Best Practices in Design for Reliability

March 9, 2016
DfR Solutions
Beltsville, MD
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
Warning: DfR Solutions’ DfR vs. Others’ DfR

- **DfR**: Focus is on activities **before** prototype
- **Others**: Focus is on the entire product lifecycle (HALT, root-cause analysis, reliability growth)

- **DfR**: Focus is on preventing single point of failures
- **Others**: Focus is on system-level failures and failure modes (safety)
Why Design for Reliability (DfR)?

- The foundation of a successful product is a robust design
  - Provides margin
  - Mitigates risk from defects
  - Satisfies the customer
Who Controls Electronic Hardware Design?

Electrical Designer
- Circuit Schematic
- Component selection
  - Bill of materials (BOM)
  - Approved vendor list (AVL)

Mechanical Designer
- PCB Layout and Outline
- Other aspects of electronic packaging

Both parties play a critical role in minimizing hardware mistakes during new product development.
When Do Mistakes Occur?

- Insufficient exchange of information between electrical design and mechanical design
- Poor understanding of supplier limitations
- Customer expectations (reliability, lifetime, use environment) are not incorporated into the new product development (NPD) process

*There can be many things that “you don’t know you don’t know”*
**Why DfR: Faster / Cheaper**

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

- Electronic OEMs that use design analysis tools
  - 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
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

- Ideas/Sketches
- Engineering/Design
- Specs/Drawings
- Lost Market Share
- Verification/Testing
- Prototype Parts
- Warranty/Recall
- Lost Production

DfR Solutions
Successful DfR efforts require the integration of product design and process planning into a cohesive, interactive activity known as Concurrent Engineering.

- Performance
- Testability
- Manufacturability
- Design
- Verify
- Review
- Produce
- Test
- Service
- Cost
- Quality

Problem prevention instead of problem solving and redesigns!
Many organizations have developed DfR Teams to speed implementation

- Success is dependent upon team composition and gating functions

**Challenges:** Classic design teams consist of electrical and mechanical engineers trained in the ‘science of success’

- DfR requires the right elements of personnel and tools
DfR Team

- Component engineer
- Physics of failure expert (mechanical / materials)
- Manufacturing engineer
  - Box level (harness, wiring, board-to-board connections)
  - Board / Assembly
- Engineer cognizant of environmental legislation
- Testing engineer (proficient in ICT / JTAG / functional)
- Thermal engineer (depending upon power requirements)
- Reliability engineer?
  - Depends. Many classic reliability engineers provide limited value in the design process due to over-emphasis on statistical techniques and environmental testing
Goal: Simultaneously optimizing the design

Reality: Need for specific gating activities (design reviews)
List of DfR Tools and Techniques (Wikipedia)

Many tasks, techniques and analyses are specific to particular industries and applications. Commonly these include:

- Built-in test (BIT) (testability analysis)
- Failure mode and effects analysis (FMEA)
- Reliability hazard analysis
- Reliability block-diagram analysis
- Dynamic Reliability block-diagram analysis
- Fault tree analysis
- Root cause analysis
- Sneak circuit analysis
- Accelerated testing
- Reliability growth analysis
- Weibull analysis
- Thermal analysis by finite element analysis (FEA) and/or measurement
- Thermal induced, shock and vibration fatigue analysis by FEA and/or measurement
- Electromagnetic analysis
- Statistical interference
- Avoidance of single point of failure
- Functional analysis and functional failure analysis (e.g., function FMEA, FHA or FFA)
- Predictive and preventive maintenance: reliability centered maintenance (RCM) analysis
- Testability analysis
- Failure diagnostics analysis (normally also incorporated in FMEA)
- Human error analysis
- Operational hazard analysis
- Manual screening
- Integrated logistics support
List of DfR Tools and Techniques (DfR Solutions)

- Failure Mode Analysis
  - Failure Mode Effect Analysis (FMEA), Fault Tree/Tolerance Analysis (FTA), Design Review by Failure Mode (DRBFM), Sneak Circuit Analysis (SCA)
- Reliability Prediction - Empirical
- Design Rules
- Design for Excellence
  - Design for Manufacturability (DfM), Design for Testability (DfT)
- Tolerancing (Mechanical, Electrical)
- Simulation and Modeling (Stress)
  - Thermal, Mechanical, Electrical/Circuit
- Simulation and Modeling (Damage)
  - EMI/EMC, EOS/ESD, Physics of Failure, Derating
Failure Mode Analysis

- A process of identifying potential failure modes and appropriate mitigations early in the design process
  - Likely the most common DfR tool for reliability engineers

- These are generic DfR tools
  - A Strength and Weakness
    - **Strength**: Can provide amazing insight
    - **Weakness**: Can be a boring, monotonous, no-value, check-the-box activity
"Unfortunately, reliability engineering has been afflicted with more nonsense than any other branch of engineering."

- Pat O'Connor (Author Practical Reliability Engineering).
The classic failure mode analysis technique
  - Developed after World War II

Forces the team to identify failure modes and their severity, their probability of occurrence, and their detectability

Executed as both a design analysis (DFMEA) and a process analysis (PFMEA)
FMEA (cont.)

- Conservative, regulated industries love FMEA
  - Very concerned about safety
  - Very concerned about having a written record of being concerned about safety

- Other industries are less certain
  - DFMEA can take too long (personal computer company completed DFMEA three months after product launch)
  - PFMEA provided by suppliers can be boilerplate
For a FMEA to be valuable, two things need to happen

One, the form should be fluid
- Functional block, geometry, etc.
- Scoring can be linear, actual measurements, etc.

Two, actions that can be measured through statistical process control should be identified
- It is not a one and done
DfR Outline

- **DfR at Concept / Block-Diagram Stage**
  - Specifications

- **Part Selection**
  - Derating and uprating

- **Design for Manufacturability**
  - Reliability is only as good as what you make

- **Wearout Mechanisms and Physics of Failure**
  - Predicting degradation in today’s electronics
What is the Latest in Design for Reliability?

- Traditional screening does not work
  - Studies on DRAM, SSD, and Ceramic Capacitors have identified metrics that indicate weaker parts, but these parts do not display infant mortality behavior
  - However, they do fail more often and earlier than the overall population

- Studies by Google have found that temperature has limited influence on the failure rate of DRAM, flash memory, or hard drives
  - Activity levels also had limited effect on failure rate
  - Overall calendar age was a better indicator, with significant increase in error rate for DRAM after 20 months
What is the Latest in Design for Reliability?

- Cold is the new Hot
  - Most state-of-the-art devices can have limited lifetimes below 0°C
DfR at Concept Stage
Can DfR mistakes occur at this stage?
- No.......... and Yes

Failure to capture and understand product specifications at this stage lays the groundwork for mistakes at schematic and layout.

Important specifications to capture at concept stage:
- Reliability goals
- Use environment
- Dimensional constraints
Reliability Goals

- 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

- Typical reliability metrics: Desired Lifetime / Product Performance

- Desired lifetime
  - Defined as when the customer will be satisfied
  - Should be actively used in development of part and product qualification

- Product performance
  - Returns during the warranty period
  - Survivability over lifetime at a set confidence level
  - Try to avoid MTBF or MTTF
Why is Desired Lifetime Important?

Electronics: Today and the Future
Electronics: 1960s, 1970s, 1980s

Failure Rate

Time

Wearout!

No wearout!
Warranty Returns: Laptops (cont.)

Laptop 3 year Failure Rates

% of Laptops Failing vs. Months since Item Purchase

- Total Failure Rate
- Malfunction Rate
- Accident Rate

SquareTrade Laptop Reliability

% of Laptops Failing:
- 0% at 1 month
- 2.5% at 11 months
- 4.7% at 13 months
- 7.2% at 17 months
- 7.0% at 21 months
- 12.7% at 25 months
- 19.7% at 29 months
- 31.0% at 35 months

20.4% at 35 months
10.6% at 35 months
Warranty Returns: iPad

- **Truly revolutionary**: A consumer electronic as reliable (or more) than typical high-reliability electronics
  - Key Drivers: More robust software, elimination of moving parts (fans, keyboard, hard drive)
Warranty Returns: Automotive Modules

- Many manufacturers of automotive electronic modules track by incidents per thousand vehicles (IPTV) (over some time interval, typically 1 year)
  - Desired IPTV highly dependent on safety and propulsion

- **Hyundai Brake** [http://www.hyundaiproblems.com/investigations/Genesis/2012/]
  - 25-30 IPTV (a problem)
  - 0.3 IPTV (no a problem)

- **GM Antilock Brake** [http://money.cnn.com/2005/05/03/Autos/gm_investigation/]
  - 0.32 IPTV (a problem)
  - 0.03 IPTV (no problem)

- **Saturn Power Steering** [http://www.carcomplaints.com/Saturn/Ion/2006/investigations/]
  - 14 IPTV (a problem)

- **Nissan Transmission** [http://www-odi.nhtsa.dot.gov/cars/problems/defect/results.cfm?action_number=PE13029&SearchType=QuickSearch&summary=true]
  - 50 IPTV (a problem)
  - 0.6 IPTV (no problem)

Product Performance: Survivability

- Some companies set reliability goals based on survivability
  - Often bounded by confidence levels
  - Example: 95% reliability with 90% confidence over 15 years

- Advantages
  - Helps set bounds on test time and sample size
  - Does not assume a failure rate behavior (decreasing, increasing, steady-state)

- Disadvantages
  - Can be re-interpreted through mean time to failure (MTTF) or mean time between failures (MTBF)
Limitations of MTTF/MTBF

- MTBF/MTTF calculations tend to assume that failures are random in nature
  - Provides no motivation for failure avoidance
- Easy to manipulate numbers
  - Tweaks are made to reach desired MTBF
  - E.g., quality factors for each component are modified
- Often misinterpreted
  - 50K hour MTBF does not mean no failures in 50K hours
- Better fit towards logistics and procurement, not failure avoidance
Wearout Mechanisms and Physics of Failure (PoF)
What is Physics of Failure (PoF)?

- Also known as reliability physics

- **Common Definition:**
  - The process of using modeling and simulation based on the fundamentals of physical science (physics, chemistry, material science, mechanics, etc.) to predict reliability and prevent failures
What are we modeling / simulating?

Packaging + Reliability ($t > 0$) = Material Movement

- Diffusion
- Creep
- Fatigue
**Diffusion**

- **Motion of electrons, atoms, ions, or vacancies through a material**
  - Typically driven by a concentration gradient (Fick’s Law)

\[
J_A(x, t) = -D_A \frac{\partial C_A(x, t)}{\partial x}
\]

\[
n(x, t) = n(0) \left[ 1 - 2 \left( \frac{x}{2\sqrt{Dt\pi}} \right) \right]
\]

- Can be driven by other forces (electromotive force, stress)
PoF-Based Reliability Prediction

- Most physics-of-failure (PoF) based models are semi-empirical
  - The basic concept is still valid
  - Requires calibration

- Calibration testing should be performed over several orders of magnitudes
  - Allows for the derivation of constants

- The purpose of PoF is to limit, but not eliminate, the influence of material and geometric parameters
  - E.g., Solder: Testing must be re-performed for each package family (ball array devices, gullwing, leadless, etc.)
Physics of Failure (PoF) Algorithms

\[ \tau_{HCI} \propto \exp\left[ \frac{b_{HCI}}{V_D} \right] \cdot \exp\left[ \frac{E_{a_{HCI}}}{kT} \right] \]

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

\[ N_f^{-0.6}D_f^{0.75} + 0.9 \frac{S_n}{E} \left\{ \frac{\exp(D_f)}{0.36} \right\}^{0.1785\log_{10}\frac{N_f}{N}} - \Delta \varepsilon = 0 \]

\[ \tau_{EM} \propto (J)^{-n} \cdot \exp\left[ \frac{E_{a_{EM}}}{kT} \right] \]

\[ L = L_t \left( \frac{V_r}{V_0} \right) \times 2^\left( \frac{T_r - T_A}{10} \right) \]

\[ \tau_{TDDB} \propto \exp[ -b_{TDDB} \cdot V_G ] \cdot \exp\left[ \frac{E_{a_{TDDB}}}{kT} \right] \]

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

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

\[ \tau_{NBTI} \propto \exp[ -b_{NBTI} \cdot V_G ] \cdot \exp\left[ \frac{E_{a_{NBTI}}}{kT} \right] \]

\[ (\alpha_2 - \alpha_1) \cdot \Delta T \cdot L = F \cdot \left( \frac{L}{E_1A_1} + \frac{L}{E_2A_2} + \frac{h_s}{A_sG_s} + \frac{h_c}{A_cG_c} + \left( \frac{2 - \nu}{9 \cdot G_ba} \right) \right) \]

Can be mind-numbing! What to do?
PoF and Wearout

What is susceptible to long-term degradation in electronic designs?

- Ceramic Capacitors (oxygen vacancy migration)
- Memory Devices (limited write cycles, read times)
- Electrolytic Capacitors (electrolyte evaporation, dielectric dissolution)
- Film Capacitors
- Resistors (if improperly derated)
- Silver-Based Platings (if exposed to corrosive environments)
- Relays and other Electromechanical Components
- Light Emitting Diodes (LEDs) and Laser Diodes
- Connectors (if improperly specified and designed)
- Tin Whiskers*
- Integrated Circuits (EM, TDDB, HCI, NBTI)
- Interconnects (Creep, Fatigue)
  - Plated through holes
  - Solder joints

Industry-accepted models exist
Ceramic Capacitor Lifetime Prediction

- Ceramic caps are typically not expected to experience ‘wearout’ during normal operation

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

- where \( t \) is time, \( V \) is voltage, \( T \) is temperature (K), \( n \) is a constant (1.5 to 7; nominally 4 to 5), \( E_a \) is an activation energy (1.3 to 1.5) and \( K_B \) is Boltzman's constant (8.62 x 10^{-5} \text{ eV/K})

- Lifetime may be limited for extended value capacitors
  - Sub-2 micron dielectric thickness
  - Greater than 350 layers (increased failure opportunity)
Inconsistency in Parameters (Different Failure Mechanisms)

<table>
<thead>
<tr>
<th>Organization</th>
<th>Voltage Exponent, n</th>
<th>Activation Energy, Ea (eV)</th>
<th>Comments</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>DfR</td>
<td>2.5</td>
<td>0.9</td>
<td>Based on case studies with clients</td>
<td></td>
</tr>
<tr>
<td>Panasonic</td>
<td>3</td>
<td>0.31</td>
<td>Roughly equivalent to 2X / 15C</td>
<td></td>
</tr>
<tr>
<td>Murata</td>
<td>3</td>
<td>0.57</td>
<td>Roughly equivalent to 2X / 8C</td>
<td></td>
</tr>
<tr>
<td>Venkel</td>
<td>3</td>
<td>0.8</td>
<td>Roughly equivalent to 10X / 20C</td>
<td></td>
</tr>
<tr>
<td>Intel</td>
<td>4.6</td>
<td>1.27</td>
<td>Average from seven types of X6S capacitors</td>
<td></td>
</tr>
<tr>
<td>Kemet-A</td>
<td>5.9</td>
<td>1.14</td>
<td>Average from three types of X7R capacitors</td>
<td></td>
</tr>
<tr>
<td>Kemet-B</td>
<td>3.4</td>
<td>1.43</td>
<td>Average from four types of X5R capacitors</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>383</th>
<th>418</th>
<th>433</th>
<th>433</th>
<th>433</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (C)</td>
<td>110</td>
<td>145</td>
<td>160</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Voltage</td>
<td>18.9</td>
<td>12.6</td>
<td>37.8</td>
<td>37.8</td>
<td>37.8</td>
</tr>
<tr>
<td>Capacitor</td>
<td>0603/10uF/6.3V</td>
<td>0603/10uF/6.3V</td>
<td>0603/10uF/6.3V</td>
<td>0805/22uF/6.3V</td>
<td>1206/47uF/6.3V</td>
</tr>
<tr>
<td>HALT Life (minutes)</td>
<td>192</td>
<td>15</td>
<td>0.75</td>
<td>23</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>Time to Failure at 38°C and 3.3V (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DfR</td>
<td>16</td>
</tr>
<tr>
<td>Panasonic</td>
<td>2</td>
</tr>
<tr>
<td>Murata</td>
<td>35</td>
</tr>
<tr>
<td>Venkel</td>
<td>273</td>
</tr>
<tr>
<td>Intel</td>
<td>8,279</td>
</tr>
<tr>
<td>Kemet-A</td>
<td>32,155</td>
</tr>
<tr>
<td>Kemet-B</td>
<td>3,132</td>
</tr>
<tr>
<td>0603 / DfR</td>
<td>6,482</td>
</tr>
</tbody>
</table>
Inconsistency in Parameters (cont.)

\[ \log(\text{MTTF}) = \text{MTTF}(\text{hr}) \]

\[ \log(E) = E(\text{V} / \mu\text{m}) \]

\[ n = 3.7 \]

\[ n = 7.3 \]
\[ t = \frac{\rho_{\text{crit}}}{\alpha \nu N q} \cdot \left( \exp \frac{-E_A}{k_B T} \sinh \frac{qaE_{\text{App}}}{2k_B T} \right)^{-1} \]

- \( \rho_{\text{critical}} \) is a critical ionic charge level, \( \alpha \) is the characteristic hoping distance, \( \nu \) is the jump frequency of the oxygen vacancy, \( N \) is concentration of oxygen vacancies, \( q \) is ionic charge of the point defect, \( E_A \) is activation energy, \( k_B \) is Boltzmann’s constant, \( T \) is temperature, \( E_{\text{app}} \) is applied electric field

Physics of Failure, Simplified

\[
\log(t_1) = C(T) - \log[\sinh(\beta E_1/T)]
\]
Physics of Failure – Sherlock

- Need for standardized physics of failure tool + easy access to necessary data (translation)

- Increasing requirement across supply chains
  - Boeing, GM, Embraer, Volkswagen, BAE Systems, etc.
DfR Case Study (Workstations)
## Use Case (Environment)

<table>
<thead>
<tr>
<th></th>
<th>Notebook Workstation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CPU</strong></td>
<td></td>
</tr>
<tr>
<td>Idle</td>
<td>22.1</td>
</tr>
<tr>
<td>Average</td>
<td>28.4</td>
</tr>
<tr>
<td>Maximum</td>
<td>52.6</td>
</tr>
<tr>
<td><strong>Northbridge</strong></td>
<td></td>
</tr>
<tr>
<td>Idle</td>
<td>21.6</td>
</tr>
<tr>
<td>Average</td>
<td>41.8</td>
</tr>
<tr>
<td>Maximum</td>
<td>46.7</td>
</tr>
<tr>
<td><strong>Memory</strong></td>
<td></td>
</tr>
<tr>
<td>Idle</td>
<td>21.6</td>
</tr>
<tr>
<td>Average</td>
<td>37.0</td>
</tr>
<tr>
<td>Maximum</td>
<td>51.0</td>
</tr>
<tr>
<td><strong>Outlet Air</strong></td>
<td></td>
</tr>
<tr>
<td>Idle</td>
<td>18.9</td>
</tr>
<tr>
<td>Average</td>
<td>20.1</td>
</tr>
<tr>
<td>Maximum</td>
<td>24.3</td>
</tr>
</tbody>
</table>

- Thermal measurements under range of use cases
- Inputted into multiple stages of the DfR process (component reliability, thermal cycling, connector reliability, etc.)
Used large, fine-pitch, stacked-die graphics DRAM and then placed them in a mirror configuration.
DfR: Connectors

- ‘Consumer-grade’ connectors can use industrial/military levels of plating (with frequent use of spot plating)
- Use of PoF to calculate lifetime based on nickel layer thickness

<table>
<thead>
<tr>
<th></th>
<th>Plating - Gold</th>
<th>Underplate - Nickel</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIMM socket</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>SATA jack/cable</td>
<td>20</td>
<td>90</td>
</tr>
<tr>
<td>DIMM socket</td>
<td>30</td>
<td>90</td>
</tr>
<tr>
<td>SATA jack/cable</td>
<td>30</td>
<td>90</td>
</tr>
<tr>
<td>DIMM socket</td>
<td>20</td>
<td>90</td>
</tr>
<tr>
<td>DIMM socket</td>
<td>40</td>
<td>120</td>
</tr>
<tr>
<td>SATA jack/cable</td>
<td>25</td>
<td>180</td>
</tr>
<tr>
<td>DIMM socket</td>
<td><strong>10</strong></td>
<td>100</td>
</tr>
<tr>
<td>SATA jack/cable</td>
<td>25</td>
<td>80</td>
</tr>
<tr>
<td>DIMM socket</td>
<td>45</td>
<td>85</td>
</tr>
<tr>
<td>DIMM socket</td>
<td>20</td>
<td>110</td>
</tr>
<tr>
<td>SATA jack/cable</td>
<td>30</td>
<td>400</td>
</tr>
<tr>
<td>DIMM socket</td>
<td><strong>10</strong></td>
<td>100</td>
</tr>
<tr>
<td>SATA jack/cable</td>
<td>20</td>
<td>70</td>
</tr>
<tr>
<td>DIMM socket</td>
<td><strong>5</strong></td>
<td>170</td>
</tr>
</tbody>
</table>
Mounting strategies can influence natural frequency and magnitude / location of displacement
Overall Design Practices

- Use of slots to prevent overconstraint or buckling and Torx screws to avoid cam-out
- Rounded corners (to prevent cracking) and channeling to direct fluids (indirect splash)
- Strain relief loops and off-glass drivers in LCD connections
Summary

- To avoid design mistakes, be aware that functionality is only the beginning

- Be aware of industry best practices
  - When to use heuristic rules; when to use physics of failure

- Maximize knowledge of your design as early in the product development process as possible

- Do not overly rely on supplier statements
  - Their view: Reliability is application dependent