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reliability designed, reliability delivered

The Synergy between Reliability & Safety in Automotive Electronics

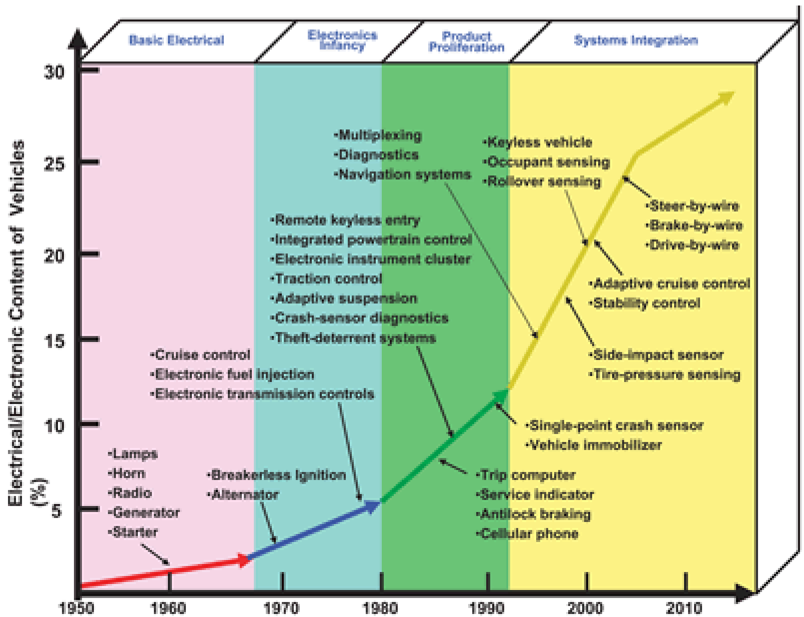
Reliability and Safety Workshop (Greenwich, UK)

April 14, 2011

Automotive Electronics

- One of the most challenging applications for automotive electronics
  - Severe use environments
  - Direct engagement with the public
  - Ten-plus (10+) year warranty
  - State-of-the-art technology
  - Low-cost / High-volume
  - System-integration of ECU's from multiple vendors
  - **Safety critical**

http://america2.renesas.com/applications/wired_connectivity/can_interface.html



http://chipdesignmag.com/display.php?articleId=57&issueId=8

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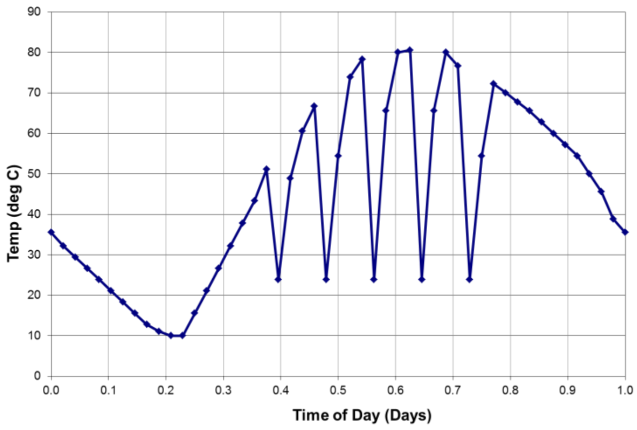
Severe Use Environments

- Passenger compartment temperatures can exceed 80C
  - Dashboard temperatures have been measured in excess of 100C in extreme circumstances
  - Engine-mounted can exceed 150C
- Heavy-users (salesman) can induce over 1,000 temp cycles per year



- Door-mounted electronics experience 40G shock over 100,000 times

Public Use

- Experience of DfR clients is transition from business-to-business (B2B) to business-to-consumer (B2C) can increase failure rates by **2X** to **10X**

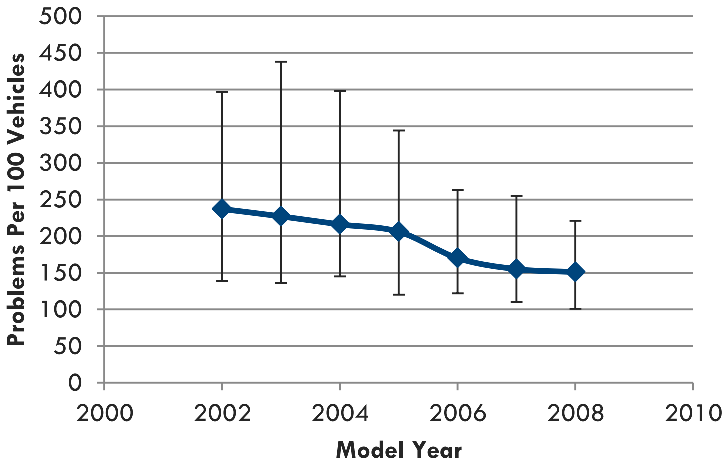
- Case study:
  Unintended Acceleration
  - Root-cause of failure seems to be public hysteria

"Miss Johnson, would you mind ordering me another computer? And you can cancel that call to tech-support."

Is Automotive Succeeding? Yes

- Automotive Electronics Council (AEC) quality and reliability requirements accepted by component industry
  - Improved design margins
  - Push towards zero-defects (ppb levels)

- Consistent drop in problems per 100 vehicles over the past 7 years (JD Power)
  - Even as electronic content soared



http://blogs.wsj.com/drivers-seat/2011/03/17/technology-can-hurt-a-cars-reliability/
http://www.jdpower.com/news/pressrelease.aspx?ID=2011029

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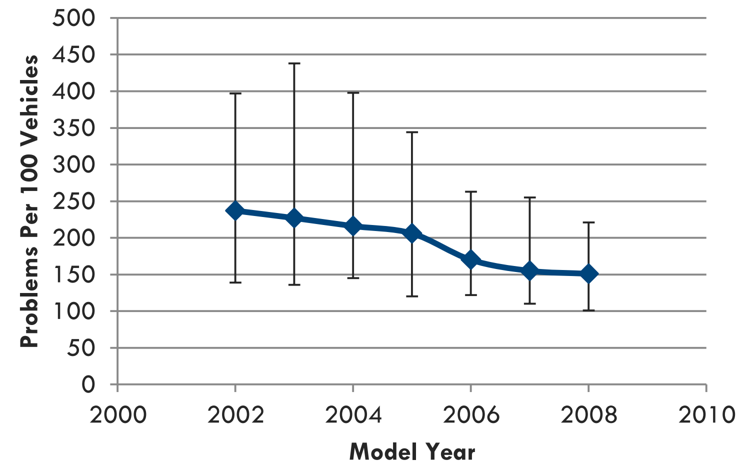
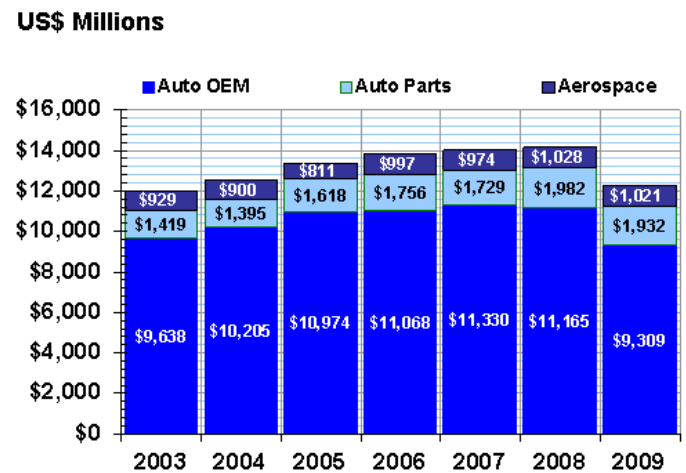
Is Automotive Succeeding? No

- Significant source of improvement is with worst performers and mechanical systems
  - JD Power indicated "increased rates of problems with electronic features"



- Other sources (Consumer Reports, Warranty Week, Hansen Report) do not report similar improvement



Warranty claims paid by US Manufacturers

Source: Warranty Week from SEC data

Opportunities for Improvement

- Management structure
  - Reliability – Quality – Safety Relationship

- Technical Approaches
  - Identifying and implementing best practices in reliability and safety
  - Data-centric engagement with suppliers

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Reliability and Quality

- 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

- "Over the desired lifetime" is a key differentiator between reliability and quality
  - Quality can be time-independent or time-limited; degree of compliance to certain specifications or other criteria

    Higher Quality can lead to improvements in Reliability, but not necessarily

    Quality is only one aspect (early life) of the overall Reliability performance of a product

Reliability and Safety

- Safety is the risk that
  - …adverse effects such as bodily harm will initiate during operation
  - As nominal operation is not expected to induce "adverse effects", this is often related to failures

- Safety is therefore often viewed as reliability + failure mode
  - The probability that failure will occur in a certain way

Reliability and Safety (cont.)

- IEC-61508: Functional safety of electrical/electronic/programmable electronic safety-related systems
  - Development of Safety Integrity Levels (SIL)

Safety Integrity Level (SIL)	Probability of Failure on Demand (PFD)
1	10^{-1} - 10^{-2}
2	10^{-2} - 10^{-3}
3	10^{-3} - 10^{-4}
4	10^{-4} - 10^{-5}

- Drives ISO 26262: Road vehicles -- Functional safety

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Management (Reliability/Quality/Safety)

- The classic structure within automotive
  - Reliability → Quality → Safety
  - Driven primarily by cost concerns (safety is perceived as the biggest cost risk, followed by quality, then reliability)

- Given the safety's dependence on reliability and reliability's broader scope than quality, a restructuring may provide

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Best Practices in Reliability / Safety

- Focus on 'Best Practices'
  - Corresponding case studies
  - Provides a "buffet" of choices
  - Select those most appropriate for your product and your company

- Similarities among Best Practices
  - Pushes activities earlier in the product life cycle and farther down the supply chain
  - Obtains fundamental information: the when, how, and why (Data-Centric)
  - Implements feedback loop (i.e., continuous improvement)

- Ultimate practitioner of Best Practices? Toyota

Toyota Approach

- Toyota's development engineers have been 4X as productive as U.S. counterparts.
- Why?
  - Focus on learning as much as possible
  - Use of that knowledge to develop a stream of excellent products

- **Western engineers**
  - Define several product concepts
  - Select the one that has the most promise
  - Draw up specifications and divide them into subsystems;
  - Subsystems are designed, built and rolled up for system testing.
  - Failures? Rework the specs and the designs accordingly (non-optimized and confusing endeavor)

- **Toyota engineers**
  - Efforts concentrated at lowest possible design level
  - Thorough understanding of the technology of a subsystem so it can be used appropriately in future designs

Toyota Example: Radiators

- Traditional approach: Design radiator for a specific vehicle based on mechanical specifications written for that vehicle

- Toyota considers a range of radiator solutions based on cooling capacities and the cooling demands of various engines that might be used.
  - How the radiator actually fits into a vehicle would be kept loose so that Toyota's knowledge of radiator technology could be used to create the optimum design

- Another way to think of Toyota's system is "test & design" rather than the traditional "design & test."
  - Toyota engineers test at the fundamental knowledge level so they don't have to test at the later, more expensive stages of design and prototyping

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Supplier Selection / Qualification

- One of the more significant unquantified risks for reliability and safety in regards to suppliers is new technology
  - Typically materials
  - Examples: Polymeric capacitors, Pb-free solder, phenolic-cured circuit boards, copper wirebonds

- Several approaches are available to the automotive industry in qualifying new suppliers and new technology

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Supplier Engagement (cont.)

- Approach 1: Do nothing
  - Subject new technology to the same industry standard or supplier required product qualification procedures
  - This is the approach of Automotive Electronics Council

- Approach 2: Modify existing qualification procedures
  - Extend qualification times, require additional samples
  - Require additional qualification procedures based on existing military/industry standards (scattershot approach)

Supplier Selection (cont.)

- Approach 3: Understand how the technology can fail
  - Physics of failure (PoF)
  - Thermal, mechanical, electrical, chemical, radiation

- New technologies can
  - Experience different failure mechanisms
  - Degrade at different rates (changes in test-to-field correlation)
  - Have different weaknesses

- Must be willing to adjust qualification procedures in response

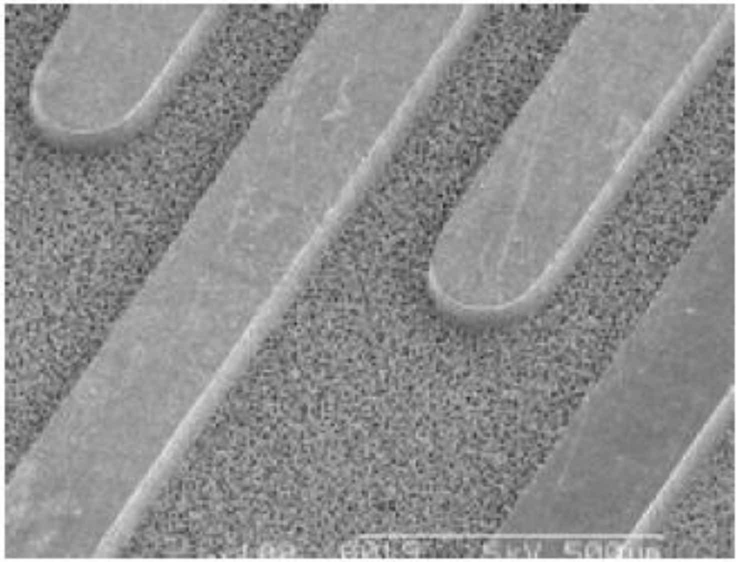
Supplier Selection (cont.)

- Approach 4: PoF with an emphasis on outliers
  - Requires understanding of material and stress distributions throughout the supply chain

- Approach 5: Require supplier to demonstrate ability to meet reliability goals
  - Like 3 and 4, rejects test-to-spec approach
  - Shifts burden and costs to supplier

Case Study 1: Solderability Plating on PCBs

- Immersion Silver (ImAg)
  - Aggressively marketed by plating suppliers
  - Claims of long shelf life (>4 years) based on existing test specifications
    - High temperature bake
    - Steam aging



- Problem:
  - No silver-copper intermetallics
  - Silver oxide is self-limiting (nanometer thickness)

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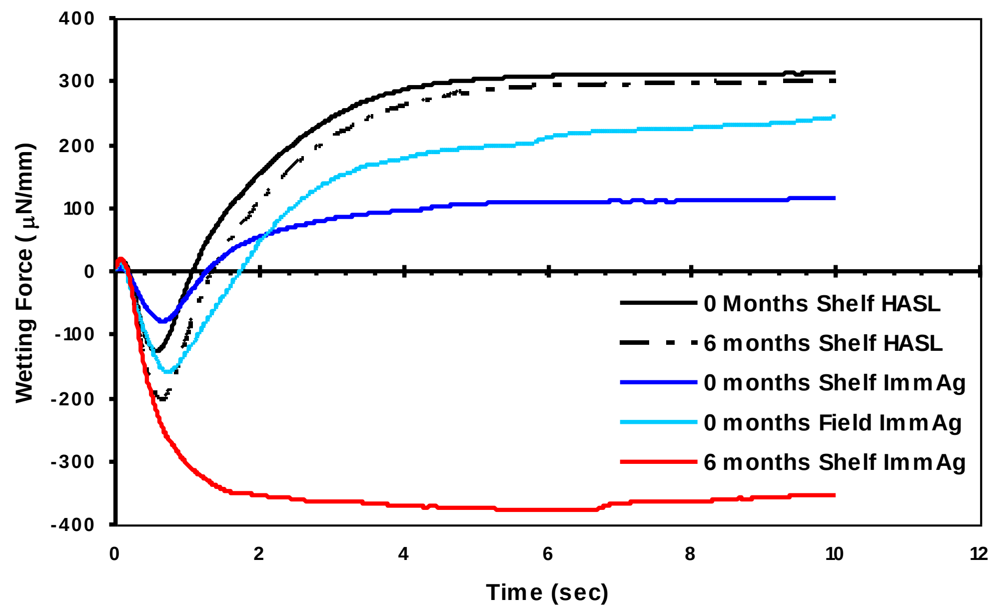
New Failure Mechanism

- Solderability is an issue
- Significant degradation when exposed to corrosive gases
  - Atypical shelf life test



- Loss of solderability after 1 day under mixed flowing gas (MFG) exposure, class II conditions
  - Equivalent to 6 months in light industrial environment

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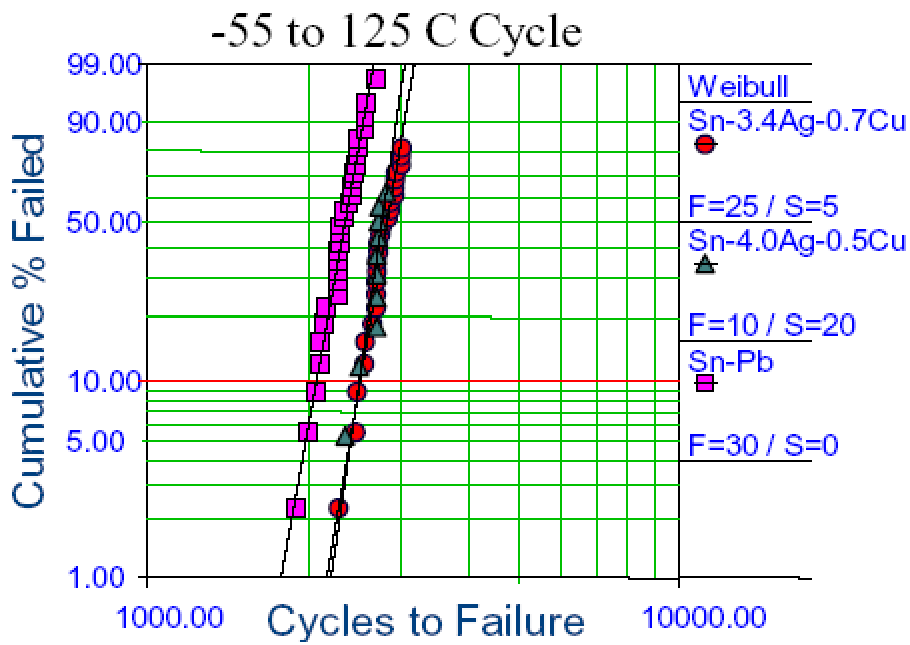
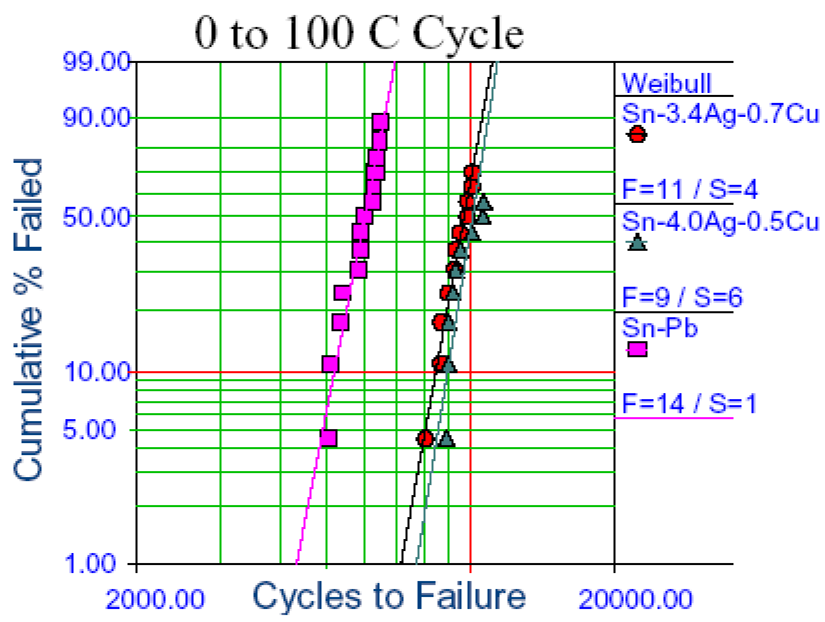
Case Study 2: Pb-Free Solder and Temp Cycling

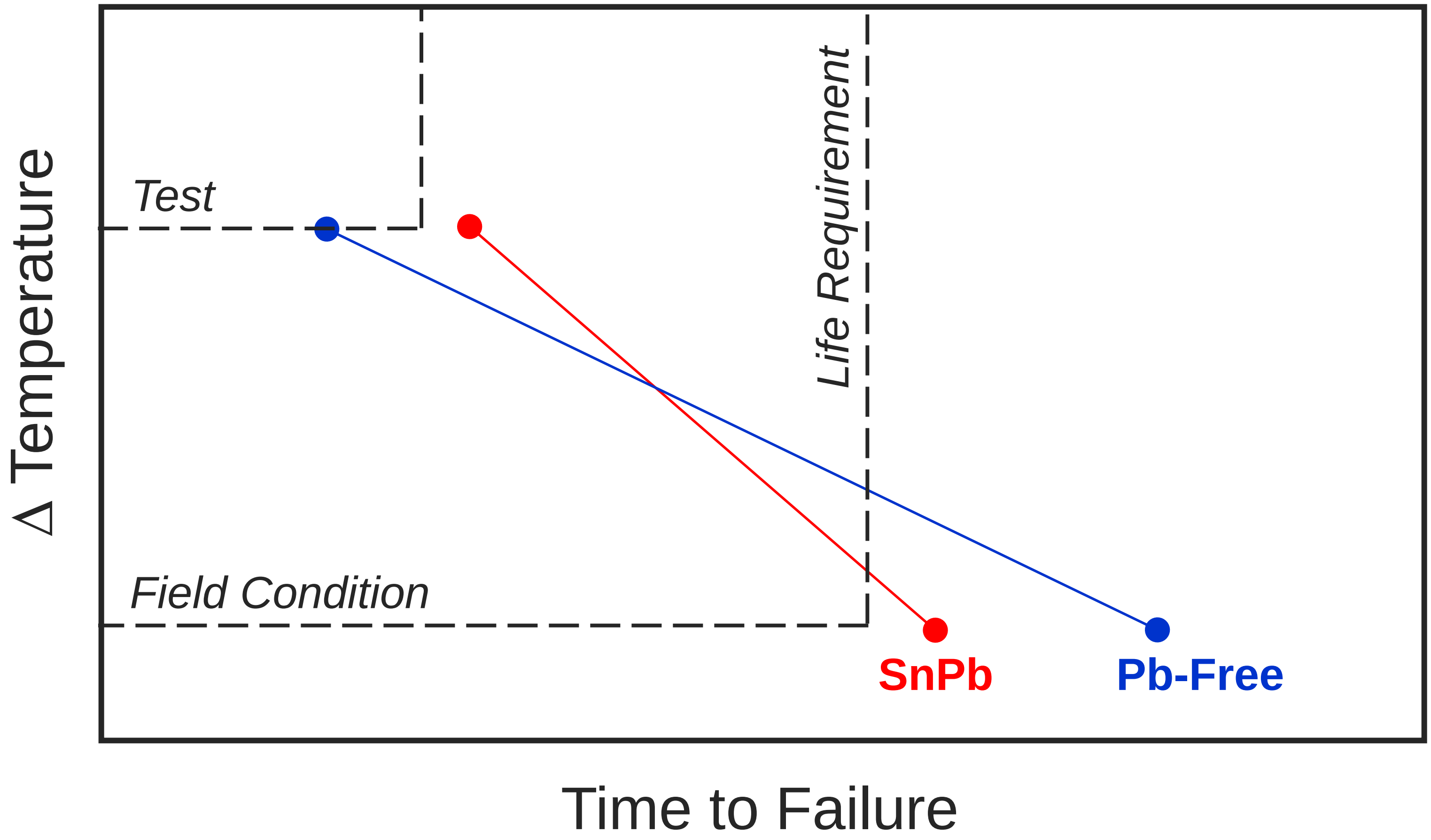




- Pb-free displays a higher acceleration factor
  - Failures under ALT equivalent to longer field life

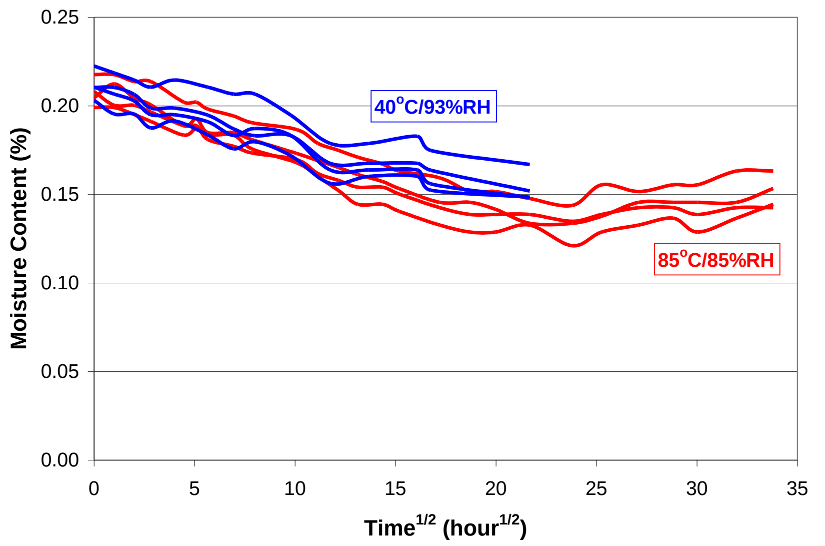
Ahmer Syed, Amkor

Shift in Test-to-Field Correlation

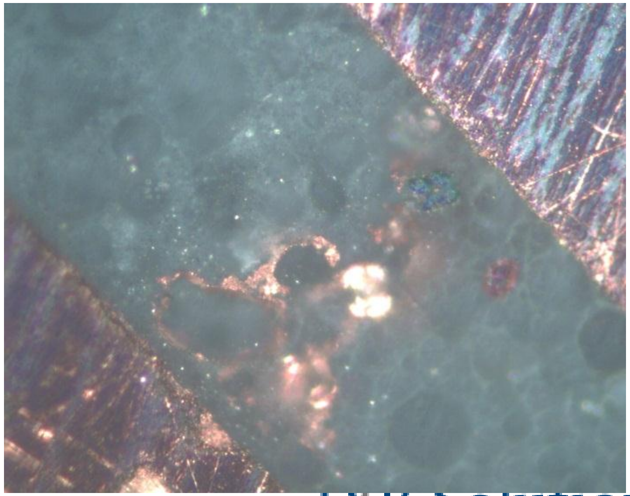


Case Study 3: Red Phosphorus

- Red phosphorus flame retardant
  - Reaction with moisture to form phosphorus-based acids
  - Minimum moisture content required (~80 to 85%RH)



- Additional chemicals and stress weaken silica-epoxy bond



- Failure behavior
  - Initially intermittent
  - Permanent over time

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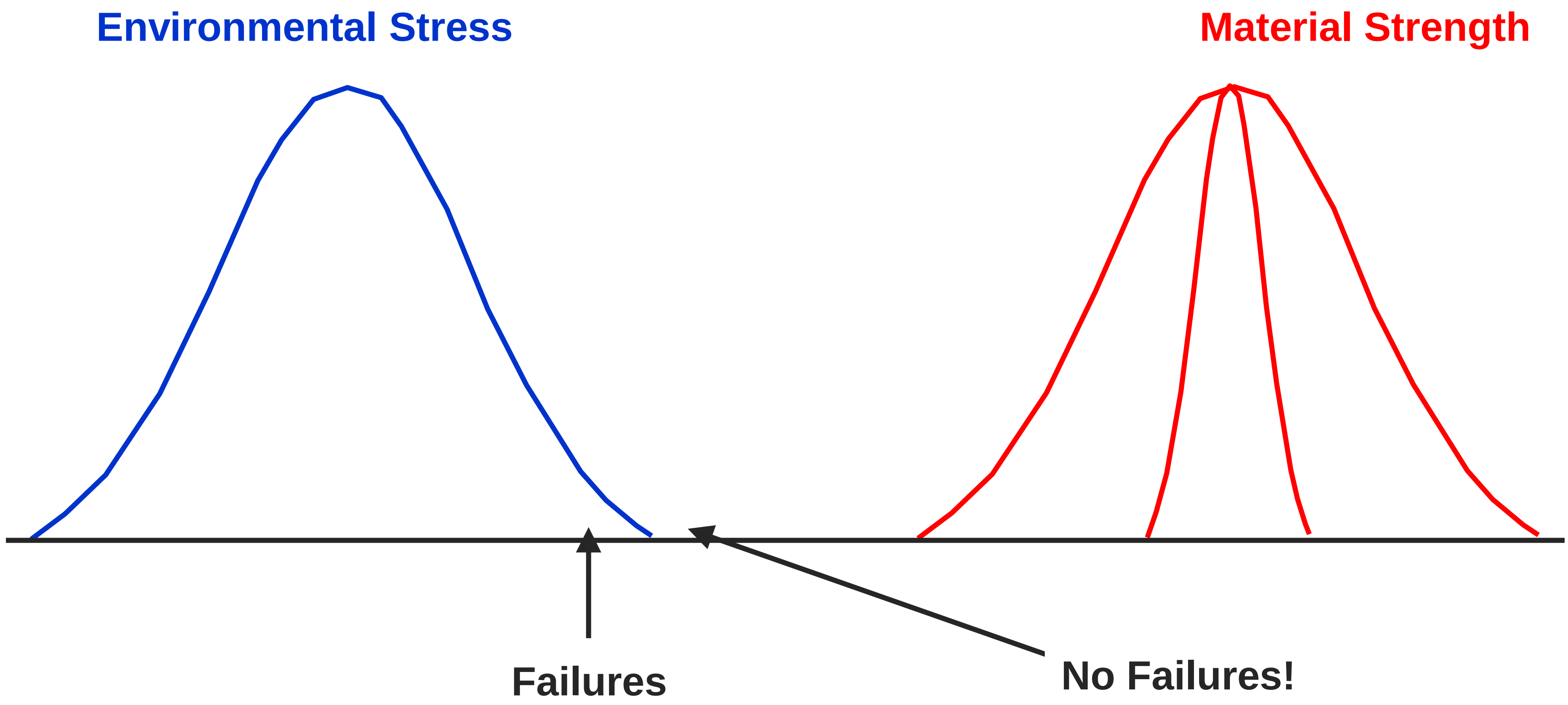
Outliers and Technology Qualification



Data-Centric Approach: Derating

- To be effective, derating must have a practical and scientific foundation
  - Problem: Manufacturer's ratings are not always based on a practical and scientific foundation
- Manufacturers' viewpoint
  - Ratings are based on specific design rules based on materials, process, and reliability testing
- The reality
  - Ratings can be driven by tradition and market forces as much as science

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Manufacturer's Derating (example)

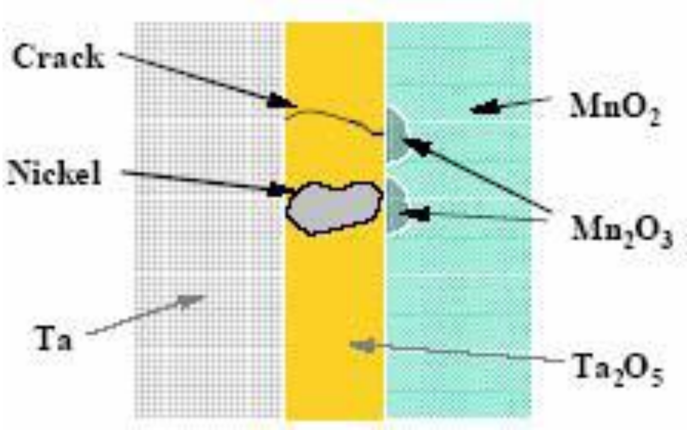
- Tantalum capacitor
  - MnO_2 cathode
- Derating based on desired failure rate
  - 10 ppm at startup
- Why not 10 ppm failure rate at rated voltage?
- Was 0.3% failure rate acceptable?
  - 50% derating is a legacy

	MnO_2 (27Batches)
100 PPM FR % V_{Rated}	68%
@50% V_{Rated} FR(PPM)	9
@80% V_{Rated} FR(PPM)	458
@90% V_{Rated} FR(PPM)	1,700
@100% V_{Rated} FR(PPM)	2,943

Courtesy of Kemet

Scientific Approach to Derating (Ta Caps)

High Impedance Circuits



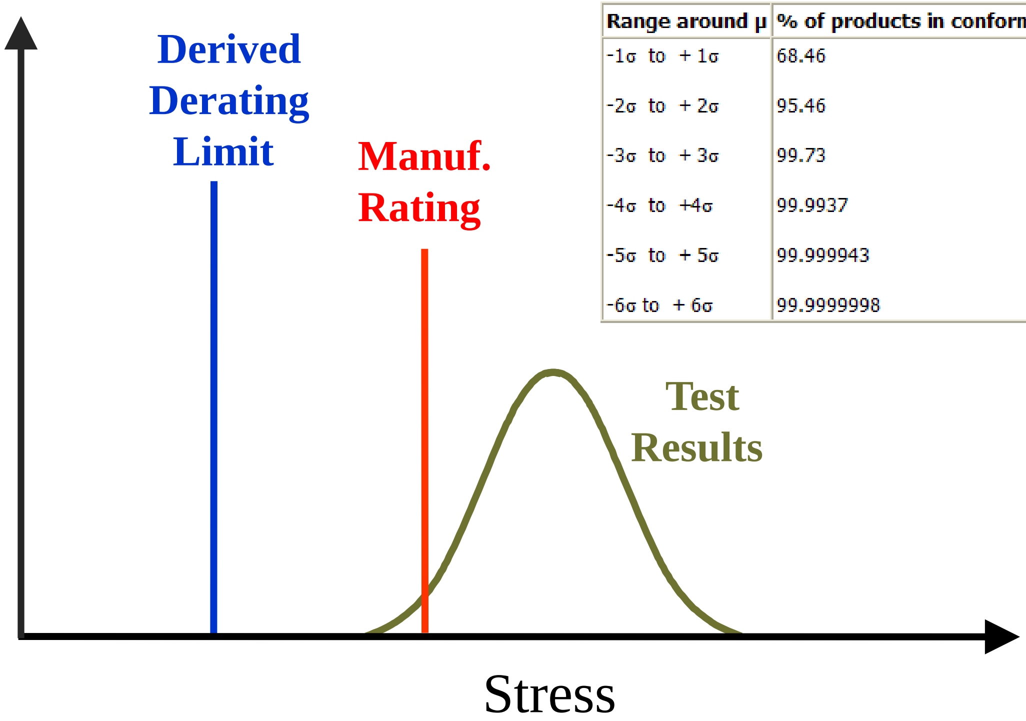
- Self healing in Ta capacitors involves leakage paths in the MnO2 being healed by the transformation to the higher resistance compound Mn2O3
- Process requires enough current to allow internal temperatures to reach 500°C
- Small amounts of current (< 50 uA) will prevent self healing
  - Leads to degradation and potential component failure
- Avoid use in circuits with impedances greater than 100 kΩ

Derating Best Practices

- Derating guidelines should be based on component performance, not ratings
  - Test to failure approach (i.e., HALT of components)
  - Quantifies life cycle cost tradeoffs
  - For smaller OEMs, limit this practice to critical components

- Opportunity for refinement based on field return data

Derating based on Test to Failure



Range around μ	% of products in conformance	% of non conforming products	Non conformance out of a million
-1σ to +1σ	68.46	31.54	315400
-2σ to +2σ	95.46	4.54	45400
-3σ to +3σ	99.73	.27	2700
-4σ to +4σ	99.9937	.0063	63
-5σ to +5σ	99.999943	.000057	.57
-6σ to +6σ	99.9999998	.00000002	.002

- OEM was concerned with voltage rating of tantalum capacitors after 2 reflows and use on low resistance line
- Performed step stress surge test (SSST)
- Derived voltage derating based on a sub-ppm failure rate

Best Practices in Reliability / Safety

- One of the major limitations of IEC-61508?
  - Allows for the SIL to be derived based on empirical prediction methodology

- Some real issues with this approach, especially for automotive
  - Rejected for reliability prediction purposes by the Big Three North American Car Manufacturers, but finding a back door through 'functional safety' (ISO 26262)

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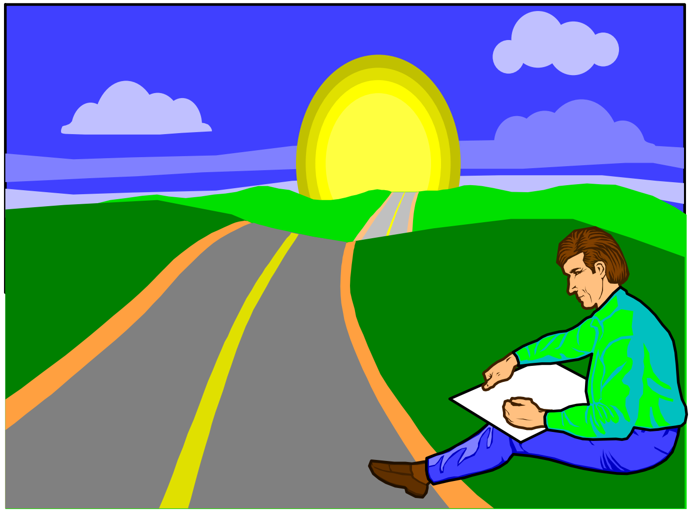
Empirical Prediction Method

- Empirical: Derived from experiment or observation
  - NOT based on theory or an understanding of the mechanism



- An Empirical Statistician, who has never seen the sun rise has no idea if or when it will rise again.
- It is observed that the sun returns in one 24 hr. period,
- A single observation correlates to a .44 probability with an 80% confidence that the sun will rise again in 24 hours.
- After 10 sun rise observations the 80C probability is .93.
- After 20 observations the 80C probability rises to .96.
- Except it is not exactly 24 hours.

Empirical Prediction Methodologies

- Primarily based on Handbooks that provide failure rates (λ) for electrical and mechanical components
  - Failure rates are summed and then inverted to calculate a mean time between failures (MTBF)

- Mother of all handbooks: MIL-HDBK-217
  - First released in Dec. 1965 by US Navy; obsoleted by U.S. DoD in 1996
  - Progeny: Telcordia TR332, PRISM, 217Plus, RDF 2000, IEC TR 62380, NSWC Mechanical, Chinese 299B, HRD5, and internally generated numbers

Empirical Prediction (cont.)

- Failure rates based on statistical projections of the "best available" Historical Field Failure Rate Data for each component type with many "simplifying" assumptions
  - Can be modified based on temperature, degree of electrical derating, and 'quality factor'
- Defined as mean time to failure (MTTF) or mean time between failures (MTBF)
  - MTTF applies to non-repairable items
  - MTBF applies to repairable items
- Based on exponential distribution

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MTBF and Part Count

- MTBF is typically calculated through a part count method
  - Every part in the design is assigned a failure rate
  - Failure rate may change with temperature or electrical stress, **but not with time**
  - Failure rates are summed and then inverted to provide MTBF
    - Most calculations assume single point of failure
    - Some calculations take into consideration parallel paths

- Variety of handbooks provide failure rate numbers

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Limitations of Empirical Prediction

- The foundation of empirical prediction, MIL-HDBK-217, was never intended to provide an absolute reliability number
  - Purpose was to provide a common basis for comparing and evaluating competing designs in regards to reliability (more difficult to capture than cost and performance)

- Unfortunately, MIL-HDBK-217 eventually proved to be inaccurate and potentially misleading

Limitations (cont.)

- Past Performance, was Not a Guarantee of Future Results.
  - Especially as the Data Base Ages and Technology Advancements Change Assumptions.
  - Diffusion Failure Mechanism Designed Out.
  - Not Updated to Account for Other Failure Mechanisms.
- Technology Dynamics - Many Types of New EE Parts Invented Used and Become Obsolete Faster that Field Data could be Collected, Analyzed and Logged.
- Average Constant Failure Rate Data Not Correlated to Failure Specifics.
- Did Not Address Infant Mortality Quality or Wear Out Issues.
- Unable to address non-part related failures (interconnects, software, etc.)

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Limitations (cont.)

- 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 <u>does not mean</u> no failures in 50K hours
- Better fit towards logistics and procurement, not failure avoidance

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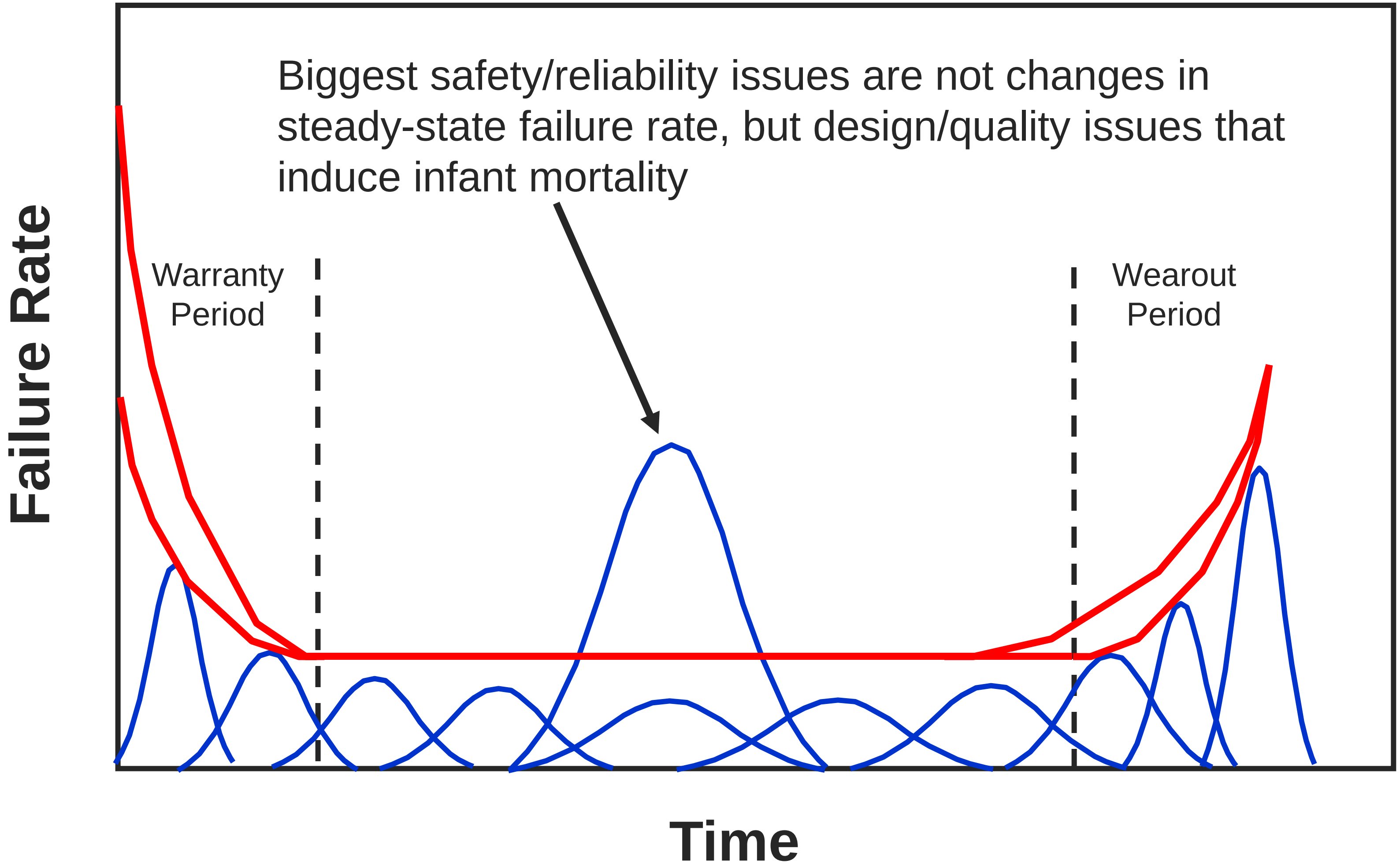
Reliability Goals



What is Physics of Failure?

- DfR Solutions: Leverages the knowledge and understanding of the processes and mechanisms that induce failure to predict reliability and improve product performance
- Army: An engineering-based approach to reliability that uses modeling and simulation to eliminate failures early in the design process by addressing root-cause failure mechanisms in a Computer-Aided- Engineering environment
- University of Maryland: Founded on the conviction that failures are governed by fundamental processes (mechanical, electrical, thermal, chemical, radiation) that initiate when the applied stress exceeds the material strength
- NASA-JPL: Modeling of failure mechanisms, based on science/ engineering first principles, that support deterministic or probabilistic predictions of reliability and *provide a scientific basis for determining the effectiveness of screens or inspections*

Empirical Prediction (summary)

- ***Fundamental Limitations***
  - ***Statistical probability should be used only when we lack knowledge of the situation and cannot obtain it at a reasonable cost.***
  - ***"Statistics are applicable only when:***
    1. You are unavoidably ignorant about a given issue,
    2. Some action is necessary and cannot be delayed."

Philosopher Leonard Peikoff
In Book & Lectures on The Art of Thinking

  - ***In other words, if you're trying to determine a course of action:***
    - Your best bet is to acquire knowledge and not to blindly use statistics to play the odds.

Physics of Failure (PoF) Modeling

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

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

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

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

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

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

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

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

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

Summary

- Reliability/Quality/Safety are heavily interdependent
- Opportunity for automotive to improve existing performance of electronics in regards to Reliability
  - And therefore Safety
- Requires implementation of data-centric best practices
  - Rely on knowledge, not statistics

Backup Slides

Percentage of Light Vehicles with Electrical Systems Problems

	2002	2003	2004
Honda/Acura	1.0	1.0	1.0
Hyundai/Kia	1.0	1.3	1.0
Subaru	1.0	1.1	1.0
Toyota/Lexus	1.0	1.0	1.1
General Motors	2.5	2.8	1.7
Nissan/Infiniti	1.3	1.4	1.8
Mazda	1.0	1.5	1.9
Ford	2.5	2.1	1.9
Chrysler	2.2	2.5	1.9
DaimlerChrysler	2.3	2.8	2.0
BMW	3.5	4.0	3.1
Mercedes	2.8	4.9	4.4
Volkswagen	4.1	2.7	4.7

[1]Hansen Report (April 2005)

Reliability and Quality (cont.)

- Quality is also time-limited (Reliability is sometimes known as Quality over Time)

  Translation: Warranty data (except for automotive) is much more effective in capturing Quality issues, not necessarily Reliability Performance