Solder Attachment Reliability
- A Physics of Failure Approach

James McLeish, CRE
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Introduction

- **Jim McLeish** >35 Yrs of Vehicular, Military & Industrial E/E Enrg. & QRD Experience
  - ESA/EFC Digital Task Force (1st Microprocessor Based Engine Controller) - Chrysler Corp.
  - 3 Patents Automotive Electronic Control Systems - GM Adv. Product Engineer
  - System Engineering and Architecture Planning - GM Saturn Project
  - E/E EGM - GM Military Vehicle
  - EE Reliability Manager – GM CPC & Mid Lux.
  - Manager Reliability Physics (Advance Reliability Method Development) – GM NAO
    - 3 GM EE Test Standards GM9123, GMW3172 GMW8288
    - 2006 GM People Make Quality Happen award
  - EE QRD Tech Expert/EE QRD Strategists – GM VEC
  - SAE EE Reliability & ISO 26262 Functional Safety Workgroups
  - Michigan Office Manager & Partner – DfR Solutions
DfR Solutions is an Failure Analysis, Engineering Consulting & CAE Software firm.

- Evolved out of a DoD/NSF consortium that developed the Physics-of-Failure approach developing Ultra Reliable Electronics for defense application & industrial competitiveness.

- DfR’s Physics of Failure research experience & our multi-disciplined team from “Hi-Rel” & related industries provides knowledge & science based QRD solutions.

(Specializing in the Physics of Failure (PoF) /Reliability Physics (RP) tools & methods.

- Forensic engineering knowledge and science based solutions for:
  - Maximizing product integrity
  - While accelerating product development

- Electrical/Electronic Robustness, Failure Prevention & Total Product Integrity >400 projects/year
  - Quality, Reliability and Durability (QRD),
  - Advanced accelerated testing methods
  - Selection & Validation of Robust EE parts appropriate for High Reliability and Harsh Environment Applications
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.
    - 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:

- 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,
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 things fail and the root causes of failures enables engineers to identify and avoid unknowingly creating 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.
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.
Key PoF Terms and Definitions

- **Failure Site**: The location of potential failures, typically the site of a designed in:
  - stress concentrator,
  - design weakness or
  - material variation or defect.

Knowledge Used to Identify and Prioritized Potential Failure Sites and Risks in New Designs During PoF Design Reviews.
Generic Failure Categories
Overstress - When Loading Stress Exceed Material Strength

How well do you understand & design for strengths & stresses?

Typical Deterministic (Nominal) Analysis

Variation of Design's Material Strengths - Related to Process Capabilities

DESIGN MARGIN SAFETY FACTOR

UNRELIABILITY = Probability that Load Exceed Strength

Stress Variation of Usage & Environments Loads & Their Interactions

FREQUENCY OF OCCURRENCE
Overview of How Things Age & Wear Out
- Stress Driven Damage Accumulation in Materials

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

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.

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.

6. **Time to Mean Failure**
   (Damage Accumulation verses Yield Strength)
   A Function of: $\Sigma$ [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).
Generic Failure Categories - Wearout (Damage Accumulation) - Over Time of Stress Exposure

How well do you understand & design for strengths & stresses?

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Errors and Excessive Variation

- Errors Broadest Category
  - Errors in Design, Manufacturing, Usage & Service.
  - Missing knowledge
  - Human factor Issues

- Variation
  - Fine line between excessive variation & out right errors.
  - Both related to quality issues.
    - Equipment wear out & failure from maintenance errors.
    - Weak materials from raw material variation or insufficient processing.
    - Equipment capabilities limits or operator set up error.

Noise Factors

- Interface
- Equipment
- People
- Usage
- Material
- Environment
- Performance
The majority of electronic failures are thermo-mechanically related*

- By thermally induced stresses and strains
- Root cause: excessive differences in coefficient of thermal expansion


Temperature Cycles in the Field

- Field conditions are based on usage and application
- The same electronics assembly can have several field conditions depending on the industry

<table>
<thead>
<tr>
<th></th>
<th>Temp range</th>
<th>Cycles/year</th>
<th>Service time</th>
<th>Failure rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumer</td>
<td>0 to 60 °C</td>
<td>365</td>
<td>1 year</td>
<td>1 %</td>
</tr>
<tr>
<td>Computer</td>
<td>15 to 60 °C</td>
<td>1460</td>
<td>5 years</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Telecom</td>
<td>-40 to 85 °C</td>
<td>365</td>
<td>7 to 20 years</td>
<td>0.01 %</td>
</tr>
<tr>
<td>Aircraft</td>
<td>-55 to 95 °C</td>
<td>365</td>
<td>20 years</td>
<td>0.001 %</td>
</tr>
<tr>
<td>Automotive</td>
<td>-55 to 95 °C</td>
<td>100</td>
<td>10 years</td>
<td>0.1 %</td>
</tr>
</tbody>
</table>

- Examples: LCD touchpanels, voltage regulators, networking modules and many more.
- Special field conditions may exist
  - Long period of storage followed by short period of usage (Munitions, launch platforms, AED, airbags)
PoF Example Solder Thermo-Mechanical Fatigue Driven by: 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.

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Coef. Of Thermal Exp. (PPM/°C)
- Chip Resistor Body: 4-5 ppm/°C
- PCB - FR4 $x_y$ axis: 14-17 ppm/°C
  - FR4 $z$ axis: 120-160 ppm/°C
The Component Package Now Influences QRD more than the IC Die
EE Component Solder Fatigue Life is Directly Related to Component Packaging & Solder Attachment Scheme

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 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

Life Varies w/Size & Conf.
Impact of E/E Component Packaging & Attachment Configuration - Through Hole Dip Chip ICs

- Double Sided (PTH) Joints are 35-55 TIMES Stronger
- Lead is constrained
- So the Rate of Fatigue Stress Aging is Much Slower

- Automotive Fatigue Life
  - Single Sided: 2-5 Yrs
  - Double Sided PTH: >10 Yrs

Since Electrical Engineers Design Most Printed Circuit Boards (PCB)
- Their only motivation to accept the added costs of Plated Through Hole (PTHs) was when increasing component density required placing component and traces on both sides of the circuit board.
- THE RELIABILITY OF MORE COMPLEX EE MODULES SKY ROCKETED with the use of Double Sided 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

DfR Solutions
Impact of E/E Component Packaging & Attachment Configuration - Leaded Surface Mount ICs

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

2nd 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.

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

<table>
<thead>
<tr>
<th>Package Type</th>
<th>Typical Thermal Cycles to Failure ((-40^\circ) to (+125^\circ)C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QFP</td>
<td>&gt;10,000</td>
</tr>
<tr>
<td>BGA</td>
<td>3,000 – 8,000</td>
</tr>
<tr>
<td>QFN</td>
<td>1,000-3,000</td>
</tr>
</tbody>
</table>

*TTCL = Typical Thermal Cycle Life During -40\(^\circ\) to +125\(^\circ\)C Testing*
Flat No Lead (FNL) Chip Scale IC Packages?

- FNL ICs help make ultra thin and light portable consumer electronic products possible.
  - Products with a short service life (2-5 years)
  - In a relative benign environment
- The vastly large size of the consumer electronics market provides significance power to influence IC suppliers to develop IC packages & products that meet their needs and priorities.
- With significantly less market influence the high reliability, harsh environment, long life market like the auto and defense industries must increasing learn to use and adapt to the components produced by the predominate market trends.
The Reliability Challenge of Keeping Up With Constantly Evolving E/E Technology

- Every time electronic component packages, attachment schemes & materials change or application usage and environmental conditions change, QRD performance also change and design rules updates are needed.

- This is why PoF CAE based microstructural stress analysis and failure mechanism modeling is becoming essential for accurate reliability assessments of new products.
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
  - $\Delta W = 0.5 \cdot \Delta \gamma \cdot \frac{F}{A_s}$
- Calculate N50 cycles-to-failure using:
  - An Energy Based model for SnPb
  - The Syed-Amkor model for SAC

DfR Solutions
PoF Models for Stress-Stain Structural Analysis of Electronics 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 deployed to EE Enrg. Depts.
Also Two Types of Circuit Board Related Vibration Durability Issues

- **Board in Resonance**
  - Components. Shaken Off/Fatigued by Board Motion.
  - By Flexing Attachment Features

- **Components In Resonance**
  - Components Shake/Fatigue themselves apart or off the Board.
  - Especially Large, Tall Cantilever Devices
    - 3 Med. Sized Alum CAPS
    - 1 Small Long Leaded Snsr
    - 1 Hall Effect Sensor
    - 1 Large Coil Assembly

**Time to Failure Determine by Intensity/Frequency of Stress Verses Strength of Material**

**Steinberg’s Criterion:**

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

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

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**Displacement**

**Bending Lead Wires**

**Gull Wing I.C.**

**Lead Motion**
- Flexed Down
- Normal
- Flexed up

**PC Board**

**Solder Fatigue Life**

Log (Peak Strain)

Log (Number of Cycles to Failure)
PCB Vibration - 1\textsuperscript{st}, 2\textsuperscript{nd} & 3\textsuperscript{rd} Harmonic Modals

1\textsuperscript{st} Harmonic

2\textsuperscript{nd} Harmonic

3\textsuperscript{rd} Harmonic

DfR Solutions
Physics of Failure Example - Shock

- Animated 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.
Many Product Engineers are Unaware of Physical CAE Capabilities and How to Use Them to Design QRD in as part of a Product Development Program.

- Many E/E Devices Have Drop/Shock Requirements.
- Most Use Test & Fix “Free Fall Drop Validation Test” of Physical Parts.
The Auto Industry Has Reaped Significant Product development Efficiencies & QRD Benefits Through Math Based, Virtual CAE Tools and Methods

A Result of Initiatives to: Migrate Evaluations from Road to Lab to Computer, at the Vehicle, Subsystem & Component Level
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.
PoF Durability/Reliability Simulations for Virtual Reliability Growth of Electronics

Start with PoF/PoS Mechanism Knowledge

Build & Validate PoF / PoS Math Models

Program Model(s) into Standalone Simple Math Data Tools

Integrated In a Sophisticated CAE Tool.

Add in Statistical Tools for Variation

Account for Operational Loading Drift
Thermal Modeling Identifies the Thermal Stress Conditions

<table>
<thead>
<tr>
<th>SR (HSink@85°C)</th>
<th>$T_J$ (°C)</th>
<th>$T_{Case}$ (°C)</th>
<th>$T_{HSink}$ (°C)</th>
<th>$P$ (W)</th>
<th>$R_{th_JC}$ (°C/W)</th>
<th>$R_{th_J-HS}$ (°C/W)</th>
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<tbody>
<tr>
<td>Q6$_{IGBT}$</td>
<td>96.29</td>
<td>89.23</td>
<td>85.0</td>
<td>6.50</td>
<td>1.09</td>
<td>1.74</td>
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<td>D6$_{Diode}$</td>
<td>103.40</td>
<td>89.52</td>
<td>85.0</td>
<td>13.80</td>
<td>1.01</td>
<td>1.33</td>
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<td>Q3$_{IGBT}$</td>
<td>98.35</td>
<td>90.20</td>
<td>85.0</td>
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<td>1.25</td>
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<td>90.99</td>
<td>85.0</td>
<td>13.80</td>
<td>1.01</td>
<td>1.45</td>
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<tr>
<td>D2$_{Diode}$</td>
<td>103.40</td>
<td>89.89</td>
<td></td>
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<td>Q1$_{IGBT}$</td>
<td>96.98</td>
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<td>D7$_{Diode}$</td>
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<td>104.64</td>
<td>87.95</td>
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</tbody>
</table>
Predicting & Confirming 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 Conditions.

Infrared Thermal Imaging Of Thermal Stress & Overstress “Hot Spots”

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

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
1020 Resistor Reliability vs AST Cycles as Demonstrated During DV Testing

Weibull Plot of 1st Detection of 3 Aux. Sw. Circuit Intermittent Events out of 6 DUTs

10 Yr/100,000 Mile (960 AST Cyc) Demonstrated Reliability Only .42 (42%)

10 Yr Durability Life = 960 Cycles

Req’d R = .97 (97%)
Predicting the Future

A Award Winning CAE App for Physics of Failure Durability Simulations & Reliability Assessments
Putting CAE to Work for Non-Experts

- Application Specific Customized CAE Solutions.
- An emerging trend where auto guided, specific function, CAE Apps or analysis templates are created
  - Provides a common, reusable semi-automated interface
    - 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
  - To see full article: http://www.sae.org/mags/SVE/10767
CAE Apps

- The shortage of time and modeling experts has limited the expansion of CAE tools in many industries.
  - More upfront CAE analysis work would be performed if engineering organizations could find and afford enough high priced CAE experts.
  - A growing trend to resolve this bottleneck is the development of CAE Apps and Templates.
  - This new generation of CAE solutions provide common, application specific, reusable, semi-automated interface for solving frequently encountered problems and performing regularly needed product optimization tasks that allow non-CAE experts to rapidly perform expert level evaluations.
  - Knowledge based, application specific, CAE Apps are now available for PoF analysis of electronic products that allow non-CAE experts to perform expert level PoF evaluations. This course will introduce and provide examples of PoF CAEs Apps for electronic equipment.

Yes - There’s a App For THAT!!!!
Sherlock is a Semi-Automated CAE App program for Physics of Failure durability simulations & reliability assessment of electronic equipment.

Sherlock is the backbone to one of the most powerful reliability tools to be released for use not just by the reliability group, but by the entire engineering design and management team. Sherlock is the future of Automated Design Analysis (ADA), the integration of design rules, best practices and a return to a physics based understanding of product reliability.

It is not at the Iphone or Droid App store. But yes there is now a Physics of Failure Durability Simulation App.
A New Revolutionary CAE Tool Suite for Electronic Design Analysis

PCD&F Announces 2011 PCB Tool NPI Winners
Written by Mike Buetow

The winners are:

- Design Verification Tools: DfR Solutions (Sherlock Automated Design Analysis)
- PCB Design Tools: Altium (Altium Designer 16)
- System Modeling and Simulation Tools: Signey (SystemS1 – Parallel Bus Analysis)

Military Embedded Systems Editor’s Choice

DfR Solutions
A Semi-Automated CAE knowledge based tool suite for:
- Performing Physics of Failure durability simulation and reliability assessments on electronic equipment.
- Semi-Automated features simplifies model creation and analysis
- Eliminates the long, complicated, model creation process and the need for a PhD level expert in PoF, FEA and CFD numerical modeling.
- Designed to be used by non-CAE experts to quickly create and perform PoF durability & reliability analysis.
- The “Knowledge Based” features customized for E/E component and materials includes customizable, preloaded libraries of:
  - Component models
  - Material properties
  - Design templates
  - Analysis wizards
  - Environmental profiles for various applications.
The 4 Parts of a Sherlock 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** – automated calculations that translates and distributes the environmental and operational loads across a circuit board to the individual parts.

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.
1) Files Imported/Exported Via Intuitive Drop Down & Side Menus

- Import PCBA Layout,
  - Gerber, ODB++, Eagle & Valor CAD formats.
- Import BOM Parts List
  - Correlated supplier component part # and industry/JEDEC package styles to auto link component to Sherlock’s libraries of component geometry and material property to the individual parts locations mounted on the PCB to create the computer models for the life assessment.
- Define PCB Laminate & Layers to Calculate Substrate Performance
- Automated FEA Mesh generation.
1) Design Capture

- Creates CAE virtual model from standard circuit board CAD/CAM design files (Gerber / ODB Format)
Files Viewable As PCB Layers
- Provides Feedback To The User
1) Design Capture - Define PCB
Laminate & Layers to Calculate

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

- CTEx: 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.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Type</th>
<th>Material</th>
<th>Thickness</th>
<th>Density (g/cc)</th>
<th>CTEx (ppm/C)</th>
<th>CTEz (ppm/C)</th>
<th>Exy (MPa)</th>
<th>Ez (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SIGNAL</td>
<td>COPPER (50%)</td>
<td>2.0 oz</td>
<td>5.2800</td>
<td>17.600</td>
<td>17.600</td>
<td>113,000</td>
<td>113,000</td>
</tr>
<tr>
<td>2</td>
<td>Laminate</td>
<td>FR408</td>
<td>19.3 mil</td>
<td>1.9000</td>
<td>13.000</td>
<td>65.000</td>
<td>23,442</td>
<td>3,450</td>
</tr>
<tr>
<td>3</td>
<td>POWER</td>
<td>COPPER (90%)</td>
<td>2.0 oz</td>
<td>8.1760</td>
<td>17.600</td>
<td>17.600</td>
<td>113,000</td>
<td>113,000</td>
</tr>
</tbody>
</table>

Edit Selected Layers

Enter values for each layer property.

Laminate Layer Properties

- Laminate Material: iso/4
- Laminate Thickness: 19.3 mil
1) Design Capture PCB Material Property Database

- **Laminate Library**
  - Defines 48 Categories Of PCB Material Properties and Characteristics
  - Currently 319 Circuit Board Laminates Materials From 20 Global Producers.
  - New Entries Can Added as New Laminate Materials are Introduced to the Market.
Minimizes data entry through intelligent parsing and embedded electronic components package and material databases.
2) Define Environments

- Handles very complex environmental or test stress profiles
3) Load Transformation

Automated FEA Mesh Creation for Calculating Stress Distribution Across the PCBA & to Each Component

- Automatic Mesh Generation
  - Days of FEA modeling and calculations, executed in minutes
  - Without a FEA modeling expert.
3) Load Transformation
- Automated FEA for Dynamic Vibration/Shock Modal Analysis

- Harmonic Vibe
  - Multiple Harmonics
- Random Vibe
- Shock

Calculates PCB Stress Distribution for use in Fatigue / Fracture Analysis

- Embedded Abacus compatible FEA engine
- Can export files and results to either Abacus or Calculix
Finite Element Analysis (FEA) and Computational Fluid Dynamic (CFD) CAE program are regularly used to identify the stress conditions that products and systems will experience under various usage conditions.

- A standard practice in mechanical and structural products.

Combining CAE Stress Analysis Tools with Failure Mechanism Models enables the creation of: **“Virtual Durability Simulations” that can Calculate Stress Driven Reliability Performance Over Time.**

- PoF Research has enabled the migration of this technology to the materials and micro structures of E/E components and circuit board assemblies.
4) PoF Durability/Reliability Risk Assessment

Thermal Cycling Solder Fatigue

- 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)

- ~84% Failure Projection Within Service Life, Starting at ~3.8 years.
Identification of specific reliability/durability limits or deficiencies, of specific parts in, specific applications, enables the design to be revised with more suitable/robust parts that will meet reliability/durability objectives.

Reliability 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%
Detailed Design and Application Specific PoF Life Curves are Far More Useful that a simple single point MTBF (Mean Time Between Failure) estimate.
Reliability/Capability Growth with Traditional D-B-T-F Product Development Processes Takes Years to Achieve Maturity

- Initial Prod. Dev. Emphasis on Performance & Functional w/ Non-Production Intend HW
- Continuous Production

---

### Capability / Reliability Growth Actually Occurs in Incremental Steps

- 94% R / 6% Fr.
- Duane Model Simplification of Reliability Growth

---

**Design Team Start**
- Alpha HW (Funct. Dev.) B-T-F1
- Beta HW (DV) B-T-F2
- Proto (PV) B-T-F3
- Pilot Prod. & Ramp up B-T-F4
- Production 1st Yr. P-W-F1
- Production 2nd Yr. P-W-F2
- Production 3rdt Yr. P-W-F3
- Production 4th Yr. P-W-F4

---

**Project Concept**
The Efficiency Improvements of a PoF Knowledge & Analysis Based Product Development Process

- **.99R => 1% Failures**
- **Simulation Based PDP Enables Dramatic “Revolutionary” Improvement in Growth Rate**
- **BETTER QRD ACHIEVED FASTER**
- **Traditional Reliability Growth**
- **More Capable Accelerated Tests Enables Faster Reliability Growth (Evolutionary Improvement)**
- **FASTER PRODUCT DEVELOPMENT = LOWER COSTS**

**Graphical Chart**

- **D-DESIGN**
- **C-CAPABILITY**
- **R-RELIABILITY**

**Key Phases**

- **Proj. Concept**
- **Dsgn Team Start**
- **Alpha HW (Funct. Dev.)**
- **Beta (DV) B-T-F1**
- **Proto (PV) B-T-F3**
- **Launch Pilot & Ramp up P-W-F1**
- **Production 1st Yr. P-W-F2**
- **Production 2nd Yr. P-W-F2**
- **Production 3rd Yr. P-W-F3**
- **Production 4th Yr. P-W-F4**

**Legend**

- Alpha HW
- Beta DV
- Proto PV
- Production P-W-F1, P-W-F2, P-W-F3, P-W-F4
- Launch, Pilot & Ramp up

**Timeline**

- **Proj. Concept to Alpha HW (Funct. Dev.)**
- **Beta DV to Proto PV**
- **Launch Pilot & Ramp up**
- **Production Phases**
Accelerating Testing Challenges  E/E Modules are Complex Assemblies of Hundred of Parts and Scores of Components Types

• Combined T&V Overstress Test Profiles that Accelerate Time to Failure Testing For *Actual Failure Mechanism* Have Been Demonstrated on Test Coupons for Various Component Types.
  
  • Accelerated Test Profiles that *Produce “Foolish Failures”* Have Also Been Experienced.

• Developing Practical Application of Accelerated Testing for “VALIDATION” is a Challenge.
  
  • *Hard to Develop an “Optimized” Overstress Profile for REAL LIFE COMPLEX E/E Modules with MANY DIFFERENT COMPONENT TYPES*
  
  • An Overstress profile appropriated for one component on a circuit board may be excessive for the next part.

• The “Weakest Links” in EACH NEW DESIGN needs to be identified and used as the pace setter in an accelerated test.
Comparing Thermal Cycling Durability - IC Packages

- Without a flexible terminal lead to absorb thermal Expansion/Contract Stresses, Flat No Lead - Chip Scale IC Packages (FNL-CSP) experience a high amount of thermal expansion stress in their 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

### Package Type | Typical Thermal Cycles to Failure
<table>
<thead>
<tr>
<th></th>
<th>(-40°C to 125°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QFP</td>
<td>&gt;10,000</td>
</tr>
<tr>
<td>BGA</td>
<td>3,000 – 8,000</td>
</tr>
<tr>
<td>QFN</td>
<td>1,000-3,000</td>
</tr>
<tr>
<td>Laminated BGAs:</td>
<td>TTCL: 3,000 to 8,000</td>
</tr>
<tr>
<td>FNL CSP:</td>
<td>TTCL: 1,000 to 3,000</td>
</tr>
</tbody>
</table>

*TTCL = Typical Thermal Cycle Life During -40°C to +125°C Testing*
PoF SAT - Simulation Aided Testing
– Accelerated Life Test to Field Correlation

1) Overstress Testing Identifies 1st Part(s) to Fail & Accelerated Test Time To Failure.

2) Rate of Damage Accumulated, Failure Point During Test

3) Worst - Best Variation Range

4) PoF Computer Simulation of Rate of Strain/Damage Accumulated During Expected Field Conditions & Range Over Build Variation

5) PoF Computer Simulation Calculates Time to Reach Failure Pt. Relative to Design Life Requirements.
Motivation for Conversion to an Upfront Analysis Based Product Development Process.

- Use Computer Simulations of “the” Design,
  - Early During the CAD Stage,
  - To Identify and Resolve Application Specific Design & Packaging Circuit, EMC, Thermal & Structural Integrity . . . etc.

- Real, value added activities to create capable designs, faster, at lower costs via:
  - Reducing prototype part build time & costs.
  - Reducing physical testing time & costs (up to 50% reduction).
  - Reducing potential for schedule & costs over runs due to late problem discovery.
  - Reducing effort & costs of test incident investigation, reporting & resolution.
- 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
- Stress load in Fracture Risk Assessments
  - ICT Test Stress Analysis
  - Compliant Pin Connector Insertion
- ISO-26262 Functional Safety FMEA and Metric Generation
Determine applied stress applied ($\sigma$)

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

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

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

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 ($N_{f50}$)

\[
N_f^{-0.6} D_f^{0.75} + 0.9 \frac{S_u}{E} \left[ \frac{\exp(D_f)}{0.36} \right]^{0.1785\log_{10}^{10^5}} - \Delta \varepsilon = 0
\]
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.
# Design Failure Mode and Effects Analysis (DFMEA)

## Circuit Card Details

<table>
<thead>
<tr>
<th>Project:</th>
<th>DFMEA Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuit Card:</td>
<td>Mother Board</td>
</tr>
<tr>
<td>Prepared By:</td>
<td></td>
</tr>
<tr>
<td>Description:</td>
<td>This project was created to show how Sherlock can be used to maintain and generate DFMEA spreadsheets.</td>
</tr>
<tr>
<td>Revision:</td>
<td></td>
</tr>
</tbody>
</table>

## SubCircuit: 1.5V Regulator and Filters

<table>
<thead>
<tr>
<th>Component: C1,C3,C5-C6 (Filters)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Failure Mode</strong></td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>DC Leakage, EPR &lt; 50K</td>
</tr>
<tr>
<td>Open</td>
</tr>
<tr>
<td>Short to circuit ground</td>
</tr>
</tbody>
</table>

**Min Value:** 1  
**Max Value:** 8

**Min SEV:** 1  
**Max SEV:** 8  
**Min RPN:** 4  
**Max RPN:** 32
New Sherlock version will handle:
- Subassemblies (stacked boards)
- Standoffs
- Heatsinks
- Daughter cards
- Tall Parts
  (Relay, Alum Caps, Inductors . . .)
Limits of PoF Modeling - Errors & Excessive Variation
Can Not Model Probability of Manufacturing Defects, But Can Model the Outcome

- PoF/RP can Provide Knowledge for Optimizing or Error Proofing Manufacturing Processes or Determining if Parts are built right.
- 5 Most Common E/E Device Manufacturing Issues:

ASSEMBLY & SOLDERING PROCESS
(Related to up to 60% of E/E Assembly Issues)

- Ionic Contaminate
  (Circuit Board Cleanliness to Prevent Humidity Related Short Circuit Growths)
  (Up to 20% Of E/E Assembly Issues).

- Electro Static Discharge (ESD)
  (Component Damage)
  (% Varies Often Related To Spills)

In Process Board Flexure
Cracked & Missing Components.
(Related to up to 15% Of E/E Assembly Issues).

- Rework & Repair
  Latent Rework & Handling Damage (% Varies)

6 Sigma

DfR Solutions
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 Growth that is:
  - Faster and cheaper than Traditional Physical Design, Build, Test and Fix Testing.
  - Determines if a Specific Design is Theoretically Capable of Enduring Intended Environmental and Usage Conditions.
  - "Stress Analysis" Followed by "Material Degradation/Damage Modeling"
  - Compatible with the way modern products are designed and engineered (i.e CAD/CAE/CAM).
  - Sherlock the PoF CAE Apps Tools Enables Rapid, Low Cost Analysis Without a Highly Trained CAE/PoF expert.
  - Produces Significant Improvement In Accelerated Fielding of High QRD Products
Want to Know More – Suggested Reading

- Simulation-Based Reliability Assessment for Structural Engineers
- Reliability Physics and Engineering
- Failure Modes and Mechanisms in Electronic Packages
- Mechanical Analysis of Electronic Packaging Systems
- Reliability-Based Mechanical Design
- The Virtual Engineer: 21st Century Product Development
- Mechanical Reliability and Design
Questions & Discussion

Thank you for your attention.

For More Information Contact

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askdfr@dfrsolution.com
301-474-0607