stronger adhesive forces between heads and media/lube
- **Failure rates are relatively independent of temp between 15 – 40C**



$$F(T) \propto \exp\left(-\frac{E_a}{kT}\right)$$

E_a = activation energy
k = 8.62 x 10^{-5} eV/K
T = absolute temperature (Kelvin)

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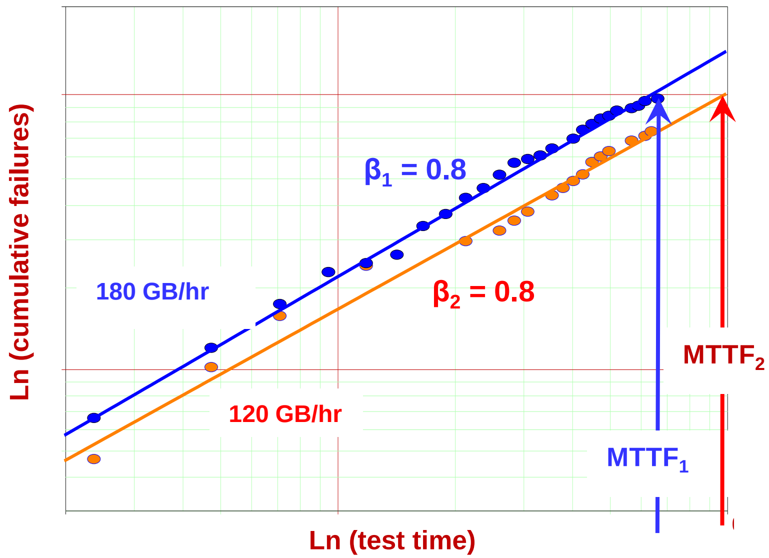
Duty Cycle

- ❑ **Is the concept of "Duty Cycle" valid?**
  - ➢ DOE with same drives built at the same time
  - ➢ Two tests with equivalent duty cycles (>95%)
  - ➢ ……..but differing workloads (1.5:1)

- ❑ Results clearly show that **failure rates scale with workload…..not duty cycle**

- ❑ **Standard (time-based) Weibull Analysis**



Same drive / same DC / two workloads = different MTTFs

Usage — Thermal Term

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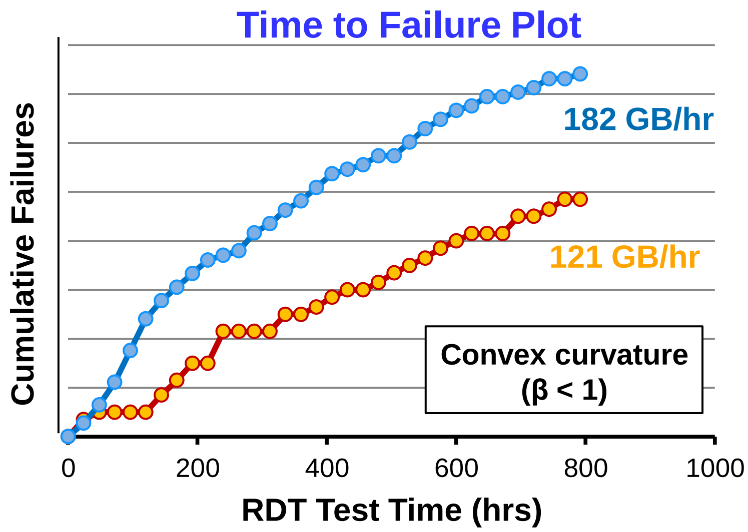


❑ Conclusions:

- ➢ **MTTF typically used to specify reliability of HDDs**
- ➢ **Since MTTF is not uniquely defined……**
- ➢ **MTTF alone is an insufficient measure of drive reliability!**

Historical Reliability Model – Duty Cycle

- **Functional duty cycle** is a useless concept for predicting HDD failure rates
  - Nebulous / ill-defined
  - Every data center claims they run at 100% duty cycle, however, actually “usage” varies dramatically between data centers and within a given data center
  - No quantitative data available

Usage Term — Thermal Term

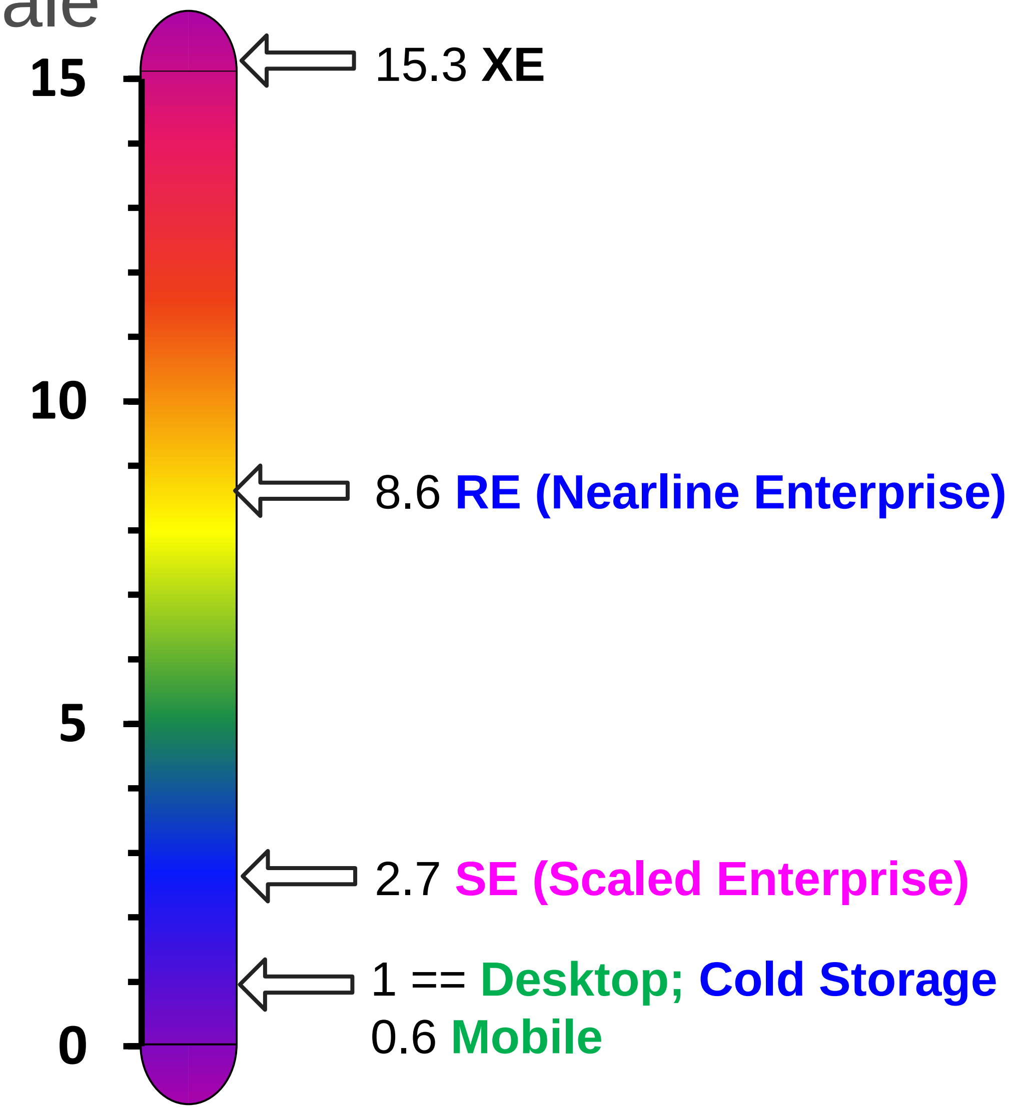
$$F(t,T) \propto \cancel{DC^{x}} \text{ x } POH^{\beta} \times \exp\left[-\frac{E_A}{kT}\right]$$

- **Workload** is a much better measure for drive usage
  - Defined as the total data transfer (sectors written + read)
  - Tightly coupled to the dominate failure modes in test and field that are caused by close proximity between heads and media.
  - Quantifiable from internal drive logs, thereby facilitating accurate field AFR predictions
  - **All HDD manufacturers now explicitly specify workload ratings**

Reliability Landscape and Trends

Rough Drive Quality Scale

- Introduced to allow comparison of basic quality requirements
- Priority list for enablers
- Reflective of
  - Intrinsic quality spec: MTTF
  - Workload
  - Temperature
- Normalized to Desktop



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Reliability Landscape and Trends

AFR = Annualized Failure Rate

$$AFR \propto test\ \ failure\,rate \times \left(\frac{field\,TB/yr}{test\,TB} \right)^{0.6} \times \exp\left(\frac{0.4eV}{kT} \right)$$

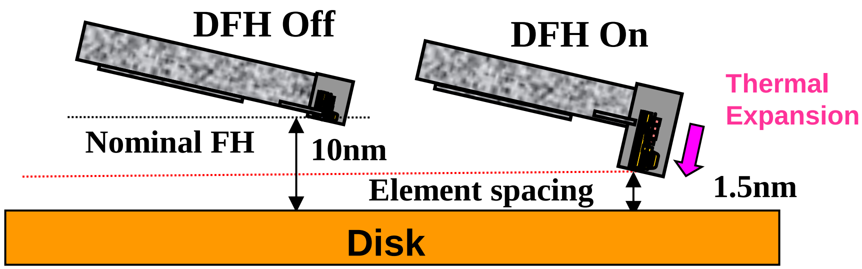
Typical Workloads for different market segments –

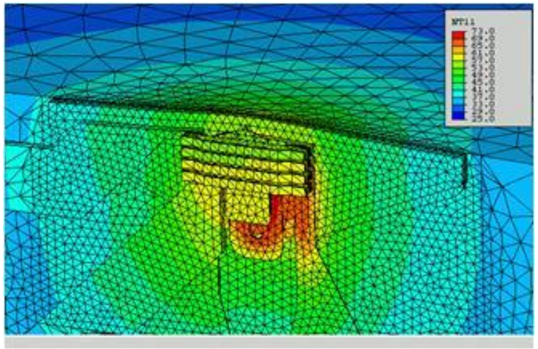
- **XE (800 TB/yr)**
- **RE: Nearline Enterprise (550 TB/yr)**
- **Cloud (180 TB/yr)**
- **Desktop usage (55 TB/yr)**

10x increase in usage from typical DT drive to Enterprise

Minimization of time spent in close proximity

- **"Dynamic Fly Height" (DFH) 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**
  - **Head-disk interface failures → when flying at 10nm**





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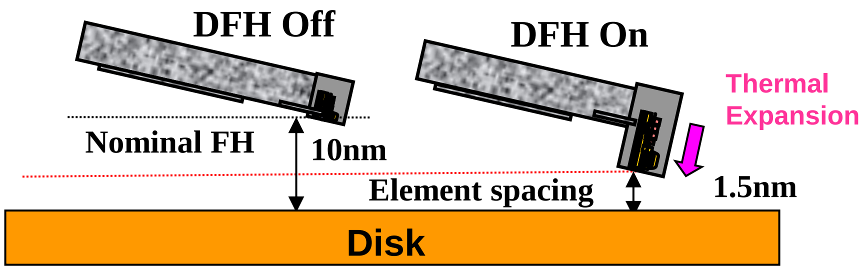

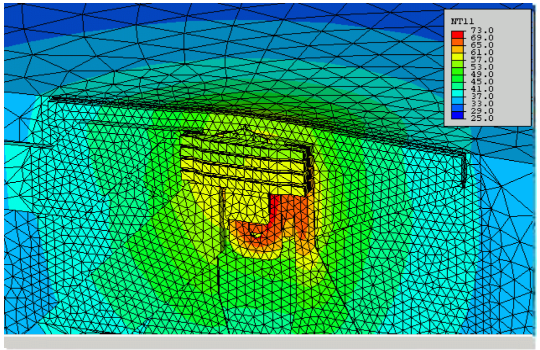

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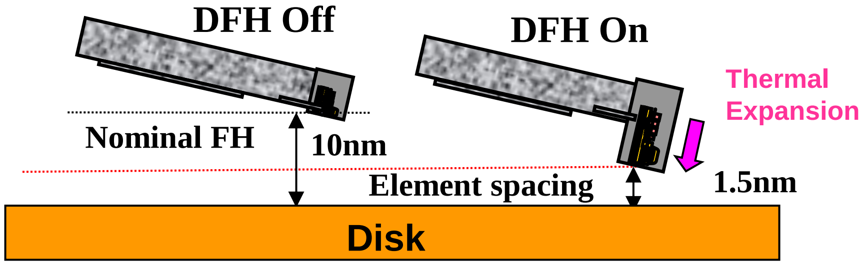

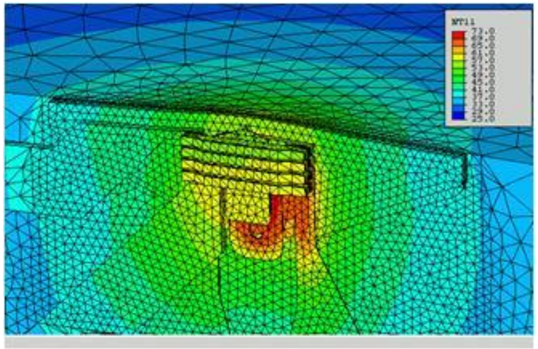

  - Head – disk interactions, if they occur, will be limited to times of DFH actuation
  - **Limits contact frequency**
  - Contact area decreased
  - **Much improved clearance sigma**

- Since contact only occurs during DFH actuation, and since DFH actuation only occurs during reads / writes, then **workload will be critical to HDD reliability**

- **Modification of our reliability prediction / testing methods needed**

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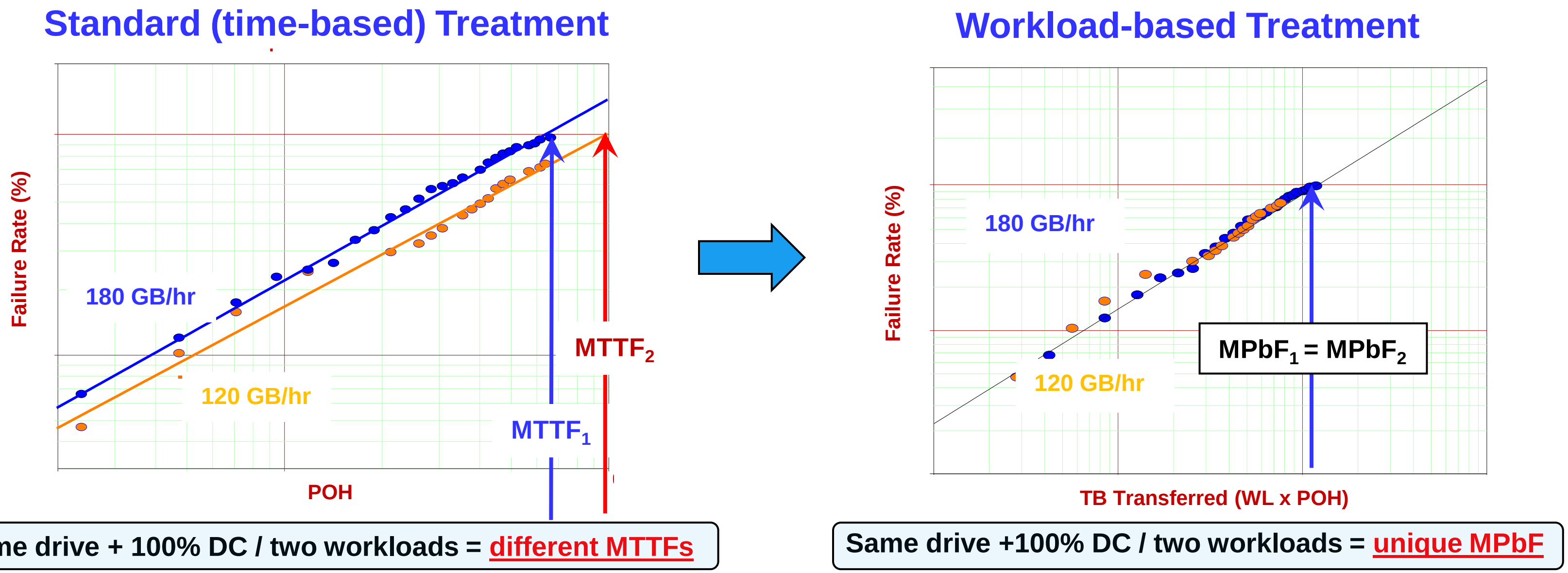
Validation of Workload Impact on HDD reliability

- Failure rates scale with the total TB transferred

$$AFR \propto (TB)^{\beta}$$

- Weibull Analysis



- Results demonstrate that TB transferred is the critical reliability parameter….not time POH
- **Natural reliability metric**: **Mean Petabytes to Failure (MPbF)**

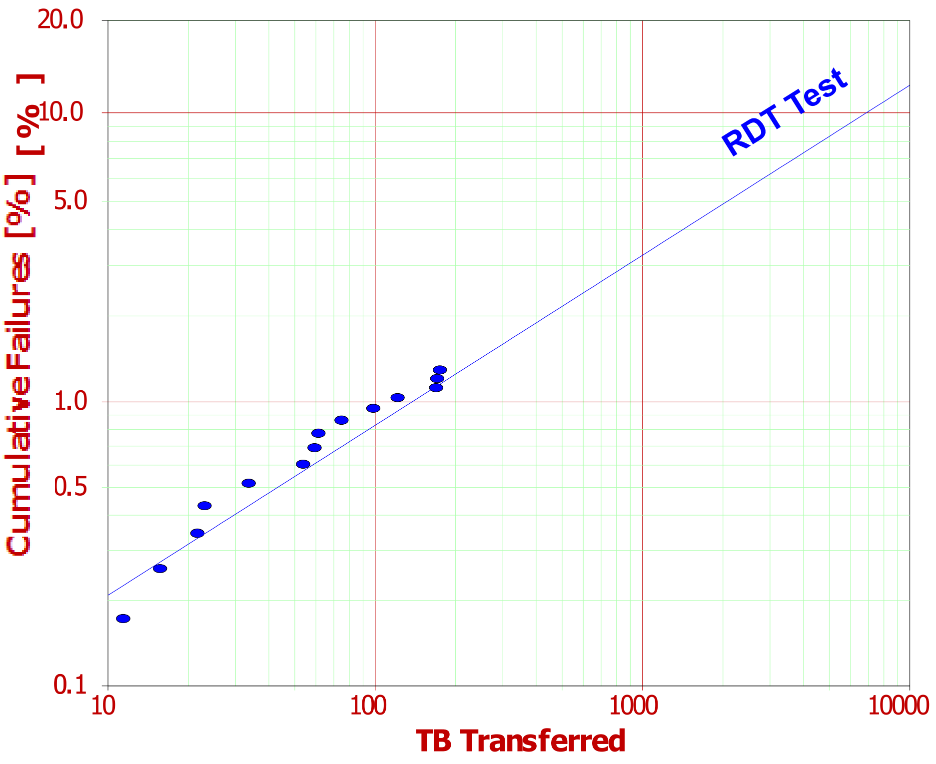
  ➔ **This naturally leads to a DWM (Drive Workload Monitor) (like an odometer)**

- **Minimum requirement**: Simultaneously define **max workload spec and MTTF**
  - **This is now done by all HDD manufacturers**

Weibull Projections

Workload Specifications: An example

- A workload Weibull analysis is performed on RDT data (1200 drives / 1000hrs / high workload script)
- Cumulative failure rate vs total TB transferred is plotted



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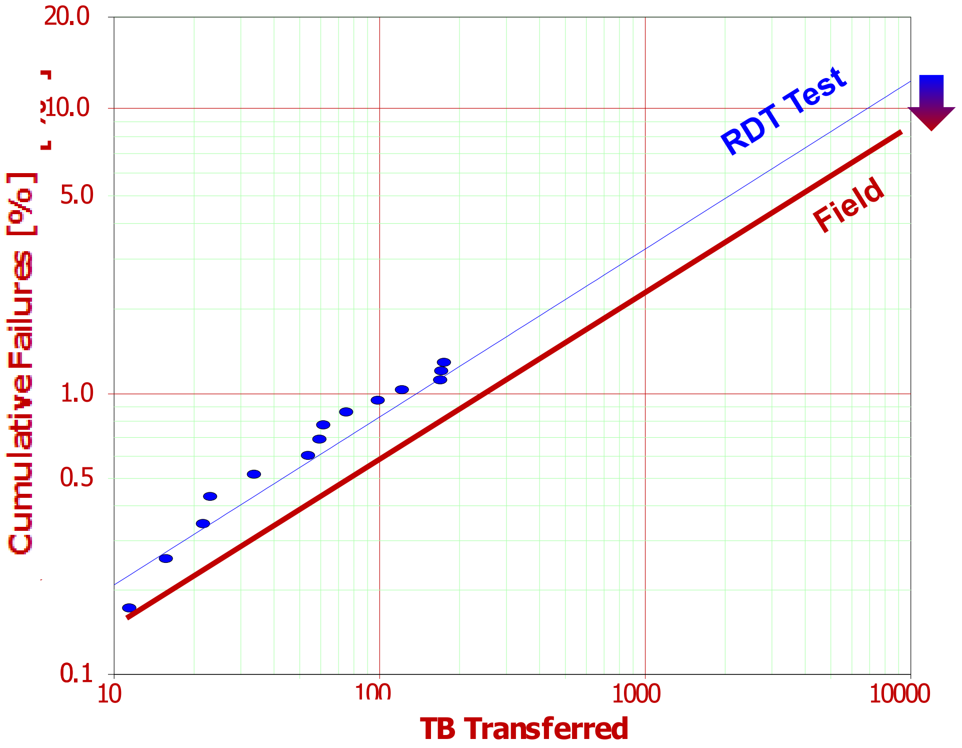

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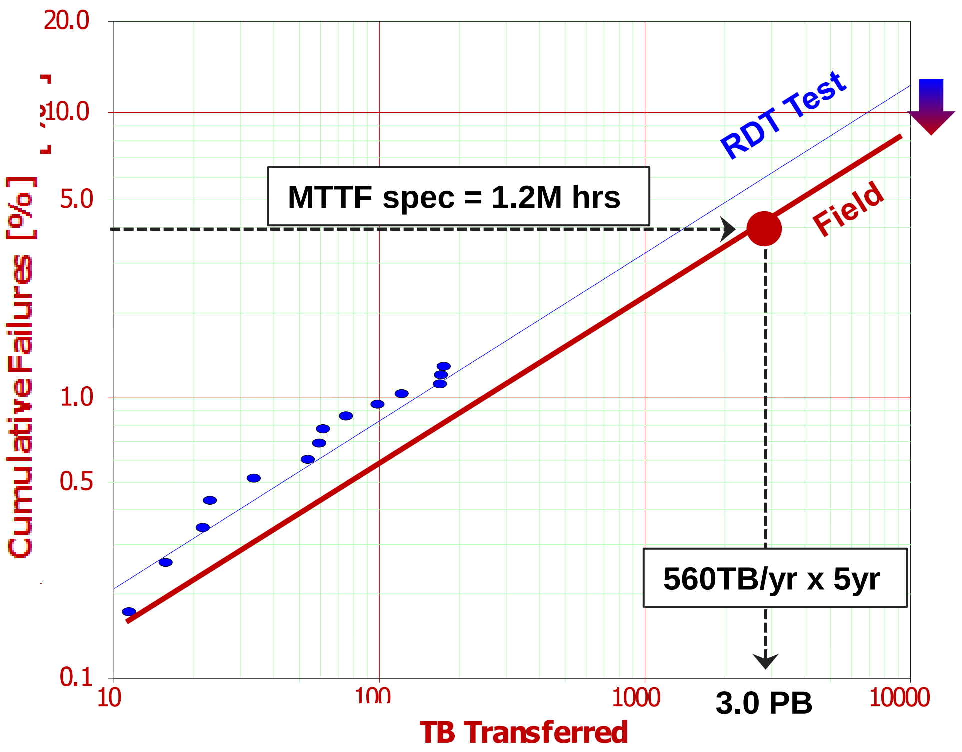

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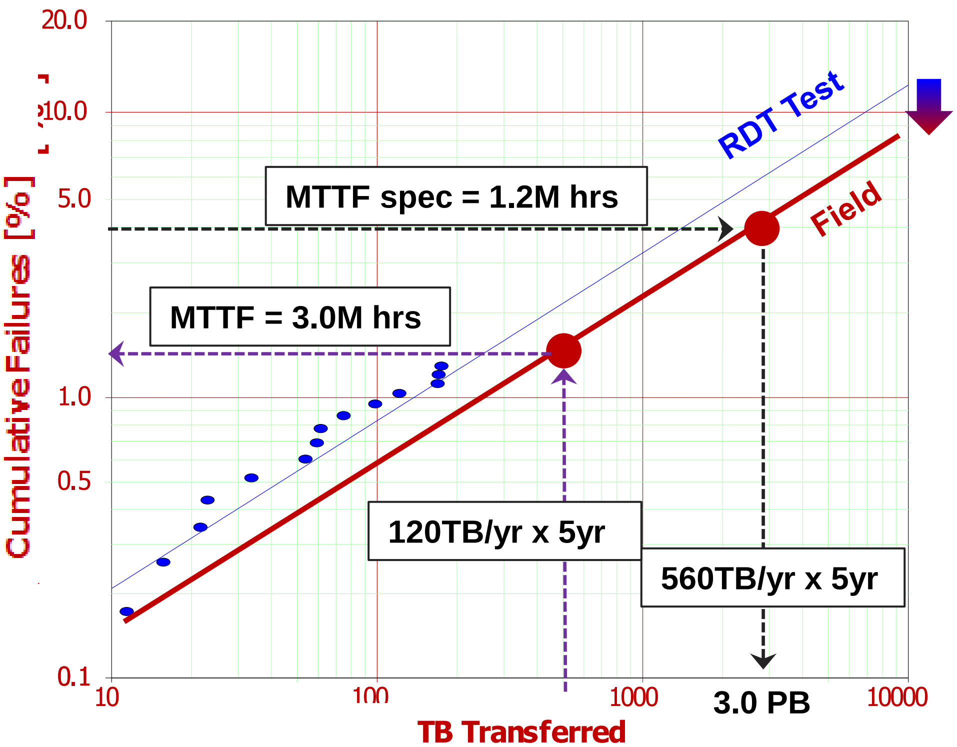
- Data validates that this drive can meet a 1.2M hr MTTF at a specified workload of 550TB/yr
- If HDD is used at lower workloads, a commensurate increase in MTTF (decrease in Failure Rate) will be realized



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Reliability Test Enhancements (last few years)

Problem Statement

- Field failure rates scale with usage / workload
- RDT workloads can be insufficient to "see" the entire drive warranty period in many applications
  - Leaves WD and customers vulnerable to late-in-life field excursions
- Need existed to enhance our reliability testing to ensure future products display the required field quality?

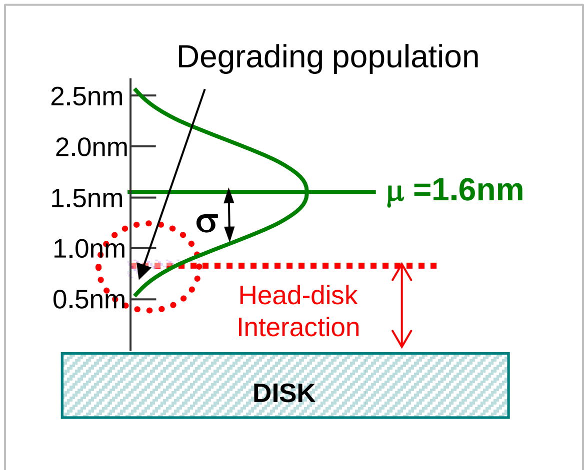
Testing Options

- RDT testing must be performed for longer times (brute force),
  - Extended Lifetime Test (19 week)

or …….

- High workload test scripts
  - Tribo RDT (highest WL script)
  - Client (new version has 4X WL increase)
  - Universal Enterprise (double workload of predecessor)
- Use of head parametric data to identify "virtual" failures
  - Virtual failures = increased failure probability

Are there precursors to HDD failure?



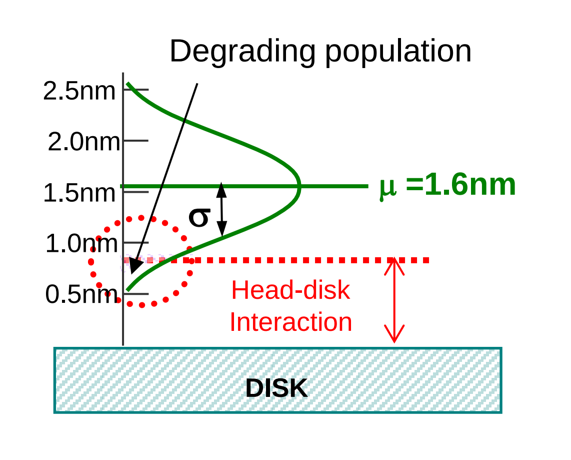
- Controlling the clearance distribution is critical for long-term field reliability
- Those heads in the low-clearance wing are far more prone to failure
- Must maintain 3σ process

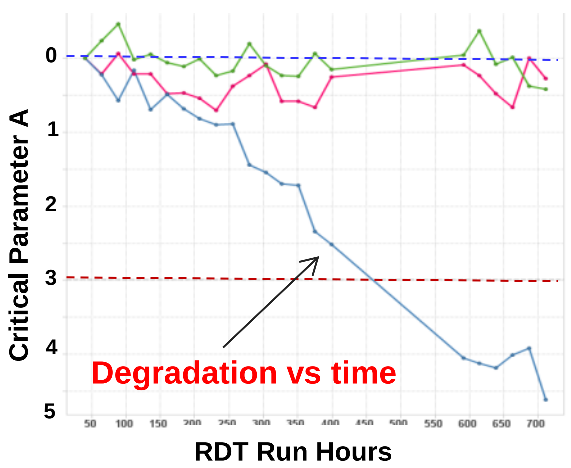
- Degradation gets severe enough that the head can no longer function.
- Failure (typically ECC) then results
- Tear down confirms wear of carbon on pole tips due to occurrence of head-disk contacts

"Virtual" Failures

❑ Overall Strategy:

- **The TMR reader is the best sensor we have in the drive**
- **Use it to calibrate the head-media interface through magnetic 'critical parameter' degradation**
- **We use about 7 critical parameters to perform in-situ characterization during test**





- Controlling the clearance distribution is critical for long-term field reliability
- Those heads in the low-clearance wing are far more prone to failure
- Must maintain 3σ process

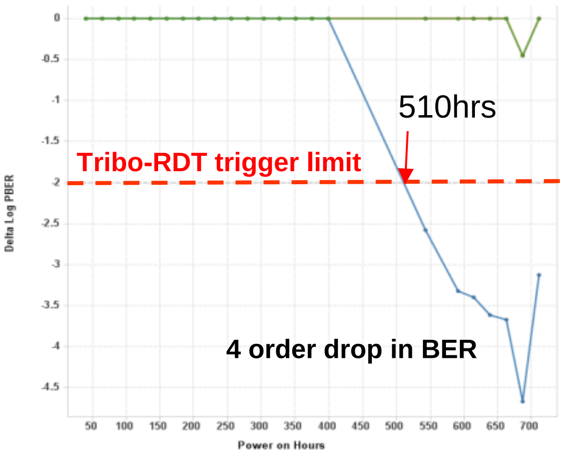
- Contact between the head and disk leads to degradation of the magnetic / electrical propeties of the head
- Monitoring degradation in the parametric data can be used to identify "virtual" failures

- Degradation gets severe enough that the head can no longer function.
- Failure (typcially ECC) then results
- Tear down confirms wear of carbon on pole tips due to occurrence of head-disk contacts

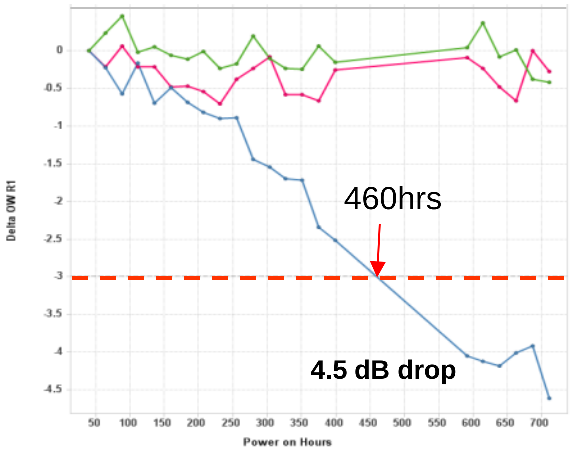
Degradation precedes vast majority of real failures

- Drive triggered all three degradation limits at 400-500 hrs in factory RDT
- Drive then failed for head-degradation at 933 hours

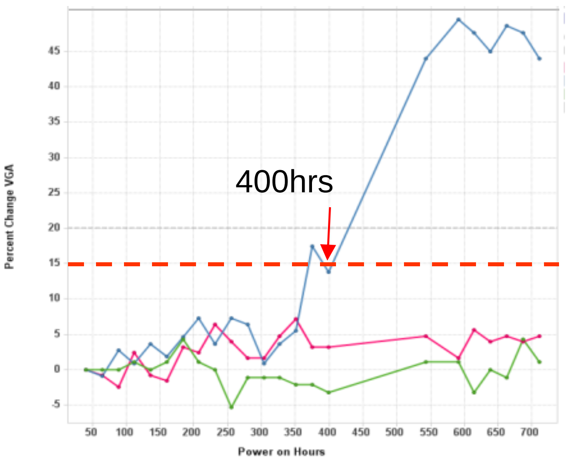
Parameter A



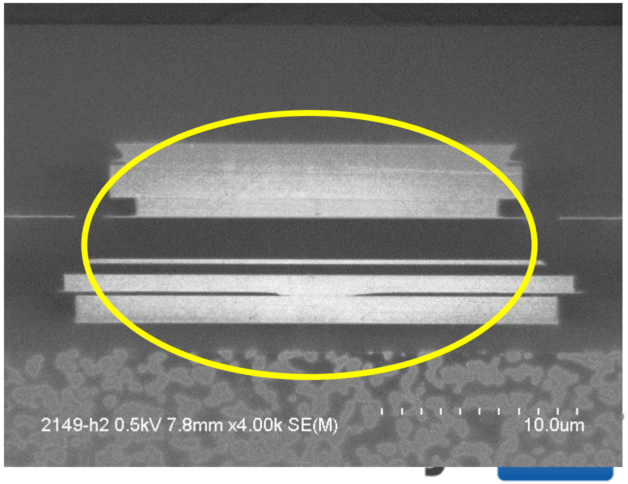
Parameter B



Parameter C



- **2nd Level / Teardown FA**
  - Scope signal on failed head showed base line popping
  - SEM on failed head showed DLC wear (others showed no wear).

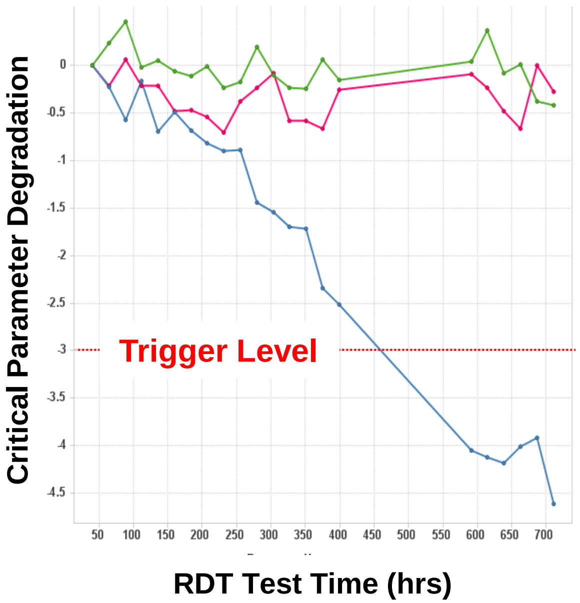


“Live” Parametric Monitoring During ORT/RDT

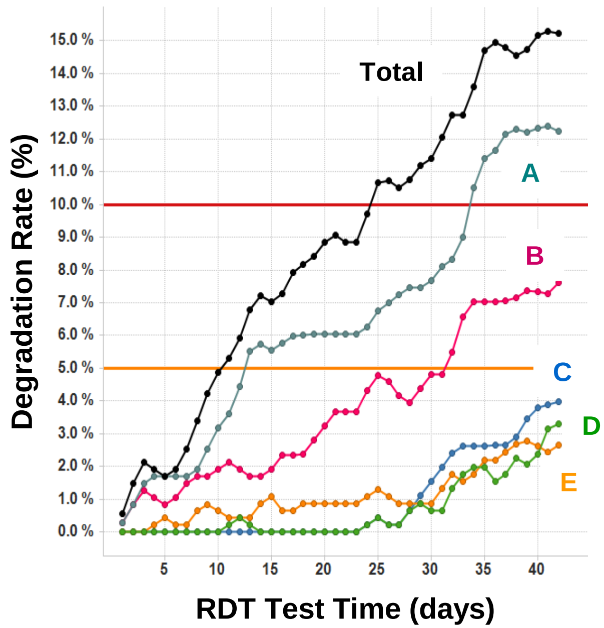
- **A web-based tool is available to monitor the progress of any drive running RDT/ORT in the factory in real time**
  - Gives temporal information on drive health that was previously unavailable
  - Provides much clearer insight into nature of root cause leading to failure
  - Allows tracking of: a) individual drives / parameters, b) entire drive population, or c) **various drive configurations.**

- **Representative Results**

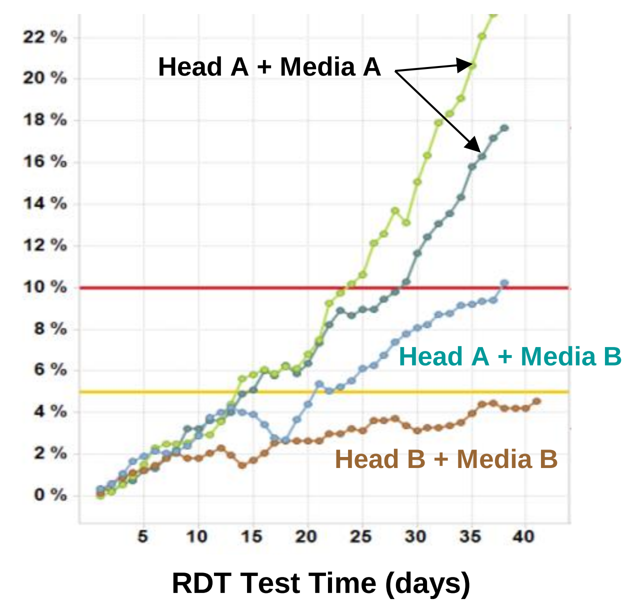
Individual Drive (any parameter)



Entire RDT Population

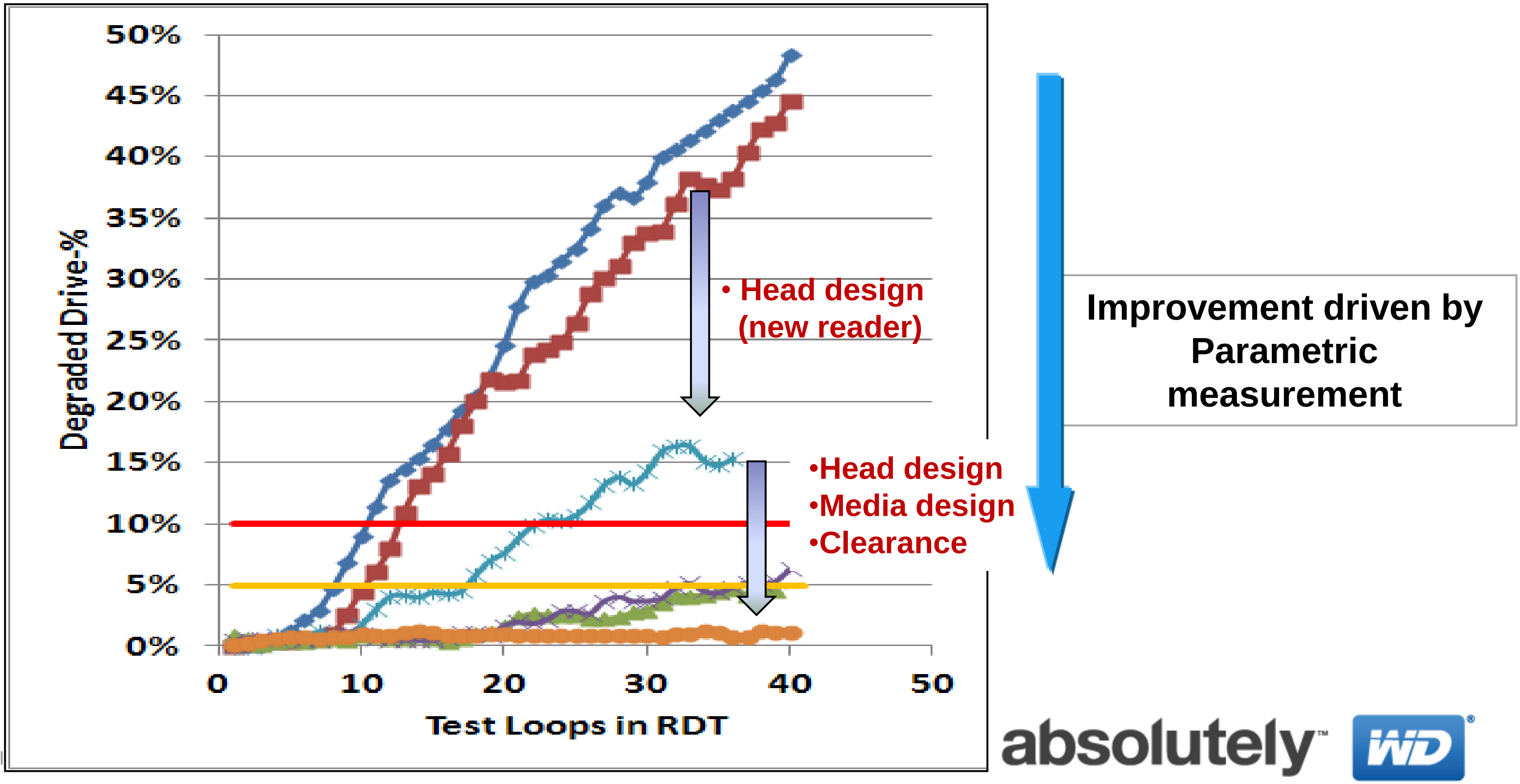


Comparison of RDTs



Product Improvements Driven by Parametric Measurements

- Parametric data provides far more granularity on product quality compared to "real" drive failures
- Quality team continually monitors Virtual Failures and uses this data to qualify any new component and / or design enhancement
- Engineering uses data to drive improvements into each HDD design



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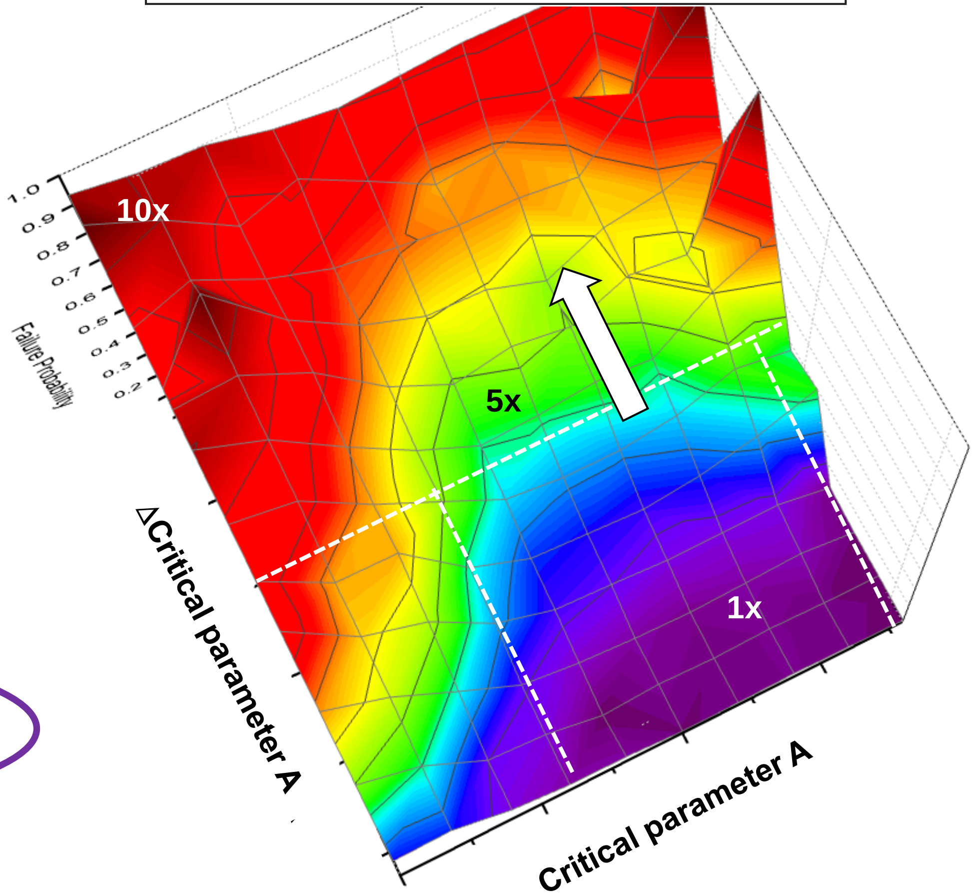
Failure probability contour plots

- Field failure probability can be plotted as a function of both the critical parameter and the degradation in the critical parameter.
- Both parameters are important
- **For the vast majority of the population, degradation in critical parameter A is more important than the absolute value of A**
- This is not universally true for all parameters
  - Degradation patterns are being used to perform virtual FA
  - Some degradation scenarios are more serious than others
- Methodology is being extended for WD's **"In-field Health Monitor"**

Failure Probability Contour Plot



Evolution of Parametric Monitoring

Decreasing head-media clearance

➔ More Head-Disk contact events

➔ Higher levels of magnetic critical parameter degradation

➔ Precursor to real failure of the drive

- ***Internal Benchmarking***: Measurement of critical parametric data now routinely performed in Reliability testing (2+ years experience)

Natural progression is to measure, and store critical parametrics at a regular interval during field operation

- ***External dry-run***: Partnership with Enterprise customers on small fleet sizes.

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Why Extend parametric measurements to the field?

- After nearly two decades, it is generally accepted that the SMART attributes are not strongly correlated to HDD failures

  "....**models based on SMART parameters alone are unlikely to be useful for predicting individual drive failures".**

  (Google: Pinheiro et al., Proc. 5th USENIX Conf. on File and Storage Technologies, February 2007)

- The obvious question arises**…..“Can we use our parametric degradation approach to improve predictability of drive failures in the field”?**

- **In-field parametric monitoring (IFPM)**
  - WD is pursuing parametric data collection for data center fleet management
  - Potential to identify poorly performing drives / heads before actual failure is the **“Holy Grail” of HDD reliability**
  - **Drives with the capability to perform critical parameter measurements (during drive idle time) have been developed and are just now becoming available**
  - Health monitor algorithms need to be optimized (6 – 9 months)

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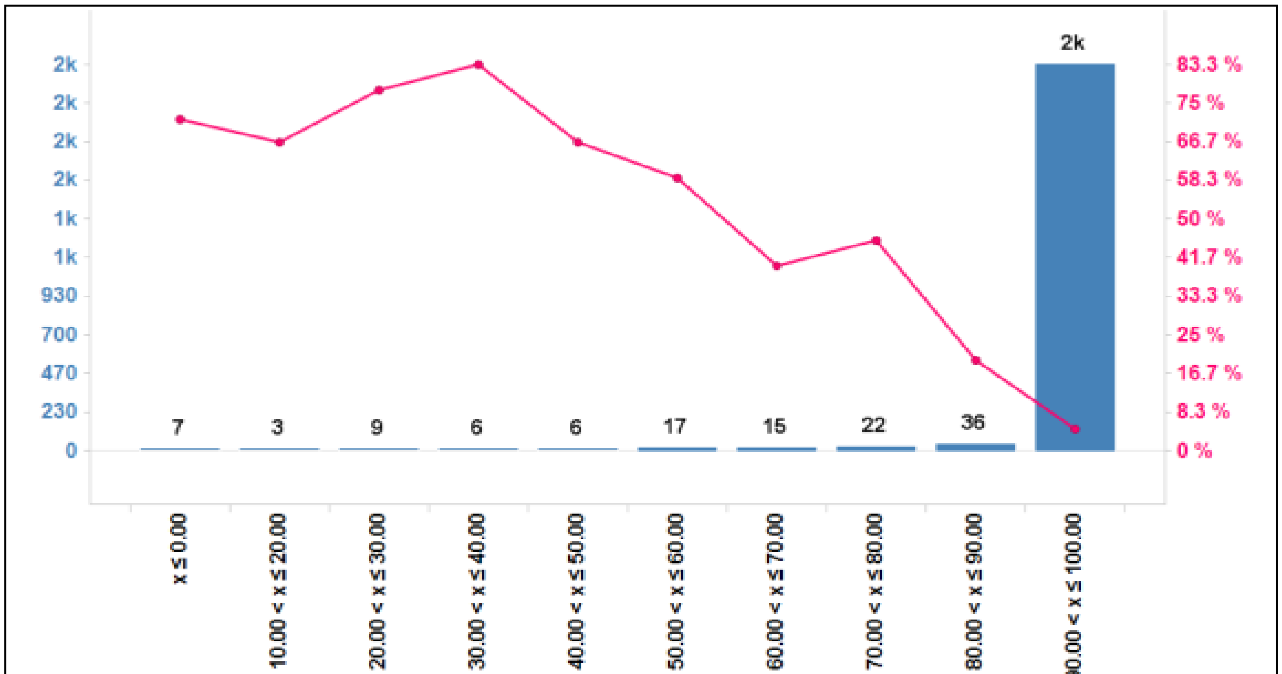
WD's 1st fleet management system: IFPM

The In-Field Parametric Monitoring (IFPM) system will measure, and store, critical parameters periodically throughout the HDD lifetime, and output a relative health index.

A 'Gas Gauge' - Failure Probability Increases as 'Health Index' gets worse

Low Score (Bad) ← **High Score (good)**

Drive Count

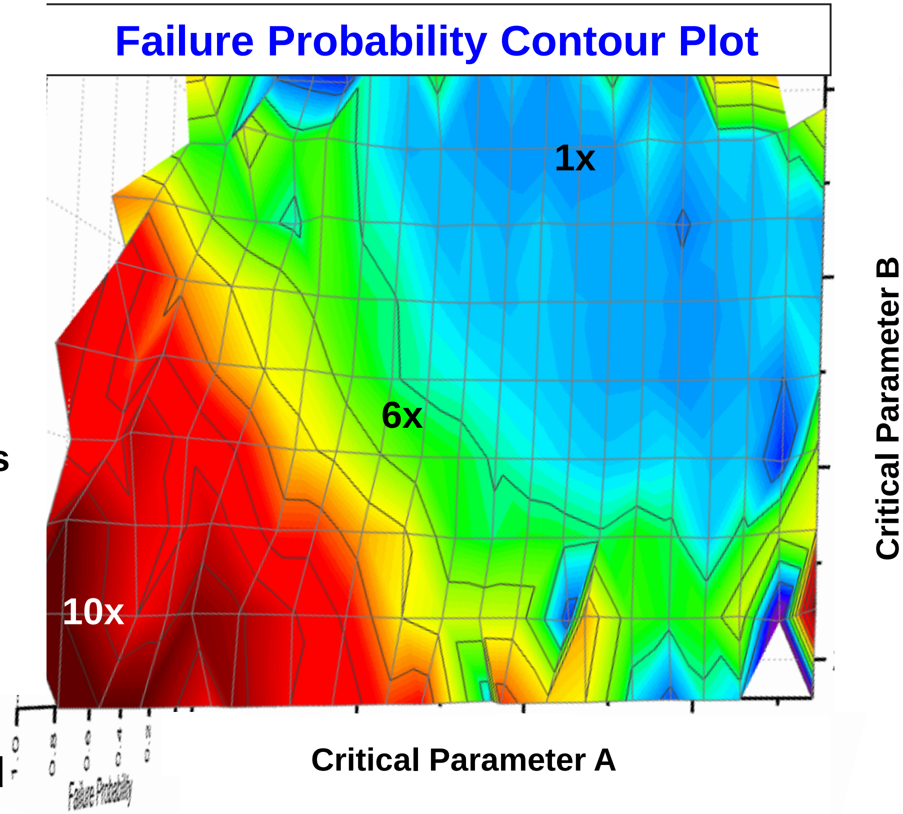


Real Failure Rate

IFPM Health Index
(derived from critical parameters)

WD's 1st fleet management system: IFPM

- Phase 1 – Drives equipped with initial parametric monitoring
  - Subset of parameters available now
  - Start field data collection with partners
- Phase 2 – "Complete" set of critical parameters will become available shortly
- Phase 3 – Algorithm development
  - Data collected from select customers
  - Refinement of failure probability algorithms
  - Define a "relative health index"
- Phase 4 – Ability to check relative health index of any drive on demand



Since the health index with change with usage, IFPM will be coupled to the DWM (Drive Workload Monitor)

Meaningful Predictive Modeling

- Powerful models that predict failures of individual drives need to make use of signals beyond SMART
- One of the main motivators for SMART was to provide enough insight into disk drive behavior to enable such models to be built
- IFPM + workload monitor + SMART may prove effective at overcoming our current inability to build predictive models.

Thank You

How does workload enter into the classical analysis?

- **All time is not equivalent in driving HDD failures**
  - Overwhelming majority of failures occur when reading / writing / transferring data
  - Failure probability for HDI issues drops to near zero when pole tip is retracted
  - Failure probability for motor, PCBA, etc issues that depend on absolute POH time constitute only small percentage of total failures

- **The critical time for is the time spent in close proximity to the disk**
  - Significant levels of head-disk interactions are limited to times of DFH actuation
  - This relatively subtle modification / realization has significantly changed the way in which HDD reliability is viewed
  - Since actuation only occurs during reads and writes….actuation time is directly proportion to the total data transferred

$$Actuation\ \ time \propto (WL \times \mathrm{POH}) = TB$$

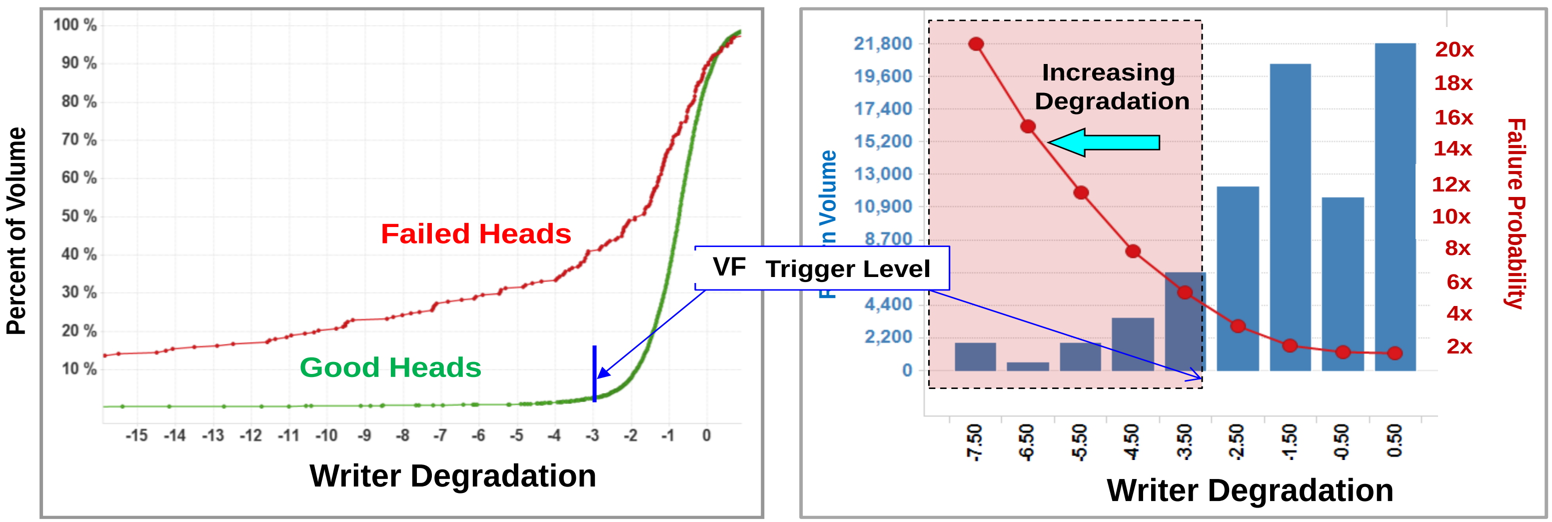
- Failure rates will be dependent on the total data transferred

$$F(t) \propto (WL \times time)^{\beta} \propto (TB)^{\beta}$$

Virtual Failure Rates - Definition

- **Virtual failure rates (parametric degradation) are monitored in all WD reliability testing**
  - Very clearly defined pass / fail criteria
- **Virtual failures defined in terms a number of critical parameters**
  - Writer health
  - Reader health (magnetic and electrical measurements)
  - Magnetic element spacing change
  - Physical head-disk spacing change
  - Bit error rate
- **Critical parameters identified from analysis of field return data**

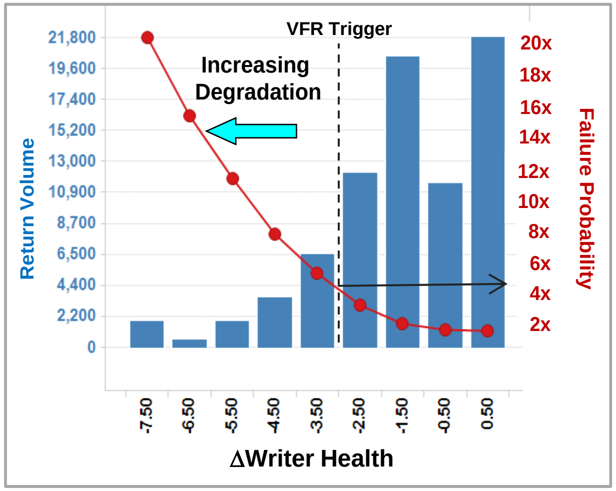
Cumulative Distribution Functions | **Failure Probability vs Degradation**



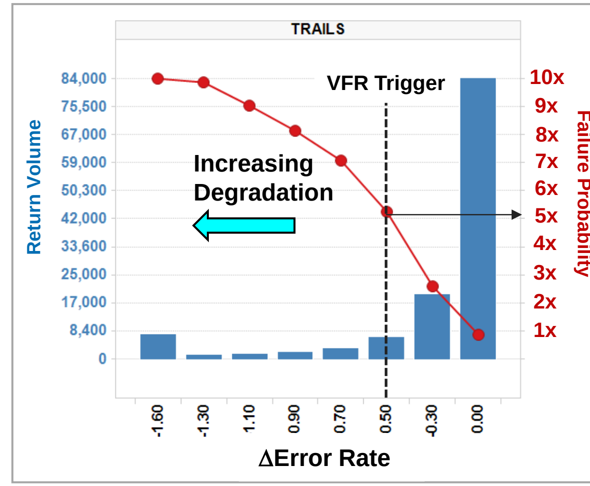
VF parameters = higher field failure probabilities

- Field / test data used to identify parameters critical to HDD reliability

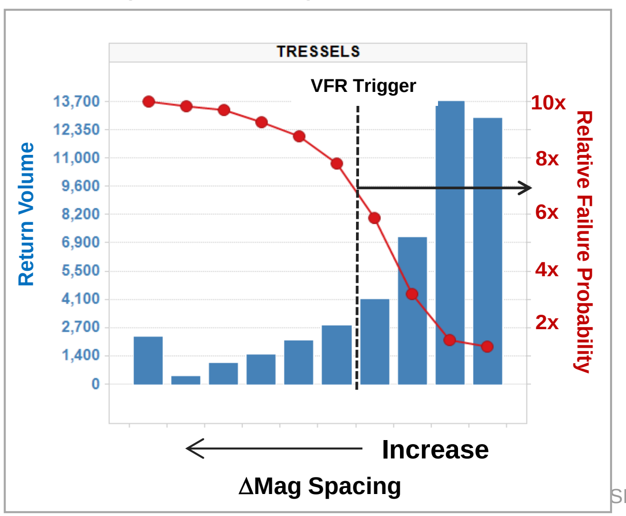
Δ Writer Health



Δ Error Rate



Δ Mag Spacing



Δ Physical Spacing