Secret to Low Cost Reliable Power Supplies

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Part 1 – Cost of Power Supply Reliability
Reliability: Earlier is Cheaper

Reduce Costs by Improving Reliability Upfront

Cost Of Unreliability 2x More

1 x 10 x 100 x 1000 x

CONCEPT DESIGN VALIDATION PRODUCTION

- Ideas/Sketches
- Engineering/Design
- Specs/Drawings
- Lost Market Share
- Verification/Testing
- Lost Production
- Warranty/Recall
- Prototype Parts
What is Physics of Failure (PoF)?

- How do we improve the reliability?
- Use Physics of Failure (POF)

**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

**DfR Solutions:**
- Leverages the knowledge and understanding of the processes and mechanisms that induce failure to predict reliability and improve product performance
Why Physics of Failure: Complexity

- Ensuring reliability is becoming increasingly difficult
  - Increasing complexity of electronic circuits
  - Increasing power requirements
  - Introduction of new component and material technologies
  - Introduction of less robust components
Before Physics of Failure: Traditional Reliability Growth

Today, This Is Not Enough!
1) Design issues are 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.

It Is Time for a Change!
Why Do Power Supplies Struggle with Reliability?

- Cost-Constrained
  - Not viewed as a product differentiator (bottom-dollar)
  - Treated no different than a resistor or capacitor
  - A necessary evil
- Space-Constrained
  - Precious real estate goes to the processor and memory
  - What’s left is for the power supply
- Tight Schedule
  - Power supply requirements are not known until the analog/digital circuits are designed
  - But the power supplies must be designed and ready when the analog/digital boards come in
Why Do Power Supplies Struggle with Reliability?

- **Multiple Packaging Technologies**
  - Must handle both SMT for small signal and PTH for high power components
  - Heatsinks must be used for high power
  - Specialized connectors and PCB for high power
  - Transformers construction and weight on PCB

- **High Voltage / High Current**
  - Power supplies that operate from the wall plug must operate up to 265VAC and handle high inrush current
  - Components run at high power density and high voltage
  - Due to high voltage, there are safety requirements (IEC 60950)
Why Do Power Supplies Struggle with Reliability?

- **Custom Magnetics**
  - Custom magnetics like transformers are a sub-assembly and need to be treated as a product
  - These require a unique skill that is not taught in school and some consider a black art

- **Connected to the Real-World**
  - Must handle Transients, Electrical Noise, Temperature and variation in AC utility
  - Requires meeting IEC 61000-4-X standards and FCC/CISPR EMC requirements

- **Miscommunication on Reliability Expectations**
  - For example power supply reliability may have been tested at 25C while the customer needs it at 50C
Challenges of Modern Power Electronics

- High Voltage – High Current Safety
- Trade-offs of: Efficiency – Cost – Reliability
- Power Density (High Power Dissipation in Small Space)
- Sustained High Temperatures of Components
  - Power Density Drives Higher Temperatures
  - High Temperature Lowers Reliability
    - Active Components: ICs, Power Transistors, Sensors
    - Passive Components: Resistors, Capacitors, Diodes, Transient Protectors
    - Dielectrics (Insulators): PCB, spacers, insulating films
      - High Electric Field – Temperature Interactions
      - Localized Heating
Challenges of Modern Power Electronics (cont)

- Active Cooling
  - Forced Air
    - Fans are unreliable and noisy
    - Dirt from air accumulates and reduces efficiency
  - Liquid Cooling
    - Expensive
    - Leaks can be very bad
    - Delta T for Automotive is worse than Air Cooled
      - Higher Delta T for Cold Weather Operation
      - Reduced Solder Fatigue Life

- New Technologies – New Failure Modes
  - SiC & GaN
Major Failure Modes of Power Electronics (cont)

- Temperature Related Degradation of Electrical Components
  - Electrical Components
    - Electrical parameters degrade with Time, Temperature and Current
    - Difficult to measure and model
      - Large Spread in the data: part to part, varies by supplier
      - Analysis must be statistically based
  - Dielectrics
    - Outgas, oxidize, degenerate (internal chemical bond degradation)
      - Shrink and become brittle (reduced impact resistance)
      - Reduced resistance to electrical breakdown
Major Failure Modes of Power Electronics (cont)

- Arcing
  - Electrical transients
  - Dielectric degradation
  - Contamination (Including moisture from condensation)
  - Creates Carbon Tracking on Organic Insulators
    - Islands of carbonized (conductive) material on surface of conductor
      - Increases probability of future arcing
      - Long term will form carbon resistor
Major Failure Modes of Power Electronics (cont)

- **Electro-Chemical Effects**
  - Driven by High Voltages and Currents
  - Accelerated by Temperature and sometimes humidity
  - Electro migration
    - Movement of conductor metal by “electron wind”
    - Driven by high temperatures, current density and mobile metals

- **Dendritic Growth**
  - Solid State Diffusion (e.g. Tin Whiskers)
    - Driven by Stress and Temperature and metallic crystalline structure
  - Electro plating
    - Driven by Electric Field, Moisture (humidity) and Ionic Contaminants
    - Copper and Silver are very susceptible (PCB & Pb Free Solder)

- **CAF (Conductive Anodic Filaments)**
  - Formation of conductive liquid films inside of PCBs
Industry Standards

- Industry Standards that are Focused on Safety where reliability is critical
  - UL 94 Flammability of materials
  - IEC 60664 Insulation-Low Voltage Systems
  - IEC 60950 Information Technology Equipment Safety
  - IEC 60601 Medical Equipment Safety
  - IEC 61010 Lab Equipment Safety
  - IEC 62061 Machine Safety
  - And so forth
  - Even software that control electrical systems may need to meet UL 1998
Design Philosophy

- Fail Safe – High Energy Failure Modes can be Catastrophic
  - Fail to “Safe State”
  - Minimize impact of each failure mode
  - Perform abnormal fault testing
- Fault Tolerance
  - Redundancy where feasible
  - Design for Component Degradation
- Conservative Design Rules
  - De-rate components sufficiently for the application
Design Philosophy

- High Quality Components
  - AEC Grade 1 or 0, Tier 1 components

- Worst Case Tolerance Analysis
  - Voltage
  - Temperature
  - Environmental Degradation

- Simulate / Verify / Validate
  - Capable Design Tools
    - Electrical, Thermal & Mechanical Simulation
    - PCB Layout with Voltage Dependent Design Rules
  - Validation plan that represents field exposure
Design Guidelines

- Principles of Design are Unchanged
- Added / Emphasized Issues:
  - High Voltage / Energy Safety: Failure Modes can be severe
  - High Voltage
    - Creepage: Surface Corrosion & Dendrites
    - Clearance: Arcing
    - CAF (Conductive Anodic Filaments): Corrosion Internal to PCB
  - High Current
    - $I^2R$ Heating
    - Voltage Drop
    - Current Density
  - High Electrical & Magnetic Fields
  - Component Degradation
Reliability Testing of Power Electronics

Test Philosophies are Common to other Electronics
  - Stress Accelerators
    - Voltage
    - Current
    - Temperature
    - Voltage & Current Transients

Testing Issues
  - Safety - Electrical & Mechanical
  - Test benches are expensive
    - Power Supplies
    - Loads
      - Static Load Cells
      - Motors – Dynamometers
    - Liquid Cooling
  - Facility costs are high
Reliability Testing of Power Electronics (cont.)

- High Cost of Test
  - Few Test Sites → Very limited number of samples
  - High reliability goals → Long Test Time
  - Cannot reasonably measure reliability!
  - Can only find gross & early life failure modes
- What to do?
- Focus on Design for Reliability methodologies
- Reliability simulation (e.g. Sherlock)
  - PoF (Physics of Failure) based Simulation
  - Simulate against validation requirements
  - Evaluate multiple mission profiles to simulate field
Reliability Testing of Power Electronics (cont.)

- Test to failure at high stress levels
  - Identify pertinent failure modes
  - Focused Simulation
  - Focused Testing
- Good design practices
- Conservative designs
Power Supply Reliability

Part 2 – Common Failure Modes
Examples of Wearout Failure Mechanisms

- **Mechanical**
  - Fatigue (thermal cycling)
  - Creep
  - Wear (fan bearings)

- **Electrical**
  - Electro-Migration Driven Molecular Diffusion & Inter Diffusion
  - Thermal Degradation

- **Chemical / Contaminate**
  - Moisture Penetration
  - Electro-Chemical-Migration Driven Dendritic Growth.
  - Conductive Anodic Filament (CAF)
  - Corrosion

- **Radiation Damage**
  - Single Event
  - High Flux Radiation (alpha, beta, gamma)
Key Power Supply Components

- A few examples of components that affect reliability
  - Fans
  - Capacitors
  - Magnetics
  - Power Devices
  - Solder Joint Fatigue
  - Tin Whiskers
Fans

- Fans for cooling
  - For high power converters, a fan is required for cooling
  - Fans are mechanical systems that wear out due to the bearings
  - There are many bearing types but all have their pluses and minuses
  - They are limited by the number of revolutions based on temperature

- There are tricks for increasing fan life
  - Use a large fan but run it at a lower speed (less revolutions)
  - Run the fan only when needed for cooling
  - Variable speed fan based on cooling requirements
  - N+1 fan cooling system
Power Supply Capacitors

Bulk (energy storage) capacitors are a critical component in all power supply topologies.
Aluminum Electrolytic (AE) Capacitors

- Switching Power Supplies Need Large Value Capacitors
- Most critical component in regards to limited lifetime
  - Failure mode is typically evaporation of liquid electrolyte through the rubber seal/stopper
- Evaporation prediction has been based on standard relationship
  - Doubling of lifetime with every 10C drop in temperature (note: This is not Arrhenius!)
    \[ L_x = L_o \times 2^{(T_o-T_x)/10} \]
  - However, there are variations from manufacturer to manufacturer
AE Capacitor Lifetime Calculations (Nichicon)

- \( L_r \) is rated lifetime
- \( T_r \) is rated temperature
- \( T \) is ambient temperature
- \( I_r \) is rated ripple current
- \( I \) is actual ripple current
- \( \Delta T_r \) is the temperature rise due to rated ripple current
- \( \Delta t \) is the temperature rise due to actual ripple current
- \( \alpha \) and \( K \) are coefficients
- Always check with the vendor if they have equations

\[
L = L_r \times 2 \frac{T_r-T}{10} \times \frac{1}{B_n} \quad \text{Miniature w/o ripple}
\]

\[
B_n = 2^\alpha \times \left(\frac{I_r}{I}\right)^2 \times 2^{-\frac{(T_r-T)}{30}}
\]

\[
L = L_r \times 2 \frac{T_r-T}{10} \times 2^\alpha 1-\left(\frac{I_r}{I}\right)^2 \times 2^{-\frac{(T_r-T)}{30}} \quad \text{Miniature w/ ripple}
\]

\[
L = L_r \times 2 \frac{T_r-T}{10} \times 2^1 \times \Delta T_r \times \frac{(I_r)^2}{K} \quad \text{Large can}
\]
Aluminum Electrolytic (AE) Capacitors

- The key to reliability is to keep the temperature low on the AE capacitor
  - Keep ambient temperature to a minimum but that’s dictated by the environment
  - Low RMS ripple current to keep self-heating down
  - Use high temperature / high ripple current endurance rated capacitors
  - Use aluminum polymer capacitors
Aluminum Polymer Capacitors

- These are also large value capacitors but voltage rating is less than 100V and cost is higher than AE caps
  - These caps use a solid “electrolyte”
  - Failure mode is failure of the solid material
  
  \[ L_x = L_0 \times 10^{(T_0-T_x)/20} \]

- Life is much better and ESR is lower than aluminum electrolytic capacitors but cost is higher
Tantalum Capacitors

- Tantalum capacitors have high capacitance/volume but care must be taken
  - Typically temperature is limited to only 85°C
  - To keep self-heating low, the ESR and/or ripple current must be low
  - Voltage derating is critical because of the grain structure of tantalum material
  - Rule is to derate by 50%
  - Most applications can now be replaced with more reliable ceramic caps
Film Electrolytic Capacitors

- Film capacitors are sometimes required for snubber circuits
  - Film caps cover the large value, non-polarized, high voltage capacitors
  - Values are still much smaller than polarized AE caps but higher values than tantalums and ceramic caps
  - Different plastics are used for different characteristics
  - Self-heating is the main cause of failure and that’s due to high ripple current
Instead of measuring the current, most vendors display the max AC ripple voltage versus frequency.

The ripple current is approximately $\frac{V_{\text{rms}}}{X_C}$ or $V_{\text{rms}} \times 2 \times \pi \times C \times F$.

The ripple current is limited by the temperature rise $I^2 \times ESR$.

For more helpful information see “Wima” capacitors which have very good technical information.
Inductors / Transformers are critical energy storage components in all medium and high power supplies.
Magnetics

- Inductor is a coil of insulated wire wrapped around a material with high magnetic permeability
  - **Purpose** – Dynamic Energy Storage

- Transformer has multiple coils of insulated wire wrapped around a common high magnetic permeability material
  - **Purpose** – Dynamic Energy Storage / Voltage Transformation
Magnetics

- Magnetics come in all shapes and sizes
  - mm to meters scale
- “Wire” coils can also be:
  - Stamped metal
  - Circuit Board Traces
Magnetics

- **Open**
  - Wire fusing:
    - Overcurrent event
    - Electromigration - Manufacturing defect – Nick or kink in wire causing localized high current density
  - Interconnect failure

- **Value Shift**
  - Wire insulation breakdown between coils
  - Change in magnetic properties due to overheating

- **Arcing**
  - Coil to Coil – Wire Insulation defect / breakdown
  - Coil to Core – Wire Insulation / Coil-Coil breakdown

- **Shorting to Core**
  - Wire Insulation breakdown between wire and core

DfR Solutions
Magnetics

- The number one issue with power supply transformer is that in most cases they are hand built
  - This means they can vary from lot to lot depending who built them
  - So the construction can be different such as the wire can be kinked or worst, not enough safety tape is applied
  - Using traces on a circuit board for windings minimized some of the hand built issues
Magnetics

- The 2\textsuperscript{nd} issue is not understanding magnetics
  - This is not taught in college and is treated as a black art
  - Many times find that saturation current is too low or the core/winding temperature is too high
- The 3\textsuperscript{rd} is not the transformer itself but the weight causing stress on the PCB
  - During shock and vibe these parts will bend or even crack your PCB if not properly supported
  - During shock/vibe these parts can come off the board
- The 4\textsuperscript{th} is the thermal mass is so high that oven profiles for assembly become an issue
  - You need long dwell times in the oven to get the part up in temperature for a decent solder but you don’t want to damage other components
Power Devices

- Power Devices
  - We all know that for power devices you like to keep the voltage and current derated
  - Keep the junction temperature below maximum
  - However there are some nuances with certain devices
Power Devices

- **Power MOSFETs**
  - Newer generation of high voltage Power MOSFETs will have forward and reverse $dV/dt$ rating

<table>
<thead>
<tr>
<th>MOSFET $dV/dt$ ruggedness</th>
<th>$dV/dt$</th>
<th>-</th>
<th>-</th>
<th>50</th>
<th>V/ns</th>
<th>$V_{DS}=0...480$ V</th>
</tr>
</thead>
</table>
| Reverse diode $dV/dt$ | $dV/dt$ | - | - | 15 | V/ns | $V_{DS}=0...400$ V, $I_{SD} \leq I_D$
|                          |        |   |   |    |     | $T_f=25$ °C |
|                          |        |   |   |    |     | (see table 22) |

- If a device is not designed for high $dV/dt$, a parasitic transistor can turn on and cause the device to fail
- Resonant converters can have high reverse $dV/dt$
- DCM Boost PFC can have high forward $dV/dt$
- To prevent this issue, find Power MOSFETs that have a high $dV/dt$ rating
High Voltage Schottky Diodes

- It's tempting to use a high voltage Schottky diode (150V to 200V) in some applications.
- However, a Schottky diode is built with a PN guard ring in parallel.
- This is to help to make the Schottky diode more immune to reverse voltage spikes.
- Typically the series resistance of the Schottky diode is more than the PN guard ring.
- In high voltage Schottky diodes, the forward drop becomes comparable to a PN diode drop.
- So at high current, the PN guard ring can become active and now you have reverse recovery to deal with.
Power Devices

- **Schottky Diodes dV/dt**
  - The capacitance of Schottky diodes are high for an active device
  - If the reverse dV/dt is high, there can be a large reverse current
  - Since the voltage can be high in the reverse direction, now you have a large power dissipation
  - The current is not uniform so you’ll have local hotspots which can damage the device
  - DfR usually sees 10V/ns as the limitation but very few vendors specify this
  - To resolve this, usually going to a larger device with more capacitance will slow the dV/dt down
New Devices

- When SiC diode was first released it was plagued with problems
  - First it was dendritic growth issues with the high voltage
    - SiC can withstand high E fields so they made them thin
    - But the edges along the die became an issue
  - Later it was found that there was a problem with materials that had a temperature coefficient mismatch
  - This took several years for devices to fail
  - It took 10 years before SiC diodes were considered reliable
Solder Joint Fatigue in Power Supplies

- Solder Joint Fatigue is more problematic in Power Supplies
  - Power Supplies are characterized by:
    - Larger Components
    - Thick Boards
    - Thick / very thick copper layers (6 oz. readily available)
    - Extensive solid plane areas
    - Embedded Heat Sinks
  - Problems:
    - Large components aggravate thermal mis-match
    - High Copper – Glass ratio increases PCB CTE
Introduction to Solder Joint Fatigue

Why do solder joints fail under thermal cycling?

- Because it is connecting two materials that are expanding / contracting at different rates (GLOBAL)
- Because the solder is expanding / contracting at a different rate than the material to which it is connected (LOCAL)
Introduction (cont.)

- This differential expansion and contraction introduces stress into the solder joint
  - This stress causes the solder to deform (aka, elastic and plastic strain)
  - The extent of this strain (that is, strain range or strain energy) tells us the lifetime of the solder joint
**PoF Example: SnAgCu Life Model**

- Modified Engelmaier
  - Semi-empirical analytical approach
  - Energy based fatigue
- Determine the strain range ($\Delta \gamma$)

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

- $C$ is a correction factor that is a function of dwell time and temperature, $L_D$ is **diagonal distance**, $\alpha$ is coefficient of thermal expansion (**CTE**), $\Delta T$ is temperature cycle, $h$ is **solder joint height**
Determine the shear force applied to the solder joint

\[(\alpha_2 - \alpha_1) \cdot \Delta T \cdot L = F \cdot \left( \frac{L}{E_1 A_1} + \frac{L}{E_2 A_2} + \frac{h_s}{A_s G_s} + \frac{h_c}{A_c G_c} + \left( \frac{2 - \nu}{9 \cdot G_b a} \right) \right) \]

- \( F \) is shear force, \( L \) 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
PoF Example – SAC Model (cont.)

- Determine the strain energy dissipated by the solder joint

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

- Calculate cycles-to-failure (N50), using energy based fatigue models for SAC developed by Syed – Amkor

\[ N_f = \left(0.0019 \cdot \Delta W\right)^{-1} \]
Knowing the mechanism and the models, we can start to identify critical drivers for solder joint fatigue.

- Volume of Solder
- Thickness of Solder
- Solder Fatigue Properties

- CTE of Component
- Elastic Modulus (Compliance) of Component
- Length of Component

- CTE of Board
- Elastic Modulus (Compliance) of Board
Drivers (cont.)

- Knowing the drivers, we can predict which components are at greatest risk of solder joint fatigue
  - Large components
  - Components with CTE far below or far above Board CTE (typically 14-17 ppm)
  - Components with a low compliance
    - High modulus, thick components
    - Leads with high stiffness (thick, short, encapsulated, no bend)
    - Leadless
Avoiding Solder Joint Failures

Chip Resistor

SOT Alloy 42

QFN

SOT Alloy 42
Tin Whiskers

- Tin whiskers are hair-like single crystal metallic filaments that grow from tin films.
- Their unpredictability is of great concern.
- The Aerospace and Defense industries consider tin whiskers the, “greatest reliability risk associated with Pb-free electronics”.
  - Manhattan project phase 2 report
What Do We Know about Tin Whiskers?

- It can take days to years before tin whiskers start to grow
- Growth rates can vary by orders of magnitude
  - 0.1 to 200 microns per day
- Maximum lengths can vary by orders of magnitude
  - Highly dependent upon plating type and substrate material
  - Bright (?) tin on steel - 25 mm; Matte tin on copper - 0.5 mm
- Diameters of 6 nm to 7 μm recorded
  - Usually 1 to 5 μm
- Current carrying capability
  - Typically 10 - 35 mA, up to 75 mA observed
  - Plasma arcing, up to 200 A possible
- Plating type plays a very important role
Root Cause of Whiskers: Stress Gradients

- The primary driving mechanism for whiskering is a compressive stress (or stress gradient) in the tin.

- This compressive stress drives the preferential diffusion of tin atoms (to lower stress regions).

- While there are additional factors that contribute to the propensity of whisker formation, such as grain structure, oxide thickness, tin thickness, base metal, etc...

- …without a compressive stress the whiskers will not form.
Bright Tin Whisker Examples

D-Sub Connectors with bright tin shells have been known to grow whiskers that can short our pins (if connector is unmated)

Whiskers also found to grow in screw holes.

Ref: L. Flasche & T. Munsun, Foresite, Inc. 9/09.

Ref: Emerson
Thanks
Any Questions