Reliability in the Automotive Industry – New Challenges and Solutions

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Andre Kleyner - Bio Appendix

• **Experience:** Validation Engineering (Reliability, Accelerated Testing); Quality (Warranty, Quality Sciences, Data analysis and simulation); Advanced Engineering: (Occupant Safety Systems), Design for Reliability

• Editor for the Wiley Series in Quality & Reliability Engineering
  John Wiley & Sons, UK

30+ professional publications including three books on the topics of reliability, statistics, warranty management, and lifecycle cost analysis. Including an engineering college textbook

*Practical Reliability Engineering, Ed. 5*
Starting Thoughts

• Why Automotive Electronics?

• Planning – 5-yr Reliability roadmap at Delphi E&S

• Focus on how reliability and product testing are affected by new technology rather than focus on technology itself

• Data collection at the OEM level is decreasing while the number of various test and industry standards is increasing. All coincided with the deceasing number of reliability experts at the OEM level.

• Engineers over-rely on the industry standards often removing the ‘human element’ from the product test and validation process.
Reliability Challenges (Automotive and beyond) - Outline

• Functional Safety
  – Reliability Prediction – moving back in time
  – ICs getting smaller and less reliable – new addition to the ISO 26262 (Semiconductors)
  – Reliability requirements are becoming more and more stringent and the effect of self-driving cars

• Power Electronics
  – Meeting new requirements
  – Cooling Systems

• Lead-Free solder
  – Temperature Cycling Acceleration Models
  – Tin Whiskers

• Testing New Technology – generic approach and Conclusions
Functional Safety (FS) Standards

- FS standards address possible hazards caused by malfunction issues within & between E/E safety-related/critical control systems.
- Cover various areas of product development including various aspects of reliability, risk assessment, risk reduction
- Introduces the concept of (A)SIL (Automotive) Safety Integrity Level
- Generate additional work for design and reliability engineers
Random Hardware Failure Risk
Used to Define (ASIL-Automotive Safety Integrity Level)

9.4.2 Evaluation of **Probabilistic Metric for Random Hardware Failures (PMHF)**

1 FIT = 1 failure per billion \( (10^9) \) hours.
10\(^9\) hours = 114,155 yr (24h/7) \~\ 2.5 million yr (1.1h/7)

<table>
<thead>
<tr>
<th>ASIL</th>
<th>Random hardware failure target values</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>(&lt;10^{-8} \text{ h}^{-1})</td>
</tr>
<tr>
<td>C</td>
<td>(&lt;10^{-7} \text{ h}^{-1})</td>
</tr>
<tr>
<td>B</td>
<td>(&lt;10^{-7} \text{ h}^{-1})</td>
</tr>
</tbody>
</table>

10.0 FIT
100 FIT
100 FIT

How do you obtain FIT (failure) rates per ISO 26262?

- Using hardware part failure rates data from a recognized industry source, such as IEC/TR 62380, MIL HDBK 217, FIDES, UTE C80-811, SN29500
- Using statistics based on field returns or tests.
- Using expert judgment founded on an engineering approach based on quantitative and qualitative arguments.
Accumulated failure rate

$$\lambda_\Sigma = \lambda_1 + \lambda_2 + \lambda_3 + ... + \lambda_n$$

<table>
<thead>
<tr>
<th>Component Name</th>
<th>Failure rate/FIT</th>
<th>Safety-related component to be considered in the calculations?</th>
<th>Failure Mode</th>
<th>Failure rate distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>R3 note 1</td>
<td>3</td>
<td>YES</td>
<td>open</td>
<td>30%</td>
</tr>
<tr>
<td>R13 note 1, note 2 and note 7</td>
<td>2</td>
<td>YES</td>
<td>closed</td>
<td>10%</td>
</tr>
<tr>
<td>R23 note 1</td>
<td>2</td>
<td>YES</td>
<td>open</td>
<td>90%</td>
</tr>
<tr>
<td>C13 note 3 and note 7</td>
<td>2</td>
<td>YES</td>
<td>closed</td>
<td>10%</td>
</tr>
<tr>
<td>C23</td>
<td>2</td>
<td>NO</td>
<td>open</td>
<td>20%</td>
</tr>
<tr>
<td>WD</td>
<td>20</td>
<td>YES</td>
<td>closed</td>
<td>80%</td>
</tr>
<tr>
<td>Out. Stuck at 1</td>
<td></td>
<td></td>
<td>open</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>closed</td>
<td>80%</td>
</tr>
</tbody>
</table>
Reliability Prediction: Problems and Solutions

- Back to the future or rather forward to the past. Handbook methods showed sizeable discrepancy in the total FIT-rates results (same circuit - different handbooks)
- Develop alternative methods, e.g. physics of failure, analysis based on field data, similarity analysis, etc.
- New reliability prediction SAE International SAE-J3083 standard is in process of voting. Delphi Electronics & Safety is using field data whenever our OEM customers agree to it (about 70% of the time)
Ohring 1998, Silicon chip lines, \( \mu \text{m} \)

**Transistor size (logarithmic scale)**

- 10\( \mu \text{m} \)
- 1\( \mu \text{m} \)
- 100nm
- 10nm

<table>
<thead>
<tr>
<th>Year</th>
<th>Transistor Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>10( \mu \text{m} )</td>
</tr>
<tr>
<td>1980</td>
<td>1( \mu \text{m} )</td>
</tr>
<tr>
<td>1990</td>
<td>100nm</td>
</tr>
<tr>
<td>2000</td>
<td>10nm</td>
</tr>
<tr>
<td>2010</td>
<td>10nm</td>
</tr>
<tr>
<td>2020</td>
<td>10nm</td>
</tr>
</tbody>
</table>

Ohring 1998, Silicon chip lines, \( \mu \text{m} \)

- Voids – open circuit failure
- Hillock growth – short circuit

10nm chips (10 billion – \(10^{10}\) transistors in a single chip) enter mass production in 2017

“Wear out” (end-of-life) failure mechanisms, such as electro-migration, time-dependent dielectric breakdown, hot carriers, or negative bias temperature instability.
IC Scaling (65→45→32→22→14nm→..) smaller feature sizes and isolation spacing, projected to continue the trend. Semiconductor failure rates and shorten service lifetimes.

1.43 failure rate multiplication factor

From Jim McLeish presentation, DfR Solutions,

**Conclusion:** we need to start paying more attention to potential IC failures during system testing and be prepared.

The automotive industry doesn’t drive the market any more, hence we can not stay on the old technology or demand automotive grade ICs.
Power Electronics-Hybrid and Electric Vehicles (HEV)

- Power electronics is the application of solid-state electronics to the control and conversion of electric power. HEV applications
- Hybrid cars were produced in the years between 1902 and 1920, by companies such as Krieger, Lohner-Porsche, and Auto-Mixte.
- Power electronic converters modify a form of electrical energy (i.e. change its voltage, current or frequency). Power electronics carries power (not information), hence the main metric becomes the efficiency.
- The power conversion systems:
  - AC to DC (rectifier)
  - DC to AC (inverter)
  - DC to DC (DC-to-DC converter)
  - AC to AC (AC-to-AC converter)
Example of a Commercial DC/DC Converter

- Input Voltage Range 240 to 400Vdc operation
- 300Vdc to 14Vdc or 24Vdc
- Bi-directional DC / DC converter
  - Rugged, compact, and sealed engine compartment mount
  - -40C to 105C ambient temperature
- Liquid cooled 70ºC

- Mass – 9 Kg (20Lb)
- 15-yr life, automotive environment
- Mounting: Passenger or engine compartment
Cost of Validation (Power Electronics Example)

44 inch
110cm
### Comparison of Engineering and Validation Requirements

<table>
<thead>
<tr>
<th>Environment</th>
<th>‘Conventional’ Automotive Electronics</th>
<th>Power Electronics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature cycling</td>
<td>2 cold cycles per day</td>
<td>Between 0.5 and 1.0 million power cycles</td>
</tr>
<tr>
<td></td>
<td>7,000 – 11,000 per lifetime</td>
<td></td>
</tr>
<tr>
<td>Operating hours</td>
<td>8,000 to 12,000 ON hours</td>
<td>30,000 to 80,000 ON hours (battery chargers)</td>
</tr>
<tr>
<td>Test equipment</td>
<td>Regular lab equipment and test racks</td>
<td>Heavy test equipment, spinning motors and other</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expensive equipment</td>
</tr>
<tr>
<td>Use of Liquid Cooling</td>
<td>Typically no liquid cooling</td>
<td>Liquid or air cooling is often applied, creating</td>
</tr>
<tr>
<td></td>
<td></td>
<td>difficulties in accelerating temperature testing</td>
</tr>
</tbody>
</table>
Example of a Requirement for a Temperature Cycling Test

Product mission life = 15 years
Requirement: 900,000 power cycles

Using Coffin-Manson Acceleration Model

\[ AF = \left( \frac{\Delta T_{\text{Test}}}{\Delta T_{\text{Field}}} \right)^m \]

\[ \Delta T_{\text{Field}} = 35^\circ C \]
\[ \Delta T_{\text{Test}} = 165^\circ C [-40; +125] \]

\[ 900,000 \left( \frac{165}{35} \right)^{2.65} = 18,650 \quad \text{Temperature cycles} \]

Total test duration: 52 months (1 cycle = 2 h)

Problem: How can we put together an adequate and practical temperature cycling test?

Solution: Run ambient temperature cycles with continuous power cycling.
Benefits: (A) in addition to the ‘traditional’ effect of temperature cycling power cycles will count towards the 900,000 cycles requirement (B) increased \( \Delta T \) due to the power cycling during the high temperature dwell time increasing the acceleration factor.
Accelerated programs fail because they are based on theory that, with nine women pregnant, you can get a baby in a month

-Werner von Braun (1912 – 1977)
German rocket scientist
Prominent figure in NASA in 1960-s and 1970-s
Other Testing Challenges and Solutions

• Power electronics use of liquid cooling—difficulty to accelerate the test
• Solution: (reduce the fluid flow rate to let the parts heat up (e.g. from 6L/min to 1L/min). Danger: overheated parts – strike a delicate balance
• Narrow operating margins of the high power ICs
• Very expensive test equipment (see next slide)
Lead Free Solder Alloys

- **Chemical Elements used in solder alloys:**
  - Ag: silver
  - Bi: bismuth
  - Cu: copper
  - Pb: lead
  - Sn: tin
  - Au: gold
  - Pd: palladium
  - Ni: nickel

- **SnPb:** Common solder alloy containing tin and lead, typically in a ratio by weight of 63% tin to 37% lead commonly referred to as “63/37”

- **SAC305:** Common SnAgCu solder alloy containing tin, silver, and copper in the ratio 3% silver, 0.5% copper, and the remainder (96.5%) tin

- **Other popular alloys include:** SAC105, SAC387, SAC405, SN100, Innolot (SAC387 with 3.0%Bi, 1.4%Sb and 0.15%Ni)

Restriction of Hazardous Substances (RoHS), EU Directive 2002/95/EC, restricts the use of six hazardous materials including Lead.
Some Reliability Considerations for Lead Free Solder

Tin Whiskers

Pad cratering

Long-Term Reliability of Pb-Free Solder Joints

Mechanical Loading (Board Flexing, Shock, Vibration)

Higher melting temperatures 270°C, board warping, more possibility of contamination and copper dissolution
Accelerated Stress Testing and Reliability Conference

Acceleration Models for Lead-Free Solder Alloy SAC305

– Coffin Manson:

\[ AF = \left( \frac{N_{\text{Field}}}{N_{\text{Test}}} \right) = \left( \frac{\Delta T_{\text{Test}}}{\Delta T_{\text{Field}}} \right)^m \]

– Coffin Manson with temp. ramp:

\[ AF = \left( \frac{N_{\text{Field}}}{N_{\text{Test}}} \right) = \left( \frac{RR_{\text{Test}}}{RR_{\text{Field}}} \right)^{\frac{1}{3}} \left( \frac{\Delta T_{\text{Test}}}{\Delta T_{\text{Field}}} \right)^m \]

– Clech:

\[ AF = \left( \frac{\Delta T_1}{\Delta T_2} \right)^2 \left[ \frac{1 - c \cdot \Delta T_1^{-1} \left( e^{-0.19275 \cdot \frac{705.5}{T_{\text{min},1}}} + e^{0.19275 \cdot \frac{705.5}{T_{\text{max},1}}} \right)}{1 - c \cdot \Delta T_2^{-1} \left( e^{-0.19275 \cdot \frac{705.5}{T_{\text{min},2}}} + e^{0.19275 \cdot \frac{705.5}{T_{\text{max},2}}} \right)} \right] \]

– Modified Norris-Landzberg:

\[ AF = \left( \frac{\Delta T_{\text{Test}}}{\Delta T_{\text{Field}}} \right)^{2.65} \left( \frac{t_{\text{dwell-Test}}}{t_{\text{dwell-Field}}} \right)^{0.136} \exp \left( 2185 \left[ \frac{1}{T_{\text{max-Field}}} - \frac{1}{T_{\text{max-Test}}} \right] \right) \]

– Salmela:

\[ AF = \left( \frac{\Delta T_T}{\Delta T_F} \right)^a \left( \frac{f_{\Delta F}}{f_{\Delta T}} \right)^b \frac{1}{\text{Corr}(\Delta T_F)} \frac{1}{\text{Corr}(\Delta T_T)} \exp \left( \frac{E_a}{k} \left( \frac{1}{T_{F_{\text{max}}}} - \frac{1}{T_{T_{\text{max}}}} \right) \right) \]

Still here

iNEMI Project
### 1. Test Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T&lt;sub&gt;min&lt;/sub&gt; °C</td>
<td>-40</td>
</tr>
<tr>
<td>T&lt;sub&gt;max&lt;/sub&gt; °C</td>
<td>125</td>
</tr>
<tr>
<td>Test ΔT °C</td>
<td>165</td>
</tr>
<tr>
<td>Thermal ramp rate °C/min</td>
<td>8.0</td>
</tr>
<tr>
<td>Dwell Time at T&lt;sub&gt;min&lt;/sub&gt;, min</td>
<td>15</td>
</tr>
<tr>
<td>Dwell Time at T&lt;sub&gt;max&lt;/sub&gt;, min</td>
<td>15</td>
</tr>
</tbody>
</table>

**Coffin-Manson AF**

\[
AF = \frac{N_{Field}}{N_{Test}} = \left( \frac{\Delta T_{Test}}{\Delta T_{Field}} \right)^m
\]

- \(m = 2.65\)
- \(f = 0.333\)

**Coffin-Manson AF w/ramp**

\[
AF = \frac{N_{Field}}{N_{Test}} = \left( \frac{RR_{Test}}{RR_{Field}} \right)^{1/3} \left( \frac{\Delta T_{Test}}{\Delta T_{Field}} \right)^m
\]

- \(c = 3.9188\)
- Denominator: 0.3027

#### Clech (HP, SMTAI'09)

\[
AF = \left( \frac{\Delta T_1}{\Delta T_2} \right)^2 \left( 1 - c \cdot \Delta T_1^{-1} \left( \frac{t_{cold,1}}{t_{cold,2}} \right) e^{-0.19275 \cdot \frac{T_{cold,1}}{T_{max,1}}} + \frac{0.19275}{T_{cold,2}} \cdot \frac{T_{max,1}}{705.5} \right)
\]

- 1 = Test; 2 = Field

### 2. Field Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T&lt;sub&gt;min&lt;/sub&gt; °C</td>
<td>-10</td>
</tr>
<tr>
<td>T&lt;sub&gt;max&lt;/sub&gt; °C</td>
<td>50</td>
</tr>
<tr>
<td>Field ΔT °C</td>
<td>60</td>
</tr>
<tr>
<td>Thermal ramp rate °C/min</td>
<td>1.5</td>
</tr>
<tr>
<td>Dwell Time at T&lt;sub&gt;min&lt;/sub&gt;, min</td>
<td>60</td>
</tr>
<tr>
<td>Dwell Time at T&lt;sub&gt;max&lt;/sub&gt;, min</td>
<td>60</td>
</tr>
</tbody>
</table>

**Modified Norris-Landzberg**

\[
AF = \left( \frac{\Delta T_{Test}}{\Delta T_{Field}} \right)^{2.65} \left( \frac{t_{dwell-Test}}{t_{dwell-Field}} \right)^{0.136} \exp \left( 2185 \left[ \frac{1}{T_{max-field}} - \frac{1}{T_{max-test}} \right] \right)
\]

**Classic Norris-Landzberg**

\[
AF = \left( \frac{\Delta T_1}{\Delta T_f} \right)^{1.9} \left( \frac{f_f}{f_1} \right) \exp \left( 1414 \left\{ \frac{1}{T_{max_f}} - \frac{1}{T_{max_1}} \right\} \right)
\]

**Mostly Leadless Solder**

\[
AF = \left( \frac{\Delta T_1}{\Delta T_f} \right)^{1.9} \left( \frac{f_f}{f_1} \right) \exp \left( 1414 \left\{ \frac{1}{T_{max_f}} - \frac{1}{T_{max_1}} \right\} \right)
\]

**Salmela (Ceramic)**

Salmela (Ceramic) 8.42

**Salmela (Plastic)**

Salmela (Plastic) 7.24

**Where:**

- \(AF\) = Calculated Acceleration Factor (on a Cycle Basis).
- \(\Delta T\) = Package/Board Temperature Difference Between T<sub>on</sub> and T<sub>off</sub> (°K).
- \(T_{max}\) = Maximum Solder Joint Temperature (°K).
- \(T_{max} - \text{Field}\) = Maximum Solder Joint Temperature (°K) in the Field.
- \(T_{max} - \text{Test}\) = Maximum Solder Joint Temperature (°K) in the Test.

**AF = Acceleration Factor**

- \(N_{Field}/N_{Test}\) = Field Test to Test
- \(RR_{Test}/RR_{Field}\) = Rate Ramp Test to Field

- \(\Delta T_{Test}/\Delta T_{Field}\) = Temperature Difference Test to Field
- \(t_{dwell-Test}/t_{dwell-Field}\) = Dwell Time Test to Field
What are “Tin Whiskers”?

- First found in the 1940’s when electronics was new. Lead was added to solder to prevent Tin Whiskers.
- “Hair-like” single crystal structures that may grow from tin (Sn) finished surfaces
- Length: Up to 10 mm (typically < 1mm)
- Diameter: from 0.006 to 10 μm (Typical ~ 1 μm)
- Grow from the base, not from the tip
Problems with Tin Whiskers

• They grow in lead-free electronics and cause problems

• The mechanism behind tin whisker growth is not well understood, but seems to be encouraged by compressive mechanical stresses including:
  – residual stresses caused by electroplating,
  – mechanically-induced stresses,
  – stresses induced by diffusion of different metals,
  – thermally-induced stresses, and strain gradients in materials.

• There is currently no test to precipitate tin-whisker growth (although there are documents, like IEC 60068-2-82 Whisker Test Methods)

• Solution: focus on preventing whisker formation, mitigation and elimination at the manufacturing stage.
Example of a Failures During Vibration (SAC 305) – Typically not observed in tin-lead solders
Additional Thoughts on Reliability Challenges

• The challenges are numerous, but on the positive side, they should help to move forward the reliability science.

• New technologies typically present reliability challenges, which need to be addressed until those technologies mature and become more reliable.

• One of the challenges is the continuously hardening reliability requirements leading to longer and longer tests. In order to address that we might be looking for some non-traditional approaches, like prognostics or degradation analysis.

• Reliability education is still lacking in the modern engineering curriculum – more on the job training, self-education, seminars, and professional conferences, like ASTR.