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reliability designed, reliability delivered

Best Practices in Design for Reliability

March 9, 2016 DfR Solutions Beltsville, MD

What is Design for Reliability (DfR)?

- Reliability is the measure of a product's ability to
  - …perform the specified function
  - …at the customer (with their use environment)
  - …over the desired lifetime

- Design for Reliability is a process for ensuring the reliability of a product or system during the design stage before physical prototype
  - Often part of an overall Design for Excellence (DfX) strategy

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Warning: DfR Solutions' DfR vs. Others' DfR

- DfR: Focus is on activities before prototype
- Others: Focus is on the entire product lifecycle (HALT, root-cause analysis, reliability growth)

- DfR: Focus is on preventing single point of failures
- Others: Focus is on system-level failures and failure modes (safety)

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Why Design for Reliability (DfR)?

- The foundation of a successful product is a robust design
  - Provides margin
  - Mitigates risk from defects
  - Satisfies the customer

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Who Controls Electronic Hardware Design?

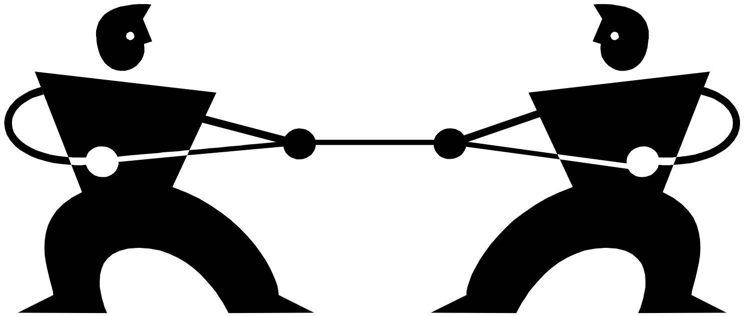
Electrical Designer

- Circuit Schematic
- Component selection
  - Bill of materials (BOM)
  - Approved vendor list (AVL)

Mechanical Designer

- PCB Layout and Outline
- Other aspects of electronic packaging

Both parties play a critical role in minimizing hardware mistakes during new product development



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When Do Mistakes Occur?

- Insufficient exchange of information between electrical design and mechanical design
- Poor understanding of supplier limitations
- Customer expectations (reliability, lifetime, use environment) are not incorporated into the new product development (NPD) process

There can be many things that "you don't know you don't know"

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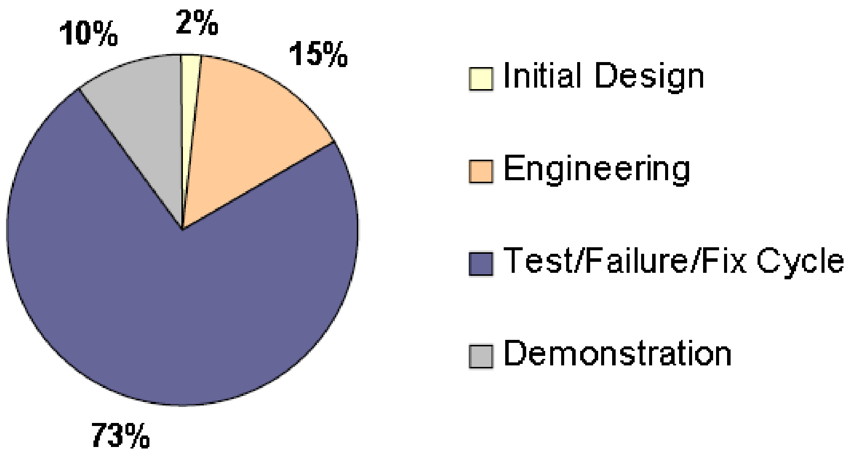
Why DfR: Faster / Cheaper

- Traditional OEMs spend almost 75% of product development costs on test-fail-fix



- Electronic OEMs that use design analysis tools
  - Hit development costs 82% more frequently
  - Average 66% fewer re-spins
  - Save up to $26,000 in re-spins

Gene Allen and Rick Jarman .Collaborative R&D; (New York John Wiley&Sons. Inc. 1999). 17.
Aberdeen Group, Printed Circuit Board Design Integrity: The Key to Successful PCB Development, 2007 http://new.marketwire.com/2.0/rel.jsp?id=730231

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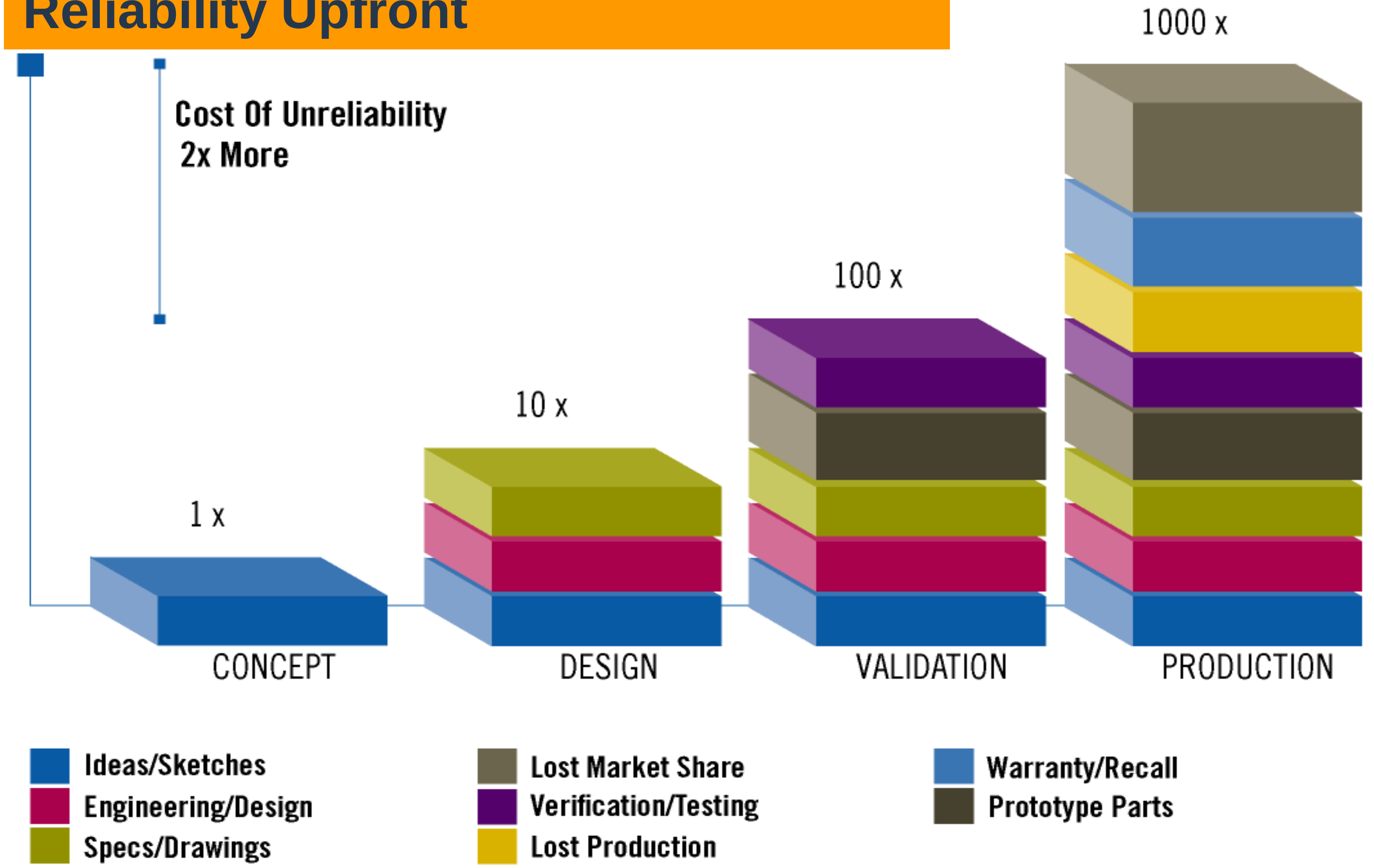
Why DfR: Earlier is Cheaper

Reduce Costs by Improving Reliability Upfront



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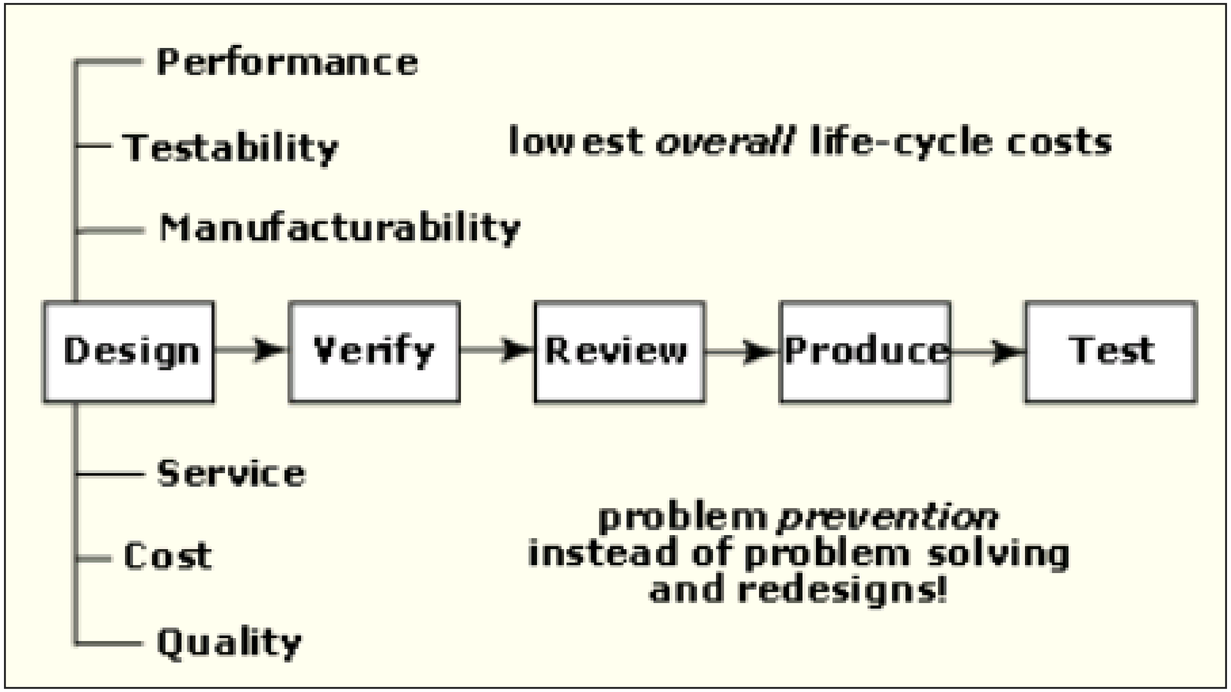
How DfR?

- Successful DfR efforts require the integration of product design and process planning into a cohesive, interactive activity known as Concurrent Engineering



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DfR Implementation

- Many organizations have developed DfR Teams to speed implementation
  - Success is dependent upon team composition and gating functions

- Challenges: Classic design teams consist of electrical and mechanical engineers trained in the ‘science of success’
  - DfR requires the right elements of personnel and tools

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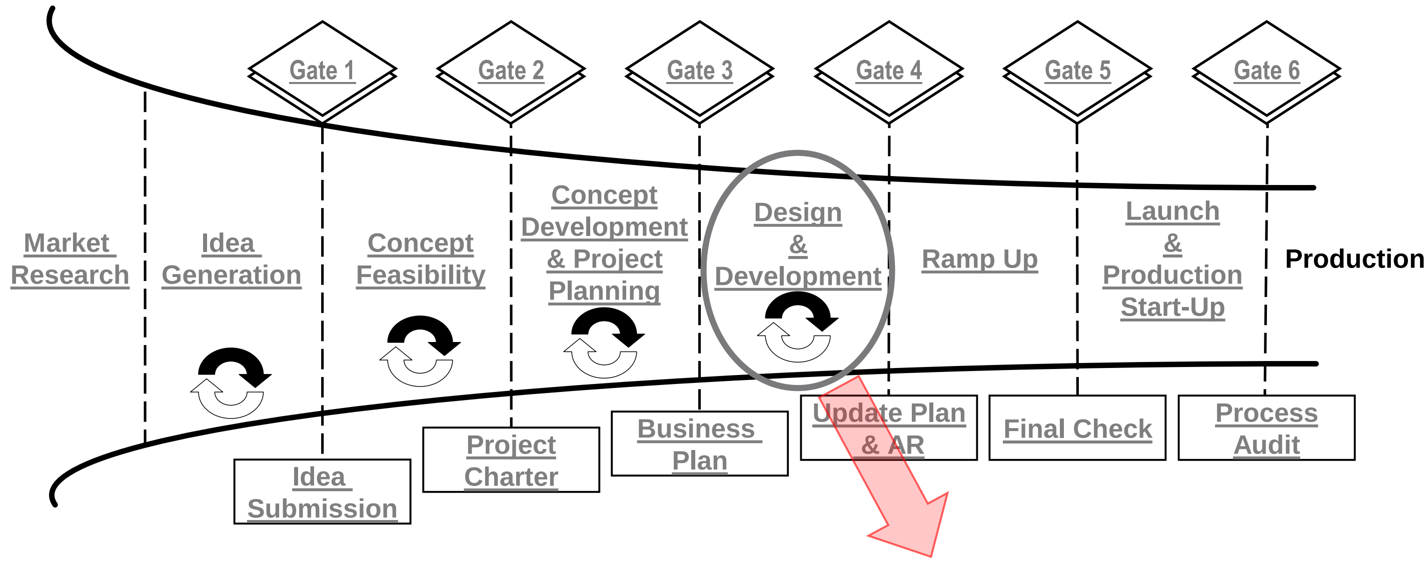
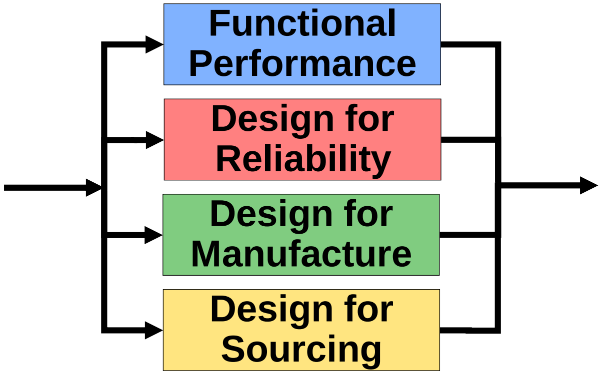
DfR Team

- Component engineer
- Physics of failure expert (mechanical / materials)
- Manufacturing engineer
  - Box level (harness, wiring, board-to-board connections)
  - Board / Assembly
- Engineer cognizant of environmental legislation
- Testing engineer (proficient in ICT / JTAG / functional)
- Thermal engineer (depending upon power requirements)
- Reliability engineer?
  - Depends. Many classic reliability engineers provide **limited** value in the design process due to over-emphasis on statistical techniques and environmental testing

Gating DfR



- Goal: Simultaneously optimizing the design
- Reality: Need for specific gating activities (design reviews)



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List of DfR Tools and Techniques (Wikipedia)

Many tasks, techniques and analyses are specific to particular industries and applications. Commonly these include:

- Built-in test (BIT) (testability analysis)
- Failure mode and effects analysis (FMEA)
- Reliability hazard analysis
- Reliability block-diagram analysis
- Dynamic Reliability block-diagram analysis[6]
- Fault tree analysis
- Root cause analysis
- Sneak circuit analysis
- Accelerated testing
- Reliability growth analysis
- Weibull analysis
- Thermal analysis by finite element analysis (FEA) and / or measurement
- Thermal induced, shock and vibration fatigue analysis by FEA and / or measurement
- Electromagnetic analysis
- Statistical interference
- Avoidance of single point of failure
- Functional analysis and functional failure analysis (e.g., function FMEA, FHA or FFA)
- Predictive and preventive maintenance: reliability centered maintenance (RCM) analysis
- Testability analysis
- Failure diagnostics analysis (normally also incorporated in FMEA)
- Human error analysis
- Operational hazard analysis /
- Manual screening
- Integrated logistics support

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List of DfR Tools and Techniques (DfR Solutions)

- Failure Mode Analysis
  - Failure Mode Effect Analysis (FMEA), Fault Tree/Tolerance Analysis (FTA), Design Review by Failure Mode (DRBFM), Sneak Circuit Analysis (SCA)
- Reliability Prediction - Empirical
- Design Rules
- Design for Excellence
  - Design for Manufacturability (DfM), Design for Testability (DfT)
- Tolerancing (Mechanical, Electrical)
- Simulation and Modeling (Stress)
  - Thermal, Mechanical, Electrical/Circuit
- Simulation and Modeling (Damage)
  - EMI/EMC, EOS/ESD, Physics of Failure, Derating

Failure Mode Analysis

- A process of identifying potential failure modes and appropriate mitigations early in the design process
  - Likely the most common DfR tool for reliability engineers

- These are generic DfR tools
  - A Strength and Weakness

- Strength: Can provide amazing insight
- Weakness: Can be a boring, monotonous, no-value, check-the-box activity

- ***"Unfortunately, reliability engineering has been afflicted with more nonsense than any other branch of engineering."***
  - Pat O'Connor (Author Practical Reliability Engineering).

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Failure Mode Effects Analysis (FMEA)

- The classic failure mode analysis technique
  - Developed after World War II

- Forces the team to identify failure modes and their severity, their probability of occurrence, and their detectability

- Executed as both a design analysis (DFMEA) and a process analysis (PFMEA)

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FMEA (cont.)

- Conservative, regulated industries love FMEA
  - Very concerned about safety
  - Very concerned about having a written record of being concerned about safety

- Other industries are less certain
  - DFMEA can take too long (personal computer company completed DFMEA three months after product launch)
  - PFMEA provided by suppliers can be boilerplate

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Valuable FMEAs

- For a FMEA to be valuable, two things need to happen

- One, the form should be fluid
  - Functional block, geometry, etc.
  - Scoring can be linear, actual measurements, etc.

- Two, actions that can be measured through statistical process control should be identified
  - It is not a one and done

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DfR Outline

- **DfR at Concept / Block-Diagram Stage**
  - Specifications
- Part Selection
  - Derating and uprating
- Design for Manufacturability
  - Reliability is only as good as what you make
- **Wearout Mechanisms and Physics of Failure**
  - Predicting degradation in today's electronics

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What is the Latest in Design for Reliability?

- Traditional screening does not work
  - Studies on DRAM, SSD, and Ceramic Capacitors have identified metrics that indicate weaker parts, but these parts do not display infant mortality behavior
  - However, they do fail more often and earlier than the overall population
- Studies by Google have found that temperature has limited influence on the failure rate of DRAM, flash memory, or hard drives
  - Activity levels also had limited effect on failure rate
  - Overall calendar age was a better indicator, with significant increase in error rate for DRAM after 20 months

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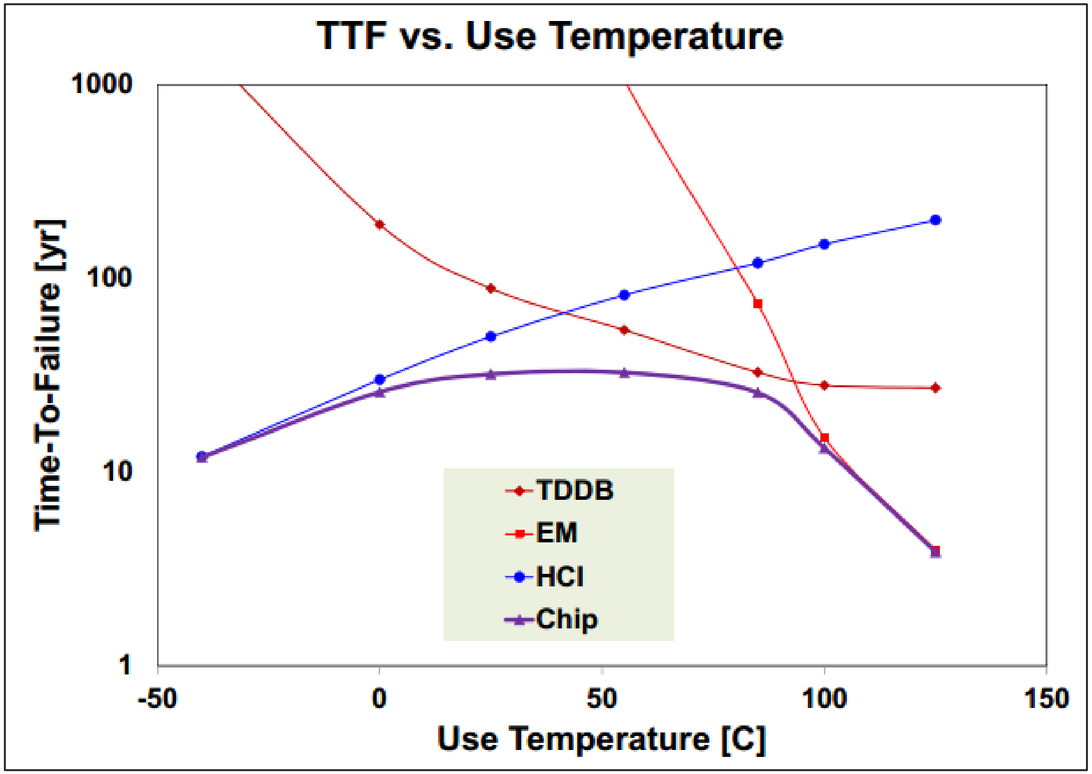
What is the Latest in Design for Reliability?

- Cold is the new Hot
  - Most state-of-the-art devices can have limited lifetimes below 0C



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DfR at Concept Stage

Concept / Block Diagram

- Can DfR mistakes occur at this stage?
  - No……….and Yes

- Failure to capture and understand product specifications at this stage lays the groundwork for mistakes at schematic and layout

- Important specifications to capture at concept stage
  - **Reliability goals**
  - Use environment
  - Dimensional constraints

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Reliability Goals

- Reliability is the measure of a product's ability to
  - ...perform the specified function
  - ...at the customer (with their use environment)
  - ...over the desired lifetime
- Typical reliability metrics: Desired Lifetime / Product Performance
- Desired lifetime
  - Defined as when the customer will be satisfied
  - Should be actively used in development of part and product qualification
- Product performance
  - Returns during the warranty period
  - Survivability over lifetime at a set confidence level
  - Try to avoid MTBF or MTTF

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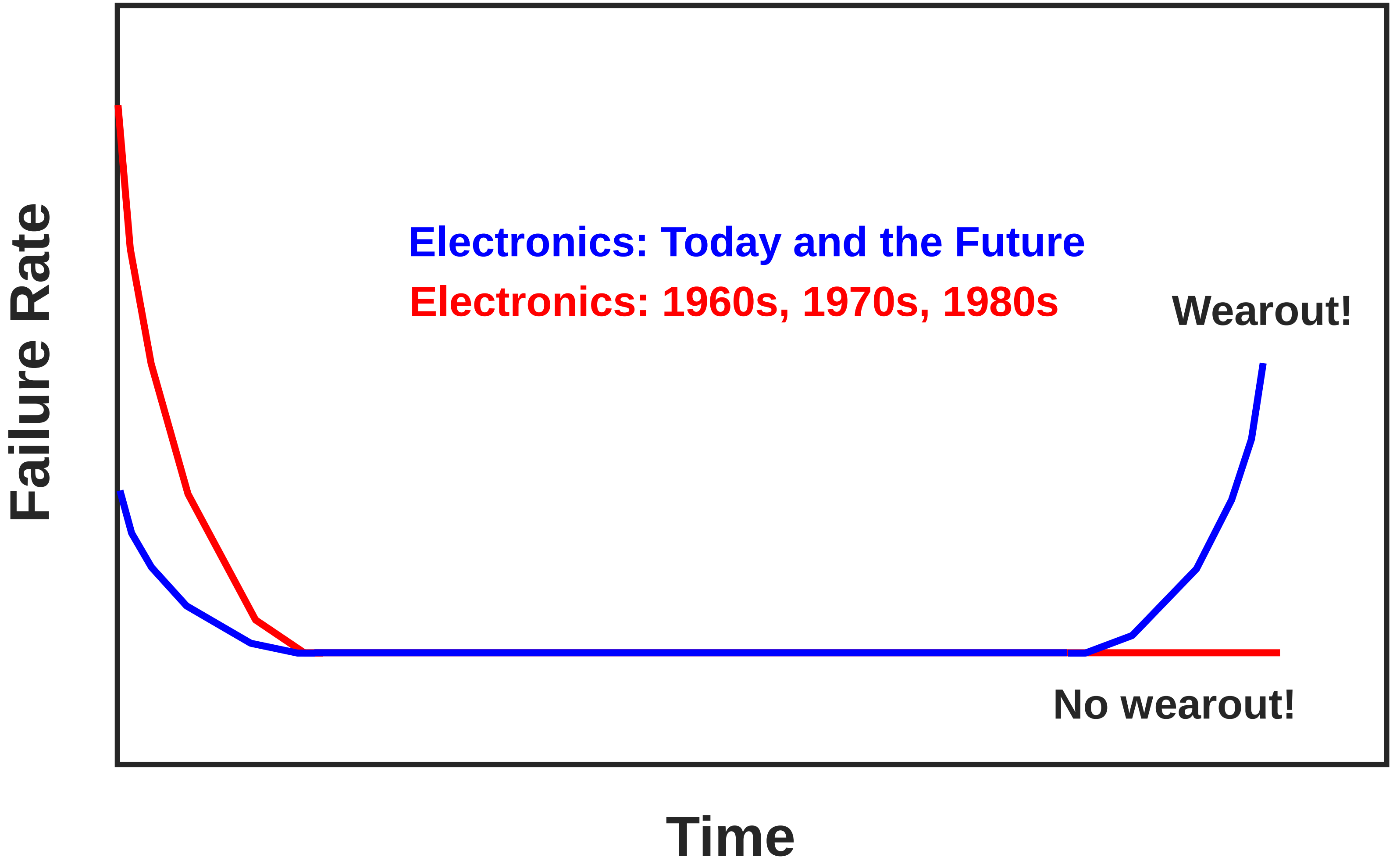
Why is Desired Lifetime Important?



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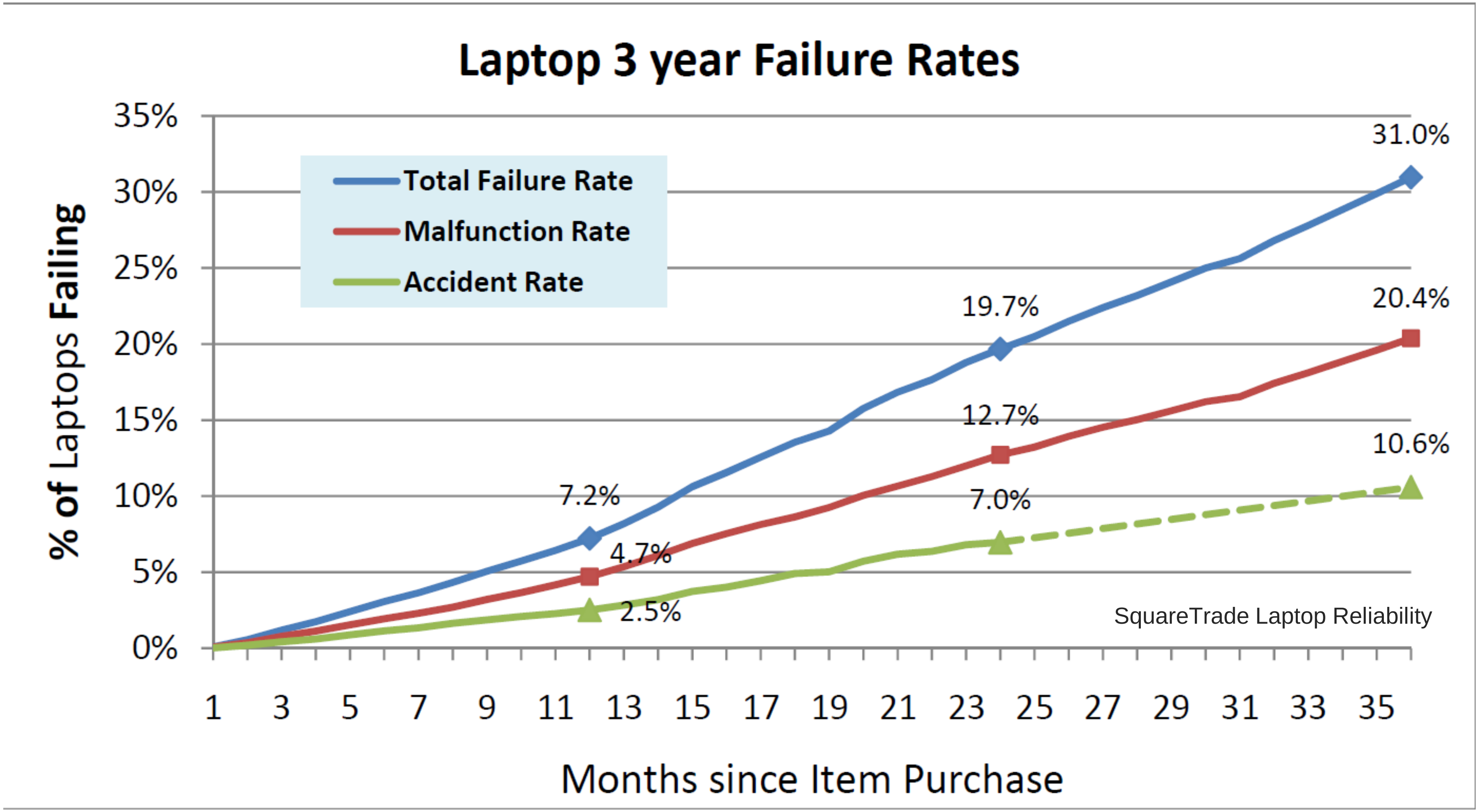
Warranty Returns: Laptops (cont.)



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Warranty Returns: iPad

Figure 2. Non-Accident Failure Reasons - iPad1 and 2

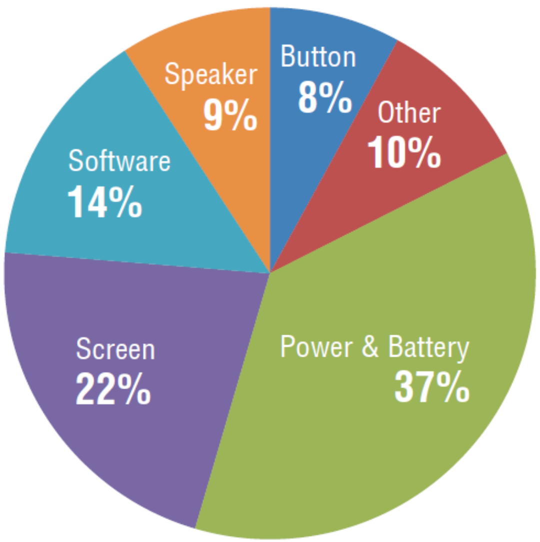
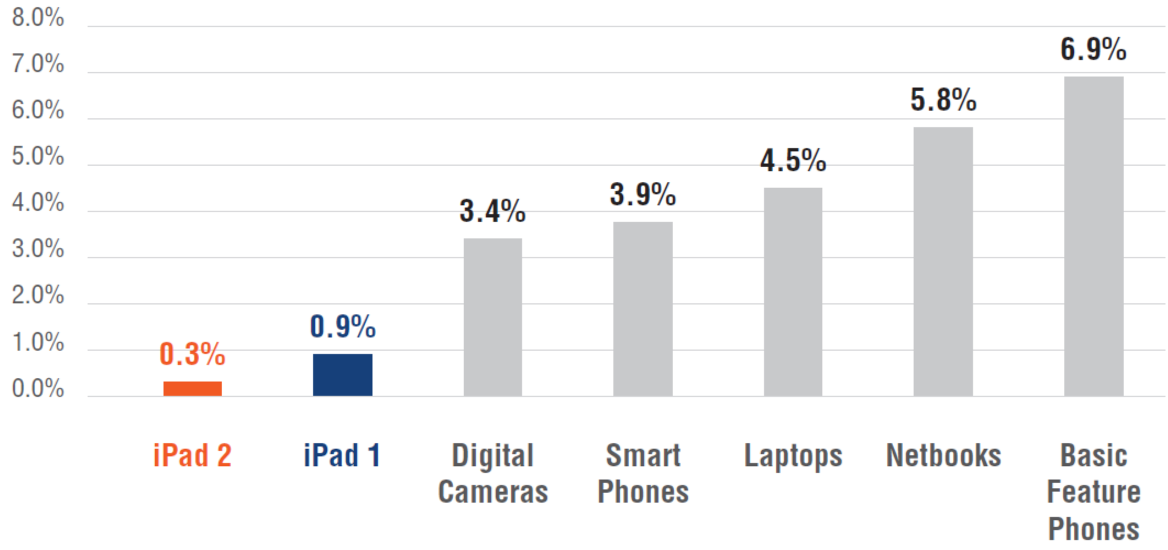


Figure 3. 12 Month Malfunction Rates of Common Portable Electronics



- Truly revolutionary: A consumer electronic as reliable (or more) than typical high-reliability electronics
  - Key Drivers: More robust software, elimination of moving parts (fans, keyboard, hard drive)

Warranty Returns: Automotive Modules

- Many manufacturers of automotive electronic modules track by incidents per thousand vehicles (IPTV)(over some time interval, typically 1 year)
  - Desired IPTV highly dependent on safety and propulsion
- Hyundai Brake http://www.hyundaiproblems.com/investigations/Genesis/2012/
  - 25-30 IPTV (a problem)
  - 0.3 IPTV (no a problem)
- GM Antilock Brake http://money.cnn.com/2005/05/03/Autos/gm_investigation/
  - 0.32 IPTV (a problem)
  - 0.03 IPTV (no problem)
- Saturn Power Steering http://www.carcomplaints.com/Saturn/Ion/2006/investigations/
  - 14 IPTV (a problem)
- Nissan Transmission http://www-odi.nhtsa.dot.gov/cars/problems/defect/results.cfm?action_number=PE13029&SearchType=QuickSearch&summary=true
  - 50 IPTV (a problem)
  - 0.6 IPTV (no problem)
- Axles (4 to 14 IPTV) http://www.mysanantonio.com/business/fool/article/Diversifying-Away-From-General-Motors-4306695.php

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Product Performance: Survivability

- Some companies set reliability goals based on survivability
  - Often bounded by confidence levels
  - Example: 95% reliability with 90% confidence over 15 years
- Advantages
  - Helps set bounds on test time and sample size
  - Does not assume a failure rate behavior (decreasing, increasing, steady-state)
- Disadvantages
  - Can be re-interpreted through mean time to failure (MTTF) or mean time between failures (MTBF)

Limitations of MTTF/MTBF

- MTBF/MTTF calculations tend to assume that failures are random in nature
  - Provides no motivation for failure avoidance
- Easy to manipulate numbers
  - Tweaks are made to reach desired MTBF
  - E.g., quality factors for each component are modified
- Often misinterpreted
  - 50K hour MTBF does not mean no failures in 50K hours
- Better fit towards logistics and procurement, not failure avoidance

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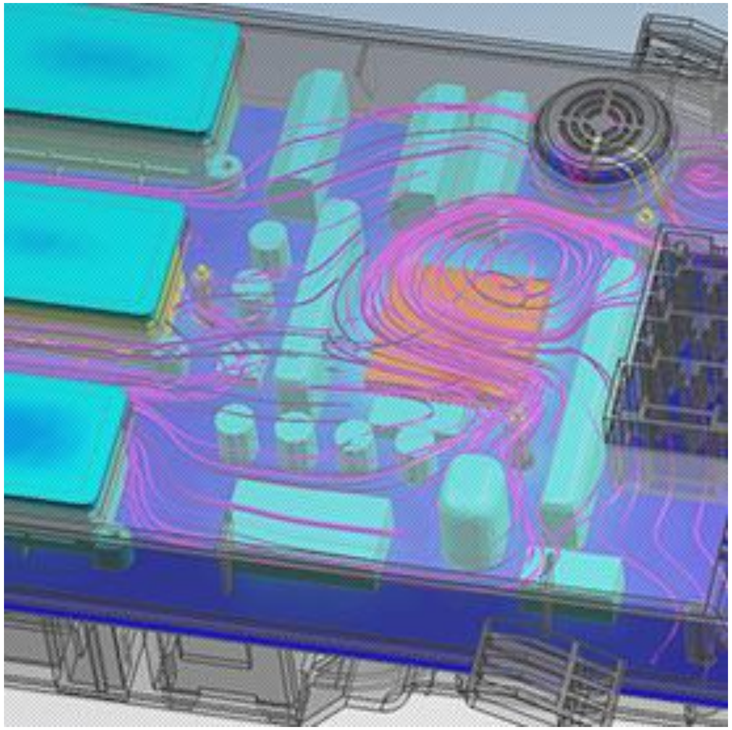
Wearout Mechanisms and Physics of Failure (PoF)

What is Physics of Failure (PoF)?

- Also known as reliability physics
- Common Definition:
  - The process of using modeling and simulation based on the fundamentals of physical science (physics, chemistry, material science, mechanics, etc.) to predict reliability and prevent failures



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Physics of Failure: Modeling and Simulation

- What are we modeling / simulating?

- Packaging + Reliability (t > 0) = Material Movement
  - Diffusion
  - Creep
  - Fatigue

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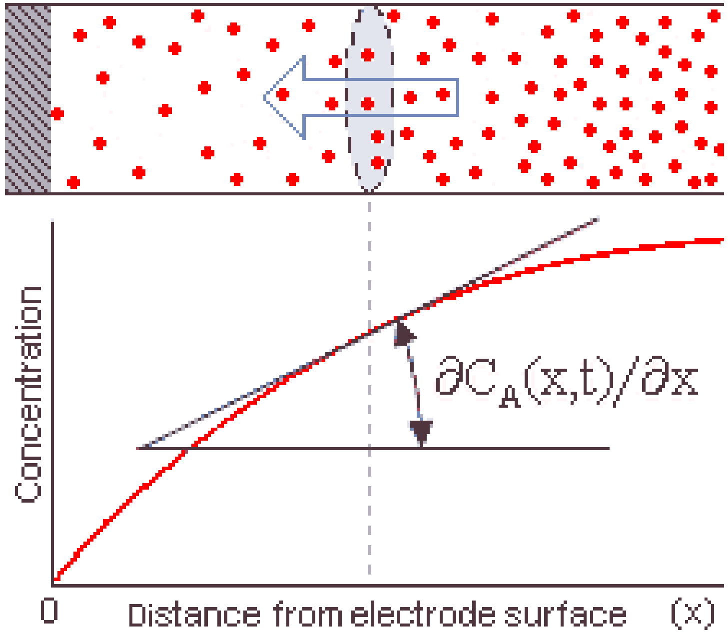
Diffusion

- Motion of electrons, atoms, ions, or vacancies through a material
  - Typically driven by a concentration gradient (Fick's Law)

$$J_A(x,t) = -D_A \frac{\partial C_A(x,t)}{\partial x}$$

$$n(x,t) = n(0)\left[1 - 2\left(\frac{x}{2\sqrt{Dt\pi}}\right)\right]$$



  - Can be driven by other forces (electromotive force, stress)

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PoF-Based Reliability Prediction

- Most physics-of-failure (PoF) based models are semi-empirical
  - The basic concept is still valid
  - Requires calibration
- Calibration testing should be performed over several orders of magnitudes
  - Allows for the derivation of constants
- The purpose of PoF is to limit, but not eliminate, the influence of material and geometric parameters
  - E.g., Solder: Testing must be re-performed for each package family (ball array devices, gullwing, leadless, etc.)

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Physics of Failure (PoF) Algorithms

$$\tau_{HCI} \propto \exp[\frac{b_{HCI}}{V_D}] \cdot \exp[\frac{E_{aHCI}}{kT}]$$

$$L = L_r \left(\frac{V_r}{V_0}\right) \times 2^{\left(\frac{T_r - T_A}{10}\right)}$$

$$T_f \propto \exp\left(\frac{\sim 0.51eV}{kT}\right) \times \exp(\sim -0.063\% RH)$$

$$\tau_{TDDB} \propto \exp[-b_{TDDB} \cdot V_G] \cdot \exp[\frac{E_{aTDDB}}{kT}]$$

$$N_f^{-0.6} D_f^{0.75} + 0.9 \frac{S_u}{E} \left[\frac{\exp(D_f)}{0.36}\right]^{0.1785 \log \frac{10^5}{N_f}} - \Delta\varepsilon = 0$$

$$\frac{t_1}{t_2} = \left(\frac{V_2}{V_1}\right)^n \exp \frac{E_a}{K_B}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

$$\tau_{EM} \propto (J)^{-n} \cdot \exp[\frac{E_{aEM}}{kT}]$$

$$\tau_{NBTI} \propto \exp[-b_{NBTI} \cdot V_G] \cdot \exp[\frac{E_{aNBTI}}{kT}]$$

$$(\alpha_2 - \alpha_1) \cdot \Delta T \cdot L = F \cdot \left(\frac{L}{E_1 A_1} + \frac{L}{E_2 A_2} + \frac{h_s}{A_s G_s} + \frac{h_c}{A_c G_c} + \left(\frac{2 - \nu}{9 \cdot G_b a}\right)\right)$$

Can be mind-numbing! What to do?

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PoF and Wearout

- What is susceptible to long-term degradation in electronic designs?
  - Ceramic Capacitors (oxygen vacancy migration)
  - Memory Devices (limited write cycles, read times)
  - **Electrolytic Capacitors** (electrolyte evaporation, dielectric dissolution)
  - Film Capacitors
  - Resistors (if improperly derated)
  - Silver-Based Platings (if exposed to corrosive environments)
  - Relays and other Electromechanical Components
  - **Light Emitting Diodes (LEDs) and Laser Diodes**
  - Connectors (if improperly specified and designed)
  - Tin Whiskers*
  - **Integrated Circuits (EM, TDDB, HCI, NBTI)**
  - **Interconnects (Creep, Fatigue)**
    - Plated through holes
    - Solder joints

Industry-accepted models exist

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Ceramic Capacitor Lifetime Prediction

- Ceramic caps are typically not expected to experience 'wearout' during normal operation

$$\frac{t_1}{t_2} = \left(\frac{V_2}{V_1}\right)^n \exp\frac{E_a}{K_B}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

- where t is time, V is voltage, T is temperature (K), n is a constant (1.5 to 7; nominally 4 to 5), E_a is an activation energy (1.3 to 1.5) and K_B is Boltzman's constant (8.62 x 10^{-5} eV/K)
- Lifetime may be limited for extended value capacitors
  - Sub-2 micron dielectric thickness
  - Greater than 350 layers (increased failure opportunity)

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Inconsistency in Parameters (Different Failure Mechanisms)

Organization	Voltage Exponent, n	Activation Energy, Ea (eV)	Comments
DfR	2.5	0.9	Based on case studies with clients
Panasonic	3	0.31	Roughly equivalent to 2X / 15C
Murata	3	0.57	Roughly equivalent to 2X / 8C
Venkel	3	0.8	Roughly equivalent to 10X / 20C
Intel	4.6	1.27	Average from seven types of X6S capacitors
Kemet-A	5.9	1.14	Average from three types of X7R capacitors
Kemet-B	3.4	1.43	Average from four types of X5R capacitors

Temperature (K)	383	418	433	433	433
Temperature (C)	110	145	160	160	160
Voltage	18.9	12.6	37.8	37.8	37.8
Capacitor	0603/10uF/6.3V	0603/10uF/6.3V	0603/10uF/6.3V	0805/22uF/6.3V	1206/47uF/6.3V
HALT Life (minutes)	192	15	0.75	23	4
Model	Time to Failure at 38C and 3.3V (years)				
DfR	16	4	8	250	43
Panasonic	2	0	1	18	3
Murata	35	17	84	2,561	445
Venkel	273	355	2,698	82,739	14,389
Intel	8,279	2,512	66,723	2,046,184	355,858
Kemet-A	32,155	4,142	404,915	12,417,401	2,159,548
Kemet-B	3,132	2,321	19,234	589,845	102,582
0603 / DfR	6,482	1,997	47,067	1,443,400	251,026

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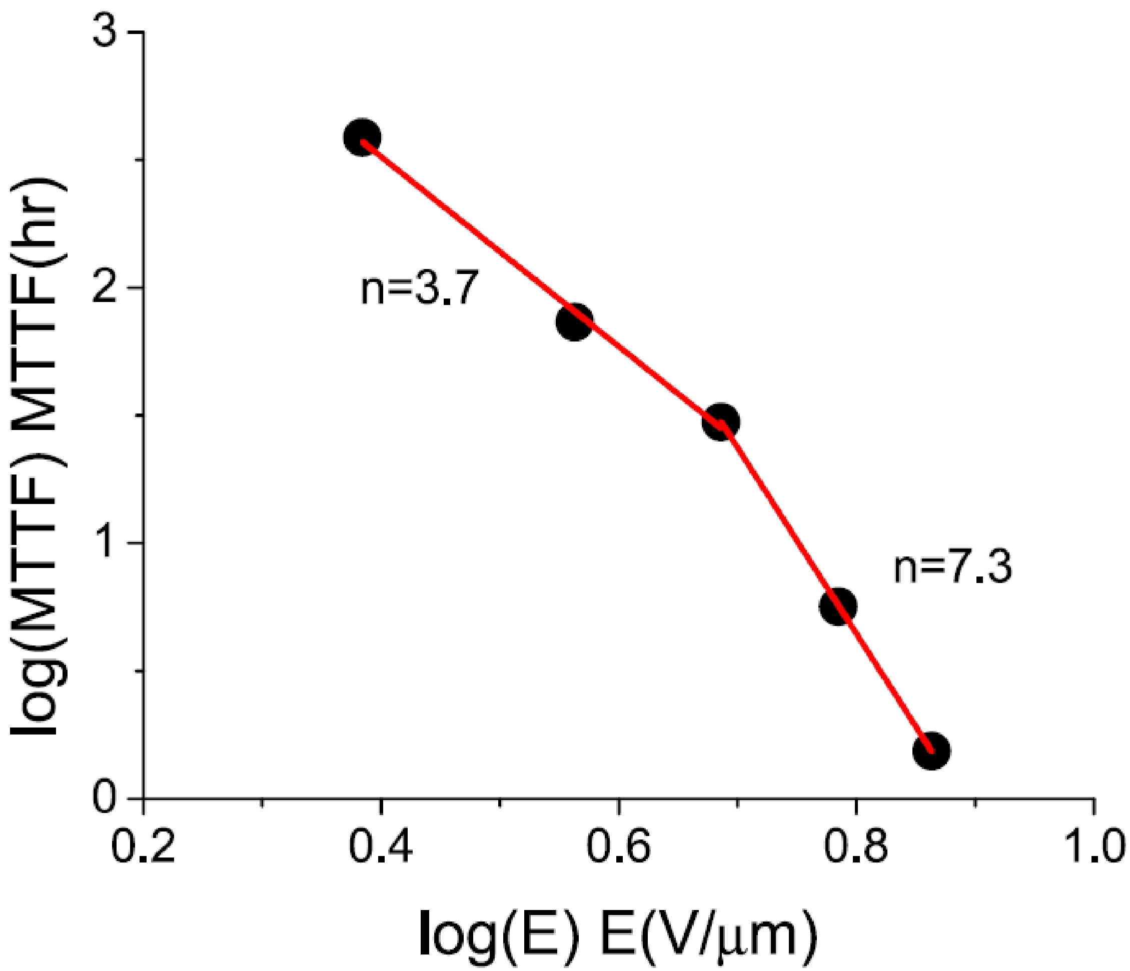
Inconsistency in Parameters (cont.)



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True Physics of Failure!

$$t = \rho_{crit}/a\upsilon Nq \cdot \left(\exp\frac{-E_A}{k_B T}\sinh\frac{qaE_{App}}{2k_B T}\right)^{-1}$$

- $\rho_{critical}$ is a critical ionic charge level, a is the characteristic hoping distance, υ is the jump frequency of the oxygen vacancy, N is concentration of oxygen vacancies, q is ionic charge of the point defect, EA is activation energy, kB is Boltzmann's constant, T is temperature, Eapp is applied electric field

Randall, et. al., J. App. Phy (2013)

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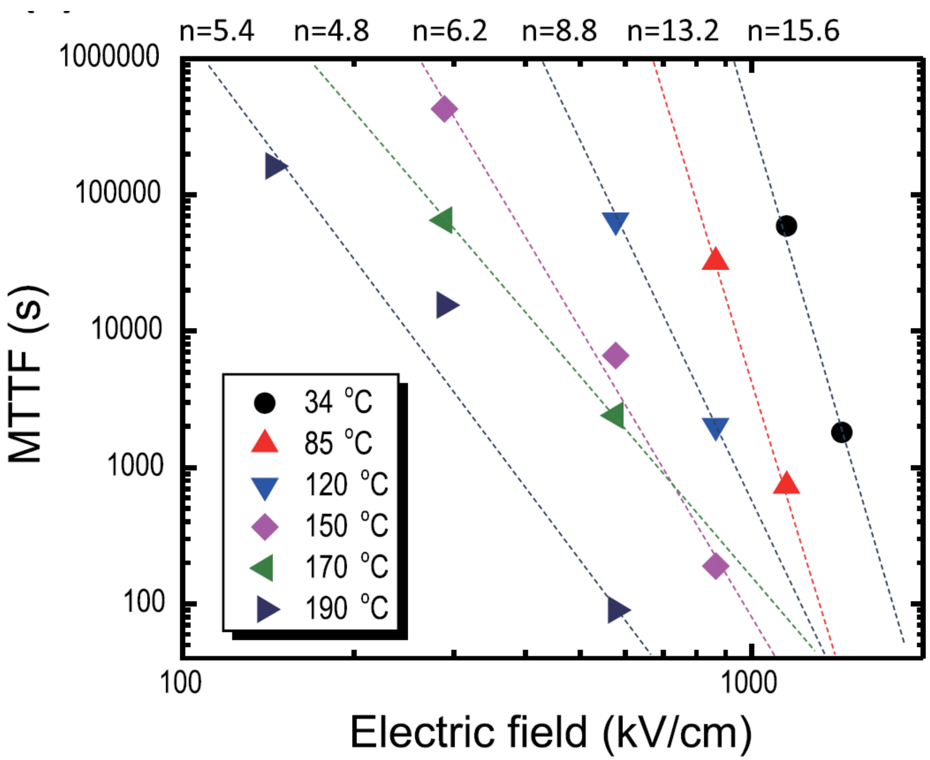
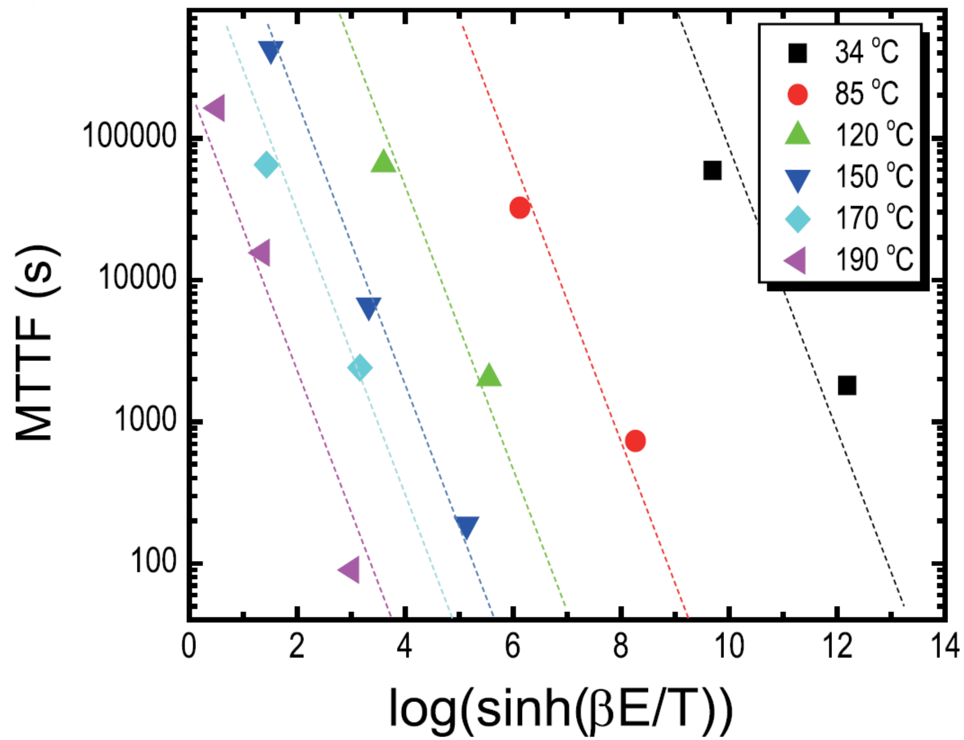
Physics of Failure, Simplified





$$\log(t_1) = C(T) - \log[\sinh(\beta E_1/T)]$$

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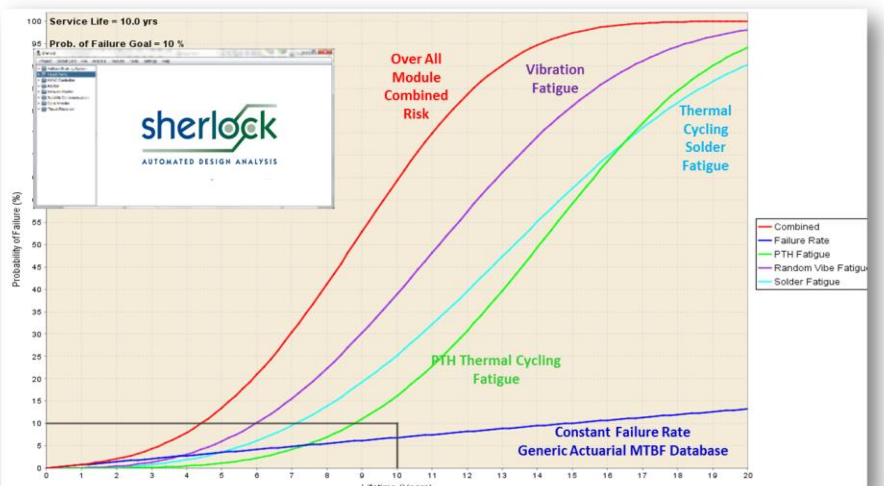
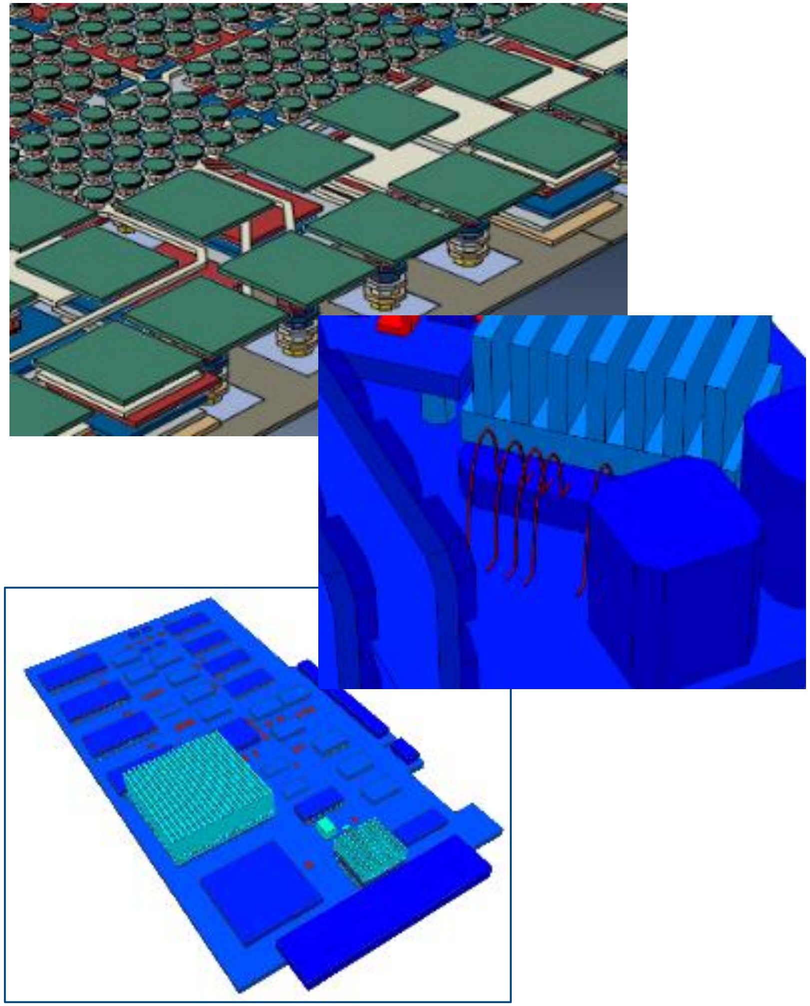
Physics of Failure – Sherlock

- Need for standardized physics of failure tool + easy access to necessary data (translation)
- Increasing requirement across supply chains
  - Boeing, GM, Embraer, Volkswagen, BAE Systems, etc.





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DfR Case Study (Workstations)

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Use Case (Environment)

Notebook Workstation				
CPU	Idle	22.1	20.9	37.1
	Average	28.4	41.2	48.4
	Maximum	52.6	63.9	69.4
Northbridge	Idle	21.6	21.0	36.8
	Average	41.8	31.8	44.6
	Maximum	46.7	61.6	55.3
Memory	Idle	21.6	20.9	38.1
	Average	37.0	35.0	46.8
	Maximum	51.0	43.9	55.6
Outlet Air	Idle	18.9	17.5	35.8
	Average	20.1	22.2	43.4
	Maximum	24.3	40.8	54.1

- Thermal measurements under range of use cases
- Inputted into multiple stages of the DfR process (component reliability, thermal cycling, connector reliability, etc.)

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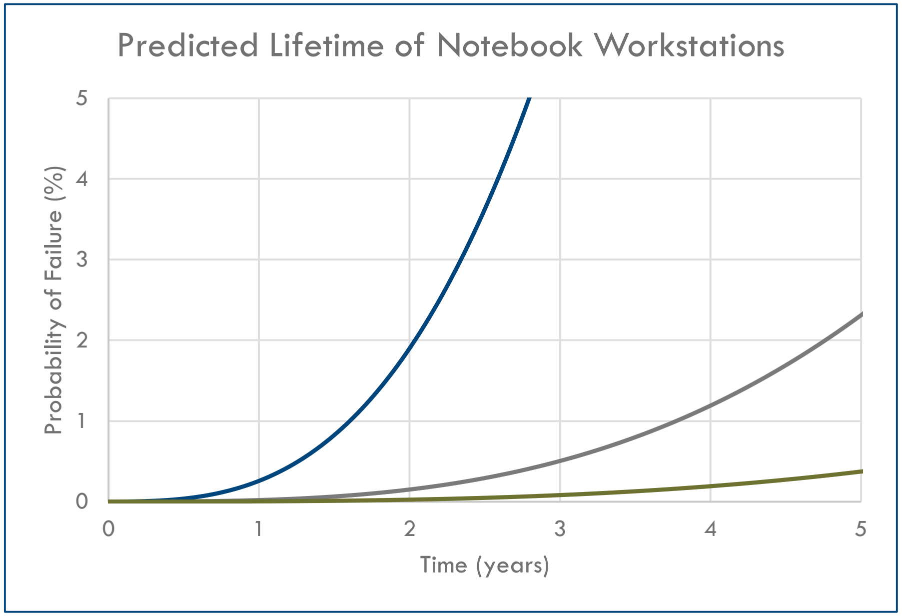
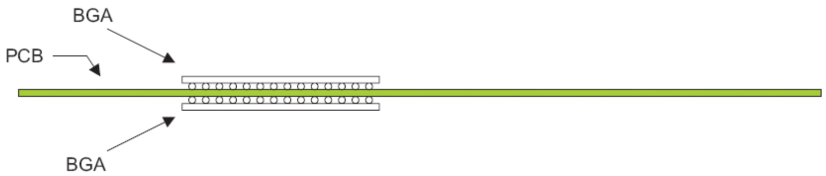
DfR: Temp Cycling



- Used large, fine-pitch, stacked-die graphics DRAM and then placed them in a mirror configuration



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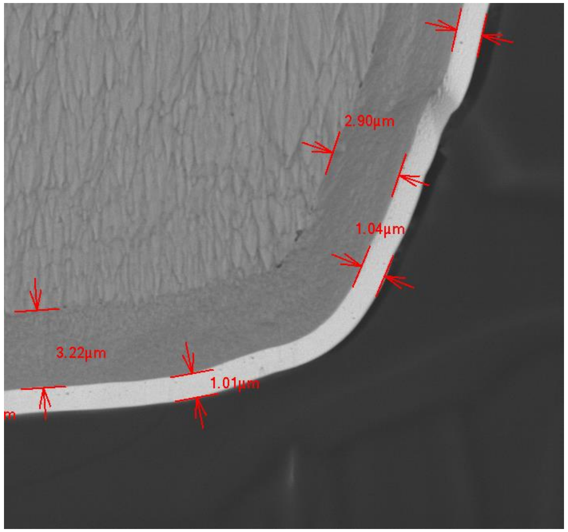
DfR: Connectors

- 'Consumer-grade' connectors can use industrial/military levels of plating (with frequent use of spot plating)
- Use of PoF to calculate lifetime based on nickel layer thickness



	Plating - Gold	Underplate - Nickel
DIMM socket	30	100
SATA jack/cable	20	90
DIMM socket	30	90
SATA jack/cable	30	90
DIMM socket	20	90
DIMM socket	40	120
SATA jack/cable	25	180
DIMM socket	10	100
SATA jack/cable	25	80
DIMM socket	45	85
DIMM socket	20	110
SATA jack/cable	30	400
DIMM socket	10	100
SATA jack/cable	20	70
DIMM socket	5	170

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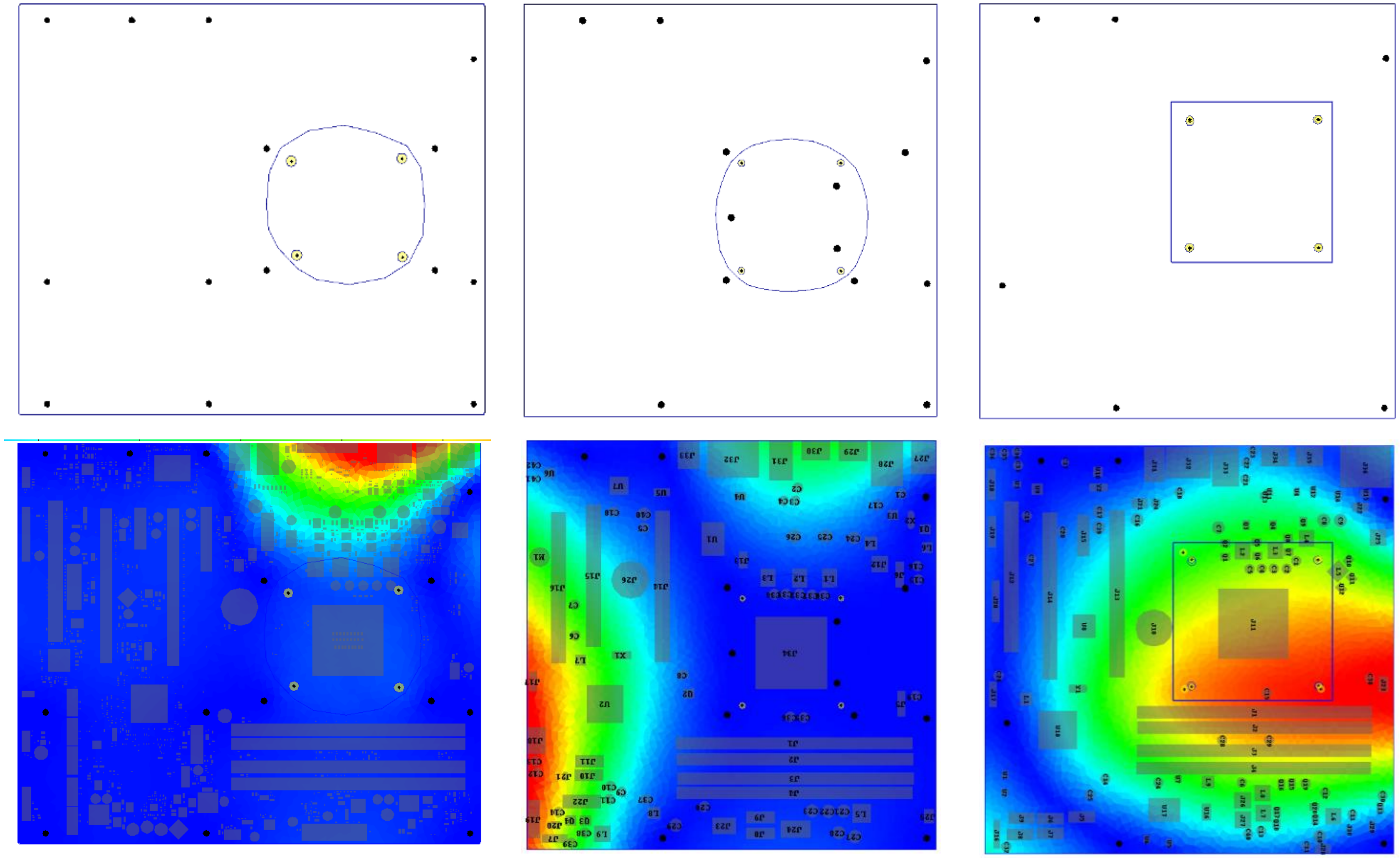
DfR: Shock and Vibration



- Mounting strategies can influence natural frequency and magnitude / location of displacement

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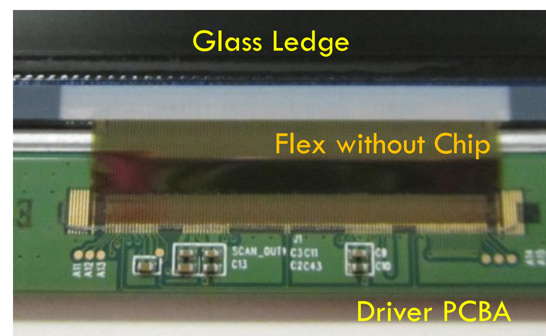
Overall Design Practices

- Use of slots to prevent overconstraint or buckling and Torx screws to avoid cam-out

- Rounded corners (to prevent cracking) and channeling to direct fluids (indirect splash)

- Strain relief loops and off-glass drivers in LCD connections



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Summary

- To avoid design mistakes, be aware that functionality is only the beginning
- Be aware of industry best practices
  - When to use heuristic rules; when to use physics of failure
- Maximize knowledge of your design as early in the product development process as possible
- Do not overly rely on supplier statements
  - Their view: Reliability is application dependent

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