Introduction to Physics of Failure Reliability Methods

Webinar

Randy Schueller, Ph.D.

Sr. Member of Technical Staff

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Introduction

- Randy Schueller, Ph.D. is located in Minneapolis, MN and has worked for DfR Solutions since 2008.
  - 7 years leading Product Development at 3M Company
  - 4 years as Engineering Director at Extreme Devices
  - 5 Years as Sr. Manager of Component Engineering and Failure Analysis at Dell Computer (helped drive Pb-free transition throughout all product lines).
    - Over 30 papers written for the electronics industry
    - Owner of 15 US patents for electronic designs
    - Lead the development and commercialization of many products and resolved countless reliability issues in IC packaging, PCBs, connectors, etc.
    - Specializes in Pb-free transition, corrosion issues, PCB quality, metallurgical issues, DfR of assemblies, etc.

- DfR Solutions is an Laboratory/Failure Analysis Services, Engineering Consulting & CAE Software Development Firm
  - Formed by senior scientists from the University of Maryland’s DoD/NSF Sponsored Consortium for developing the Physics-of-Failure approach to achieving Ultra Reliability & Total Product Integrity for Electrical/Electronic Technology

- Quality, Reliability and Durability (QRD) and Failure Analysis of Electronics
  - The Sherlock ADA Durability Simulation Reliability Assessment CAE Program
  - Advanced Accelerated Testing
  - E/E Component Robustness & Supply-Chain Selection and Management
Agenda: Physics of Failure Reliability Methods

1) Overview Of PoF and Design for Reliability (DfR) and their importance
2) Limitations of Traditional Reliability Prediction Methods
3) CAE Methods for Failure Mechanism Modeling of PCBAs
4) Physics of Failure & Reliability Testing
5) Summary & Conclusions
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
What is Physics of Failure?

- **DfR Solutions:** The leveraging of 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.

- **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.

PoF is an important component of DfR.
Why is DfR Important?

Total product cost is largely locked in during the design stage.

Architectural Design for Reliability, R. Cranwell and R. Hunter, Sandia Labs, 1997
Leverage in Product Design

Development

Final Product

70% of a Product’s Total Cost is Determined by its Design

Source: *Six Sigma* by M. Harry and R. Schroeder (Published by Doubleday)
Why DfR? Earlier is Cheaper

Reduce Costs by Improving Reliability Upfront

Cost Of Unreliability
2x More

1 x
CONCEPT

10 x
DESIGN

100 x
VALIDATION

1000 x
PRODUCTION

Ideen/Skizzen
Engineering/Design
Schemen/Darstellungen

Verlust der Markanteile
Verifikation/Prüfung
Verlust von Produktion

Garantie/Recall
Prototype Parts
Product Performance: Warranty Returns

- **Consumer Electronics**
  - Table on right

- **Low Volume, Non Hi-Rel**
  - 1 to 2%

- **Industrial Controls**
  - 500 to 2000 ppm (1st Year)
  - Depends on complexity, production volumes, and risk sensitivity

- **Automotive**
  - 1 to 5% (Electrical, 1st Year)
  - Can also be reported as problems per 100 vehicles

<table>
<thead>
<tr>
<th>Product</th>
<th>Repair rate (%) [First 3 Yrs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desktop PC</td>
<td>37</td>
</tr>
<tr>
<td>Laptop PC</td>
<td>33</td>
</tr>
<tr>
<td>Refrigerator: side-by-side (with icemaker and dispenser)</td>
<td>28</td>
</tr>
<tr>
<td>Washing machine</td>
<td>22</td>
</tr>
<tr>
<td>Refrigerator: top- and bottom-freezer (with icemaker)</td>
<td>17</td>
</tr>
<tr>
<td>Projection TV</td>
<td>16</td>
</tr>
<tr>
<td>Vacuum cleaner (excluding belt replacement)</td>
<td>13</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>13</td>
</tr>
<tr>
<td>Clothes dryer</td>
<td>13</td>
</tr>
<tr>
<td>Microwave oven (over-the-range)</td>
<td>12</td>
</tr>
<tr>
<td>Electric range</td>
<td>11</td>
</tr>
<tr>
<td>Camcorder</td>
<td>8</td>
</tr>
<tr>
<td>Digital camera</td>
<td>8</td>
</tr>
<tr>
<td>Refrigerator: top- and bottom-freezer (without icemaker)</td>
<td>8</td>
</tr>
<tr>
<td>TV: 30- to 36-inch</td>
<td>7</td>
</tr>
<tr>
<td>TV: 25- to 27-inch</td>
<td>5</td>
</tr>
</tbody>
</table>

Consumer Reports 2006
Desired Lifetime: Examples

- Low-End Consumer Products (Toys, etc.)
  - Do they ever work?
- Cell Phones: 18 to 36 months
- Laptop Computers: 24 to 36 months
- Desktop Computers: 24 to 60 months
- Medical (External): 5 to 10 years
- Medical (Internal): 7 years
- High-End Servers: 7 to 10 years
- Industrial Controls: 7 to 15 years
- Appliances: 7 to 15 years
- Automotive: 10 to 15 years (warranty)
- Avionics (Civil): 10 to 20 years
- Avionics (Military): 10 to 30 years
- Telecommunications: 10 to 30 years
How has DfR been traditionally performed?

- Trial and Error (Design-Build-Test-Fix)
- Lessons-learned
- Failure Mode Effects Analysis (FMEA)
- MTBF Calculations (Mil-HBK-217 type analysis)
- Relying only on Industry Standard Test Methods (component and board level)
Traditional Reliability Growth in Product Development

*Empirical “TRIAL & ERROR” Method to Demonstrate Statistical Confidence*

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.

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**DESIGN - BUILD - TEST - FIX (D-B-T-F)**
Design Costs

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

Limitations of Current DfR Techniques

- Too much emphasis on techniques (e.g., FMEA and FTA) and not answers
  - FMEA/FTA rarely identify DfR issues because of limited focus on the failure mechanism
- Incorporation of HALT and failure analysis (HALT is test, not DfR; failure analysis is too late)
  - Frustration with ‘test-in reliability’, even HALT, has been part of the recent focus on DfR
- Limiting testing to standard tests
- Overreliance on MTBF calculations
Classical Actuarial Reliability Prediction (i.e. MIL – 217 MTBF)
- 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
    \[ \lambda_{\text{total}} = \sum_{i=1}^{n} N_i (\lambda_g \Pi_Q)_i \]
    - \( \lambda_{\text{total}} \) = Total equipment failure rate
    - \( N_i \) = Quantity of the ith generic part
    - \( \lambda_g \) = Generic constant (random) failure rate for the ith generic part
    - \( \Pi_Q \) = Quality factor for the ith generic part

- Parts Stress Prediction
  - Augments the parts count methods by 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
  - Solder joints won’t fail
Accuracy of Reliability Prediction

- Reliability predictions based on MIL-HBK-217 are known to be widely inaccurate
- Loughborough University found deviations greater than 500%
- Senior fellow at NASA
  - “MIL-217 can be off as much as $10^4$”

Only considers failure of components and this is based on historical standards. Does not account for the electronic assembly (solder joints, PCB, mechanical stresses, etc.)
Many other Industries (such as U.S. Automakers) Reached Similar Conclusion and also Phased out Actuarial Reliability Predictions Methods in the 1990s.
What are some elements of the Best DfR Practices Today?

1. Build a solid DfR team and provide with the right tools
2. Understand the primary wear-out failure modes in electronics (incorporate Physics of Failure)
3. Understand the environment the product needs to withstand (qualification/shipping/storage/user)
4. Perform modeling of these failure mechanisms in the expected environments based on known algorithms
5. Perform testing (virtual and real) which accelerates the primary failure mechanisms
6. Perform failure analysis of higher risk components after testing (whether or not they pass electrical verification)
Build a Team

- Prioritize DfR and assemble a cross functional team at the beginning of product design

- **Challenges:** Classic design teams consist of electrical and mechanical engineers trained in the ‘science of success’ (not used to thinking about failure)
  - DfR requires the right elements of personnel and tools
    - Involve reliability engineers
    - Use modeling tools early in design process
  - Product must be designed with consideration of test conditions, transportation, storage, possible user environments and how these influence various failure mechanisms
What Team Members are Suggested for DfR?

- Component engineer
- Physics of failure expert (mechanical / materials)
- Manufacturing engineer
  - Box level (harness, wiring, board-to-board connections)
  - Board / Assembly
- Systems Engineer
- Engineer cognizant of environmental legislation
- Thermal engineer (depending upon power requirements)
- Reliability engineer
  - Understanding of design guidelines, physics of failure, and systems lifecycle engineering experience
Why Wear-out is more important today

Electronics: 1960s, 1970s, 1980s

Electronics: Today and the Future

Design limits of materials are being stressed

Equipment, processes, and process controls have been greatly improved

No wearout!

Wearout!

Failure Rate

Time
Overview of How Things Age & Wear Out

- Stress Driven Damage Accumulation in Materials

1. **Loads**
   - Thermal
   - Mechanical
   - Chemical
   - Etc.

2. **Stress**
   Loads create stress on components and systems

3. **Strain**
   Strain results from Stress

4. **Damage Accumulation** (or Stress Aging):
   Permanent change degradation retained after loads are removed.

5. **Failure Site & Type**:
   Eventually failure occurs.

6. **Time to Mean Failure**:
   Time to failure depends on strength of materials.
Wearout Examples

- What is susceptible to wearout in electronic designs?
  - Ceramic Capacitors (oxygen vacancy migration and dielectric breakdown)
  - Electrolytic Capacitors (electrolyte evaporation, dielectric dissolution)
  - Corrosion failures (silver platings on PCBs or resistors/capacitors, conductive anodic filament formation)
  - Relays and other Electromechanical Components
  - Integrated Circuits (EM, TDDB, HCI, NBTI)
  - PCB Assemblies
    - Plated through hole fracture (Z-axis expansion)
    - Solder joint fracture (thermal cycle, mechanical vibration/shock)
Solder Joint (SJ) Wearout

- Elimination of leaded devices
  - Provides lower RC and higher package densities
  - Reduces compliance

Cycles to failure
-40 to 125°C

QFP: >10,000

BGA: 3,000 to 8,000

CSP / Flip Chip: <1,000

QFN: 1,000 to 3,000
SJ Wearout (cont.)

- Design change: More silicon, less plastic
- Increases mismatch in coefficient of thermal expansion (CTE)

\[ y = 341.16x^{-3.2274} \]
\[ R^2 = 0.9886 \]
Thermal – Mechanical Effects

- The majority (65%) of electronic failures are thermo-mechanically related. 
  - By thermally induced stresses and strains (root caused to CTE differences).
  - By accelerated transport phenomena at higher temperature.


Many algorithms have been developed to predict failure mechanisms based from first principles.
Computer modeling is the best method to leverage all the previous work done to create algorithms that predict failure.

Modeling tools have been used for:
- Thermal modeling (Flotherm for example)
- Circuit board layout
- Electrical parameter modeling
- Finite element analysis for stress/strain

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

Aberdeen Group, Printed Circuit Board Design Integrity: The Key to Successful PCB Development, 2007 http://new.marketwire.com/2.0/rel.jsp?id=730231
Working Smarter – not just harder

- **Maker / Creative Age**

  - Agrarian
  - Industrial
  - Information
  - ????

  Timeline:
  - 4000 BC
  - 1760
  - 1948
  - Beyond
Creative Age is Now

- **3D Printing** *(Individualized Manufacturing)*
- **Genetic Sequencing** *(Individualized Treatments)*
  - **Kickstarter** *(Individualized Financing)*
  - **Open Hardware** *(Individualized Designs)*

- Increasing % of Revenue from New Products
- Companies Driving ‘Designs per Head’
The Future
Will be
Modeled
Available Computer Modeling Tools

Vehicle Structure

Safety

Energy

Performance Integration

Thermal

Vehicle Dynamics

Aerodynamics

Durability

Noise & Vibration

DfR Solutions
Why the Automotive Industry Is Using More Virtual Computer Aided Engineering Methods

- Growing complexity and vehicle electrification prompting a major change in design processes.
- Intense competitive pressure to improve efficiency & effectiveness to shortened development cycles and reduce costs.
- The combination of physical and virtual testing accelerates the product development process by early identification of deficiencies.
- Physics based models makes it easier to try out new designs, since evaluations can be performed without building physical prototypes.
- Simulations can be created and run in far less time & cost than building and testing physical prototype, models can than be quickly revised to evaluation alternative configurations and option content.
As the use of CAE based modeling & simulation methods increase, dependence on physical testing can be reduced and refocused.

By 2004 GM was able to reduce vehicle road testing to the point that the southern portion of their Mesa Az. Proving Grounds was sold. In 2006 the remaining northern 5 square miles, that formerly operated with 1,200 people, was sold for Real Estate Development. GM now operates with a much smaller DPG in Yuma Az. and realized a significant reduction in structural costs.
Reliability Modeling of Electronics – with Sherlock

- Sherlock – a new computer modeling tool created by DfR Solutions that will perform a finite element analysis of a fully assembled board mounted in the product enclosure.

- The environment for the product is input and the expected reliability for the PCBA is calculated (taking into account various common failure mechanisms).

- We now live in an age where the electronics can be virtually tested and virtually put into service before any physical samples are built.

- We can determine weaknesses of the product and fix them prior to ordering first prototypes.
Sherlock Failure Mechanism Coverage

- 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
Data Import

- ODB++ files are preferred since they contain all the data necessary for modeling
  - Component details and placement
  - PCB outline & stack-up
  - Drill hole file with mount points
  - Metal layers, silkscreen, solder mask layers

Gerber Data can also be imported
PCB Details Required for Modeling

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
### Establish Part Parameters

- **Components identified along with packaging properties.**
- **Minimizes data entry through intelligent parsing and embedded package and material databases.**

#### Parts Listing

<table>
<thead>
<tr>
<th>RefDes</th>
<th>Part Number</th>
<th>Part Type</th>
<th>Packaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>R100</td>
<td>CRCW0402100RFKED</td>
<td>RESISTOR</td>
<td>SMT 0402</td>
</tr>
<tr>
<td>R101</td>
<td>CRCW0402100RFKED</td>
<td>RESISTOR</td>
<td>SMT 0402</td>
</tr>
<tr>
<td>R126</td>
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<td>RESISTOR</td>
<td>SMT 0402</td>
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<tr>
<td>R127</td>
<td>RK73H1JTD2002F</td>
<td>RESISTOR</td>
<td>SMT 0603</td>
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<tr>
<td>R128</td>
<td>RK73H1ETTP3092F</td>
<td>RESISTOR</td>
<td>SMT 0402</td>
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<td>R129</td>
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<td>SMT 0402</td>
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<td>U1</td>
<td>LTC4358IDE</td>
<td>IC</td>
<td>SMT QFN-14 (MO-200VGBE)</td>
</tr>
<tr>
<td>U2</td>
<td>LTC4358IDE</td>
<td>IC</td>
<td>SMT QFN-14 (MO-200VGBE)</td>
</tr>
<tr>
<td>U9</td>
<td>MAX3311ECUB</td>
<td>IC</td>
<td>SMT MSOP-10</td>
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<td>U10</td>
<td>MCF51AC256BVLKE</td>
<td>IC</td>
<td>SMT QFP-80 (MO-200VGBE)</td>
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<tr>
<td>U14</td>
<td>LT1490ACDD</td>
<td>IC</td>
<td>SMT QFN-8 (MO-200VGBE)</td>
</tr>
<tr>
<td>U15</td>
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<td>SMT SOT-3 (TO-278BC)</td>
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<td>SMT SOT-23-6</td>
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<td>SMT QFN-8 (MO-200VGBE)</td>
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<td>M41T83SQA6F</td>
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<tr>
<td>U27</td>
<td>LT1493FDCB</td>
<td>IC</td>
<td>SMT QFN-16 (MO-220VGBE)</td>
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</tbody>
</table>
Defining The Durability & Reliability Objectives

- Define the Expected Service Life
  - Sets The Analysis Range And The Scale For Reliability Over Time Plots
- Life Cycle Phases
  - Shows relative time spent at each phase
Handles very complex environments
Thermal cycle conditions during transportation can be taken into account.

http://www.ista.org/forms/LEINBERGER_Dimensions06_paper.pdf
Test and Field Conditions

- Qualification test conditions or environmental stress screening conditions can be modeled to provide confidence product will meet specifications
  - Thermal cycle
  - Vibration
  - Mechanical Shock
- Field use conditions can also be modeled (can be complex)
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 an FEA modeling expert.
PCB Vibration - 1st, 2nd & 3rd Harmonic Modals

1st Harmonic

2nd Harmonic

3rd Harmonic
Influence the Natural Frequency by Adding/Changing Mount Point

- Mount points can be modified to achieve desired results.
Automated 3D Model Generation

- Tetra- and Hexahedral Elements
- Balance of accuracy and speed
- Standoffs
- Heatsinks
- Daughter cards
**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

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<table>
<thead>
<tr>
<th>Support</th>
<th>Original</th>
<th>CAE Guided Redesign Adds Back Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board Displacement (mils)</td>
<td>13.95</td>
<td>1.15</td>
</tr>
<tr>
<td>Natural Frequency (Hz)</td>
<td>89</td>
<td>489</td>
</tr>
<tr>
<td>Vib. Durability Calculation</td>
<td>25 Days</td>
<td>&gt; 50 Years</td>
</tr>
</tbody>
</table>
Module Vibration Durability Simulation Results  
- For Alternative Board Support & Transformer Locations

### ORIGINAL TRANSFORMER LOCATION

<table>
<thead>
<tr>
<th>DAYS TO FAILURE @ 2 Hrs Vib / Day</th>
<th>R101</th>
<th>R102</th>
<th>R825</th>
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</thead>
<tbody>
<tr>
<td>Edge1 (Connector)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge1 &amp; Corners</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge1 &amp; Middle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge1, Corners &amp; Middle, Edge2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All Edges</td>
<td></td>
<td></td>
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</table>

### TRANSFORMER RELOCATED

<table>
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<tr>
<th>DAYS TO FAILURE @ 2 Hrs Vib / Day</th>
<th>R101</th>
<th>R102</th>
<th>R825</th>
</tr>
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<tbody>
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<td>Edge1 &amp; Corners</td>
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<td>Edge1 &amp; Middle</td>
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<tr>
<td>All Edges</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

- 3650 Days (10 Years)

9000 Virginia Manor Rd Ste 290, Beltsville MD 20705 | 301-474-0607 | www.dfrsolutions.com
## Vibration Results – Component Breakdown

Components most at risk for vibration fatigue damage are listed first.

<table>
<thead>
<tr>
<th>RefDes</th>
<th>Package</th>
<th>Part Type</th>
<th>Material</th>
<th>Solder</th>
<th>Max Disp</th>
<th>Max Strain</th>
<th>TTF (yrs)</th>
<th>Score</th>
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<tbody>
<tr>
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<td>IC</td>
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<td>SAC305</td>
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<tr>
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<td>OVERMOLD-LEADED</td>
<td>SAC305</td>
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<tr>
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<td>&gt;150</td>
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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.
### Shock Results – Component Breakdown

Components listed in order of maximum strain experienced.

<table>
<thead>
<tr>
<th>RefDes</th>
<th>Package</th>
<th>Part Type</th>
<th>Material</th>
<th>Max Disp</th>
<th>Max Strain</th>
<th>Score</th>
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<td>5.6</td>
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<tr>
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<td>IC</td>
<td>OVERMOLD-LEADED</td>
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<td>5.6</td>
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<td>LCCC-44</td>
<td>IC</td>
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<td>3.9E-4</td>
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Thermal Cycling Solder Fatigue Model
(Modified Engelmaier – Leadless Device)

- Modified Engelmaier
  - Semi-empirical analytical approach
  - Energy based fatigue
- Determine the strain range ($\Delta \gamma$)
  - Where: $C$ is a function of activation energy, temperature and dwell time,
    $L_D$ is diagonal distance, $\alpha$ is CTE, $\Delta T$ of temperature cycle & $h$ is solder joint height
- Determine the shear force applied at the solder joint
  - Where: $F$ is shear force, $L_D$ 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
- Calculate N50 cycles-to-failure using:
  - An Energy Based model for SnPb
  - The Syed-Amkor model for SAC

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

$$F \cdot \left( \frac{L_D}{E_{A_1}} + \frac{L_D}{E_{A_2}} + \frac{h_s}{A_{G_s}} + \frac{h_c}{A_{G_c}} + \left( \frac{2-v}{9 \cdot G_b} \right) \right)$$

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

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

$$N_f = (0.0006061 \cdot \Delta W)^{-1}$$
TC Fatigue Analysis – Example Plot

SnPb, SAC305, or SN100C alloys can be selected.

Cumulative failure curve is plotted (2x target life is shown).
Thermal Cycle Modeling (solder joints)

- Cumulative failure curve is predicted and components are listed in their order of risk of solder joint failure

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<th>RefDes</th>
<th>Package</th>
<th>Part Type</th>
<th>Model</th>
<th>Side</th>
<th>Solder</th>
<th>Max dT (C)</th>
<th>Max TSF</th>
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Plated Through-Hole Reliability Modeling

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.
PTH Via Barrel Cracking Fatigue Life Based On IPC TR-579

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

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

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

- Determine strain range ($\Delta \varepsilon$)
  
  $$\Delta \varepsilon = \frac{\sigma}{E_{Cu}} \text{, for } \sigma < S_y$$

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

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

- Iteratively calculate cycles-to-failure ($N_{f50}$)
  
  $$N_f^{0.6} D_f^{0.75} + 0.9 \frac{S_u}{E} \left[ \exp \left( \frac{D_f}{0.36} \right) \right]^{0.1785 \log_{10}^{10^5} N_f} - \Delta \varepsilon = 0$$

R Solutions
**PTH Fatigue Results - Example**

The plated through hole failure plot (-40/80C ATC)

Takes into account:
- via diameter
- Cu thickness
- Plating quality
- PCB thickness
- Z-axis CTE
Detailed Design and Application Specific PoF Life Curves are Far More Useful than a simple single point MTBF (Mean Time Between Failure) estimate.
Risk for Conductive Anodic Filament Formation (CAF)

- CAF formation becomes a risk when plated through hole vias are so close together that damage from drilling can open up a pathway between vias.
- Copper from the via can migrate along the pathway and eventually cause shorting.
CAF Analysis

- The primary variables that effect the probability of CAF formation are:
  - Distance between vias
  - Damage during drilling process
  - Temperature and humidity conditions
  - Voltage differential between vias

- The analysis takes into account the first two variables only (measures distance between all PTH pairs).
- Vias identified as being too close are flagged.
CAF Analysis

- Software will flag vias at high risk for CAF formation
Additional Uses for Modeling

- Use Sherlock to determine thermal cycle test requirements.
- Use to modify mount point locations
- Use to determine ESS conditions
- Component Replacement
- Determine impact of changing to Pb-free solder
- Determine expected warranty costs
- Select proper PCB laminate for the product (can save cost by not over specifying)
Using Modeling to Design an Accurate Test

- How to ensure 10 year life in a realistic worst-case field environment for industrial controls?
  - American Southwest (Phoenix)
  - Dominated by diurnal cycling

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<tr>
<th>Month</th>
<th>Cycles/Year</th>
<th>Ramp</th>
<th>Dwell</th>
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<th>Min. Temp. (°C)</th>
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<td>6 hrs</td>
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<td>10</td>
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<tr>
<td>April+October</td>
<td>60</td>
<td>6 hrs</td>
<td>6 hrs</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>May+September</td>
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<td>6 hrs</td>
<td>35</td>
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<tr>
<td>June+July+August</td>
<td>90</td>
<td>6 hrs</td>
<td>6 hrs</td>
<td>40</td>
<td>25</td>
</tr>
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</table>

+10°C at max temperature due to solar loading
PoF Example – SAC Reliability (cont.)

- Total damage in desert environment over 10 years: 0.02604
- Total damage in one cycle of -40C to 85C test environment: 0.00012
- Total cycles at -40C to 85C to replicate 10 yrs in desert: 222 cycles

At 1 cycle/hour, approximately 1 day of test equals 1 year in the field

DfR Solutions
Environmental Stress Screen - Determination

- Highly reliable products often require an environmental stress screen of all products prior to shipping.
- Thermal cycling or vibration are common methods to lightly stress the solder joints, causing weak joints to fail.
- Screen should not use more than 5% of the useful life.
- Modeling can show the expected life at the screen conditions.
- One can be sure that number of cycles selected for the screen use no more than 5% of the life.
The Reliability Limiting Component is Identified – changes made if needed

Replace QFN with leadframe
Comparison of SnPb to SAC305 - Example

Assume:
- Eutectic SnPb
- -40°C to 101°C
- 1 cycle per day

Assume:
- Eutectic SAC305
- -40°C to 101°C
- 1 cycle per day

SnPb performed better in this case
Software can be used to compare laminate material performance with your product design – can aid with material selection.
Impact of 4 PCB Materials on PCB Performance, Life & Reliability

Provides ability to optimize for cost while meeting reliability requirements.
Validation of Modeling Results

BGA Validation Graph

Cycles to Failure (Experimental Results)

Cycles to Failure (Predicted by Software)
Validation – Chip Resistors

![Graph showing cycles to failure for experimental and predicted data.](image)

Cycles to Failure (Experimental) vs. Cycles to Failure (Predicted)
## Validation Example

### QFN

<table>
<thead>
<tr>
<th>Solder Material</th>
<th>Cycles to Failure (calc)</th>
<th>Cycles to Failure (exprm)</th>
<th>Stress</th>
<th>Strain Energy</th>
<th>Name</th>
<th>Author(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tin-Lead</td>
<td>496</td>
<td>631</td>
<td>2.28E+01</td>
<td>3.326</td>
<td>QFN-52</td>
<td>Tee, Ng, Yap, Zhong</td>
</tr>
<tr>
<td>Lead-Free</td>
<td>7938</td>
<td>7800</td>
<td>3.639</td>
<td>6.63E-02</td>
<td>HVQFN-24</td>
<td>de Vries, Jansen, van Driel</td>
</tr>
<tr>
<td>Lead-Free</td>
<td>9079</td>
<td>5250</td>
<td>2.828</td>
<td>5.80E-02</td>
<td>HVQFN-48</td>
<td>de Vries, Jansen, van Driel</td>
</tr>
<tr>
<td>Lead-Free</td>
<td>3366</td>
<td>4500</td>
<td>5.528</td>
<td>0.4021</td>
<td>HVQFN-72</td>
<td>de Vries, Jansen, van Driel</td>
</tr>
<tr>
<td>Tin-Lead</td>
<td>2463</td>
<td>1635</td>
<td>8.932</td>
<td>0.67</td>
<td>QFN-44</td>
<td>Tee, Ng, Yap, Zhong</td>
</tr>
<tr>
<td>Tin-Lead</td>
<td>976</td>
<td>2015</td>
<td>17.76</td>
<td>1.702</td>
<td>QFN-36</td>
<td>Tee, Ng, Yap, Zhong</td>
</tr>
<tr>
<td>Tin-Lead</td>
<td>956</td>
<td>2165</td>
<td>19.36</td>
<td>1.725</td>
<td>QFN-28</td>
<td>Tee, Ng, Yap, Zhong</td>
</tr>
<tr>
<td>Tin-Lead</td>
<td>3542</td>
<td>2928</td>
<td>10.23</td>
<td>0.4658</td>
<td>QFN-20</td>
<td>Tee, Ng, Yap, Zhong</td>
</tr>
<tr>
<td>Lead-Free</td>
<td>1437</td>
<td>1280</td>
<td>10.04</td>
<td>0.3663</td>
<td>QFN-40</td>
<td>Mukadam, Meilunas, et al</td>
</tr>
<tr>
<td>Lead-Free</td>
<td>1448</td>
<td>2063</td>
<td>10.92</td>
<td>0.3635</td>
<td>QFN-42</td>
<td>Mukadam, Meilunas, et al</td>
</tr>
<tr>
<td>Lead-Free</td>
<td>3651</td>
<td>803</td>
<td>5.565</td>
<td>0.1442</td>
<td>QFN-44</td>
<td>Mukadam, Meilunas, et al</td>
</tr>
<tr>
<td>Tin-Lead</td>
<td>760</td>
<td>947</td>
<td>16.77</td>
<td>2.17</td>
<td>QFN-20</td>
<td>Zhang and Lee &amp; Kim, Han, et al</td>
</tr>
</tbody>
</table>

---

The diagram shows the validation profile for QFN packages, comparing experimental data with predicted values for cycles to failure. The table lists various materials, their calculated and experimental cycles to failure, along with stress and strain energy values, and cites the authors of each data set.
Physics of Failure & Reliability Testing

- PoF Definition: The use of science (physics, chemistry, etc.) to capture an understanding of failure mechanisms and evaluate useful life under actual operating conditions.

- Using PoF, design, perform, and interpret the results of accelerated life tests.
  - Starting at design stage
  - Continuing throughout the lifecycle of the product

- Start with standard industry specifications.
  - Modify or exceed them
  - Tailor test strategies specifically for the individual product design and materials, the use environment, and reliability needs.
First we should understand that there are different types of testing performed for various products depending on their field of use:

- **Feasibility (or Functional) Testing**
  - Proof of concept and functionality

- **V&V: Validation & Verification**
  - Conforms to specifications & standards

- **Production Testing**
  - Optimize production processes
  - Environmental stress screening (sort out weak units)

- **Reliability Testing**
  - Prove ability to withstand user environment
  - Reveal any weaknesses

- **Safety / Regulatory Testing**
Test Plan Development – Define Use Environment

- The critical first step is a good understanding of the shipping and use environment for the product.
- Do you really understand the customer and how they use your product (even the corner cases)?
- How well is the product protected during shipping (truck, ship, plane, parachute, storage, etc.)?
- Do you have data or are you guessing?
  - Temp/humidity, thermal cycling, ambient temp/operating temp.
  - Salt, sulfur, dust, fluids, etc.
  - Mechanical cycles (lid cycling, connector cycling, torsion, etc.)
Use PoF Principles to Create Effective Reliability Tests

- **General Reliability Testing Approach**
  - Use various methods to identify the primary stressors expected in the production and use of the product
    - Historical experience
    - Literature search
    - Consult experts in the applicable field
  - Identify the likely failure mechanisms based on product design and stressors
    - Perform FMECA (Failure Modes, Effects & Criticality Analysis)
    - Examine failure mechanisms on similar product types
    - Consult literature
  - Use test methods that simulate stressors (accelerate in some cases – without creating non-realistic failures) – component level, board level, and system level
    - Determine pass/fail criteria
    - Determine analytical methods to identify failures (x-ray, x-section, dye-n- pry, etc.)
Failure Inducing Loads - Examples

- Temperature Cycling
  - Tmax, Tmin, dwell, ramp times
- Sustained Temperature
  - T and exposure time
- Humidity
  - Controlled, condensation
- Corrosion
  - Salt, corrosive gases (Cl\textsubscript{2}, etc.)
- Power cycling
  - Duty cycles, power dissipation
- Electrical Loads
  - Voltage, current, current density
  - Static and transient
- Electrical Noise
- Mechanical Bending (Static and Cyclic)
  - Board-level strain
- Random Vibration
  - PSD, exposure time, kurtosis
- Harmonic Vibration
  - G and frequency
- Mechanical shock
  - G, wave form, # of events
Failure Inducing Temperature: Transport & Storage

Temp. Variation In a Trucking Container

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>95F (35C)</td>
<td>0.375%</td>
<td>0.650%</td>
<td>11% (948)</td>
<td>13% (1,140)</td>
</tr>
<tr>
<td>105F (40.46C)</td>
<td>0.087%</td>
<td>0.050%</td>
<td>2.3% (198)</td>
<td>3.8% (331)</td>
</tr>
<tr>
<td>115F (46.11C)</td>
<td>0.008%</td>
<td>0.001%</td>
<td>0.02% (1.4)</td>
<td>0.1% (9)</td>
</tr>
</tbody>
</table>
Humidity / Moisture (Rules of Thumb)

- **Non-condensing**
  - Standard during operation, even in outdoor applications
  - Due to power dissipation

- **Condensing**
  - Can occur in sleep mode or non-powered
  - Driven by mounting configuration (attached to something at lower temperature?)
  - Driven by rapid change in environment
  - Can lead to standing water if condensation on housing

- **Standing water**
  - Indirect spray, dripping water, submersion, etc.
  - Often driven by packaging
General Test Plan Development Outline – PCBA Example

- Component qualification (with end product in mind)
  - Thermal cycling, high temp, T&H, etc.
- PCBA qualification
  - Thermal cycling
  - HALT/HAST
  - Drop/shock
  - Heat age
- System level qualification
  - Shock and Vibration
  - Dust testing
  - Torsion
  - Etc.
Test Plan Development – for PCBAs continued...

- Develop a comprehensive test plan
- Assemble boards at optimum conditions
- Rework specified components on some boards
- Visually inspect and electrically test
- C-SAM & X-ray inspect critical components on 5 or more boards (+3 reworked for BGAs)
- Use these boards for further reliability testing (TC, HALT, S&V)
- Perform failure analysis
- Compile results and review
Don’t Overlook Failure Analysis!

- Effective failure analysis is critical to reliability!
- Without identifying the root causes of failure, true corrective action cannot be implemented
  - Risk of repeat occurrence increases
- Use a systematic approach to failure analysis
  - Proceed from non-destructive to destructive methods until all root causes are identified.
- Techniques based upon the failure information specific to the problem.
  - Failure history, failure mode, failure site, failure mechanism

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Perform Failure Analysis on Good Samples?

- Yes!
- A unit can be functional after testing but still have a great deal of physical damage indicating it is on the verge of failure
- An example is pad cratering (perform dye and pry)
Examples of component failure mechanisms that should be considered when designing electronics

- Tin whiskers (use proper risk mitigation techniques)
- Corrosion of silver on resistors (use AgPd in S environments)
- Properly derate resistors and capacitors
  - Electrolytic caps should maintain a min of 25% of rated voltage to maintain dielectric
- Avoid resistors > 500 kOhms unless board cleanliness is assured
- Connectors should have proper plating materials and thicknesses
- PCB laminates should be heat rated for Pb-free
- Use the proper PCB surface finish for the application (corrosion concerns, brittle fracture, manufacturability issues)
- Multilayer ceramic caps are vulnerable to thermal shock cracking
Summary

- Physics of Failure is here to stay and we will continue to get better at understanding what drives failure mechanisms.
- As algorithms get more sophisticated the modeling capability and accuracy will continue to improve.
- The Sherlock modeling tool provides a glimpse into the future of designing in reliability before building of physical product.
- More effective reliability testing is accomplished with an insight into physics of failure concepts.
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- **ANALYSIS INFORMATION**
  This report may include results obtained through analysis performed by DfR Solutions' Sherlock software. This comprehensive tool is capable of identifying design flaws and predicting product performance. For more information, please contact sales@dfrsolutions.com.

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**Best Regards,**

**Dr. Craig Hillman, CEO**