2012 ARS, North America, New Orleans

Track 2, Session S7

Begins at 10:30 AM, June 14th

Current Time:
10:53 PM

The Transition from MTTF Reliability Predictions to Physics of Failure Reliability Assessments

James McLeish – DfR Solutions

DfR Solutions
reliability designed, reliability delivered

Introduction

- James McLeish - Michigan Office Manager DfR Solutions (since 2006)
  Rochester Hills, Michigan (jmcleish@dfrsolutions.com)
  - 35 Years of Vehicular, Military & Industrial Product Engineering Experience
    E/E Product Design, Development, Systems Enrg. & Production (Chrysler & GM)
    - **Help Invent 1st Microprocessor Engine Controller (1979-82 Chrysler ESA/EFC System)**
    - **3 Patents Automotive Electronic Control Systems**
    - **E/E Engineering Manager - GM Military Vehicle**
    - **GM E/E Reliability Manager & QRD Technical Expert**
    - **Manager GM Reliability Physics (Advance QRD, A/D/V & Test Technology Development)**
    - **Author/Co-author of 3 GM Reliability/Validation Test Standards**
    - **Member SAE Reliability & ISO-26262 Functional Safety Committees**

- DfR Solutions is an Laboratory/Failure Analysis Services,
  Engineering Consulting & CAE Software Development Firm
  - Specializing in the Physics of Failure (PoF) approach to investigating & learning from all types of failures in all E/E technologies with a focus on failure prevention.
  - DfR provides forensic engineering knowledge and science based solutions that maximize product integrity and accelerates product development activities, known as the Reliability Physics or Physics-of-Failure (PoF) approach to Total Product Integrity
  - (i.e. Quality, Reliability and Durability (QRD)) of electronics along with advanced accelerated testing, E/E parts selection and supply-chain management techniques

Agenda: The Transition from MTTF Reliability Predictions to Physics of Failure Reliability Assessments

1) Overview Of Traditional Reliability Prediction Methods for Electronic Equipment
2) Limitations of These Traditional Reliability Prediction Methods
3) Introduction to PHYSICS OF FAILURE Basics
4) Failure Mechanism Examples & Models for Electronic Equipment
5) CAE Methods for Failure Mechanism Modeling Durability Simulations and Reliability Assessments
6) Summary & Conclusions

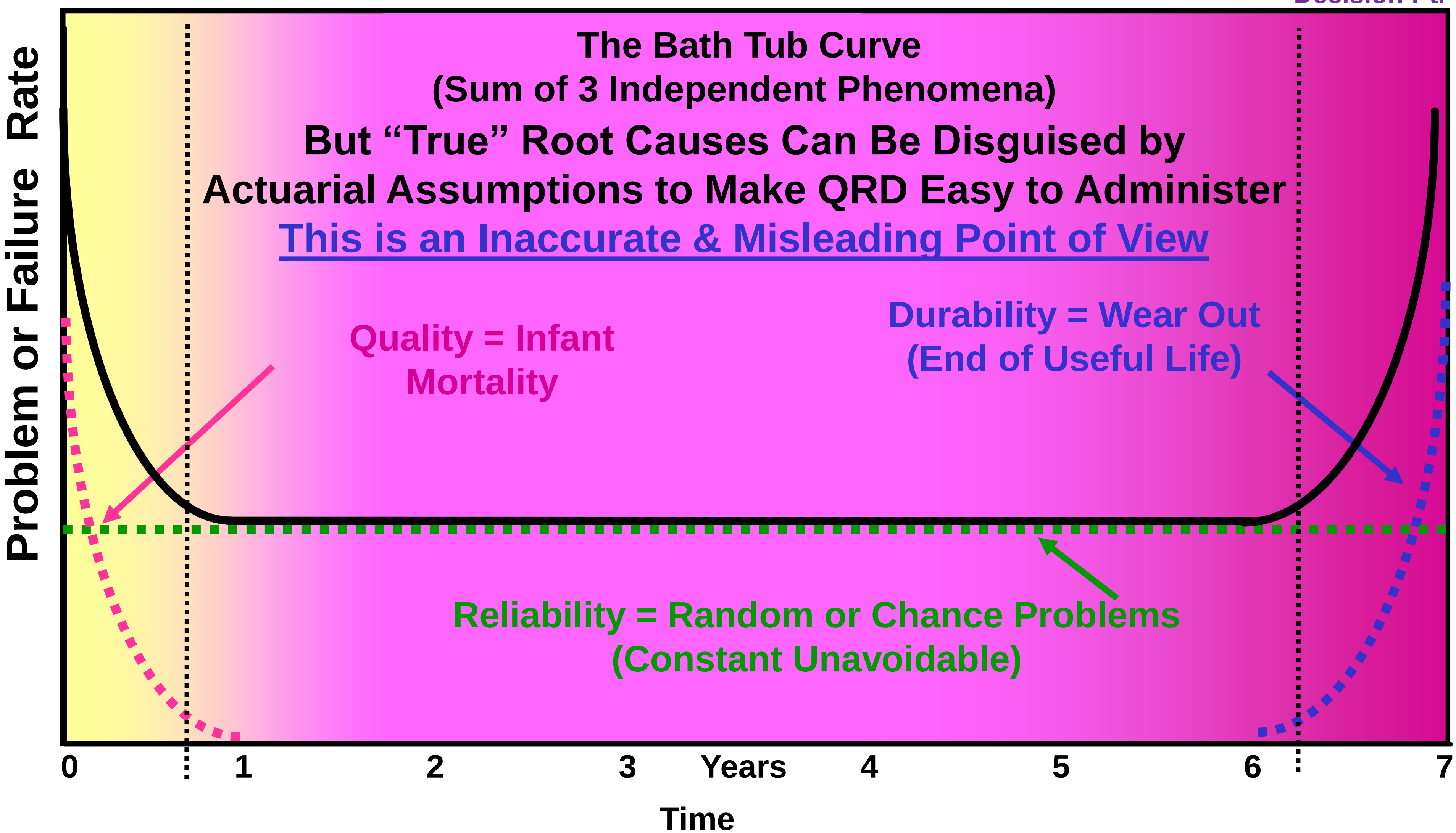
Acronyms

CAE – Computer Aided Engineering
PCB – Printed Circuit Board
PCBA – Printed Circuit Board Assembly
QRD – Quality, Reliability & Durability

1) The Traditional View of Quality, Reliability & Durability (QRD) - Product Life Cycle Failure Rate "Bath Tub" Curve

Focuses on 3 Separate & Individual Life Cycle Phases
each with Separate Control & Improvement Strategies
Produced the Misguided Belief that Reliability Efforts
Should Focus Only On Random Failure Issues

End of Useful Life
/Typ. Replacement
Decision Pt.



1) Classical Actuarial Reliability Prediction
- From Historical "Random Failure" Handbook Tables

- Parts Count / Actuarial Failure Rate Table Prediction Methods
  - Equipment failure rate is determined by summing the failure rates (from generic tables) for each component type in an electronic device

$$\lambda_{total} = \sum_{i=1}^{i=n} N_i(\lambda_g \Pi_Q)_i$$

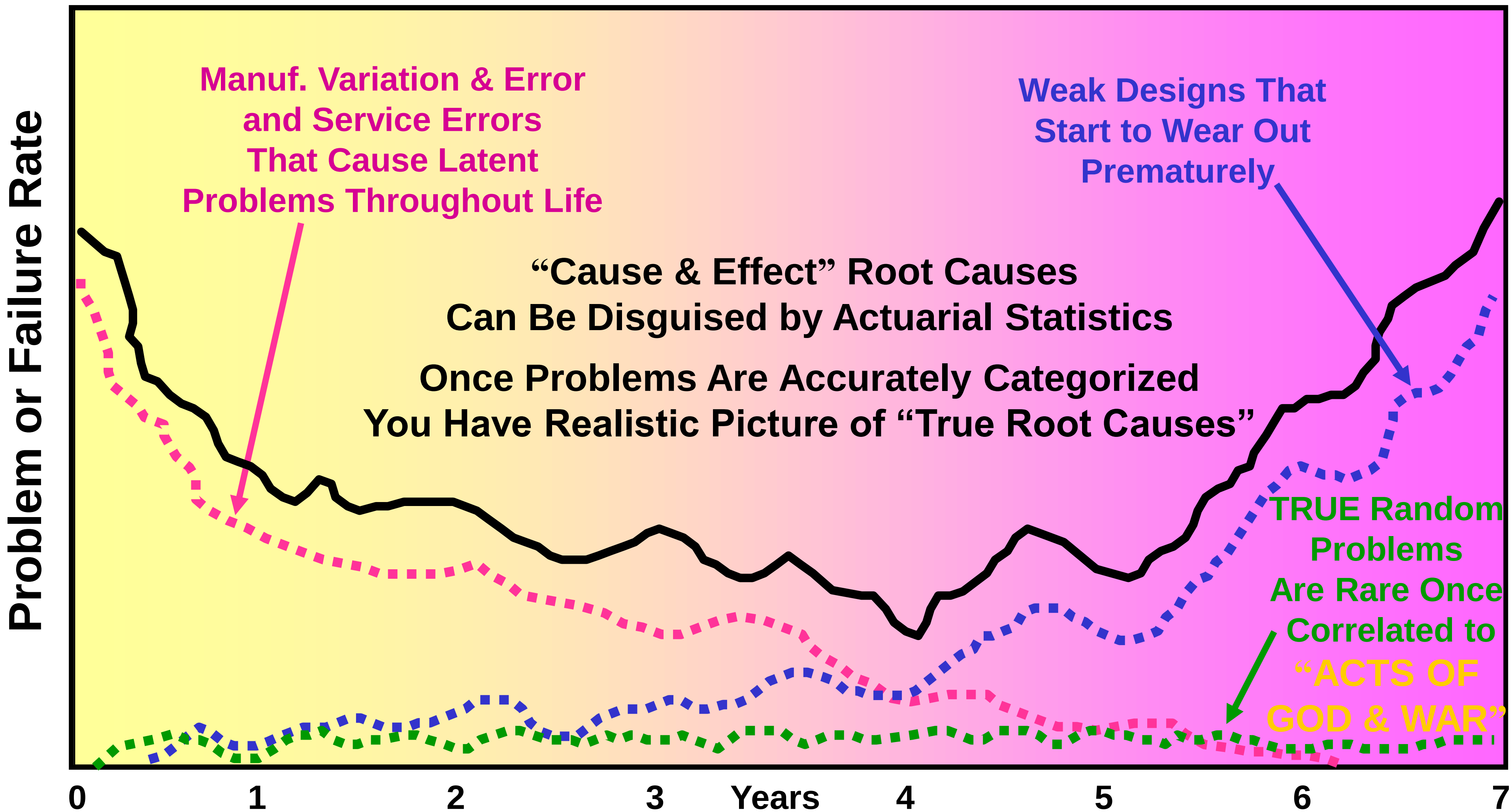
    - λtotal = Total equipment failure rate
    - Ni = Quantity of the ith generic part
    - λg = Generic constant (random) failure rate for the ith generic part
    - ΠQ = Quality factor for the ith generic part

- Parts Stress Prediction
  - Augments the parts count methods be applying scaling factors for temperature and service application
    - (i.e. Ground benign, Ground Mobile, Navel, Airborne, Missile . . . Etc)

- Bases on Assumptions that:
  - Infant Mortality issues don't need to be accounted for
  - Wear Out Issues will not occur until well past the intended service life

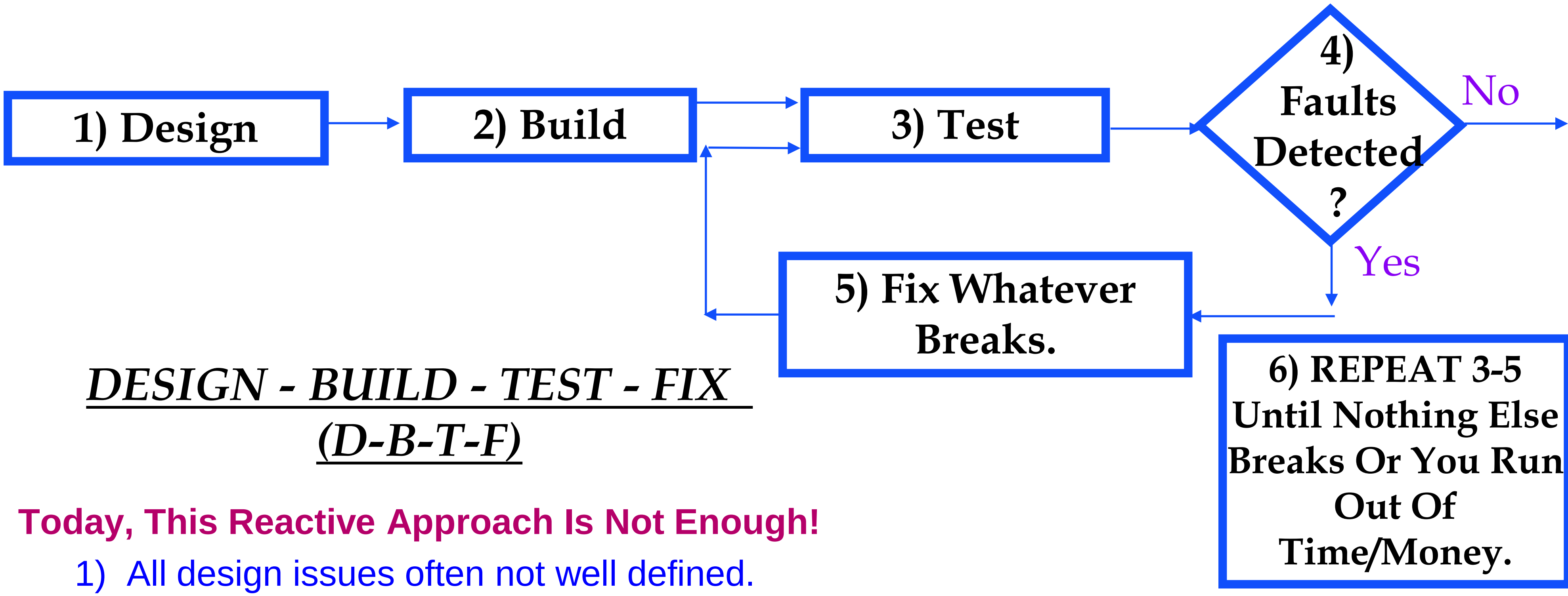
1) A "PoF FAILURE MECHANISM" Based "REALISTIC" View Reveals the True Interactive Relationships Between Q, R & D

- Real failure rate curves are irregular, dynamic and full of valuable information, not clean smooth curves to simplify the data plots.



1) Traditional Reliability Growth in Product Development

Empirical "TRIAL & ERROR" Method to Demonstrate *Statistical Confidence*

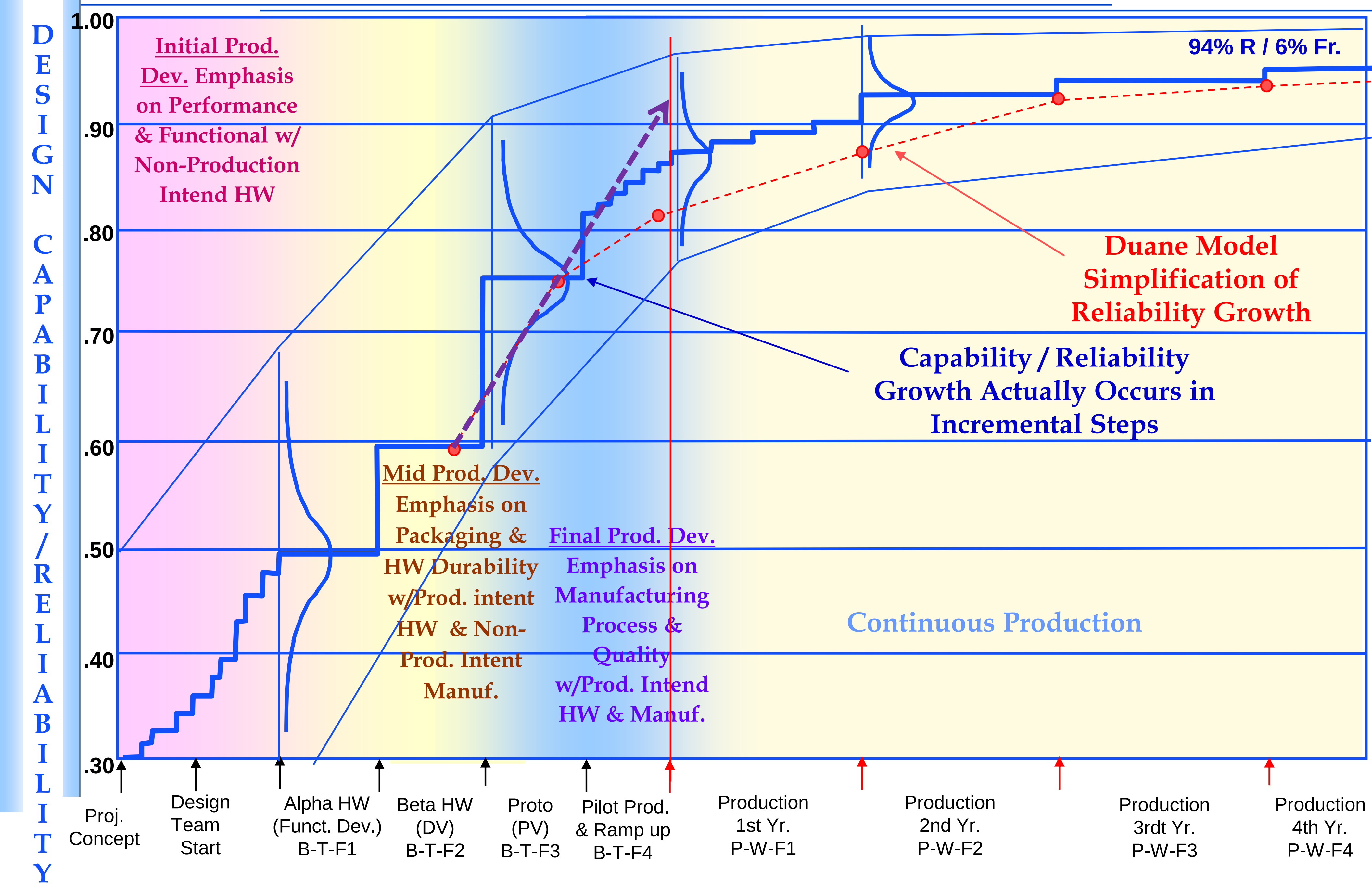


DESIGN - BUILD - TEST - FIX
(D-B-T-F)

Today, This Reactive Approach Is Not Enough!

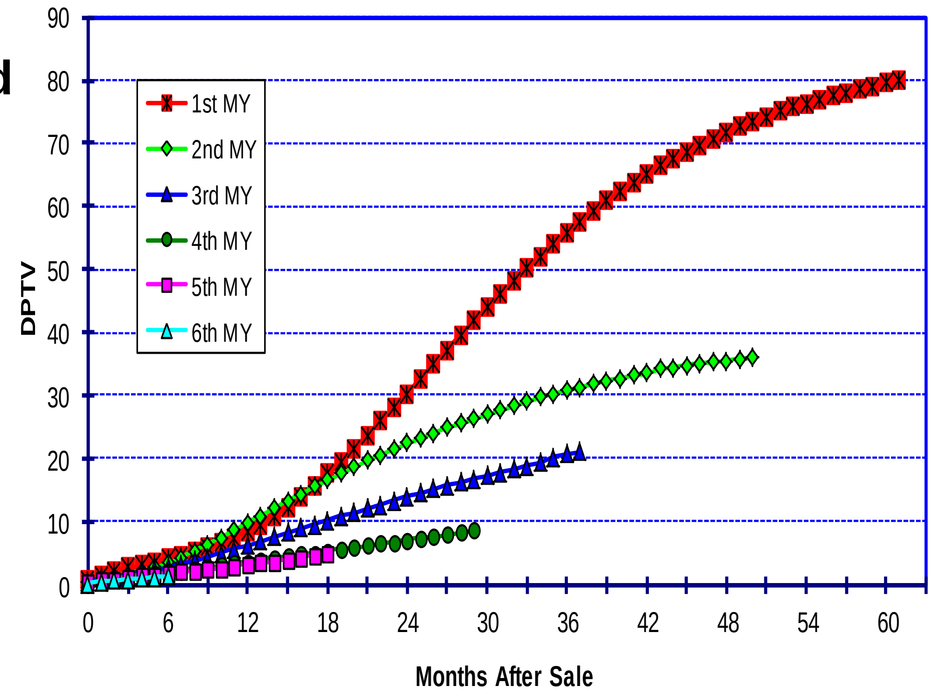
1) All design issues often not well defined.
2) Early build methods do not match final processes.
3) Testing doesn't equal actual customer's usage.
4) Improving fault detection catches more problems, but causes more rework.
5) Problems found too late for effective corrective action, fixes often used.
6) **Testing more parts & more/longer tests "seen as only way" to increase reliability.**
7) Can not afford the time or money to test to high reliability.
8) Incremental improvements from faster more, capable tests still not enough.

1) Reliability/Capability Growth in Traditional D-B-T-F Product Development Process Takes Years to Achieve Maturity



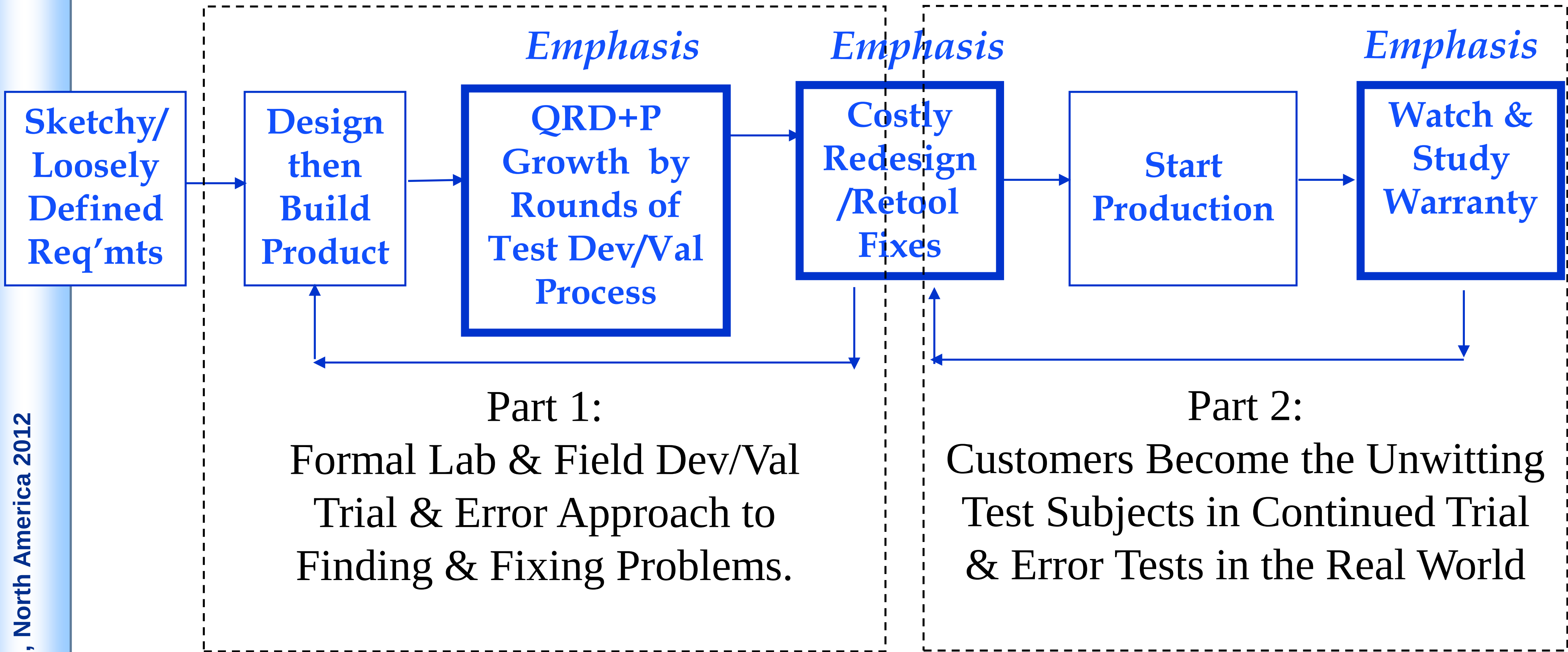
1) Reliability Growth Continues Into Production with Continuous Improvement Warranty Reduction Efforts

- **Warranty Continuous Improvement Team**
  - **Typically Reduce Annual Warranty Rates by 50% each year**
  - **Until the Product Reaches Maturity of Improvement Resources are Redeployed to a new product line.**



- **Reasons for Warranty Uptick with New Product Introduction**
  - **Rapid & Constant Technology Growth**
    - o Lesson Learned Constantly Changing Rapidly Outdated
  - **Lack of Understanding & Confusion on:**
    - o Design Issues That Effect QRD
    - o Manufacturing Issues That Effect QRD
  - **Use if Outdated Paradigms**
    - o Actuarial Reliability Assessment that Can Not Account for New Technologies
    - o "Test & Fix" Dev./Val. Growth
    - o Lack of Reliability by Design
  - **Annual Reappearance of Problems**
    - o Fire Fighting Without Lessons Learned Feedback
    - o Reappearance of Problems that are Never Root Caused i.e. Hardy Perennials
    - o Uneven Supply Chain Learning Curve

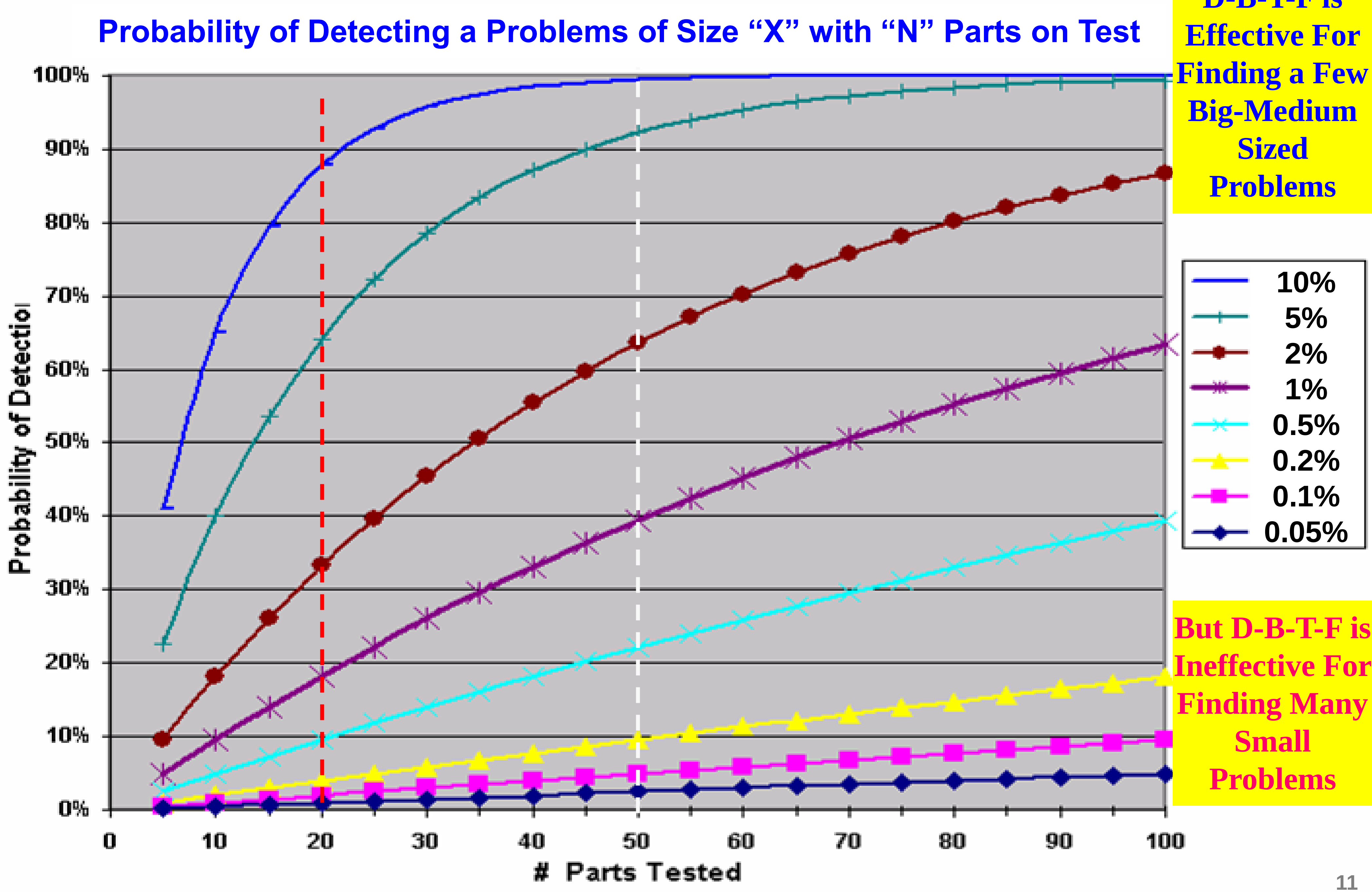
1) The Traditional Product Development Process (PDP) is Actually a Series of Design - Build - Test - Fix Growth Events



Essentially Formalized Trial & Error

That Starts With Product Test – To Be Good Enough To Start Production
Then Evolves Into Continuous Improvement Activates
In Responses to Warranty Claims

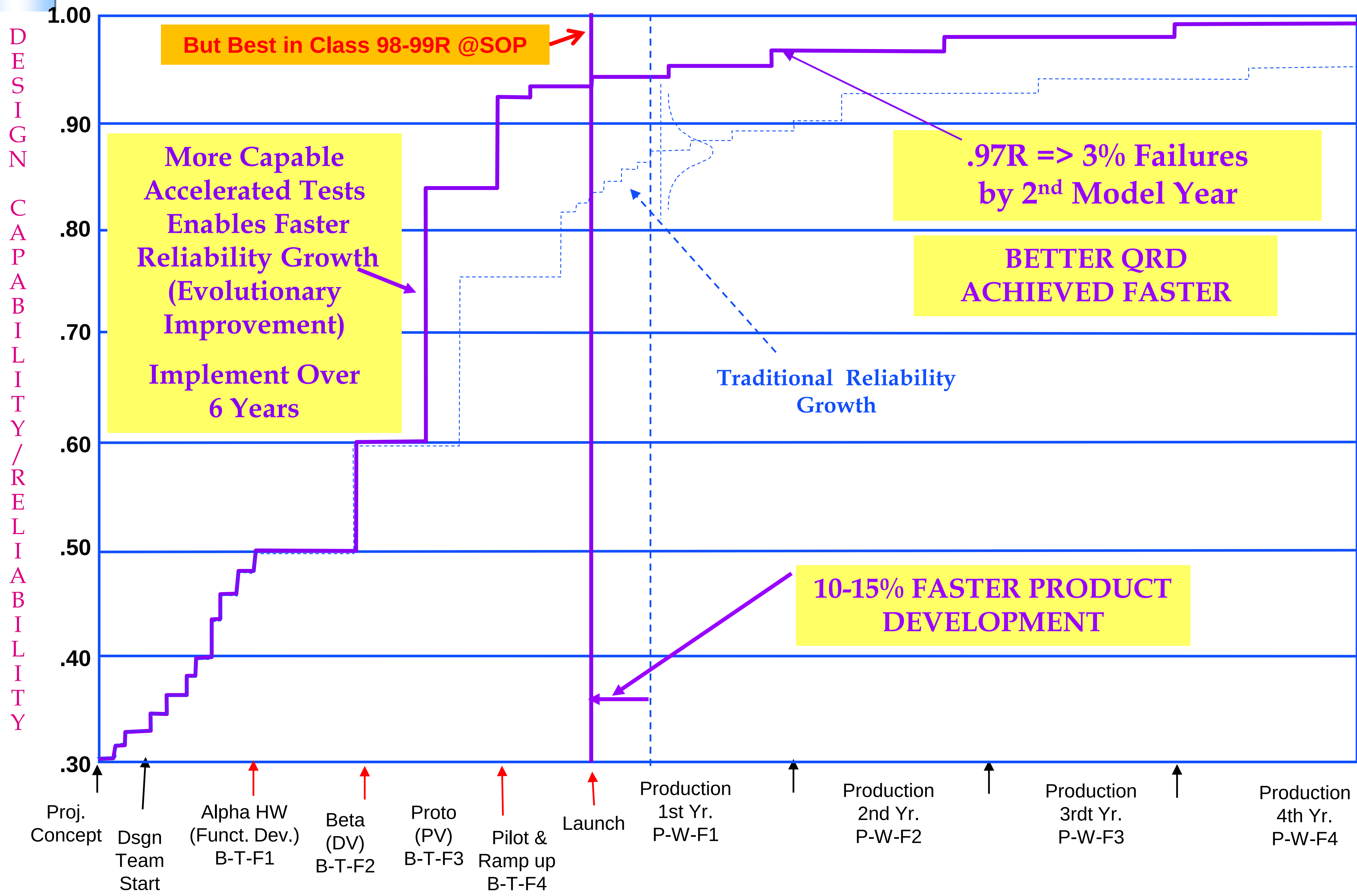
1) If Parts Pass Qualification Testing , Why Do Field failures Still Occur
Statistically Confident - Probability of Detection X Sized Issues out of # of Y Parts
Not Very Effective for Issues Below 5% of Population



D-B-T-F is Effective For Finding a Few Big-Medium Sized Problems

But D-B-T-F is Ineffective For Finding Many Small Problems

1) Better Faster Reactive Methods Applied Like HALT Testing and Enhance Efforts to Find Field Problems Faster Applied.
- These Methods Do Find/Fix Problems Faster, But is this Enough?



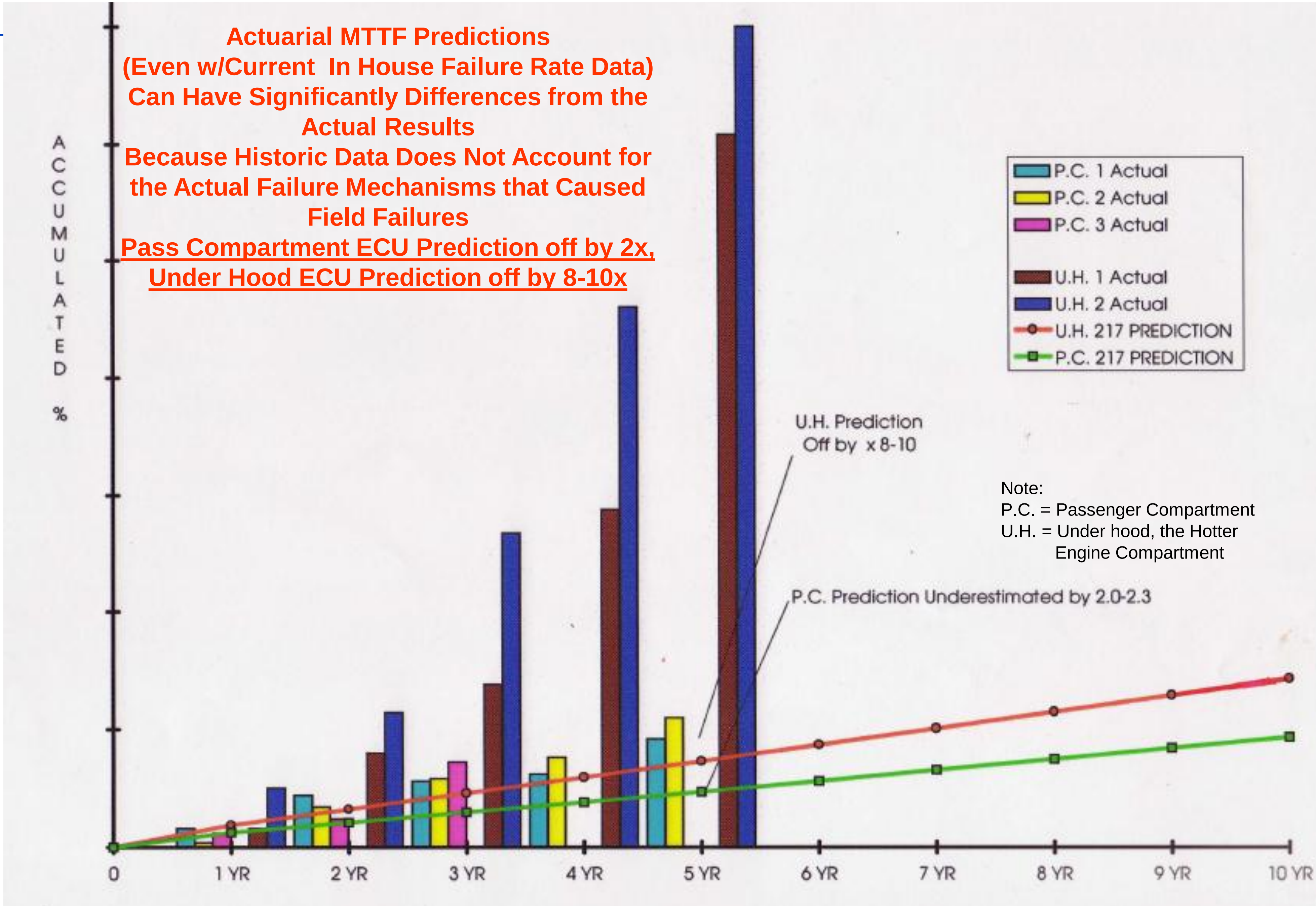
2) Limitation of Current Historical Actuarial Approach to MTBF Reliability Prediction

- **Constant failure rate (i.e. random failure) approach ignores infant mortality and wearout related failures.**
- **Industry wide average failure rates are not vendor, device nor event specific and ignores the physics & mechanics of failure.**
- **At least 78% of electronic failures not modeled by Actuarial Method like MIL-HDBK-217***

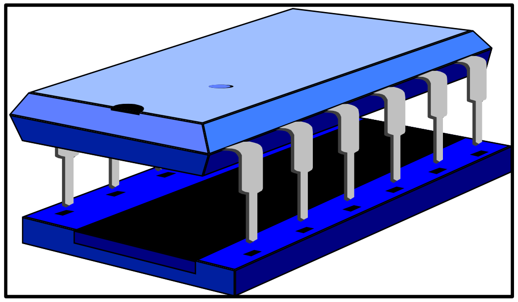
  **** Ref: "A Comprehensive Reliability Assessment Tool for Electronic Systems",***
  RIAC RAMS 2001 - even worst today 2012

  - **Many Issues not covered:**
    - **Design errors, assembly issues, solder, wiring failures, PCB insulation breakdown and via failures, software errors . . . etc.**
  - **Over emphasis on the Arrhenius model and steady state temperature as the primary factor in electronic component failure.**
  - **Keeping failure rate data up to date difficult & costly**
    - **Current rapid rate of technology advancement, quality/reliability growth and the vast number of component types and suppliers.**

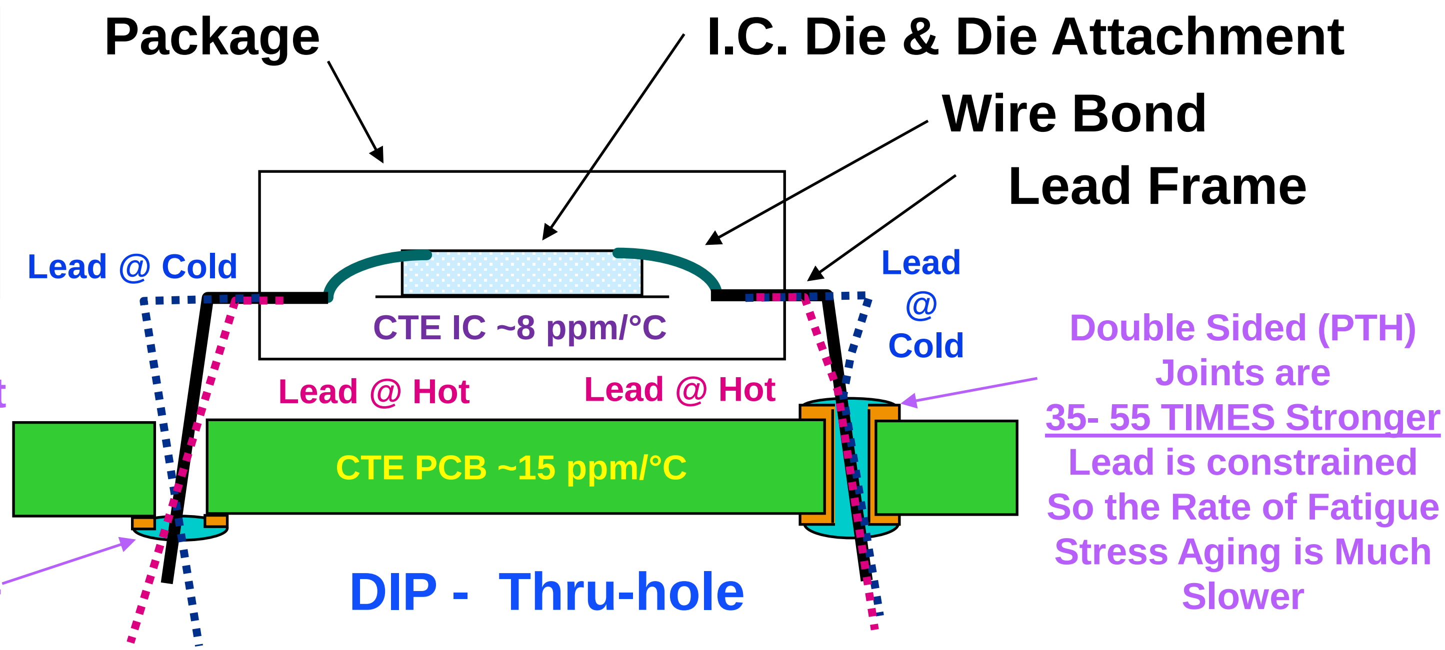
2) Vehicle EE Module Reliability Prediction Case Study (1990s) - Actuarial Predictions Compared to Actual Field Failure Rate



2) What Happen in the Case Study – Actuarial Failure Rate Data Correlated to Core E/E Technology - Impact of Package Configuration & Size Not Accounted For Historical Failure Rata Data was from ICs in DIP Chip Packages



Single Sided Solder Joint Allow Leads to Wiggle Under Vib., Shock & Thermal Exp/Contraction the Joint Fatigues Faster



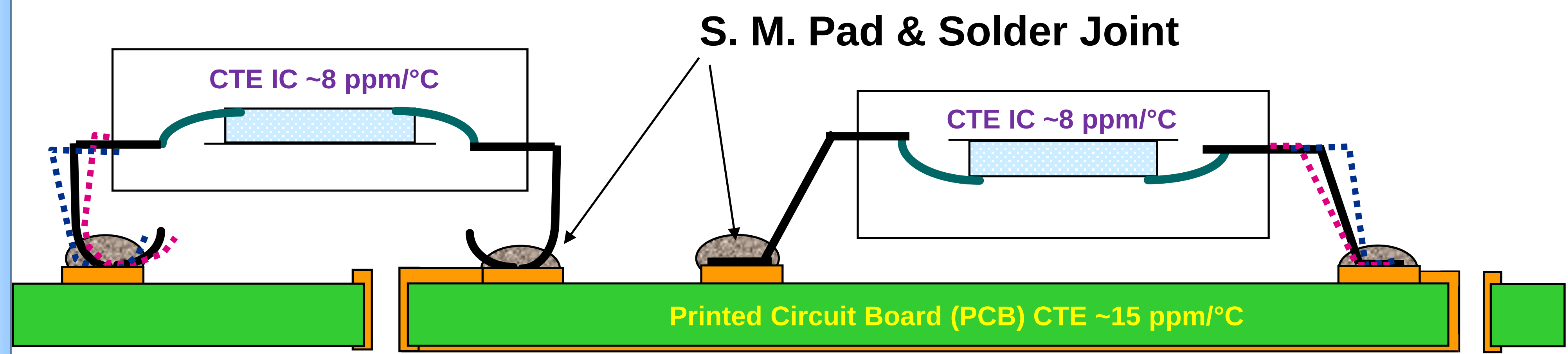
Automotive Fatigue Life Single Sided 2-5 Yrs

Automotive Fatigue Life Single Sided >10 Yrs

- **Since Electrical Engineers Design Most Printed Circuit Boards (PCB)**
  - **Their only motivation to accepted the added costs of Plated Through Hole (PTHs) was when increasing component density required placing component and traces on both sides of the circuits board.**
  - **THE RELIABILITY OF MORE COMPLEX EE MODULES SKY ROCKETED with the use of Double Sides PCB.**
  - **Thus More Complexity DOES NOT ALWAYS HAVE TO RESULT IN LESS RELIABILITY. A More Capable or Smarter Design Approach Can Overcome the Inherent QRD Risks of Increased Complexity**

2) The Case Study EE Module Use Integrated Circuits in a New Packaging Style – J Leaded Surface Mount

- Impact of Structural Configuration & Size on Fatigue Durability WAS NOT Accounted for in Actuarial Reliability Prediction



1st Generation
Surface Mount Devices
J lead - Thermal
Expansion/Contraction
Cause Rapid Fatigue Due To
Lead Rocking

2 Generation Surface Mount Devices
Have Gull Wing Fine Pitch Leads
Are Designed as an Articulated Spring,
Their Leads Flex at Two Bend Points
Instead of Transmitting Stress to the Weaker Solder
Similar Sized GWFP Devices
Avg. 10x the Durability Life of Similar Sized J Leaded Parts
under the Same Thermal Cycling Conditions.

GW FP Devices Take Up More Board Areas
So a Larger Boards May Be Require to
Hold the Same Number of Components

2) Limitations of Actuarial Reliability Prediction

- *Actuarial probabilities should be a last resort, used only when there is a lack of knowledge on a situation and knowledge cannot obtain 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."*

***Leonard Peikoff** - Art of Thinking*

- *In other words, if you're trying to determine a course of action:*
  - *Your best bet is to acquire knowledge and do not rely primarily on statistics and probabilities to play the odds (use only as a last resort strategy).*

Can We Really Afford to Gamble On Product Reliability
"Past Performance DOES NOT Guarantee Future Results".
(Standard Investment Prospectus Disclaimer).

2) Army 1995 Memo Prohibiting Further Use of MIL-HDBK-217 Actuarial Reliability Prediction Methods

DEPARTMENT OF THE ARMY
OFFICE OF THE ASSISTANT SECRETARY
RESEARCH DEVELOPMENT AND ACQUISITION
103 ARMY PENTAGON
WASHINGTON DC 20310-0103

REPLY TO ATTENTION OF

1 5 FEB 1995

SARD-ZD

MEMORANDUM FOR COMMANDER, U. S. ARMY MATERIEL COMMAND, 5001 EISENHOWER AVENUE, ALEXANDRIA, VA 22333-0001
PROGRAM EXECUTIVE OFFICERS
PROGRAM MANAGERS

SUBJECT: Policy on Incorporating a Performance-Based Approach to Reliability in Request for Proposals (RFPs)

Sound reliability requirements are important components of an RFP. This memorandum provides policy on reliability requirements in performance-based RFPs.

Reliability requirements should be included in RFPs by specifying: (1) quantified reliability requirements and allowable uncertainties, (2) failure definitions and thresholds, (3) life-cycle usage conditions. Requirements for reliability predictions, reliability M&S, and reliability testing can be included to support the assessment of risk in achieving quantitative reliability requirements and to support the Program Manager's plan for risk management. RFPs should solicit adequate information for evaluating the source data, models, reasonableness of modeling assumptions, methods, results, risks and uncertainties. Requirements to use particular models or statistical test plans should not be specified in RFPs.

Failure definitions and life-cycle usage conditions are necessary to fully define the quantitative reliability requirements. The extent to which failures and usage conditions are defined should be determined on an acquisition-specific basis.

2

The best RFPs will directly specify performance-based reliability requirements and avoid citing any specification, standard or handbook. Language specifying "how to" design, manufacture or test for reliability is not to appear in RFPs. Use of any reliability specification, standard or handbook (military or not) in an RFP, even for guidance, requires a waiver using the existing waiver process for military specifications and standards. In particular, MIL HBK 217, Reliability Prediction of Electronic Equipment, is not to appear in an RFP as it has been shown to be unreliable and its use can lead to erroneous and misleading reliability predictions.

The Army Materiel Systems Analysis Activity will provide guidance to the field by April 15, 1996. Please work with AMSAA, the Army Standardization Improvement Executive's Executive Agent for Reliability and Maintainability Standardization Improvement, on the development and refinement of guidance to implement this policy.

Gilbert F. Decker
Assistant Secretary of the Army
(Research, Development and Acquisition)

CF:
Deputy Under Secretary of the Army, Rm 2E660
Principal Deputy for Acquisition, USAMC, Rm 10N06
Director for Assessment and Evaluation, OASA(RDA), Rm 2E673
Director, U. S. Army Materiel Systems Analysis Activity

Many other Industries (such as U.S. Automakers) Reached Similar Conclusion and also Phased out Actuarial Reliability Predictions Methods in the 1990s.

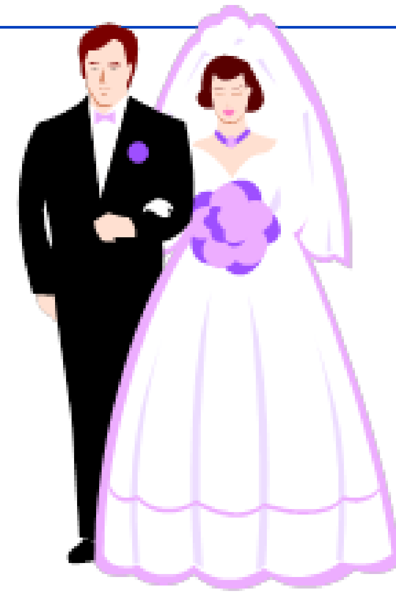
3) Physics of Failure / Reliability by Design Methods Encourages a New Definition for Reliability

- **Classical Definition of Reliability:**
  - ***"The Probability of an item to perform required functions, under stated conditions, for a stated period of time"***
  - ***Focus on "The Number" often leads to "Number Games" to look good & appear to meet requirements***
  - ***MTBF studies often not used or respected by product designers***

- **The Emerging New Definition of Reliability:**
  - ***"The Ability of an item to perform required functions, under stated conditions, for a stated period of time".***
  - ***Focus is on Achievement rather than Probability Number Games***
  - ***Aligns with modern Computer Aided Engineering (CAE) tools used by product designers.***

3) Physics of Failure / Reliability Physics Definitions

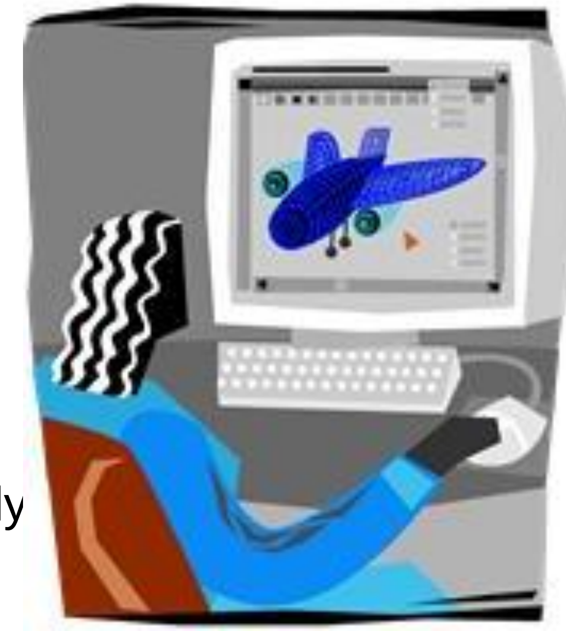
- **Physics of Failure** - A Formalized and Structured approach to Root Cause Failure Analysis that focuses on total learning and not only fixing a current problem.
  - To achieve an understanding of "CAUSE & EFFECT" Failure Mechanisms AND the variable factors that makes them "APPEAR" to be Irregular Events.
  - Combines Material Science, Physics & Chemistry with Statistics, Variation Theory & Probabilistic Mechanics.
    - A Marriage of Deterministic Science with Probabilistic Variation Theory for achieving comprehensive Product Integrity and Reliability by Design Capabilities.



  - **Failure of a physical device or structure (i.e. hardware) can be attributed to the gradual or rapid degradation of the material(s) in the device in response to the stress or combination of stresses the device is exposed to, such as:**
    - **Thermal, Electrical, Chemical, Moisture, Vibration, Shock, Mechanical Loads . . .**
  - Failures May Occur:
    - Prematurely because device is weaken by a variable fabrication or assemble defect.
    - Gradually due to a wear out issue.
    - Erratically based on a chance encounter with an Excessive stress that exceeds the capabilities/strength of a device,

3) Physics of Failure / Reliability Physics Definitions

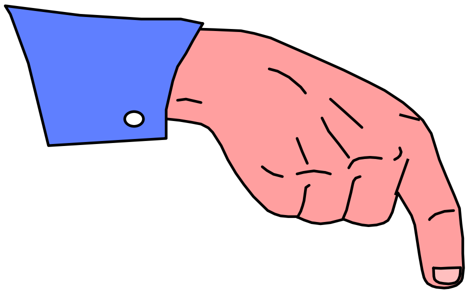
- **Reliability Physics** *(a.k.a. the PoF Engineering Approach)*
  - A Proactive, Science Based Engineering Philosophy for applying PoF knowledge for the Development and Applied Science of Product Assurance Technology based on:



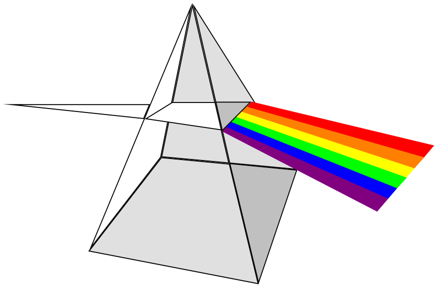
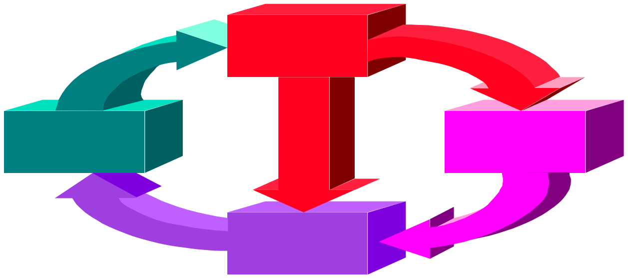
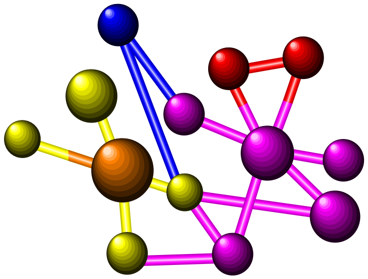
  - Knowing how & why things fail is equally important to understand how & why things work.
  - Knowledge of how thing fail and the root causes of failures enables engineers to identify and avoid unknowingly inherent potential failure mechanisms in new product designs and solve problems faster.
  - Provides scientific basis for evaluating usage life and hazard risks of new materials, structures, and technologies, under actual operating conditions.
  - Provides Tools for achieving Reliability by Design
  - Applicable to the entire product life cycle
    - Design, Development, Validation, Manufacturing, Usage, Service.

3) Key PoF Terms and Definitions

- **Failure Mode:**
  - The EFFECT by which a failure is OBSERVED, PERCEIVED or SENSED.

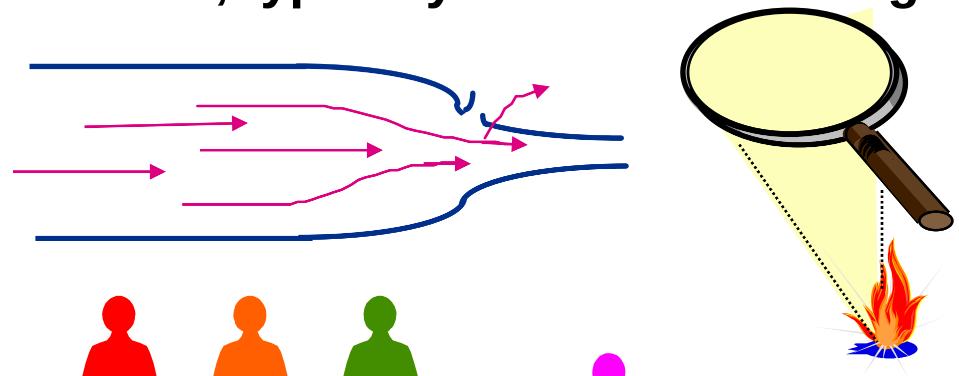

- **Failure Mechanism :**
  - The PROCESS (elect., mech., phy., chem. ... etc.) that causes failures.

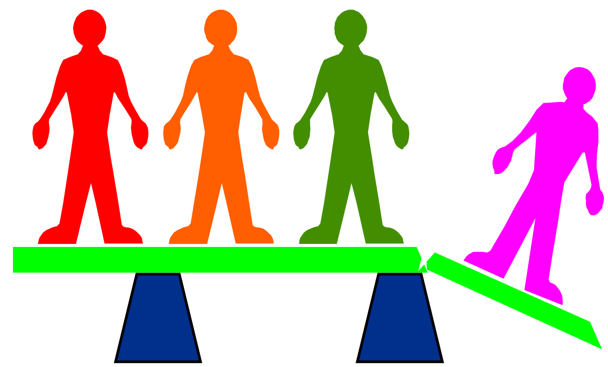
  - FAILURE MODE & MECHANISM are NOT Interchangeable Terms in PoF.

3) Key PoF Terms and Definitions

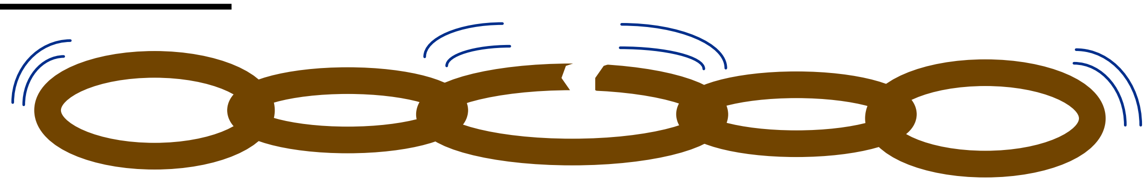
- **Failure Site :**
  - **The location of potential failures, typically the site of a designed in:**
    - ***stress concentrator***



    - ***design weakness***



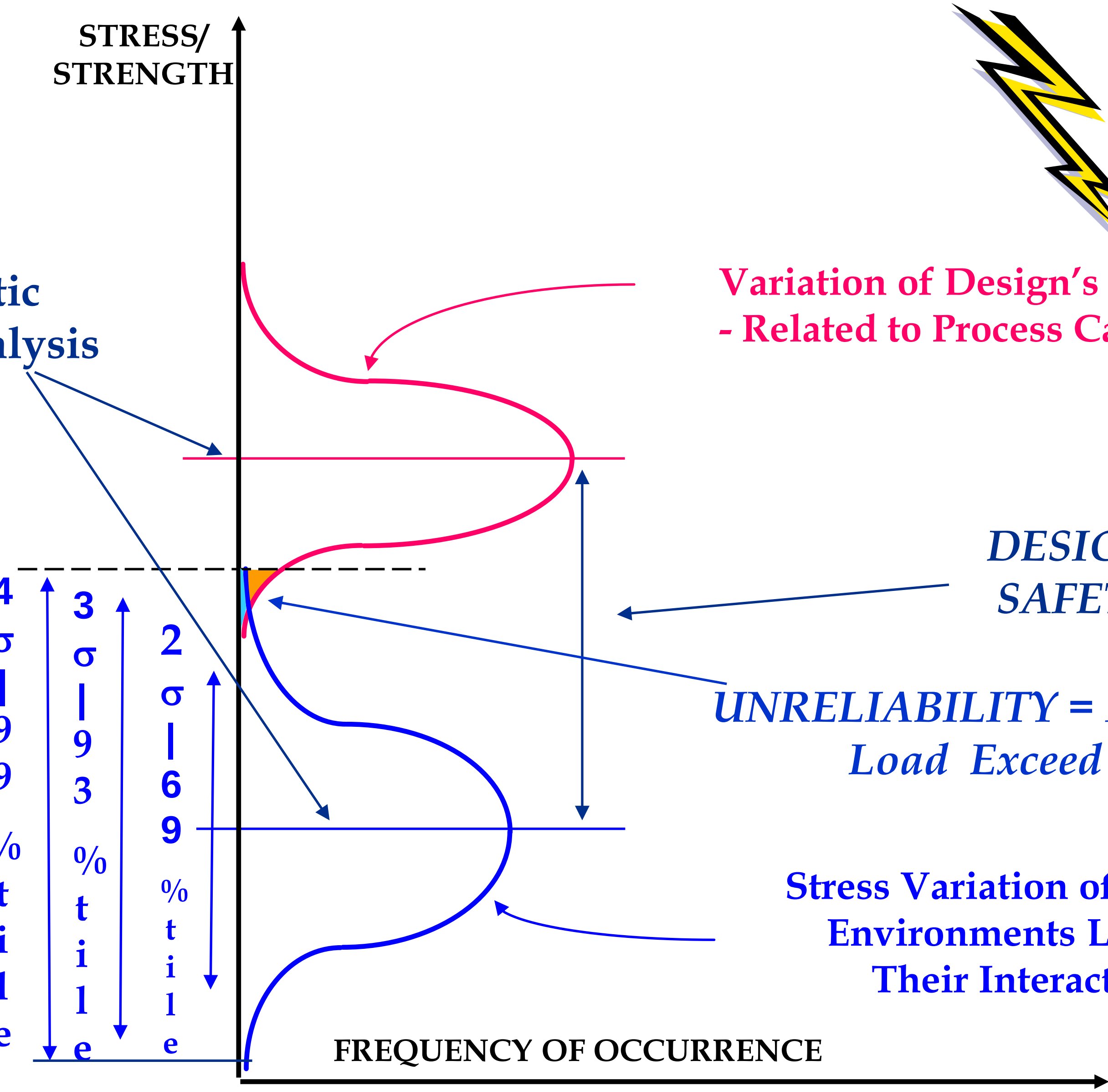
    - ***material variation or defect.***

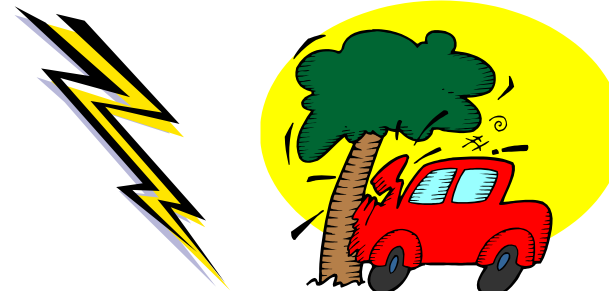


  - **Knowledge Used to Identify and Prioritized Potential Failure Sites and Risks in New Designs During PoF Design Reviews.**

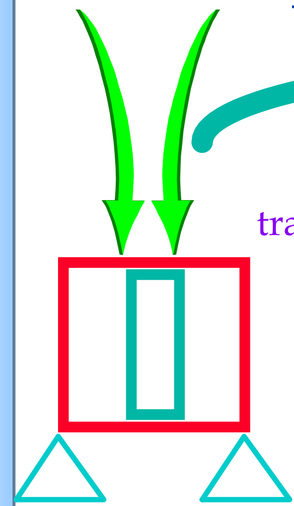
3) PoF Generic Failure Categories

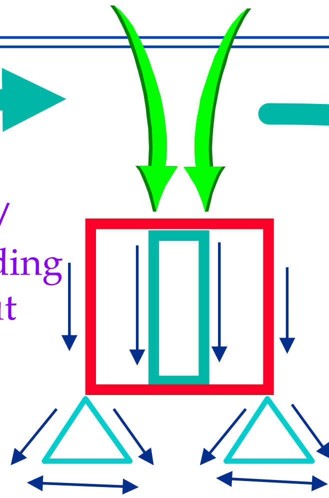
Overstress - When Loading Stress Exceed Material Strength



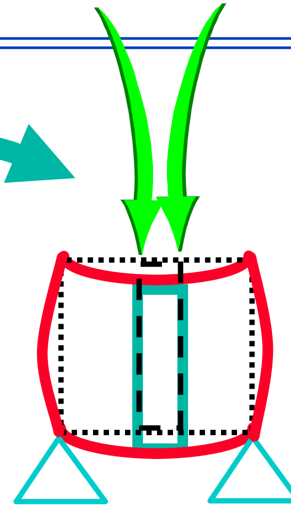


3) Overview of How Things Age & Wear Out
- Stress Driven Damage Accumulation in Materials





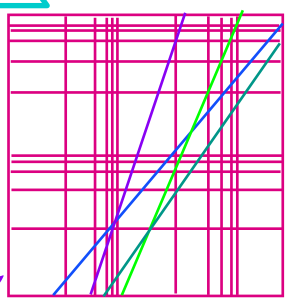
2. Stress
The distribution/ transmission of loading forces throughout the device.



3. Strain :
Instantaneous changes (materials\structural) due to loading, different loads interact to contribute to a single type of strain.

Knowledge of how/ which "Key Loads" act & interact is essential for "*efficiently*" developing good products, processes & evaluations.

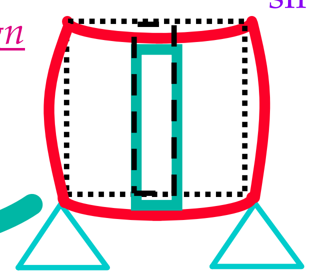
1. Loads
Elect. Chem. Thermal, Mech… Individual or combined, from environment & usage act on materials & structure.



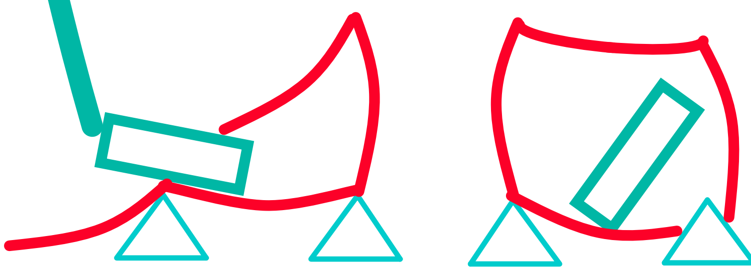
6. Time to Mean Failure:
(Damage Accumulation verses Yield Strength
A Function of: Σ [Stress Intensity, Material Properties, & Stress Exposure Cycles/Duration].

7. Project the Distribution About the Mean i.e. Rate of Failure (Fall out)
A function of variation in; Usage, Device Strength & Process Quality Control (i.e. latent defects).

4. Damage Accumulation (or Stress Aging):
Permanent change degradation retained after loads are removed. From small incremental damage, accumulated during periods/cycles of stress exposure.

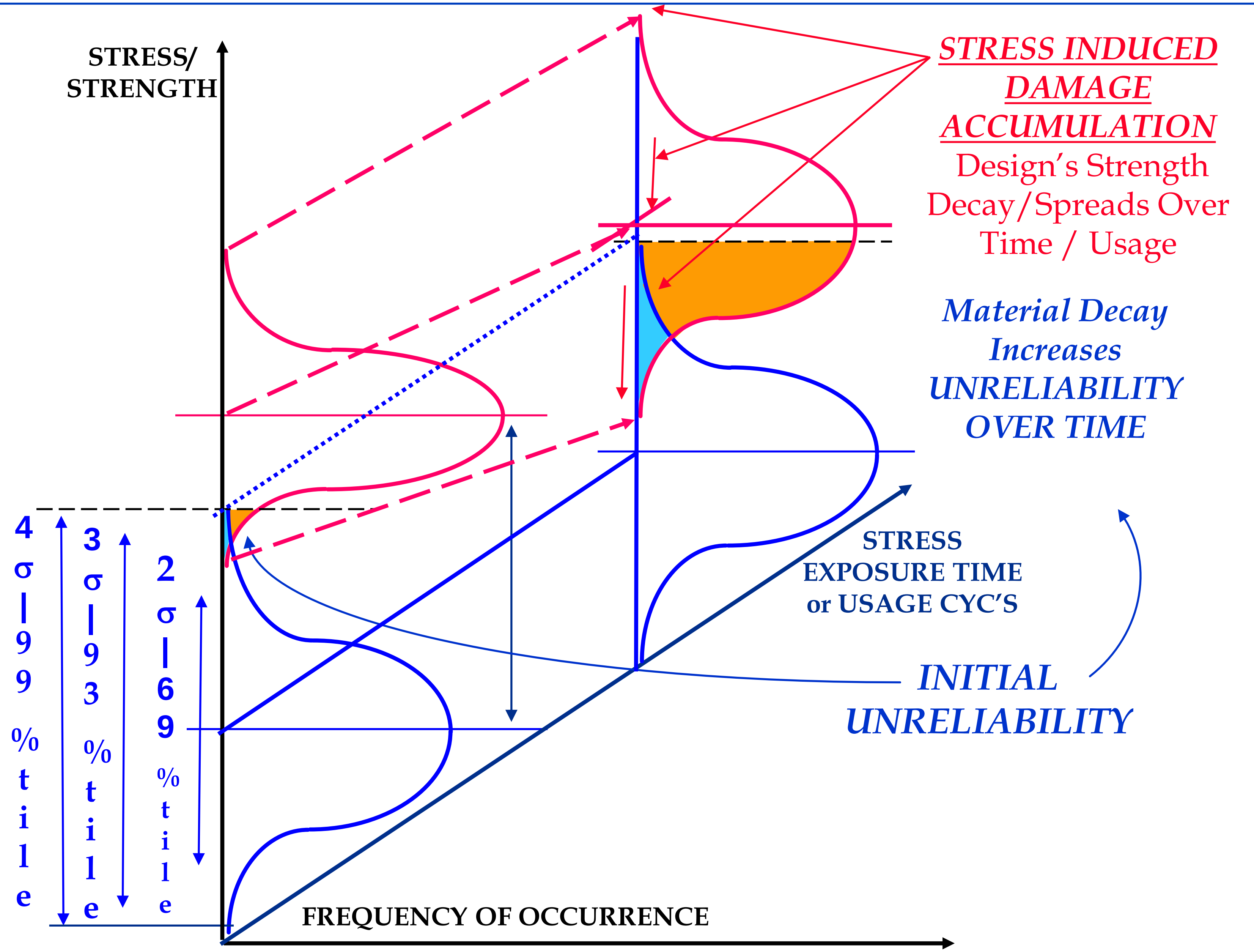


5. Failure Site & Type:
Typically due to a designed in: *stress concentrator* , *design weakness*, *material/process variation* or *defect*.



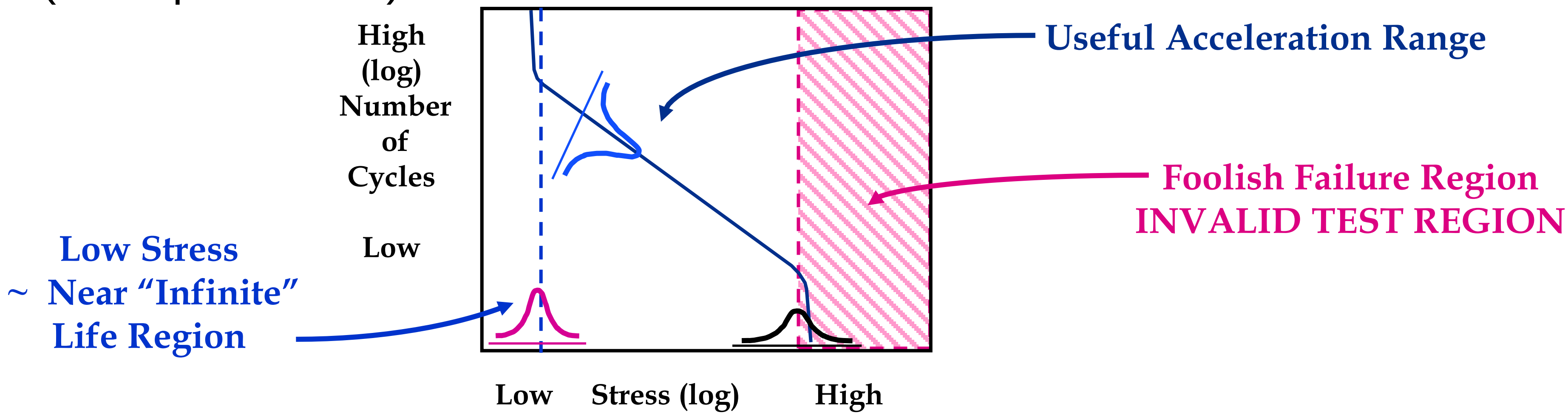
3) Generic Failure Categories - Wearout (Damage Accumulation) - Over Time of Stress Exposure

How well do you Understand & Design For Strengths & Stresses?

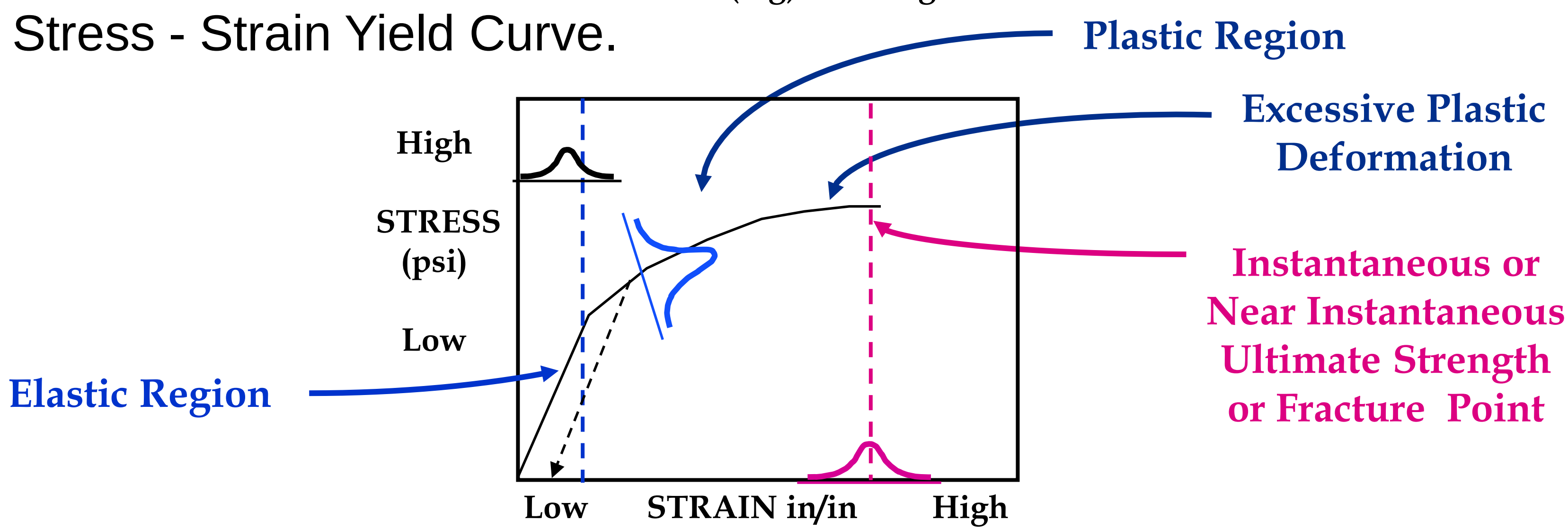


3) Correlation Between: Stress Driven Damage Accumulation in Materials and Life Consumption Rates

- Material N-S Curve (Number of Life Cycle at a Stress Level) (Transposed S-N)

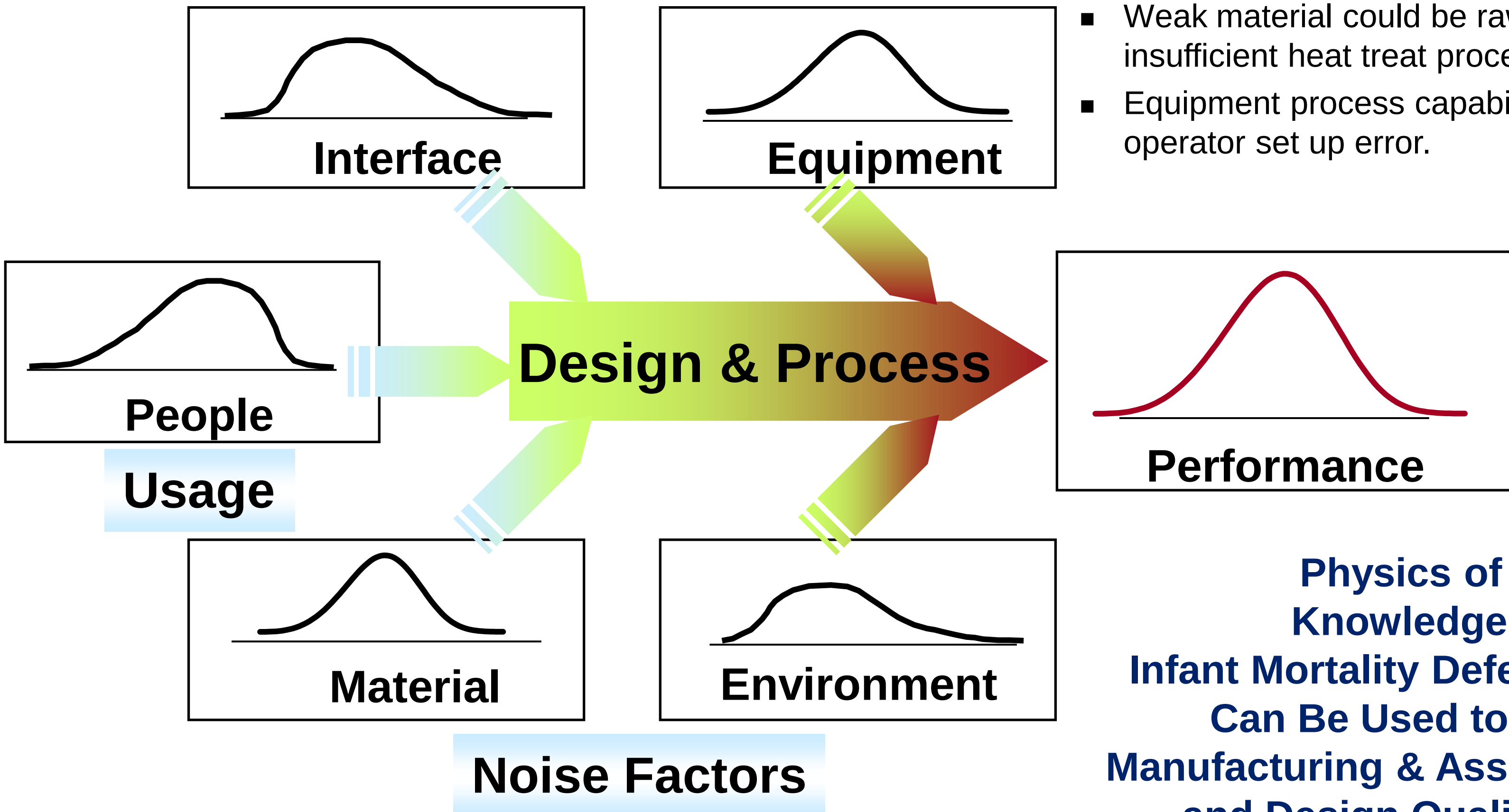


- Stress - Strain Yield Curve.



3) Generic Failure Categories: Infant Mortality Quality Errors and Variation Issues are Everywhere

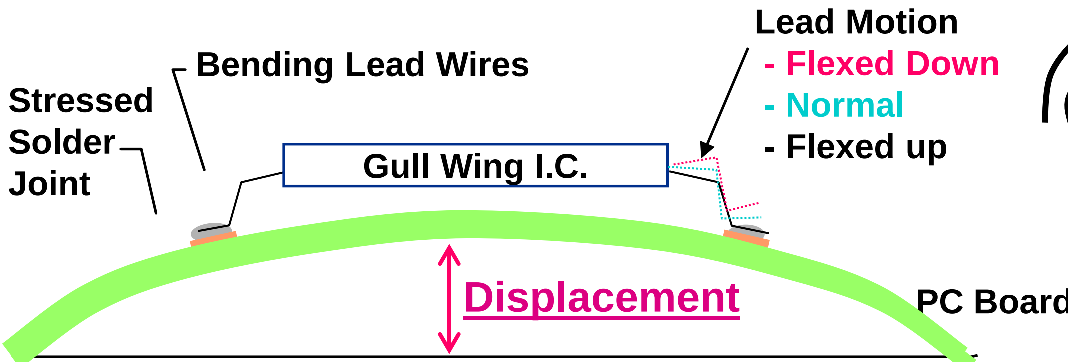
- Errors Broadest Category
  - Errors can occur in Design, Manufacturing, Usage & Service.
  - Missing knowledge
  - Human factor Issues.
- Variation
  - Fine line between excessive variation & out right errors.
  - Both related to various quality issues.
    - Manufacturing equipment wear out & failure could be related to maintenance errors.
    - Weak material could be raw material variation or insufficient heat treat processing errors.
    - Equipment process capabilities limitation or operator set up error.



Physics of Failure Knowledge of How Infant Mortality Defects Are Created Can Be Used to Error Proof Manufacturing & Assembly Processes and Design Quality Evaluation Procedures

4) PoF Examples: Circuit Board Related Vibration Durability - Two Issues To Consider

- 1) Circuit Board in Resonance
  - Components Shaken Off/Fatigued by Board Motion of Flexing Attachment Features



- Time to Failure Determine by Intensity/Frequency of Stress Verses

  Strength of Material

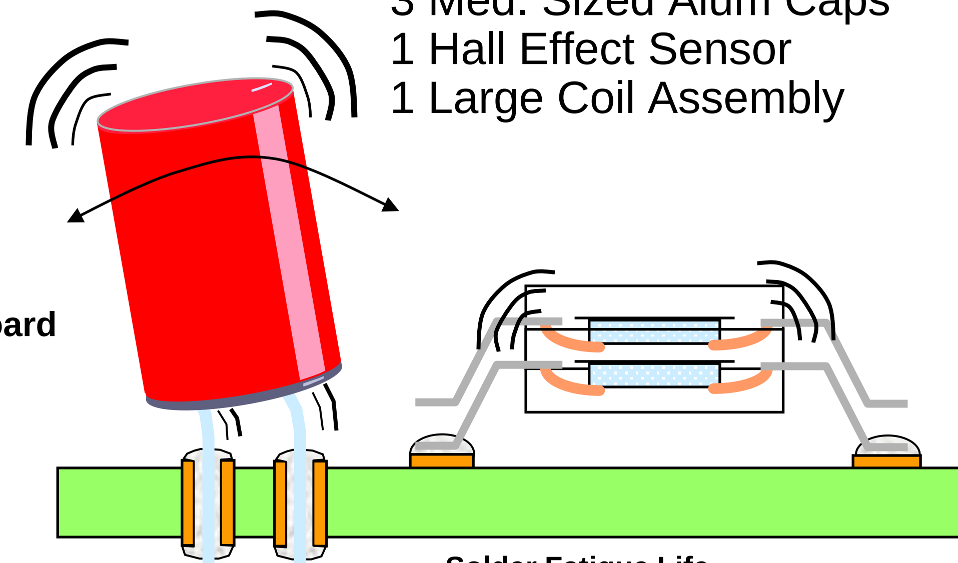
Steinberg's Criterion:

For a 10 million cycle life, $Z < 0.0008995 \cdot B/(C \cdot h \cdot r\ (L^{1/2}))$.

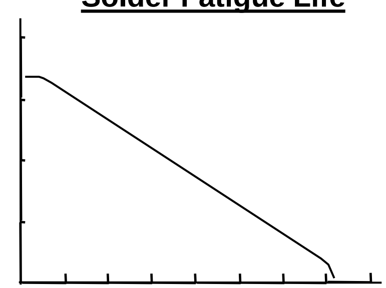
Ref: Vibration Analysis for Electronic Equipment, by David S. Steinberg

- 2) Components In Resonance.
  - Components Shake/Fatigue themselves apart or off the Board.
  - Especially Large, Tall Cantilever Devices

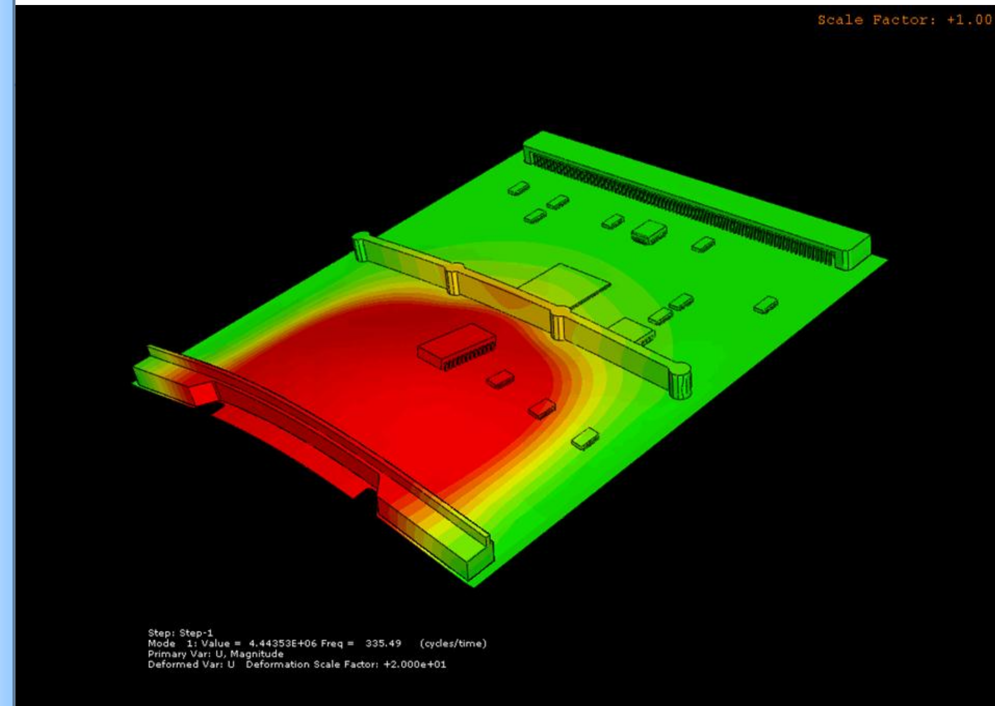
    3 Med. Sized Alum Caps
    1 Hall Effect Sensor
    1 Large Coil Assembly

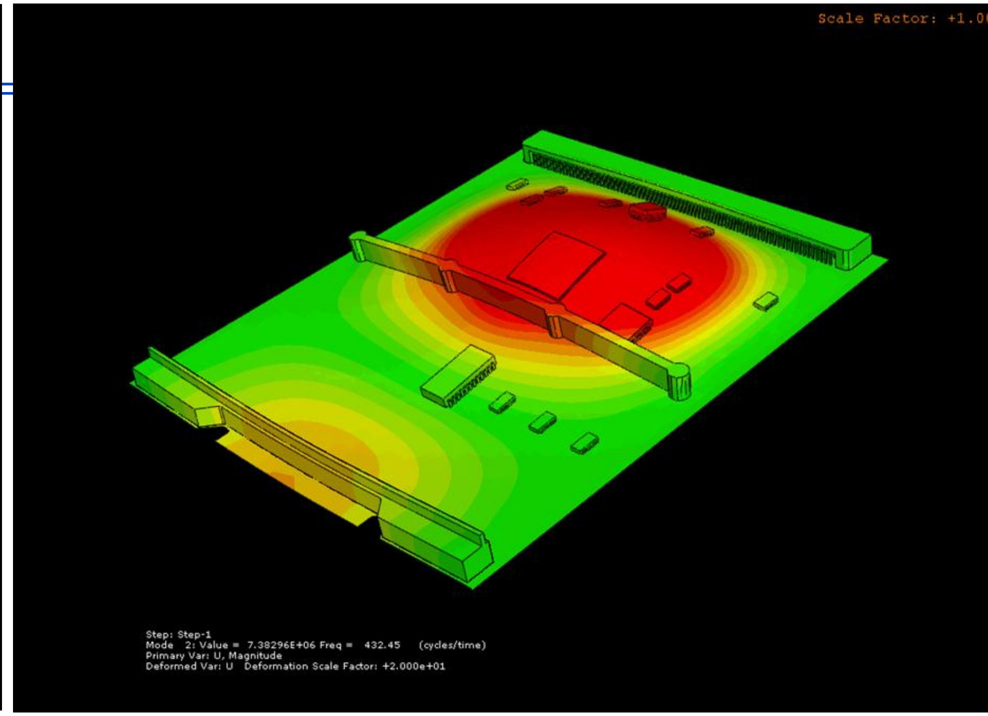


Solder Fatigue Life



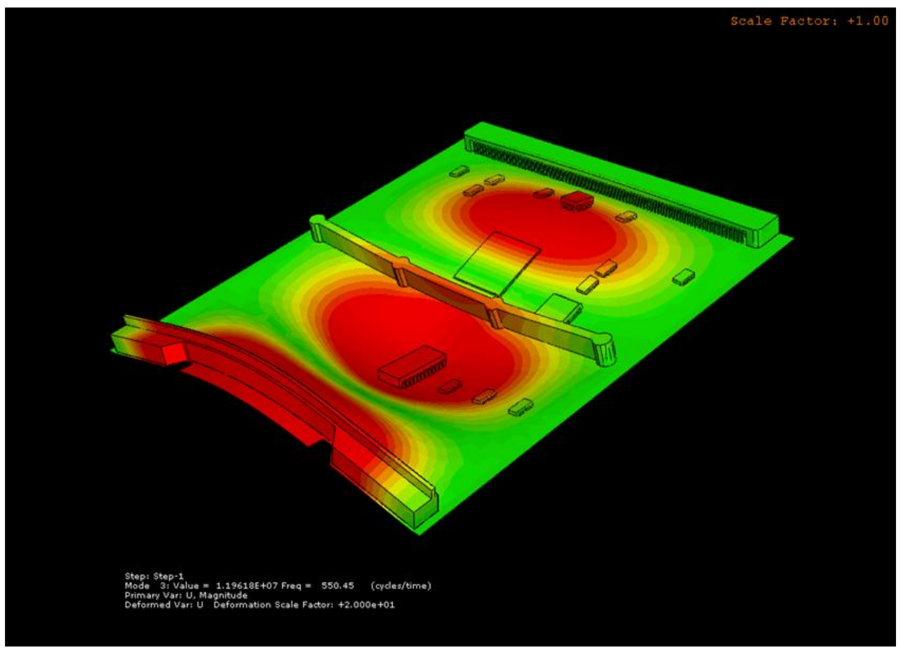
4) PCB Vibration - 1st, 2nd & 3rd Harmonic Modals





1st Harmonic

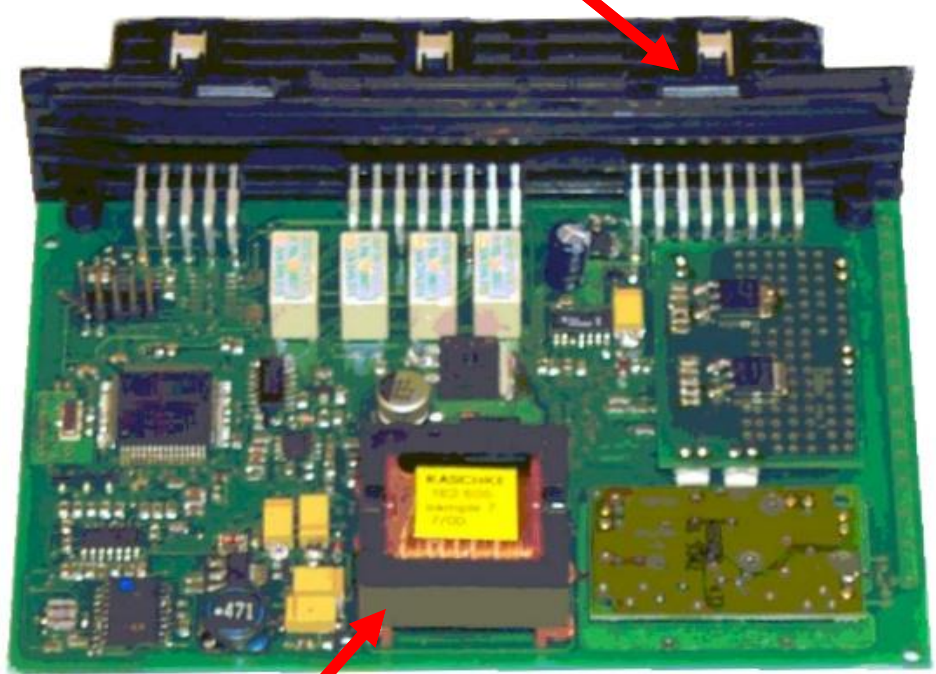
2nd Harmonic



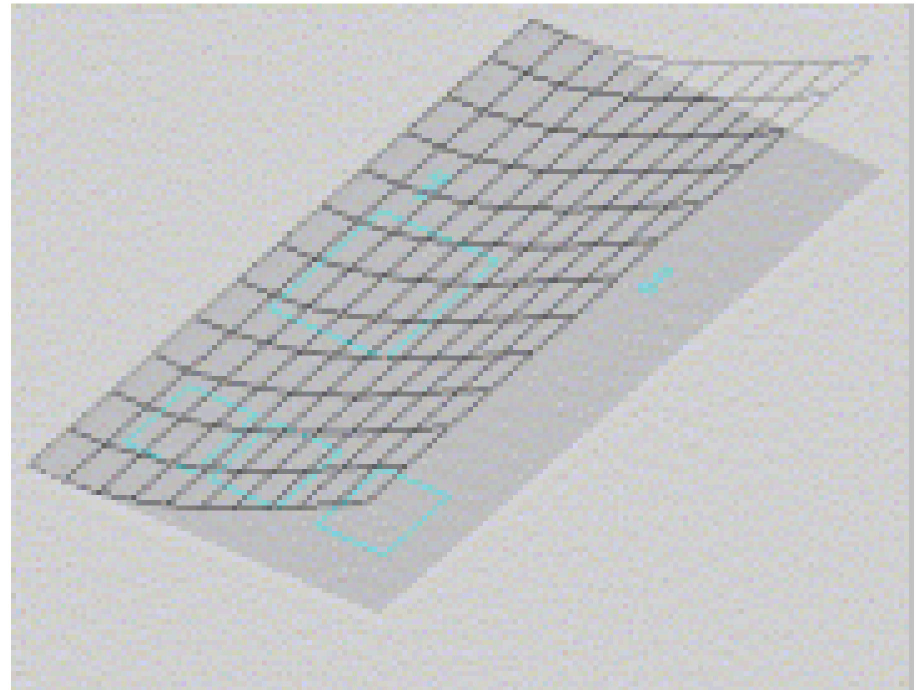
3rd Harmonic

3) PoF Example – Electronic Module Vibration Analysis

Connector Provides Primary PCB Support



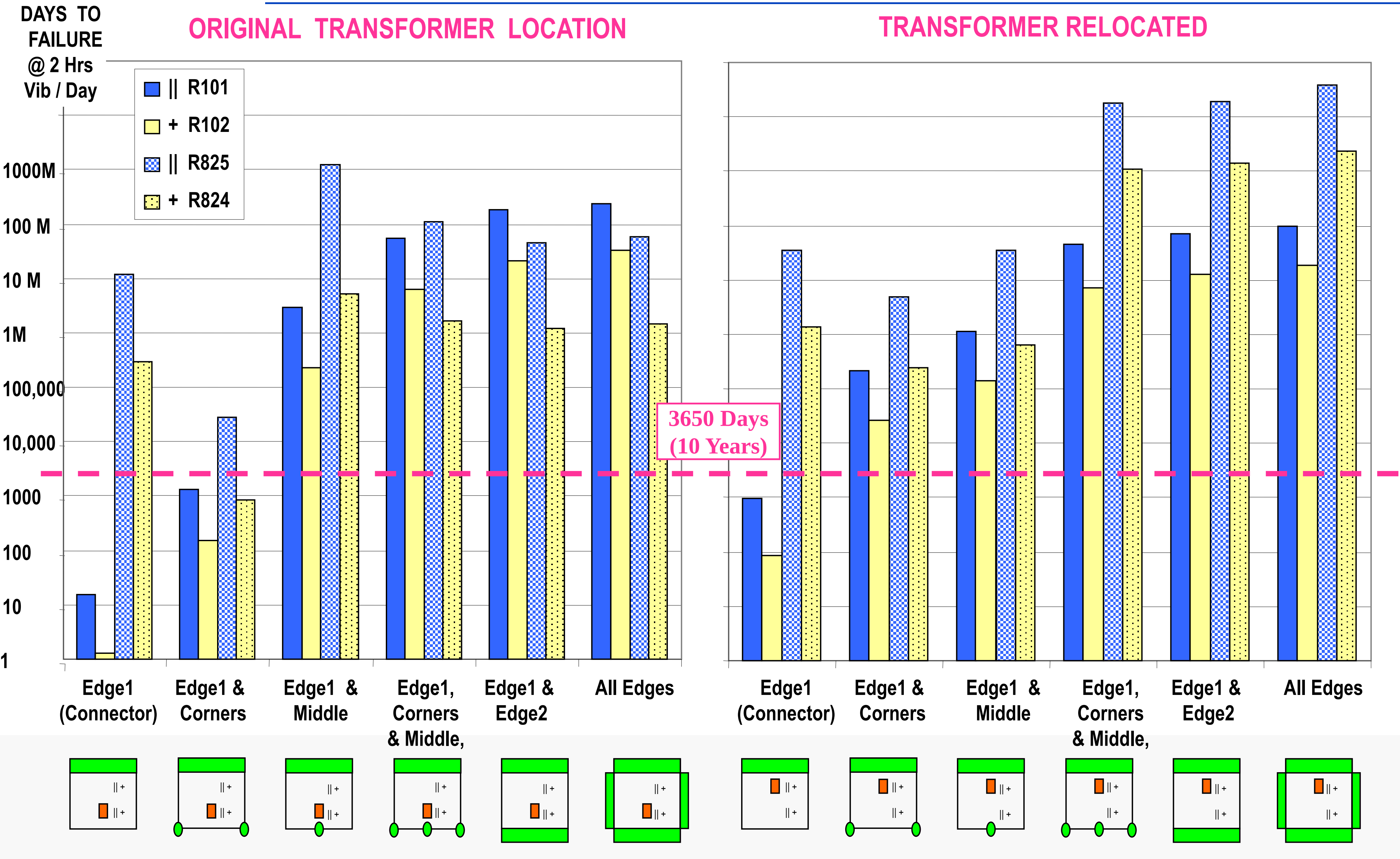
CAE Modal Simulation of Circuit Board Flexure



Transformer
A Large Mass, will drive a Large Vibration Modal Response

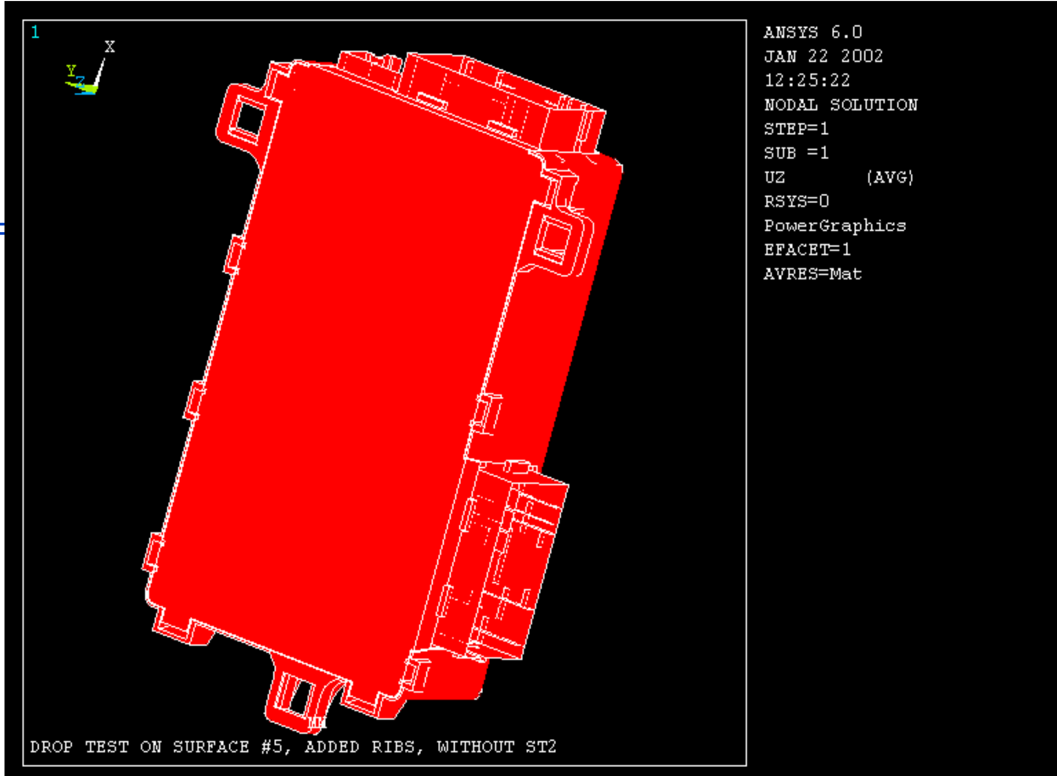
	Original	CAE Guided Redesign Adds Back Edge Support
Board Displacement (mils)	13.95	1.15
Natural Frequency (Hz)	89	489
Vib. Durability Calculation	25 Days	**> 50 Years**

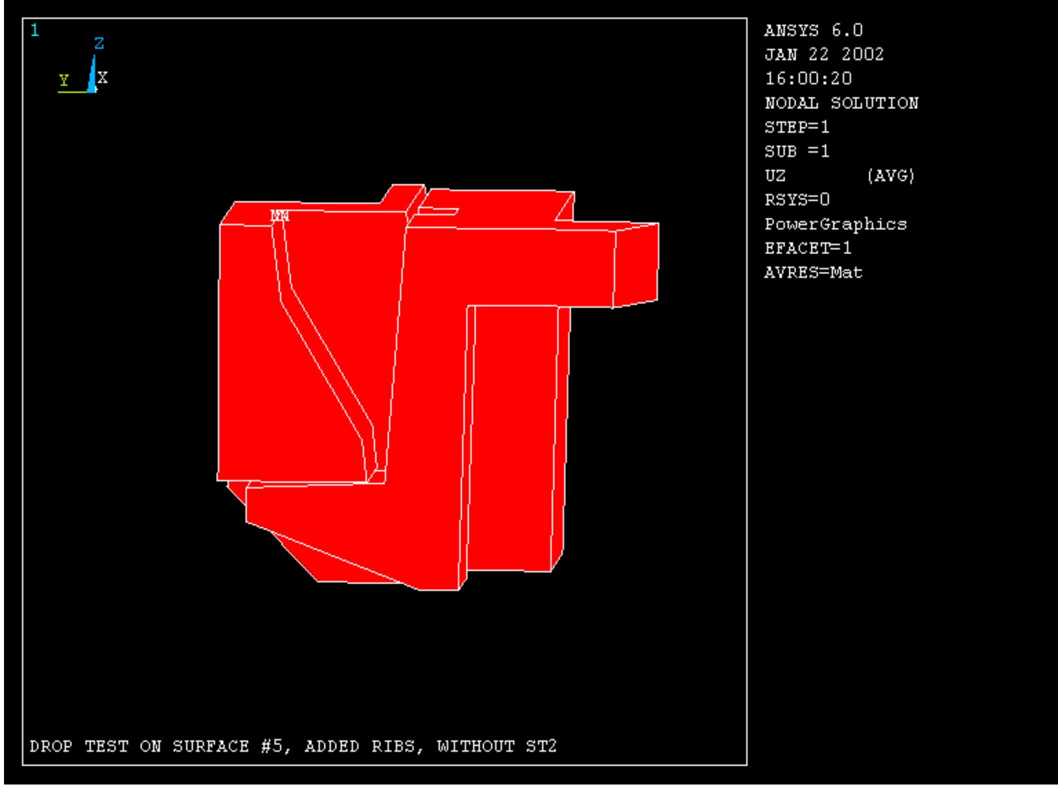
4) Module Vibration Durability Simulation Results
- For Alternative Board Support & Transformer Locations



4) Physics of Failure Example - Shock

- Computer Simulation Visualizes Transition of the Shock Wave Through the Structure of the Module.
- Peak Stresses, Material Strain, Motions & Displacements Can be Identified.
- Potential Failure Sites Where Local Stresses Exceed Material Strength Can Be Identified & Prioritized.
- Zoom In On Surface Such as Potential for Snap Lock Fastener Release
- Wire Frame View Allows Xray Vision of Internal Features.



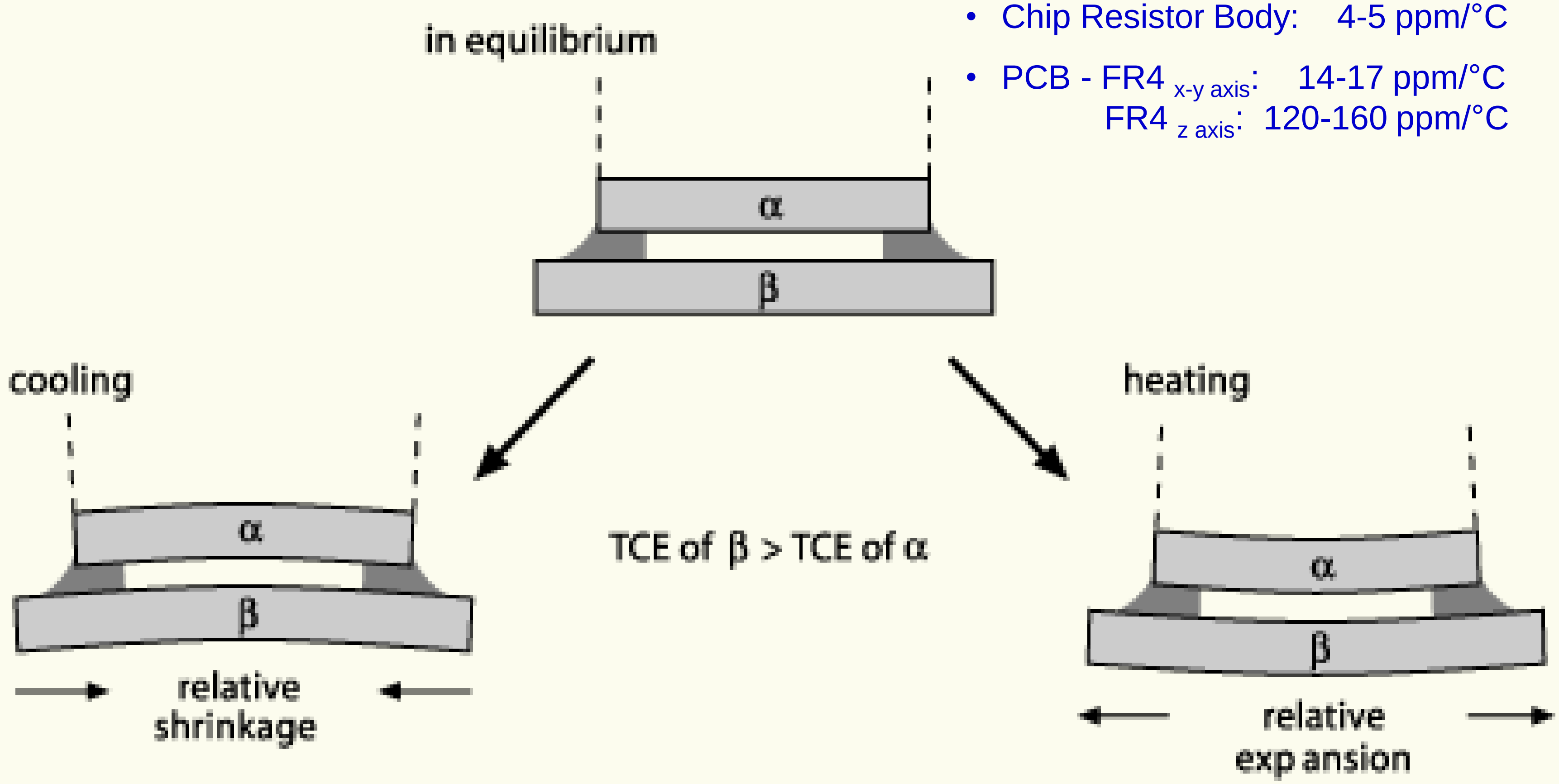


4) PoF Example Solder Thermo-Mechanical Fatigue Driven by:
Coefficient of Thermal Expansion/Contraction (CTE) Mismatch During Thermal Cycling

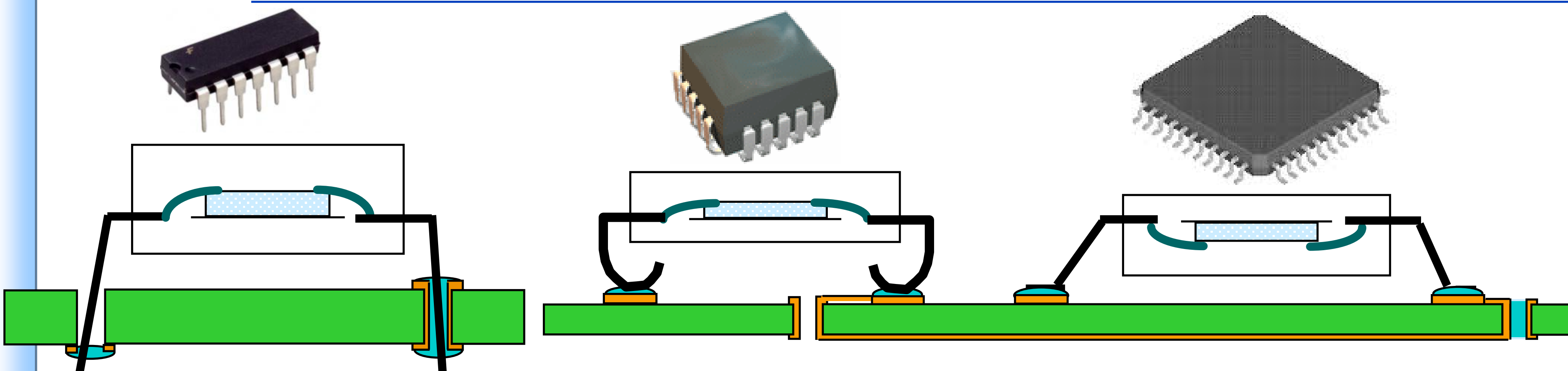
- As a circuit board and its components expand and contract at different rates the differential strain between them is absorbed by the attachment system leads and solder joints which drives metal fatigue.

Coef. Of Thermal Exp. (PPM/°C)

- Chip Resistor Body: 4-5 ppm/°C
- PCB - FR4 $_{x\text{-}y\ axis}$: 14-17 ppm/°C
  FR4 $_{z\ axis}$: 120-160 ppm/°C



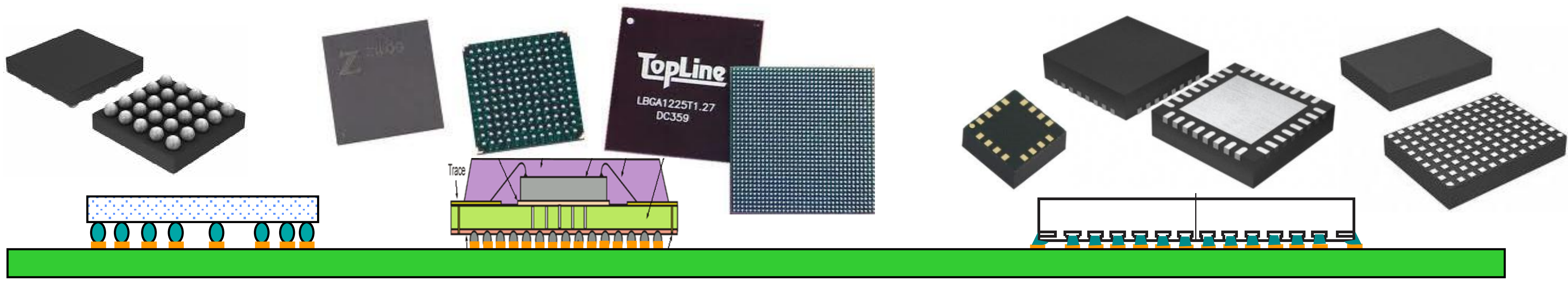
4) Solder Fatigue Life is Directly Related to Component Packaging & Solder Attachment Scheme
The IC Package Often Influences QRD more than the IC Die.



Single Sided Then Thru-hole
DIP Integrated Circuits
1970 ‘s- Today
~4 up to 68 I/O, 1” x 3.5”
Up to 10 Meg Hz Speeds.

1st Generation Quad Surface Mount
J Lead PLCC, 1982 - Today
~6 Up to 160 I/O, 1.5 in sq.,
Up to 100 Meg Hz Speeds
Source of Many Reliability Problems.

2nd Generation Quad Surface Mount
Fine Pitch Gull Wing I.C, 1993 - Today
~54 Up to 450 I/O, 1.75 in sq
Up to 250 Meg Hz Speeds
>10 Time the Life of J Lead in Auto ECMs.

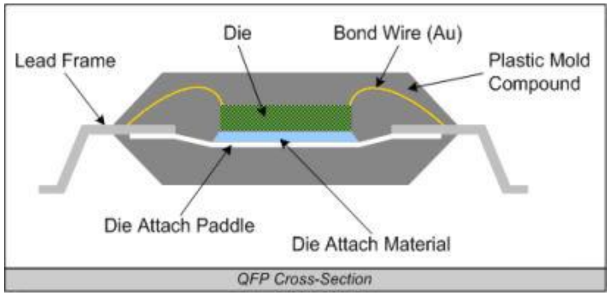


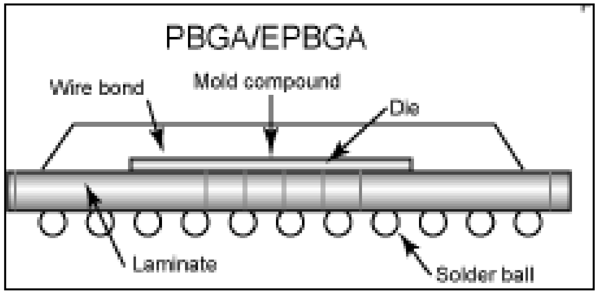
Bump & Ball Grid Arrays
Leadless Attachments
1996 - Today
~24 - 1000 I/O 1.2 in. sq
500+ 1000 Meg Hz Speeds.
Life Varies Greatly w/Size & Conf.

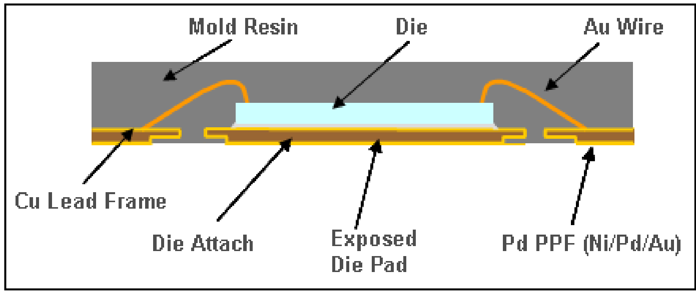
No Lead Chip Scale Packaging (NLCSP)
(LCCC, QFN, DFN, SON, LGA)
2002 - Today
~8 - 480 I/O, .75 in SQ
Gigi Hz Speeds
Can have significantly reduces life

4) Comparing Thermal Cycling Durability of Flat No Lead (FNL) IC Package Reliability: Thermal Cycling

- **Without a flexible terminal lead to absorb thermal Expansion/Contract motions, a high amount of thermal expansion stress is applied to the low profile under body solder joints, which accelerate solder fatigue failure.**
- **Solder Attachment Cycles to Failure**
  - **Order of magnitude (10X) reduction from QFPs**
  - **3X reduction from BGAs**







Gull Wing Leaded QFPs
TTCL: >10,000

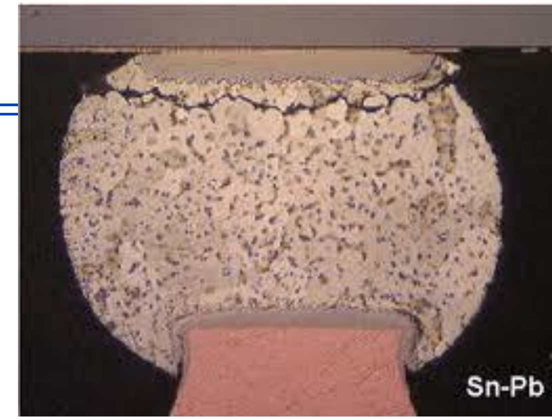
Laminated BGAs:
TTCL: 3,000 to 8,000

FNL CSP:
TTCL: 1,000 to 3,000

**TTCL = Typical Thermal Cycle Life During -40° to +125°C Testing*

Package Type	Typical Thermal Cycles to Failure (-40C to 125C)
QFP	>10,000
BGA	3,000 – 8,000
QFN	1,000-3,000

4) Thermal Cycling Solder Fatigue Model
(Modified Engelmaier – Leadless Device)



- Modified Engelmaier
  - Semi-empirical analytical approach
  - Energy based fatigue

$$\Delta\gamma = C\frac{L_D}{h_s}\Delta\alpha\Delta T$$

- Determine the strain range (Δγ)
  - Where: C is a function of activation energy, temperature and dwell time, LD is diagonal distance, a is CTE, DT of temperature cycle & h is solder joint height

- Determine the shear force applied at the solder joint

$$(\alpha_2-\alpha_1)\cdot\Delta T\cdot L_D = F\cdot\left(\frac{L_D}{E_1A_1}+\frac{L_D}{E_2A_2}+\frac{h_s}{A_sG_s}+\frac{h_c}{A_cG_c}+\left(\frac{2-\nu}{9\cdot G_b a}\right)\right)$$

  - Where: F is shear force, LD is length, E is elastic modulus, A is the area, h is thickness, G is shear modulus, and a is edge length of bond pad.
  - Subscripts: 1 is component, 2 is board, s is solder joint, c is bond pad, and b is board
  - Takes into consideration foundation stiffness and both shear and axial loads (Models of Leaded Components factor in lead stiffness / compliancy)

- Determine the strain energy dissipated in the solder joint

$$\Delta W = 0.5\cdot\Delta\gamma\cdot\frac{F}{A_s}$$

- Calculate N50 cycles-to-failure using:
  - An Energy Based model for SnPb
  - The Syed-Amkor model for SAC

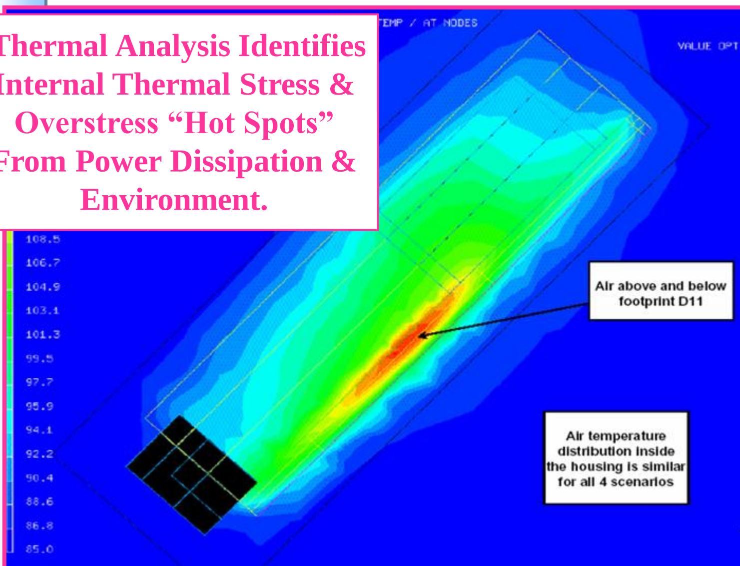
$$N_f = (0.0019\cdot\Delta W)^{-1}$$

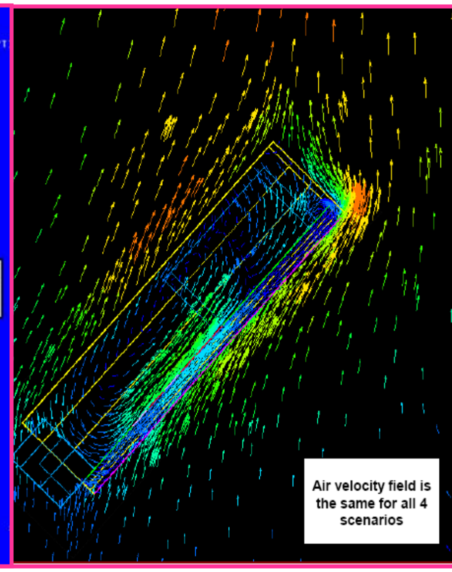
$$N_f = (0.0006061\cdot\Delta W)^{-1}$$

5) Thermal Stress & Thermal-Mech. Reliability

- Detection of the Module's Durability Weak Link,
- Two Large 1020 Resistors, Located in the High Temperature Zone

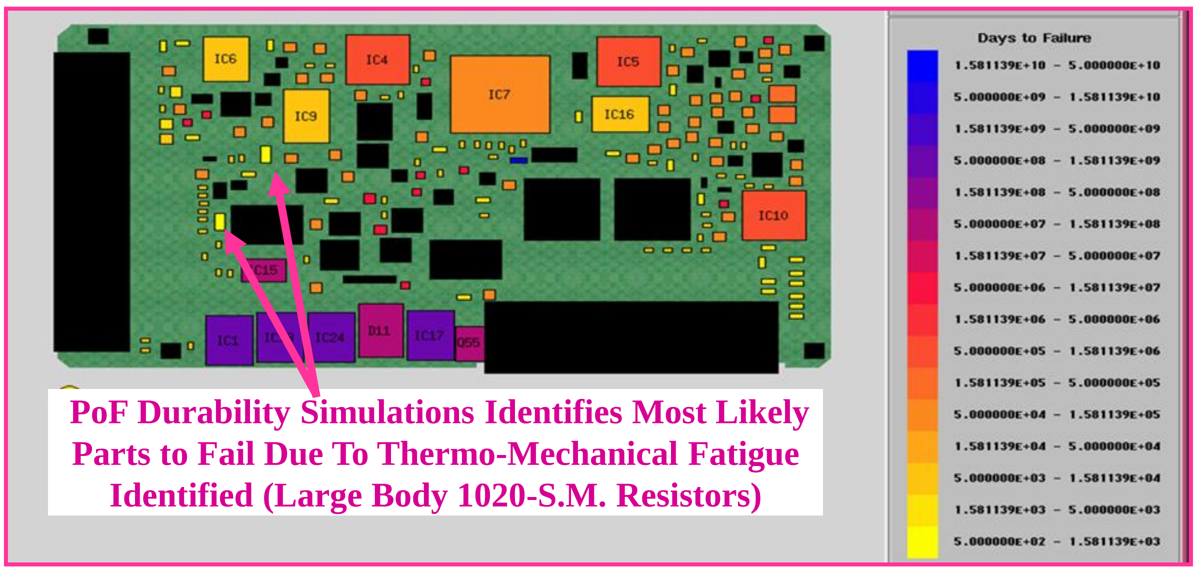
Thermal Analysis Identifies Internal Thermal Stress & Overstress "Hot Spots" From Power Dissipation & Environment.



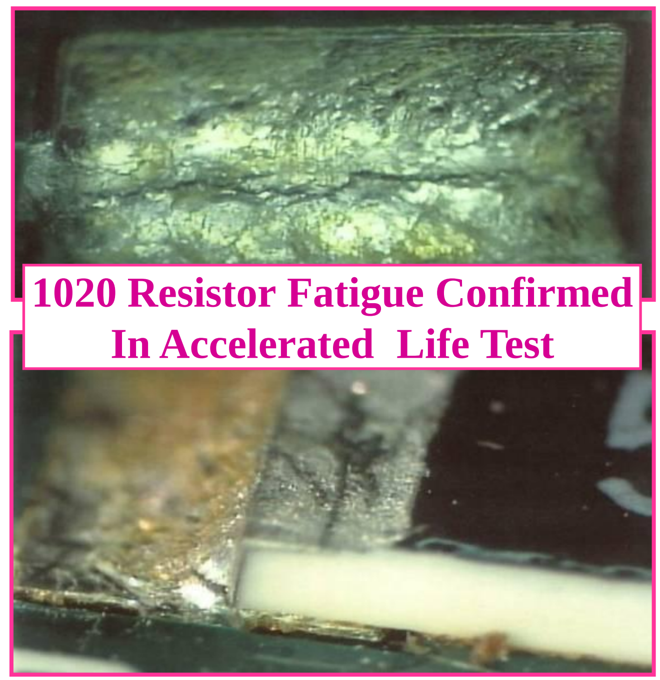


Infrared Thermal Imaging Of Thermal Stress & Overstress "Hot Spots"

Thermal-Mechanic Durability Modeling to Identify Potential Intermittent Circuits Due to Themo-Mechanical Fatigue

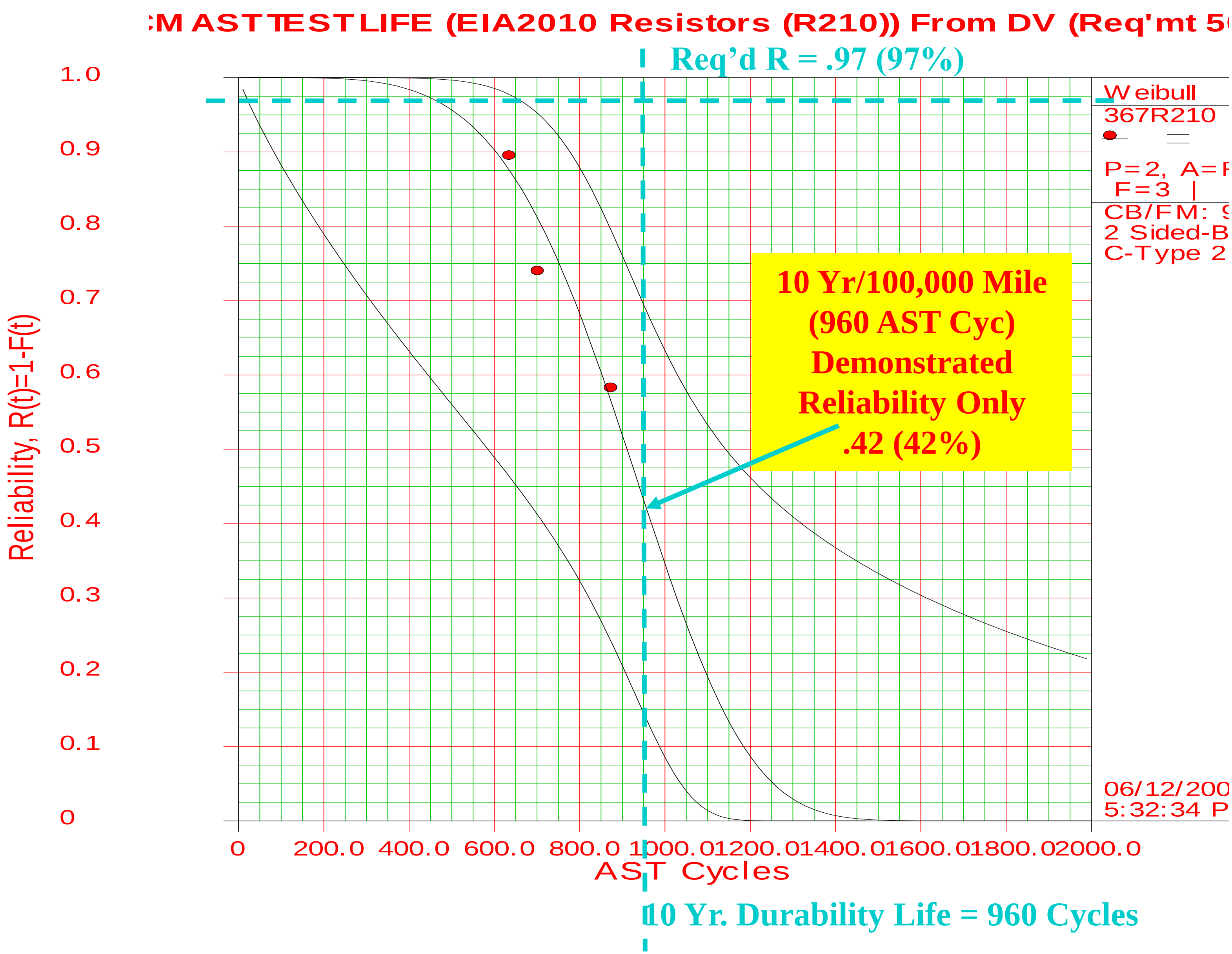


PoF Durability Simulations Identifies Most Likely Parts to Fail Due To Thermo-Mechanical Fatigue Identified (Large Body 1020-S.M. Resistors)



1020 Resistor Fatigue Confirmed In Accelerated Life Test

5) Resistor Reliability vs Thermal Cycles



5) Plated Through Hole Via Barrel Cracking Fatigue Life Based On IPC TR-579

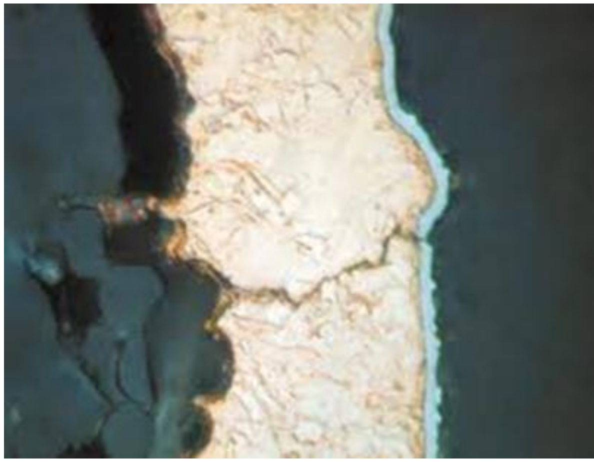
- Determine applied stress applied (σ)

$$\sigma = \frac{(\alpha_E - \alpha_{Cu})\Delta T A_E E_E E_{Cu}}{A_E E_E + A_{Cu} E_{Cu}}, \text{for } \sigma \le S_y$$

$$\sigma = \frac{\left[(\alpha_E - \alpha_{Cu})\Delta T + S_y \frac{E_{Cu} - E'_{Cu}}{E_{Cu} E'_{Cu}}\right] A_E E_E E'_{Cu}}{A_E E_E + A_{Cu} E'_{Cu}}, \text{for } \sigma > S_y$$

$$A_E = \frac{\pi}{4}\left[(h+d)^2 - d^2\right]$$

$$A_{Cu} = \frac{\pi}{4}\left[d^2 - (d-2t)^2\right]$$



- Determine strain range (Δε)

$$\Delta\varepsilon = \frac{\sigma}{E_{Cu}}, \text{for } \sigma < S_y$$

$$\Delta\varepsilon = \frac{S_y}{E_{Cu}} + \frac{\sigma - S_y}{E'_{Cu}}, \text{for } \sigma > S_y$$

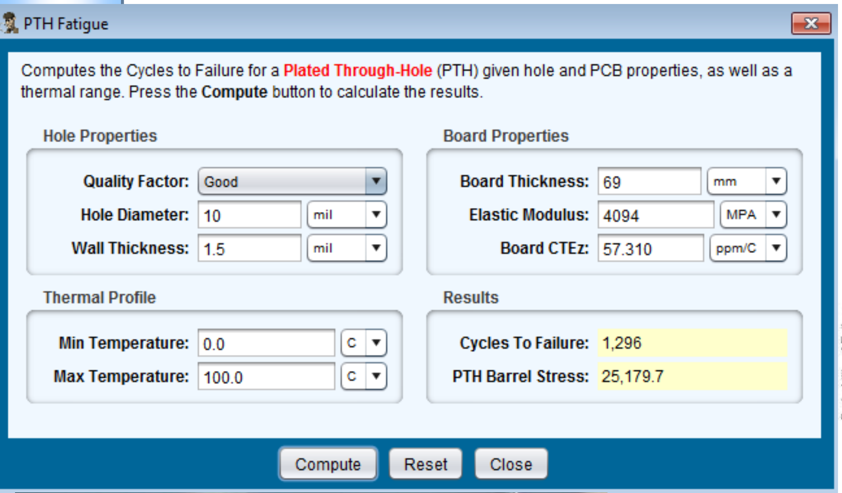
- Apply calibration constants
  - Strain distribution factor, K_d(2.5 –5.0)
  - PTH & Cu quality factor K_Q(0 –10)

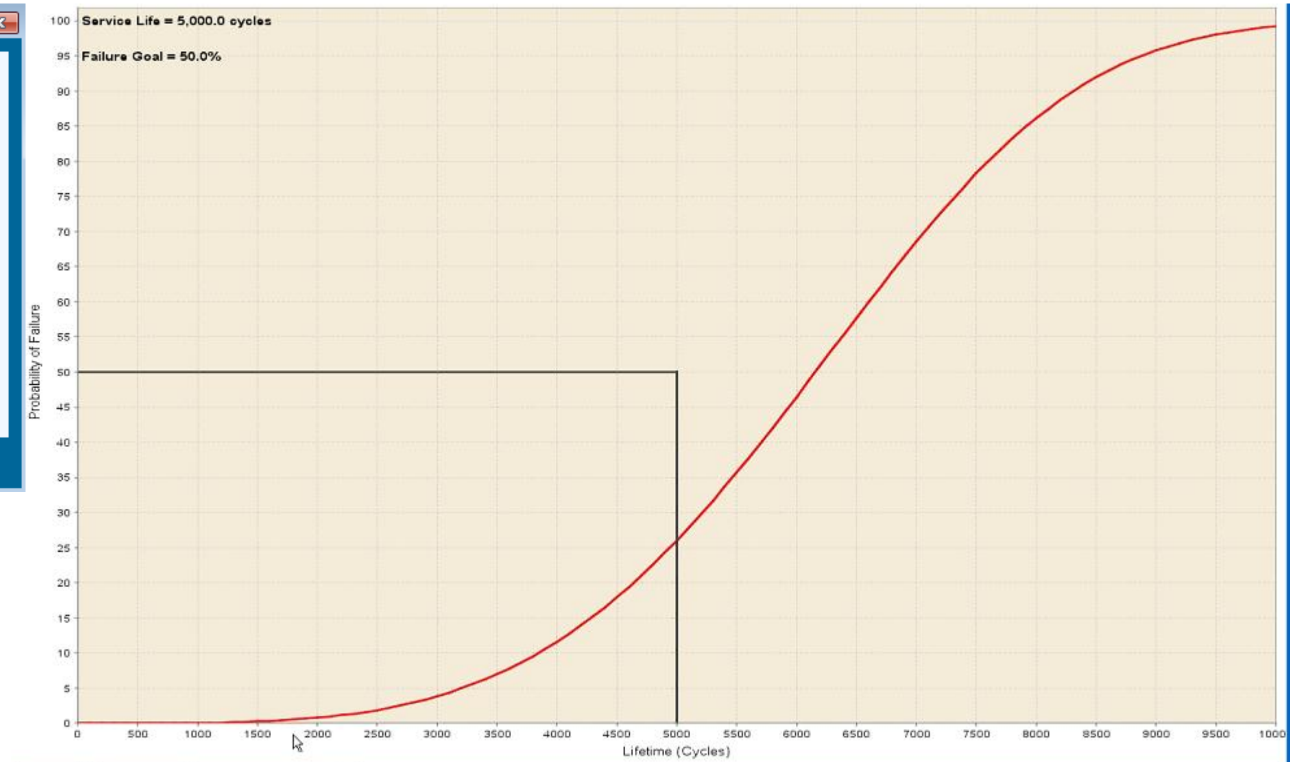
$$\Delta\varepsilon_{eff} = \Delta\varepsilon\left(K_d \frac{10}{K_Q}\right)$$

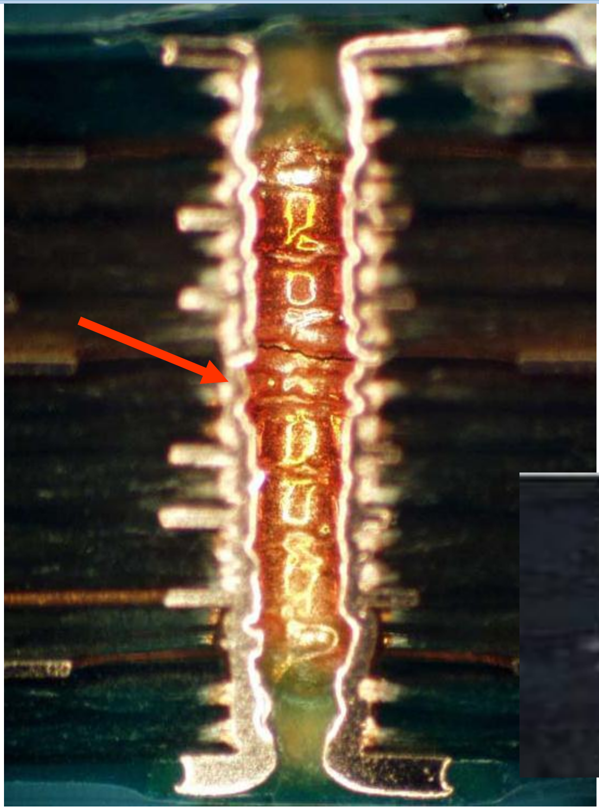
- Iteratively calculate cycles-to-failure (N_{f50})

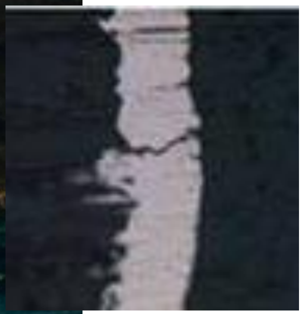
$$N_f^{-0.6} D_f^{0.75} + 0.9 \frac{S_u}{E}\left[\frac{\exp(D_f)}{0.36}\right]^{0.1785 \log \frac{10^5}{N_f}} - \Delta\varepsilon = 0$$

5) PoF Durability/Reliability Risk Assessments
PCB Plated Through Hole Via Fatigue Analysis



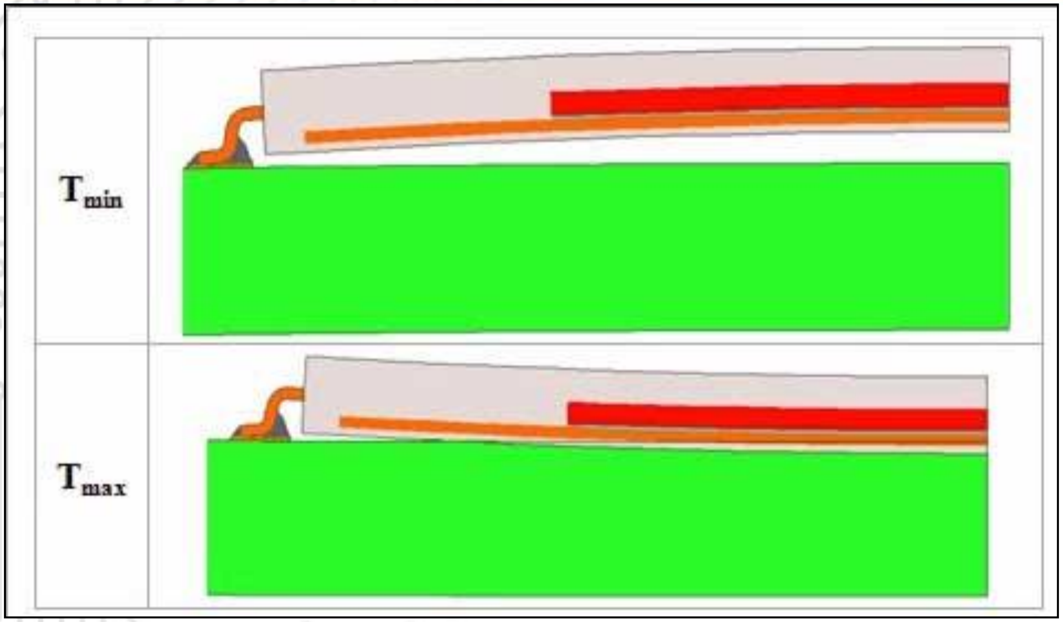




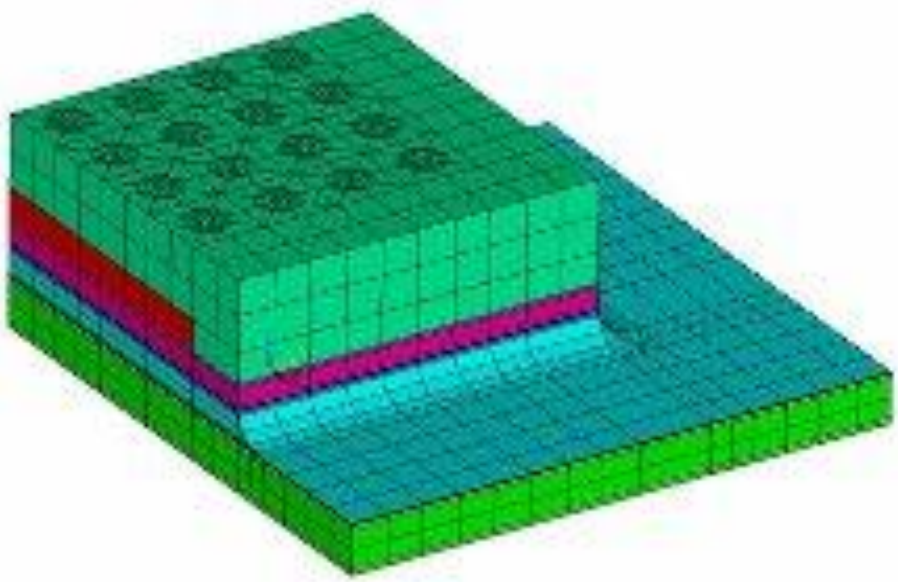


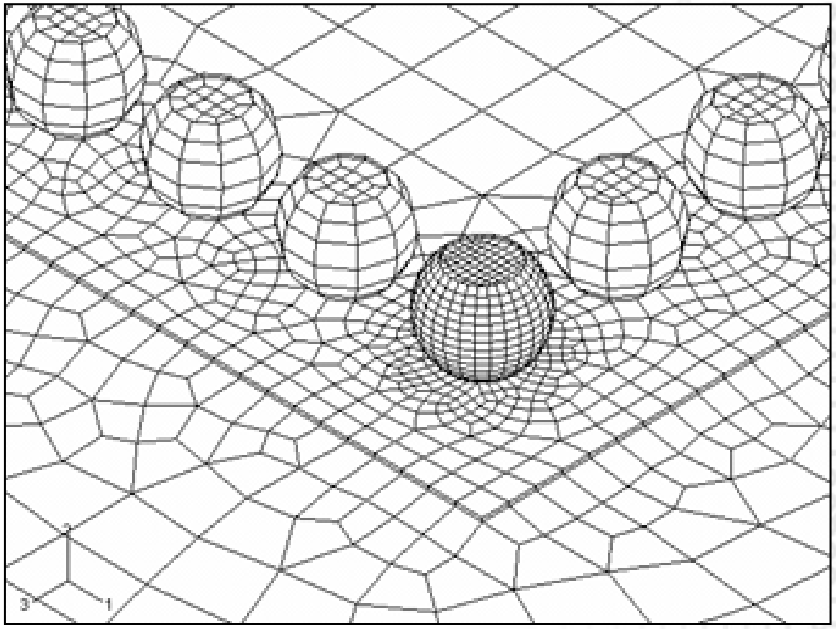
When a PCB experiences thermal cycling the expansion/ contraction in the z-direction is much higher than that in the x-y plane. The glass fibers constrain the board in the x-y plane but not through the thickness. As a result, a great deal of stress can be built up in the copper via barrels resulting in eventual cracking near the center of the barrel as shown in the cross section photos below.

5) Originally Stress Analysis & PoF Modeling was a Time Consuming Process Requiring a Experienced CAE & PoF Expert to Create a Custom Finite Element Model of “Each” Individual Issues



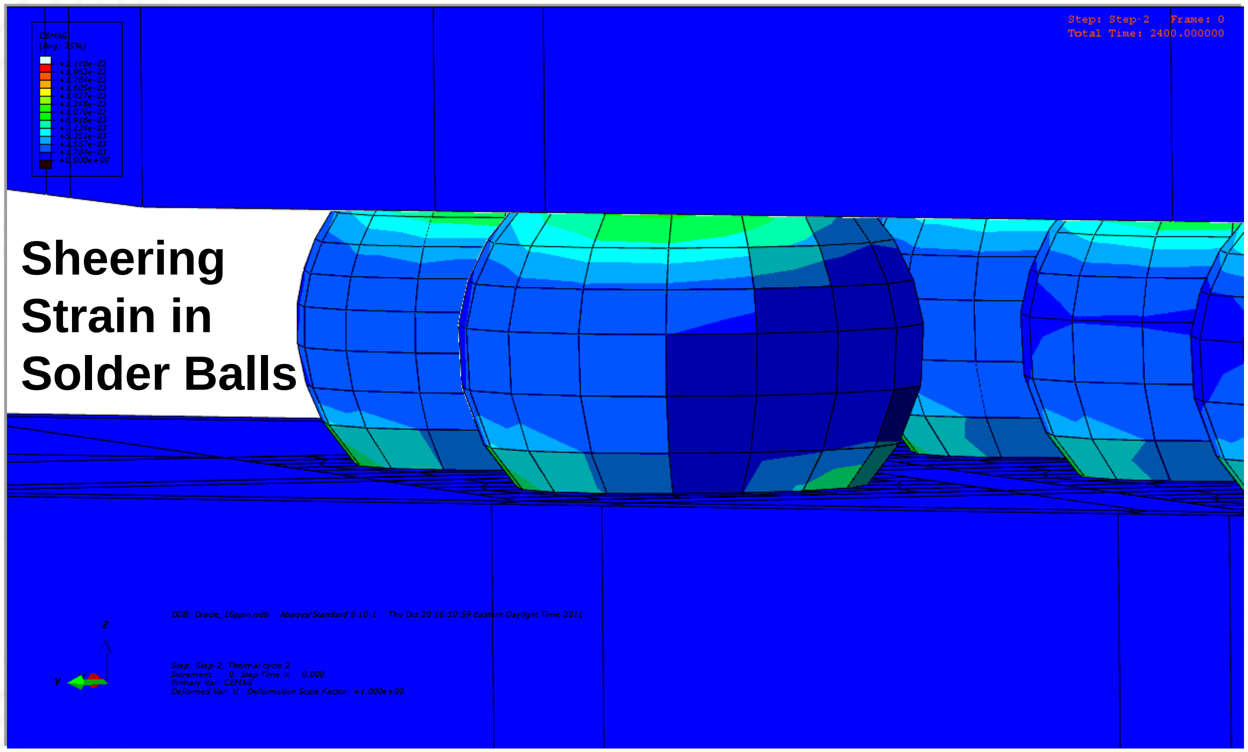
- PoF Models for Stress-Stain Structural Analysis are well proved.
- But creating custom FEA models of EE modules is not easy:
  - Time Consuming & Expensive
  - Shortage of PoF CAE modelers.
  - Structural analysis CAE resources are not always deployed to EE Enrg. Depts.





5) PoF CAE Thermal Cycling Simulation - Reveals Issues That Could Never Be Seen or Measured in a Physical Test

BGA IC CTE = 10 PPM/°C



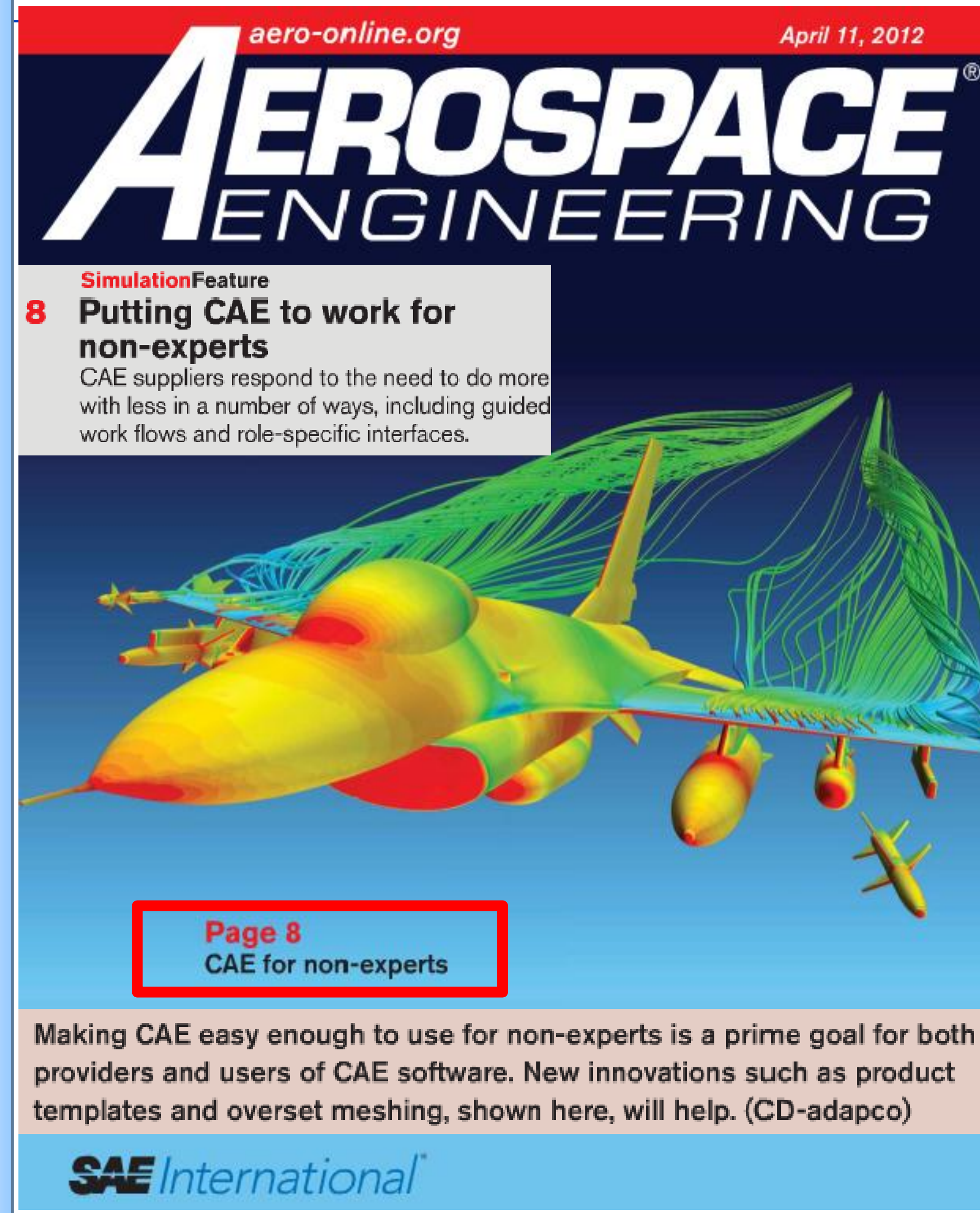
Circuit Board CTE = 15 PPM/°C

Simulated Thermal Cycle of 0 to +100°C

- PoF Models for Stress-Stain Structural Analysis are well proved.
- But creating custom FEA models of EE modules is not easy:
  - Time Consuming & Expensive
  - Shortage of PoF CAE modelers.
  - Structural analysis CAE resources are not always deployed to EE Enrg. Depts.

5) CAE PoF Durability Simulations and Reliability Analysis is a Natural Progression of Math Based, Virtual, Computer Aided Engineering Tools Used in Structural Analysis of Vehicles, Aircraft, Buildings, Bridges . . .

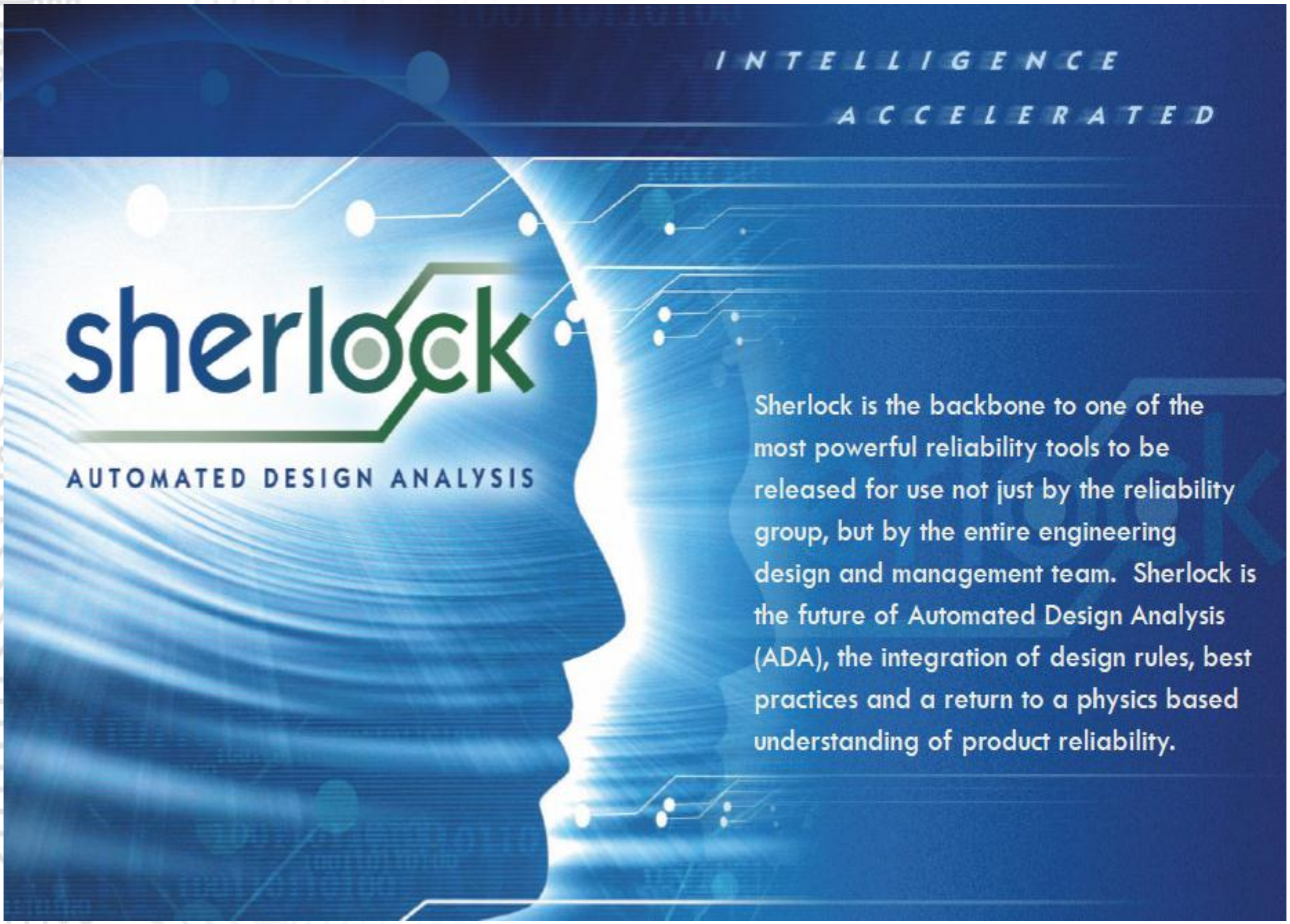
5) An Emerging Trend:
- Application Specific CAE Simulations Apps



- Application Specific Customized CAE Solutions.
- An emerging trend where auto guided, specific function, CAE Apps or analysis templates are created to Provides a common, reusable semi-automated interface for:
  - Perform regularly needed product optimization modeling
  - Solving frequently encountered problems.
  - Allows product teams to perform expert level CAE analysis without a rare, high cost PoF CAE expert
  - Link to article summary: http://www.sae.org/mags/SVE/10767 **or full article** http://magazine.sae.org/12aerd0411 **(subscription may be required)**

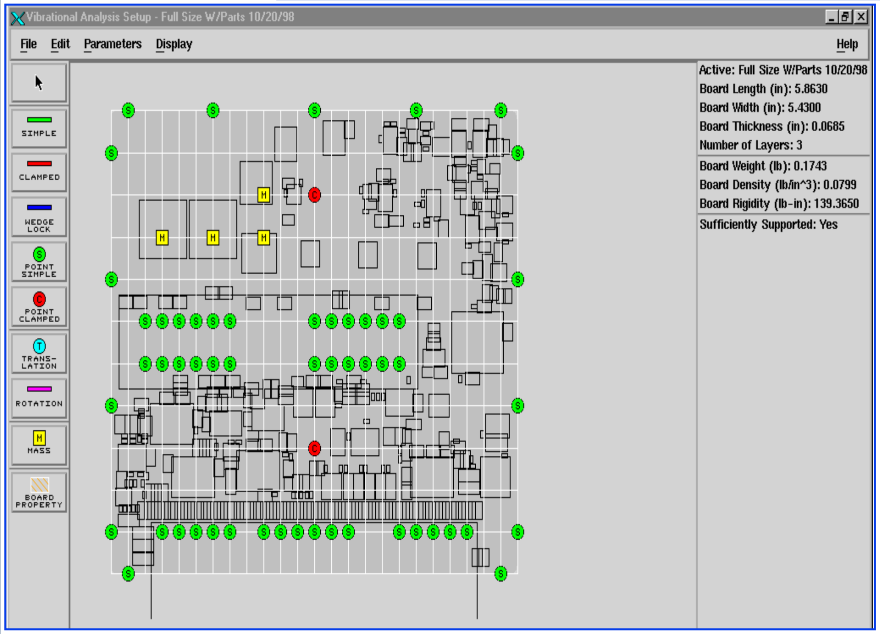
5) A Physics of Failure CAE App for Electronics

- A Semi-Automated CAE App / CAE Tool Suite for Physics of Failure Durability Simulations & Reliability Assessment of Electronic Equipment

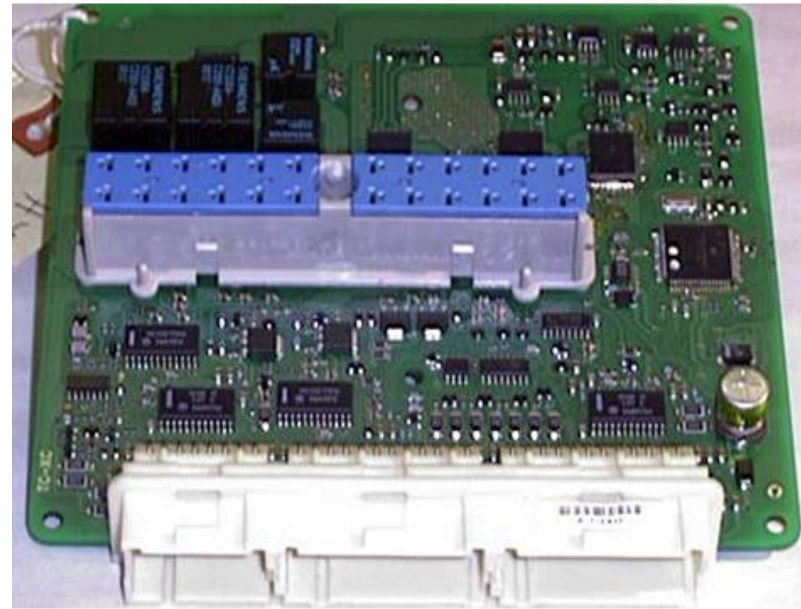


It is not at the Iphone or Droid App store.
But yes there is now a Physics of Failure Durability Simulation App

5) A PoF App Enables Math Based Product Development Processes & Tools For Electronics



MATH TO HARDWARE



A) Durability / Reliability Simulations – "A" Analysis

- Evaluate Durability Capability and
- Identify Specific Reliability Risks
- While Still on the CAD Screen

B) First Article Evaluation via Direct Quality Assessments – "D" Development

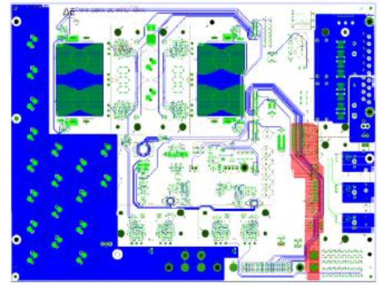
- Verify PCB Fabrication and Assembly Quality Meets Design Requirement
- Before Starting Stress Life Testing

C) Refocused Physical Durability Testing – "V" Validation w/Simulation Aided Accelerated Testing

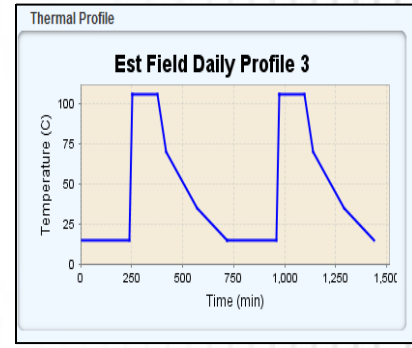
- Optimized and Refocused from a Discover Process to a Final Conformation Procedure

5) The 4 Steps of a Sherlock PoF Analysis

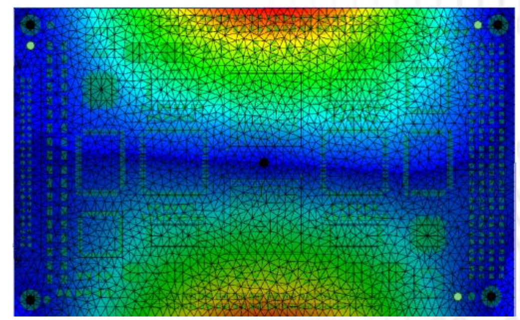
1) Design Capture - provides the detailed inputs to the modeling software and calculation tools



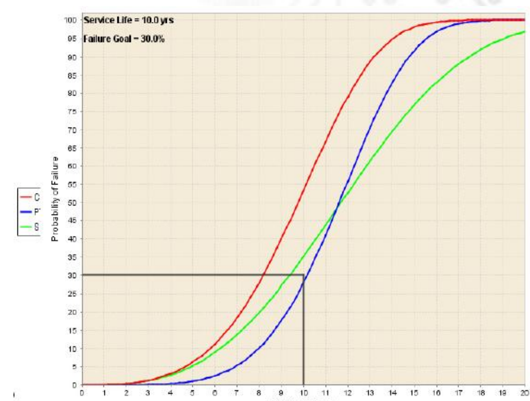
2) Life-Cycle Characterization - define the reliability/durability objectives and expected environmental & usage conditions (Field or Test) under which the device is required to operate



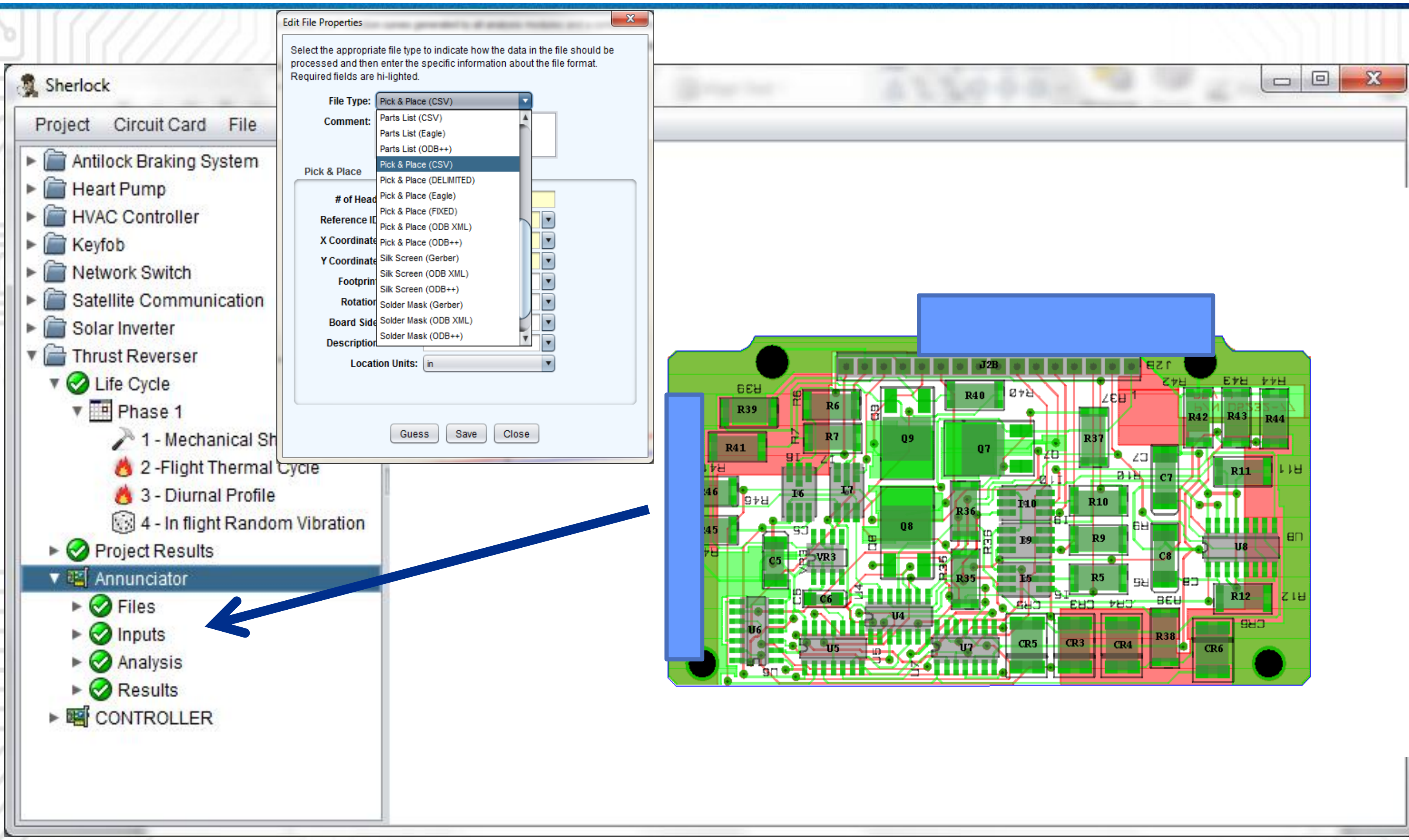
3) Load Transformation – auto creates a Finite Element Analysis to calculate and distribute the environmental and operational loads across a circuit board to the individual parts and features.



4) PoF Durability Simulation/Reliability Analysis & Risk Assessment – Performs a design and application specific durability simulation to calculates life expectations, reliability distributions & prioritizes risks by applying PoF algorithms to the virtual PCBA model created in steps 1, 2 & 3



5) Step 1 - Design Capture



- Creates CAE virtual model from standard circuit board CAD/CAM design files (Gerber / ODB Format)

5) Step 1 - Design Capture - Define PCB Laminate & Layers to Calculate Substrate Performance

- Calculates
- Thickness
- Density
- CTE x-y
- CTE z
- Modulus x-y
- Modulus z
- From the material properties of each layer
- Using the Built in Laminate Data Library

Stackup Properties

The following board properties are based on the currently defined board outline and the individual layer properties shown below:

Board Size: 193 x 115 mm [7.6 x 4.5 in]
Board Thickness: 1.8 mm [69.0 mil]
Board Density: 2.6833 g/cc
Copper Layers: 4

CTExy: 13.576 ppm/C
CTEz: 57.310 ppm/C
Exy: 37,972 MPa
Ez: 4,094 MPa

Stackup Layers

Double click any row to edit the properties for that layer or select one or more rows and press the **Edit Selected** button below to edit properties for a batch of layers. Press the **Generate Stackup Layers** button to replace all layers using a given PCB thickness and default layer properties.

Layer	Type	Material	Thickness	Density (g...	CTExy (pp...	CTEz (pp...	Exy (MPa)	Ez (MPa)
1	SIGNAL	COPPER (50%)	2.0 oz	5.2800	17.600	17.600	113,000	113,000
2	Laminate	FR408	19.3 mil	1.9000	13.000	65.000	23,442	3,450
3	POWER	COPPER (90%)	2.0 oz	8.1760	17.600	17.600	113,000	113,000
4	Laminate	FR408						
5	POWER	COPPEF						
6	Laminate	FR408						
7	SIGNAL	COPPEF						

Select All | Select C

Edit Selected Layers

Enter values for each layer property.

Laminate Layer Properties

Laminate Material: Isola | FR-4 | FR408

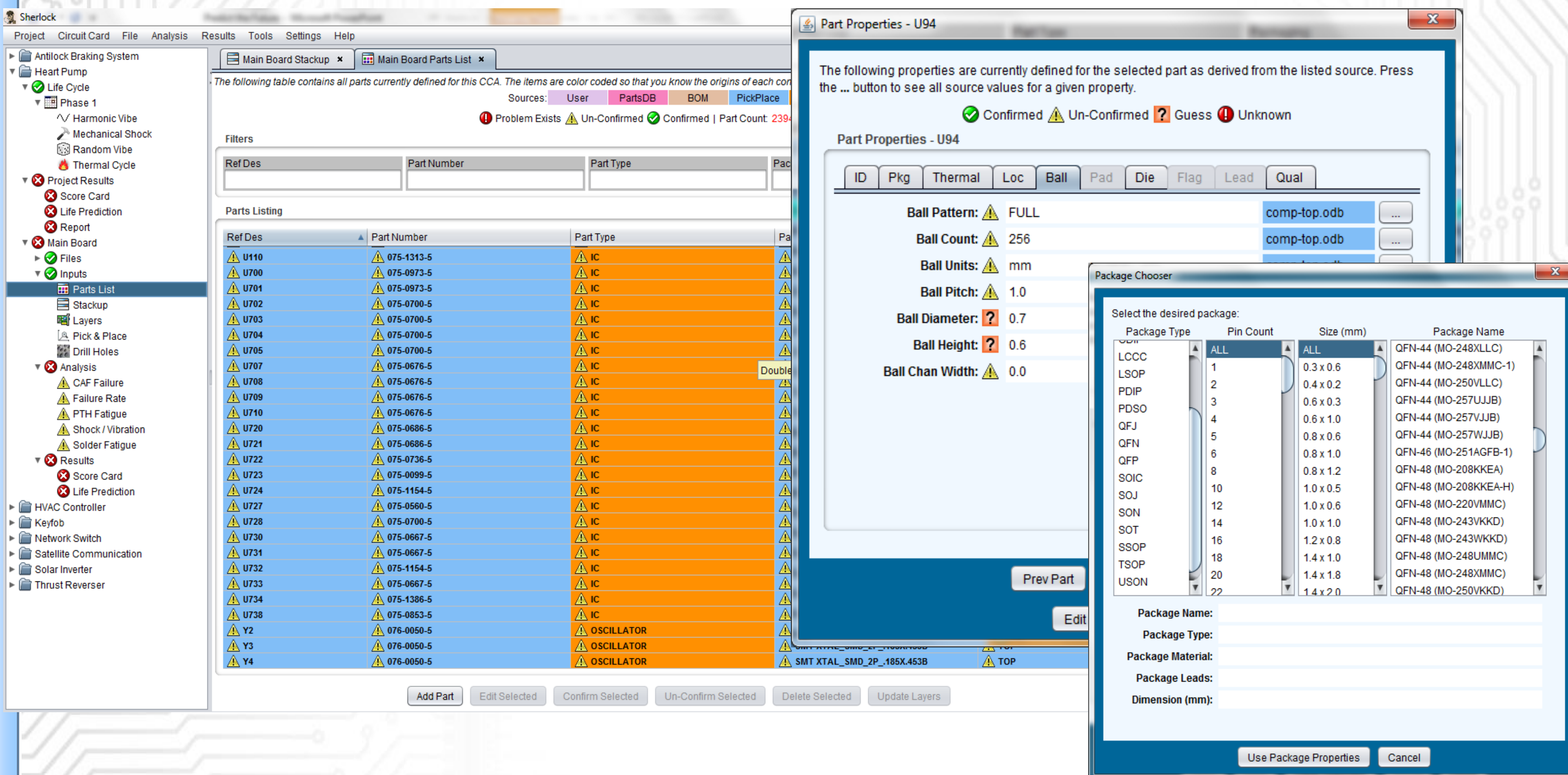
Laminate Thickness: 19.3 mil

250 HR
254
370 TURBO
370HR
370HR-CORE
DE104/104ML
DE104TS
DE104i

Save | Reset | Cancel

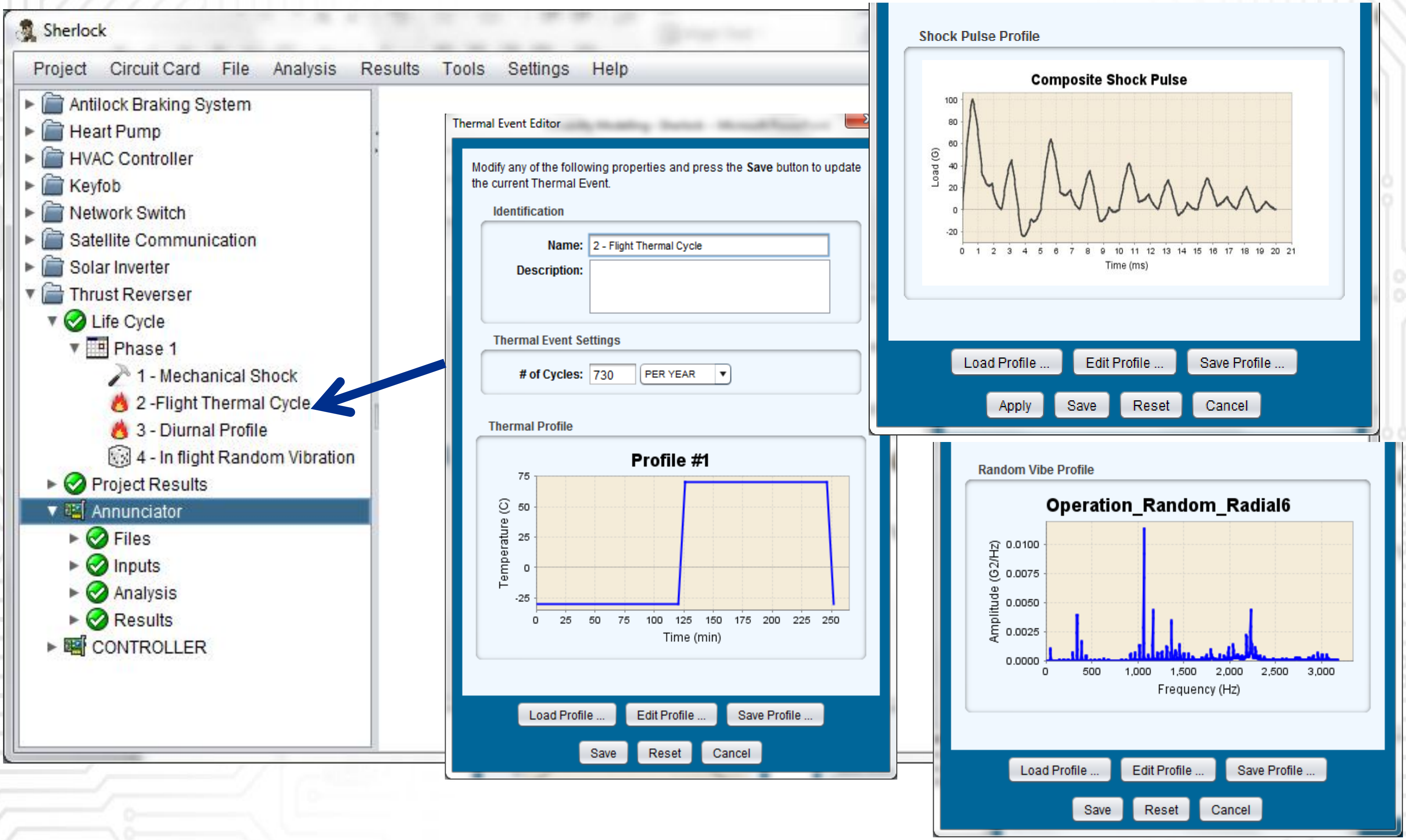
.6 x 4.5 in]

5) Step 1 - Parts ID, Management & Linkage to Build In PoF Component Model Library



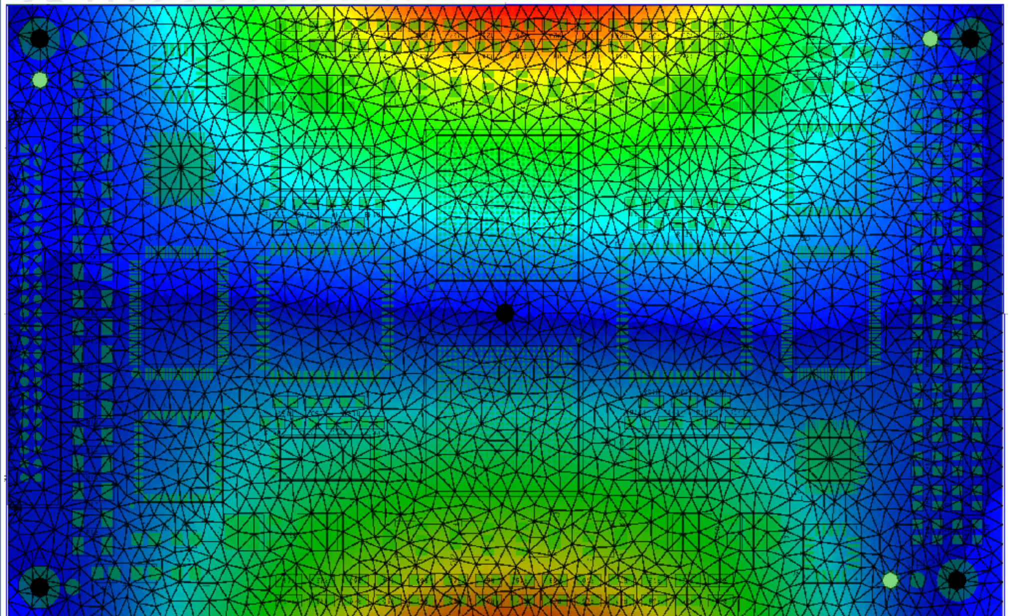
- Minimizes data entry through intelligent parsing and embedded electronic components package and material databases

5) Step 2 – Life Cycle Characterization Define Field or Test Usage & Environmental Conditions

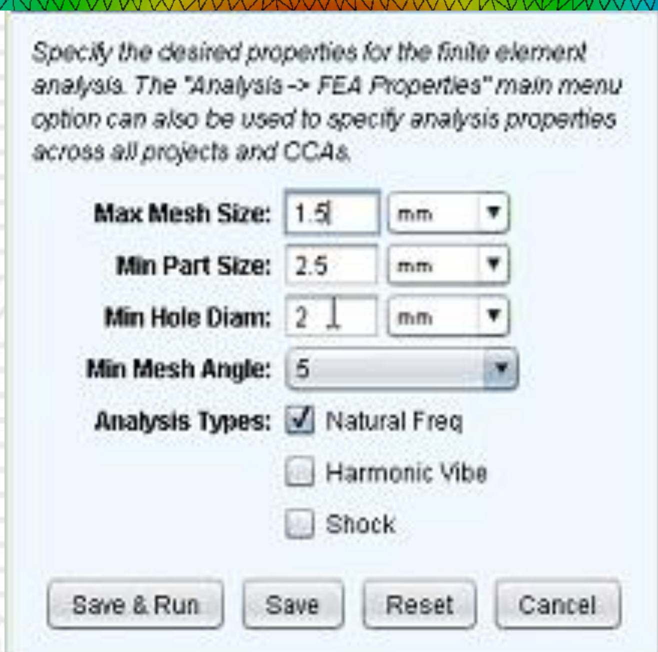


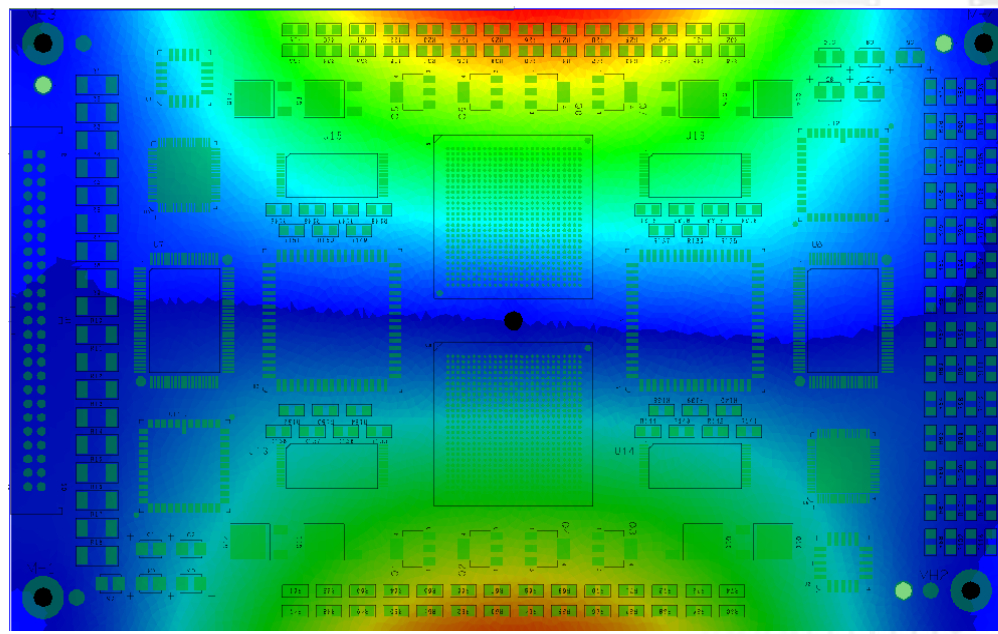
- Define Detail Lifetime Thermal, Vibration & Shock Stress Profiles

5) Step 3 - Load Transformation
Automated FEA Mesh Creation for Calculating Stress Distribution Across the Circuit Board & to Each Component



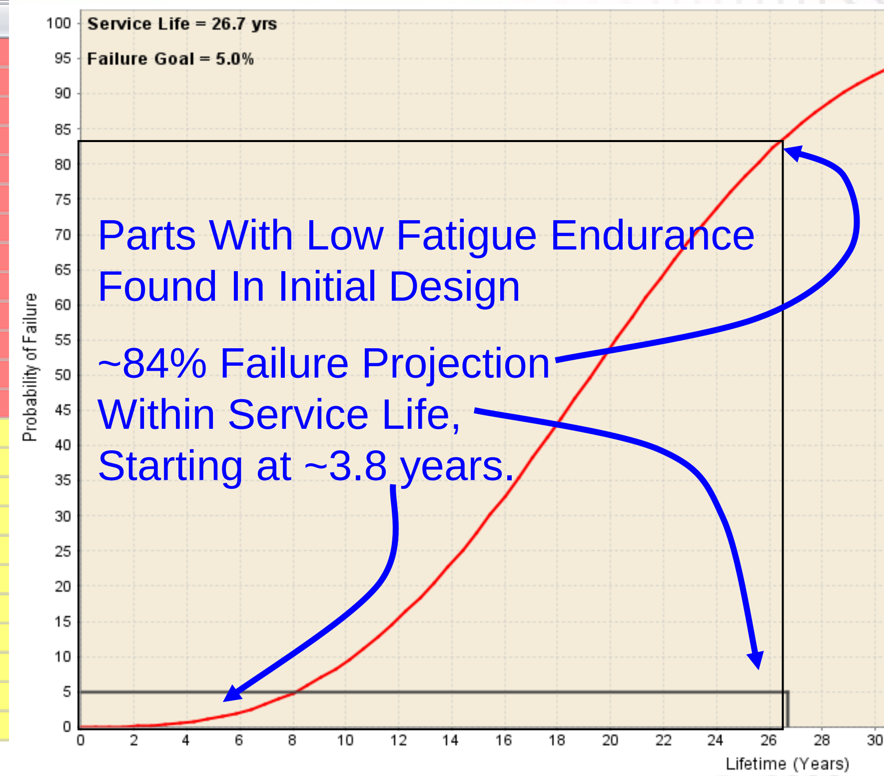
- Automatic Mesh Generation
  - Days of FEA modeling and calculations, executed in minutes
  - Without a FEA modeling expert.





5) Step 4 - PoF Durability Simulation & Reliability Risk Assessment Thermal Cycling Solder Fatigue

RefDes	Package	Part Type	Part Number	Solder	Temp Rise	Cycles to Fail ▲	TTF (yrs)
R355	2512	RESISTOR	SCD	63Sn37Pb	0.0	90,605	93.89
R339	2512	RESISTOR	SCD	63Sn37Pb	0.0	90,605	93.89
R347	2512	RESISTOR	SCD	63Sn37Pb	0.0	90,605	93.89
R435	2512	RESISTOR	SCD	63Sn37Pb	0.0	90,605	93.89
R363	2010	RESISTOR	SCD	63Sn37Pb	0.0	96,085	99.57
R364	2010	RESISTOR	SCD	63Sn37Pb	0.0	96,085	99.57
R6	2010	RESISTOR	SCD	63Sn37Pb	0.0	96,085	99.57
R126	2010	RESISTOR	SCD	63Sn37Pb	0.0	96,085	99.57
R123	2010	RESISTOR	SCD	63Sn37Pb	0.0	96,085	99.57
R337	2010	RESISTOR	SCD	63Sn37Pb	0.0	96,085	99.57
R338	2010	RESISTOR	SCD	63Sn37Pb	0.0	96,085	99.57
R464	2010	RESISTOR	SCD	63Sn37Pb	0.0	96,085	99.57
R461	2010	RESISTOR	SCD	63Sn37Pb	0.0	96,085	99.57
R19	1206	RESISTOR	SCD	63Sn37Pb	0.0	114,710	118.87
R15	1206	RESISTOR	SCD	63Sn37Pb	0.0	114,710	118.87
R304	1206	RESISTOR	SCD	63Sn37Pb	0.0	114,710	118.87
R305	1206	RESISTOR	SCD	63Sn37Pb	0.0	114,710	118.87
R421	1206	RESISTOR	SCD	63Sn37Pb	0.0	114,710	118.87
R422	1206	RESISTOR	SCD	63Sn37Pb	0.0	114,710	118.87
R424	1210	RESISTOR	SCD	63Sn37Pb	0.0	114,710	118.87
R413	1206	RESISTOR	SCD	63Sn37Pb	0.0	114,710	118.87
R419	1206	RESISTOR	SCD	63Sn37Pb	0.0	114,710	118.87
R262	1206	RESISTOR	SCD	63Sn37Pb	0.0	114,710	118.87
R265	1206	RESISTOR	SCD	63Sn37Pb	0.0	114,710	118.87

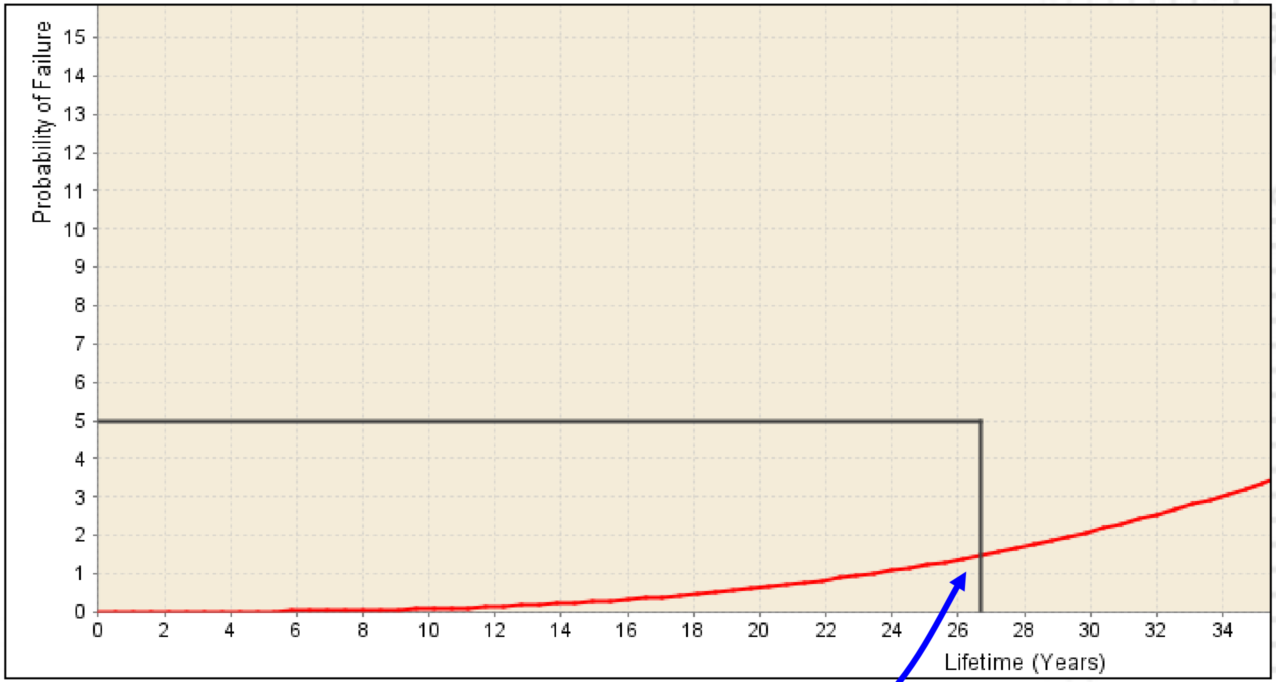


- **N50 fatigue life calculated for each of 705 components (68 unique part types), with risk color coding, prioritized risk listing and life distribution plots based on known part type failure distributions (analysis performed in <30 seconds) after model created.**
  - **Red - Significant portion of failure distribution within service life or test duration.**
  - **Yellow - Lesser portion of failure distribution within service life or test duration.**
  - **Green - Failure distribution well beyond service life or test duration.**

  (Note: N50 life - # of thermal cycles where fatigue of 50% of the parts are expected to fail)

5) Step 4 - PoF Durability/Reliability Risk Assessment Enables Virtual Reliability Growth

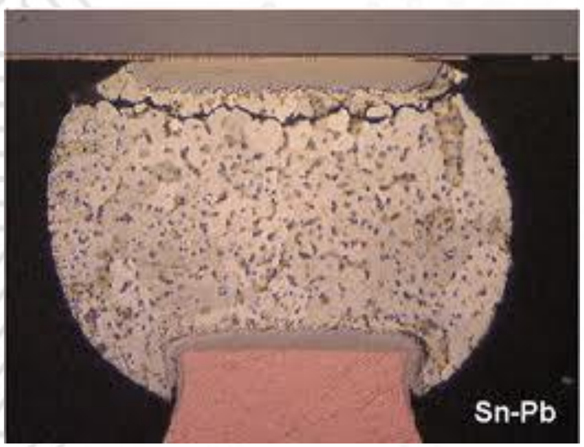
- Identification of specific reliability/durability limiting or deficiencies, of specific parts in, specific applications
- Enables the design to be revised to meet reliability/durability objectives
  - **WHILE STILL ON THE CAE SCREEN**
- Failure Risk Plot of the same project after fatigue susceptible parts replaced with electrically equivalent parts in component package suitable for the application.

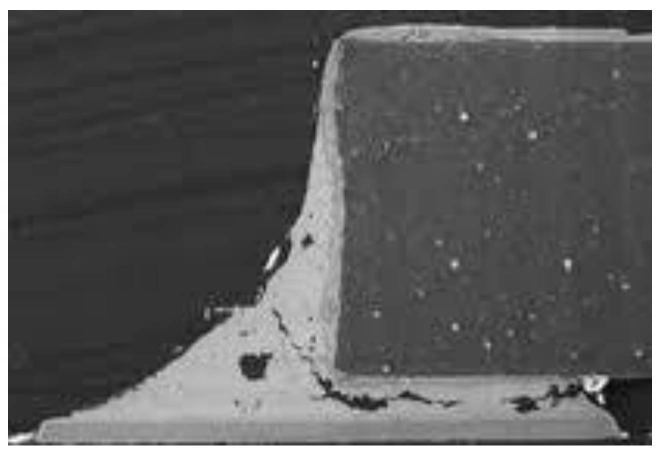


- Life time failure risks reduced from ~84% to ~1.5%

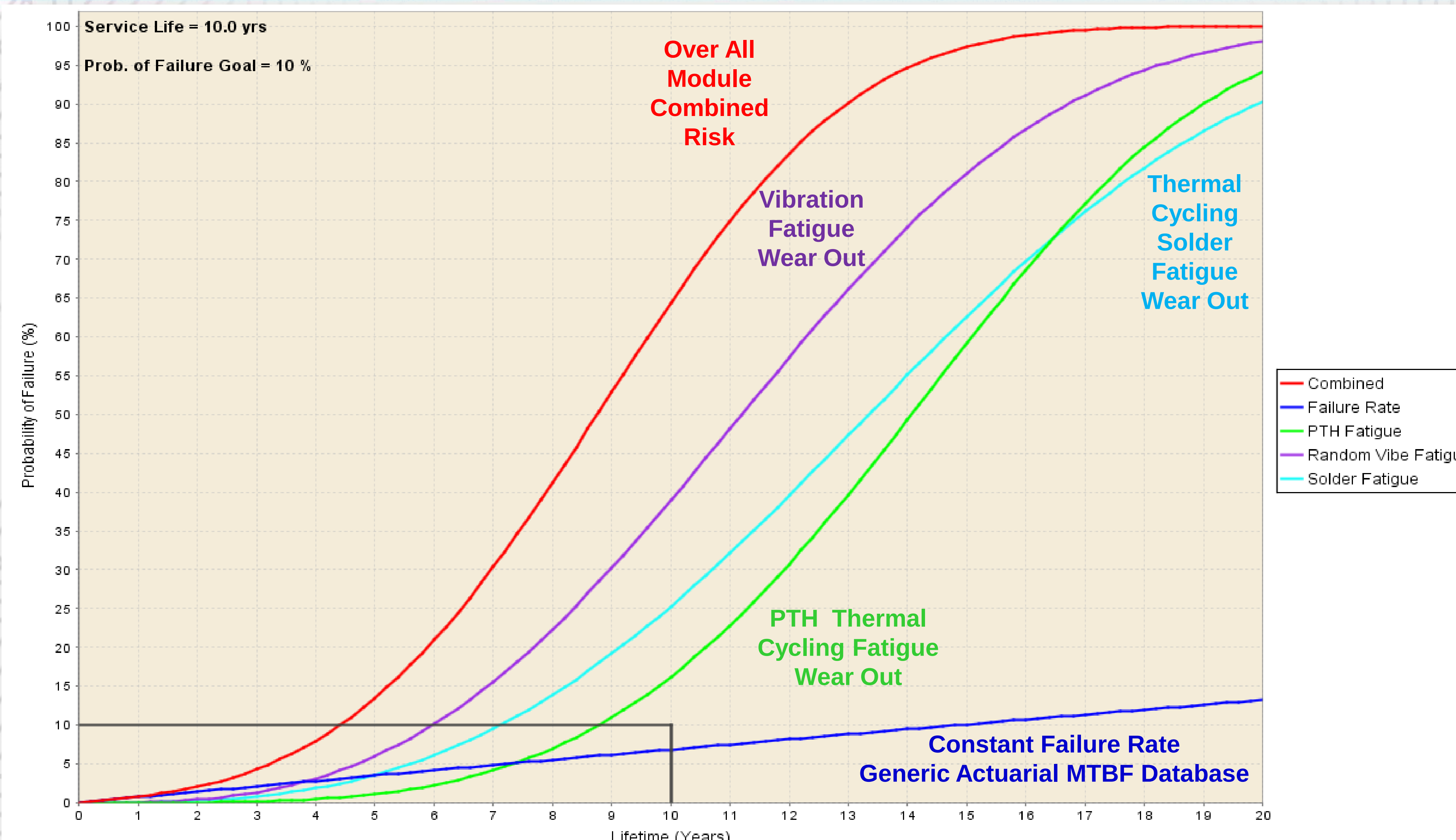
5) PoF Durability/Reliability Capabilities

- Thermal Cycling Solder Attachment Fatigue Life
- Thermal Cycling PCB PTH Via Barrel Cracking Fatigue Life
- Vibration Solder Fatigue Life
- Shock Solder Fracture Life
- Conductive Anodic Filament Risk Assessment
- ISO-26262 Functional Safety FMEA and Metric Generation



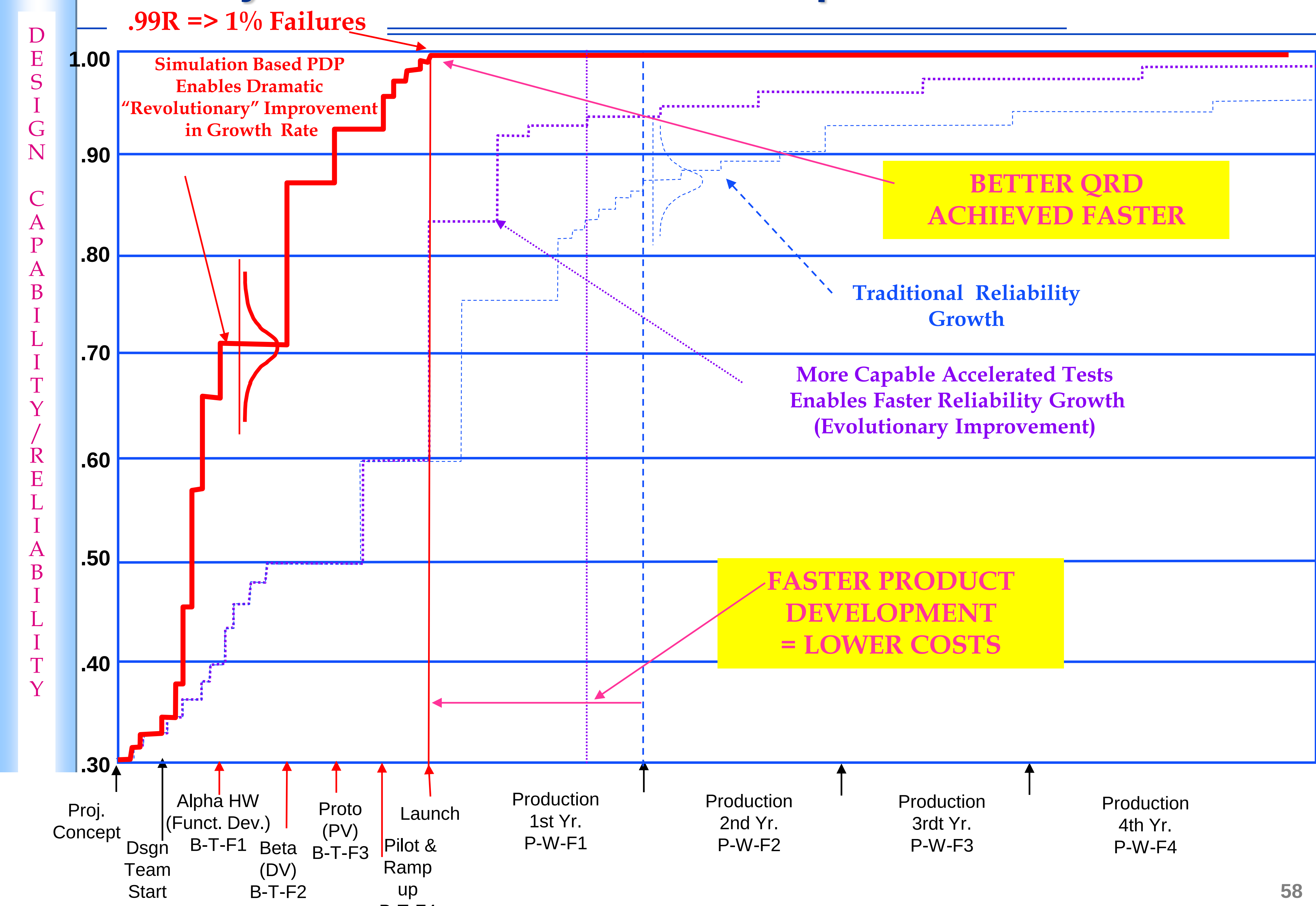


5) PoF Durability Simulations/Failure Risk Life Curves for Each Failure Mechanism Tallied to Produce a Combined Life Curve for the Entire Module



- Detailed Design and Application Specific PoF Life Curves are Far More Useful that a simple single point MTBF (Mean Time Between Failure) estimate.

5) The Efficiency Improvements of a PoF Knowledge & Analysis Based Product Development Process



6) Summary - Physics of Failure/Reliability Physics is Reliability Science for the Next Generation

- PoF Science based Virtual Validation Durability Simulation/Reliability Assessments Tools Enable Virtual Reliability.
- PoF Computer Aided Engineering (CAE) Apps Eliminates the Complexity and Need for a CAE Expert in creating and running PoF analysis models/
  - Makes PoF Analysis Faster and Cheaper than Traditional Physical Design, Build, Test & Fix Reliability Growth Tests
  - Determines if a Specific Design is Theoretically Capable of Enduring Intended Environmental and Usage Conditions.
  - Create New Roles for Reliability Professions to Define, Perform, Connect to or Oversee PoF Analysis Tasks
- Compatible with the way modern products are designed and engineered (i.e CAD/CAE/CAM).
- PoF CAE Aps Produces Significant Improvement In Accelerated Fielding of High QRD Products

Want to Know More – Suggested Reading

Questions

Thank you for your attention.

Do you have any questions?

For More Information Contact

jmcleish@dfrsolutions.com

askdfr@dfrsolution.com

301-474-0607