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A Solder Joint Reliability Model for the Philips Lumileds LUXEON Rebel LED Carrier Using Physics of Failure Methodology

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Rudi Hechfellner[1], Michiel Kruger[1], Tewe Heemstra[2]
Greg Caswell[3], Nathan Blattau[3], Gregg Kittlesen[3], Vikrant More[3]

Philips Lumileds – San Jose, CA
408-964-2644
Philips Lumileds - Eindhoven, Netherlands
+31-40-27—56557
DfR Solutions, LLC – Beltsville, MD
301-474-0607

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Outline

- Introduction
- Overview
- Background
- LED Solder Joint Reliability Model Development Methodology
  - LUXEON Rebel LED
  - Multiple Circuit Board Constructions
- Solder Fatigue Strain Energy Calculations
- Finite Element Models –Shear Stress and Strain Range
- Validation Approach
- Philips Lumileds Tool for Demonstrating Solder Joint Reliability Characteristics

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Introduction

- With the advances in materials, design and manufacture of LED devices, we are seeing a wide spectrum of LEDs that are more colorful, more efficient, more intense, and more reliable.
- At the same time the manufacturing capacity increases and market price declines significantly
- Todays main market segments for LEDs are Automotive, Consumer (TVs and Cell Phones), General Illumination
  - Each of these market segments has it's specific requirement on reliability
    - Automotive – very high reliability requirements for a "very short" time (<4000 hours)
    - Consumer – cost and applications driven – (i.e. cell phones <100 hours)
    - General Illumination – very high expectations (>50k hours in some cases for outdoor)
- Philips Lumileds, in a proactive approach, decided to develop **solder joint** reliability models for their LUXEON Rebel LEDs enabling customer applications to meet the expected reliability targets
- **LUXEON Rebel has been accepted as an industry leading LED product, widely used in MTBF sensitive applications. Customers use various mounting platforms, such as FR4 PCB, FR4 PCB with thermal via's, Aluminum & Copper MCPCB, Super MCPCB, etc. As in other LEDs, when mounting to a platform where a large DCTE exists between the LED & the PCB, Solder fatigue could become an issue that may affect system level lifetime.**

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Overview

- "In this presentation we will examine extreme cases and how a solder joint can impact system level reliability.
- We will model the conditions & form a means to predict system level reliability
- We will compare the prediction modeling with empirical tests for validation of the models.
  - It is vital to understand system level reliability factors to build lighting solutions that match the application and customer expectations.
  - It is impractical to test LEDs and other components for 50k hours ~5 years since the device evolution is much faster than that – on average one LED generation every 12-18 month. Hence we need models and prediction methods …..

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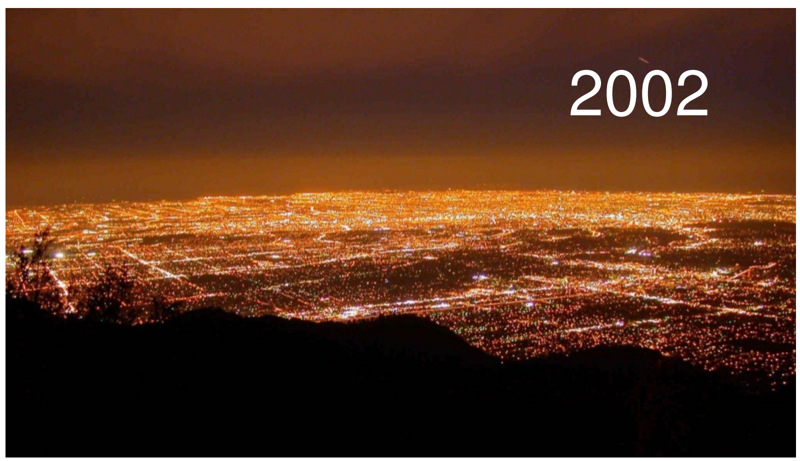
LEDs can help Reduce Light Pollution



Los Angeles

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Background - LED Lighting (General Illumination)

- Retrofit Lamps
- Signage
- Architectural
- Residential
- Shops and Hospitality
- Office
- Entertainment
- Commercial/Industrial

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Global Trends in Outdoor Illumination

Highway, Street, Tunnel, Parking, Canopy, Area

Market Insights

- Outdoor lighting >25% of a city's electrical cost.
- New LED lights have a payback period of just a few years.
- 70CRI minimum becoming more common
- Preference for warmer color temperatures
  - 4000K: most roadway lighting
  - 3000K: pedestrian lighting & roadways in urban/historical areas
  - 5700K still used in tunnel lighting

Performance Requirements

Designed for Lowest Cost

- Driving LEDs hard for cost reduction.
- Typically designed for L70 >50,000 hours
- Typical efficacy >70lm/W

Designed for Highest Efficiency

- Under driving LEDs for maximum efficiency
- Typically design for L80 or L90 at >50,000-70,000 hours
- Typical efficacy >90-100lm/W

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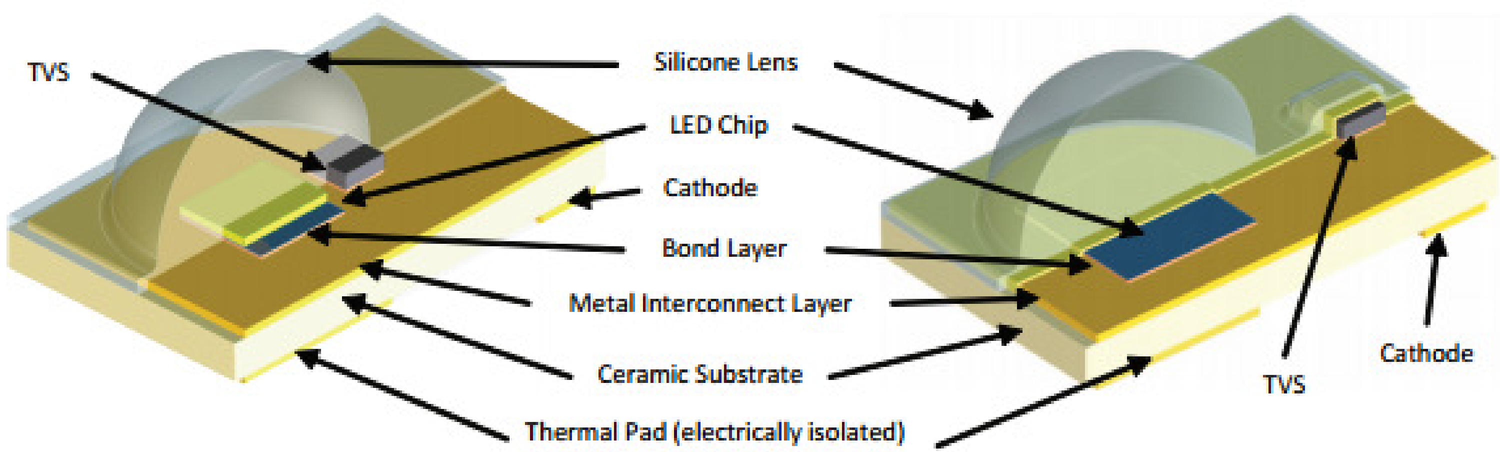
Elements of a Typical LUXEON Rebel LED



Note that the LUXEON Rebel is the only LED on the market without bondwires. This approach eliminates one of the failure modes – an electrical open – which simplifies reliability projections dramatically.

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LUXEON Rebel LED Failure Modes

- LUXEON Rebel LEDs are constructed with a single - pre-defined failure mode - electrical short - to limit its system level impact.
  - This is not the case with any other LED on the market as they still have bond wires that can cause an electrical open at LED level.
- The solder joints are the only way to have an electrical open failure.
- System level impact of an electrical open in a chain of serially connected LEDs are:
  - All LEDs in affected string are dark
  - Unbalanced current distribution in a serial/parallel architecture

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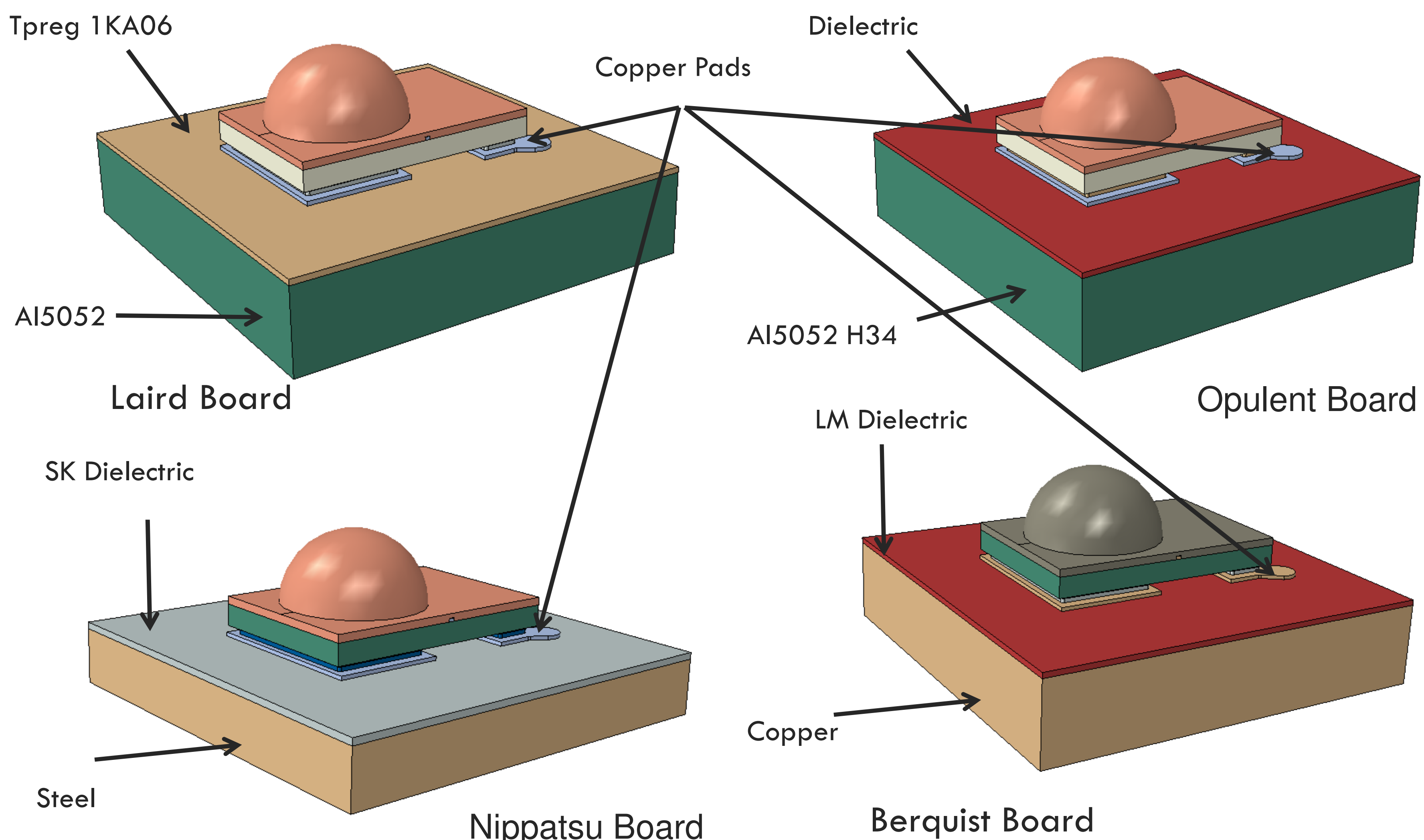
Test Setup

- Level 1 material-Philips Lumileds LUXEON® Rebel
- Level 2 materials-See next slide for cross sectional views
  - MCPCB-1:….Laird Substrate
  - MCPCB-2:….Nippatsu Substrate
  - MCPCB-3:…. Opulent Substrate
  - MCPCB-4:….Berquist Substrate
- Test Conditions
  - TC1: -40°C to +125°C, N Cycles
  - TC2: -20°C to 100°C, N Cycles

MCPCB DOE-Example Constructions



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Material properties

Ceramic

Modulus of Expansion	300,000 MPa
Poisson's ratio	0.21
Coefficient of Expansion CTE x,y	8.2 ppm

Gold

Modulus of Expansion	79000 MPa
Poisson's ratio	0.44
Coefficient of Expansion CTE x,y	14.2 ppm

Nickel

Modulus of Expansion	200,000 MPa
Poisson's ratio	0.31
Coefficient of Expansion CTE x,y	13.4 ppm

Copper

Modulus of Expansion	120,000 MPa
Poisson's ratio	0.3
Coefficient of Expansion CTE x,y	17.6 ppm

Silicon

Modulus of Expansion	160,000 MPa
Poisson's ratio	0.18
Coefficient of Expansion CTE x,y	2.8 ppm

Silicone

Modulus of Expansion	185,000 MPa
Poisson's ratio	0.28
Coefficient of Expansion CTE x,y	2.6 ppm

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Solder Alloy Properties

Creep behavior of SAC405 using Garafola's Hyperbolic Creep model

$$\dot{\varepsilon} = C[sinh(\alpha\sigma)]^n e^{\left(\frac{-Q}{RT}\right)}$$

C= Material Dependent Constant
σ = Applied Stress
T= Temperature in Kelvin
n = stress exponent
Q= Activation Energy
$\dot{\varepsilon}$ = Strain rate

Using Schubert Constant (ECTC 2003)

C	α $(MPa)^{-1}$	n	Q (KJ/mol)
2.78E5	0.0245	6.41	54.2

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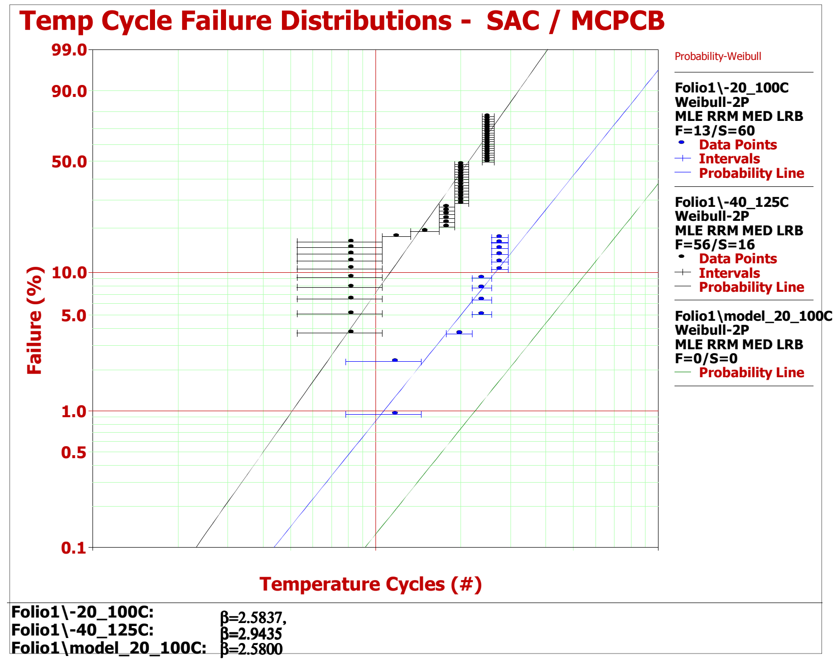
LED Solder Joint Reliability Model Development Methodology

- Solder Joint Initial Test Data
  - -40 to 125°C
    - $\beta \sim 2.9$
  - -20 to 100°C
    - $\beta \sim 2.6$
  - Observe ~ 2.6x acceleration factor (AF)

3 Test Conditions



- DfR and Philips Lumileds performed a substantial DoE to generate sufficient data to enable statistically relevant modeling.

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LED Solder Joint Reliability Model Development Methodology

- Compare -40 to 125°C vs. -20 to 100°C results
  - Observe AF = 2.62
  - Calculate AF = 2.57 using Modified NL equation

Modified Norris-Landzberg Equation

$$AF = \frac{N_o}{N_t} = \left(\frac{\Delta T_t}{\Delta T_o}\right)^{a} \left(\frac{t_t}{t_o}\right)^{b} \exp\left\{c \left(\frac{1}{T_{max,o}} - \frac{1}{T_{max,t}}\right)\right\}$$

AF – acceleration factor
N – thermal fatigue life
ΔT - temperature difference
t – dwell time (min)
T_{max} – maximum cycle temperature (K)
o, t – operating or test conditions
a, b, c - coefficients 1.84, 0.11, 2167, respectively

Miremadi, et. al., "Lead-Free Solder-Joint-Reliability Model Enhancement", IMAPS 2009.

Again, the model correlates with the test data with regard to the solder joint fatigue

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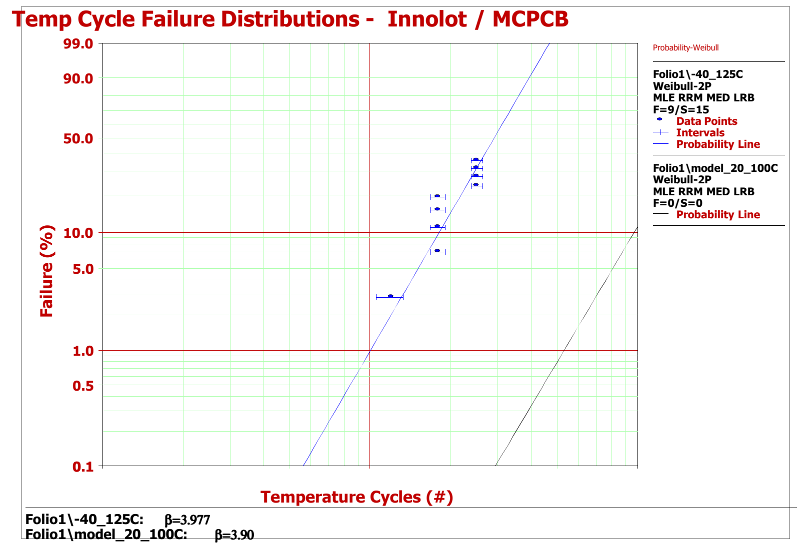
LED Solder Joint Reliability Model Development Methodology

- Test Results
  - -40 to 125°C
    - $\beta \sim 4.0$
  - -20 to 100°C
    - No failures at 3327 cycles
  - Model prediction for 20 to 100°C test
    - $\eta \sim$ 17,277 cycles
    - For $\beta \sim 3.9$

2 Test Conditions



How do we translate the cycles to failure into a life expectancy for the solder joints on the various substrates?

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Temp Cycles to Lifetime Correlation-Derivation Process

- Purpose is to accelerate and identify potential thermo-mechanical degradation mechanisms
  - Solder joint fatigue
  - Plated through hole fatigue
- How to derive a test condition representative of the field environment?
  - Acceleration factor based on physics of failure (PoF)
- What is the realistic worst-case field environment?
  - American Southwest (Phoenix)
  - Dominated by diurnal cycling

Month	Cycles/Year	Ramp	Dwell	Max. Temp (°C)	Min. Temp. (°C)
Jan.+Feb.+Dec.	90	6 hrs	6 hrs	20	5
March+November	60	6 hrs	6 hrs	25	10
April+October	60	6 hrs	6 hrs	30	15
May+September	60	6 hrs	6 hrs	35	20
June+July+August	90	6 hrs	6 hrs	40	25

+10C at max temperature due to solar loading

- Derivation of how 24 temperature cycles = 1 year of operation
- 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 correlation factor that is a function of dwell time and temperature, L_D is diagonal distance, α is CTE, ΔT is temperature cycle, h is solder joint height

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Temp Cycles to Lifetime Correlation-Derivation Process

SnAgCu Life Model (continued)

- 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

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Temp Cycles to Lifetime Correlation-Derivation Process

SnAgCu Life Model (continued)

- 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 (N_{50}), using energy based fatigue models for SAC developed by Syed – Amkor

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

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Temp Cycles to Lifetime Correlation-Derivation Process

Thermal Cycle Test

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

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

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Requirements to Build Solder Joint Reliability SW Model

- LUXEON Rebel ceramic carrier odb++ files (or Gerber files)
  - Carrier for InGaN LED
  - Carrier for AlInGaP LED
- LUXEON Rebel ceramic carrier material composition
  - Ceramic
  - Metal
  - LED, TSV, Silicone lens excluded from analysis if attachments have sufficient reliability
- Solder stress-strain curves and creep test data
  - Heraeus F640HT1 – 89M30
  - Heraeus F640-IL – 89M30

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Thermal Requirements

- Temperature cycle data
  - Thermal pad data
    - Across each board type (thermal gradient)
    - Across each thermal cycle range
      - -30 to 110°C, 30 min dwells, 30 sec transitions, 2 chambers
      - -40 to 125°C, 30 min dwells, 30 sec transitions, 2 chambers
      - -50 to 140°C, 30 min dwells, 30 sec transitions, 2 chambers

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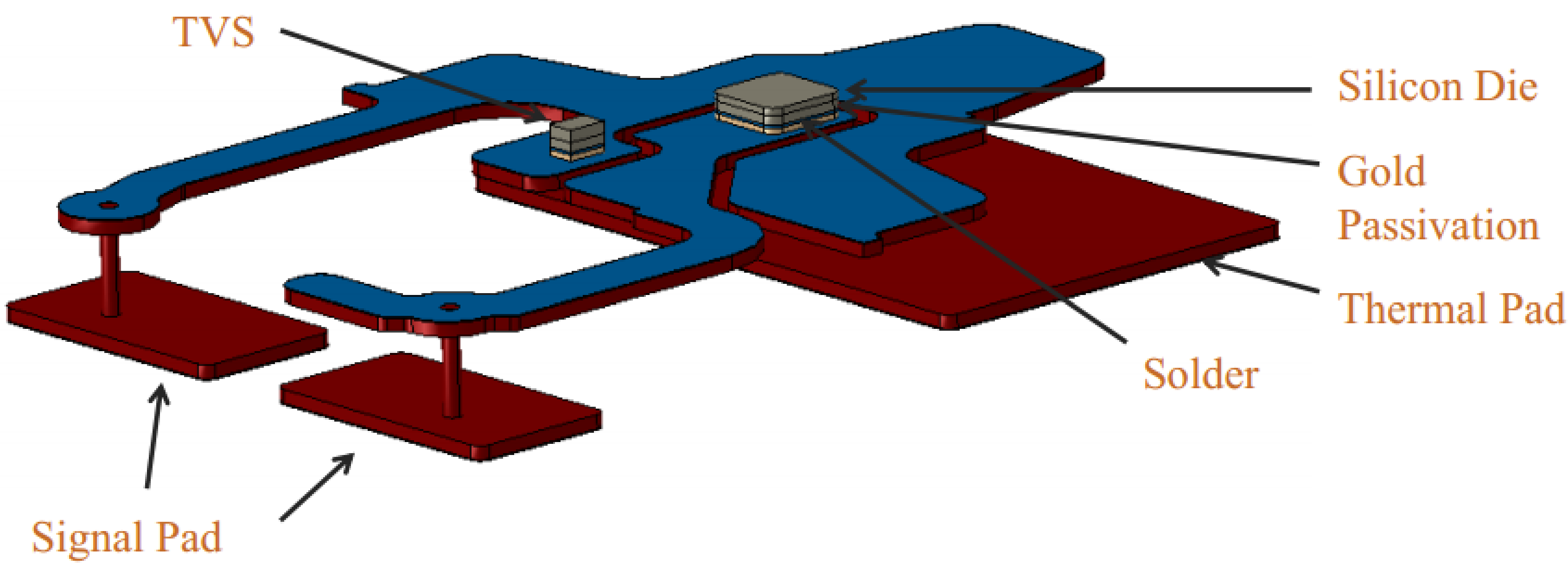
Typical Submount Design for Modeling



Layers view

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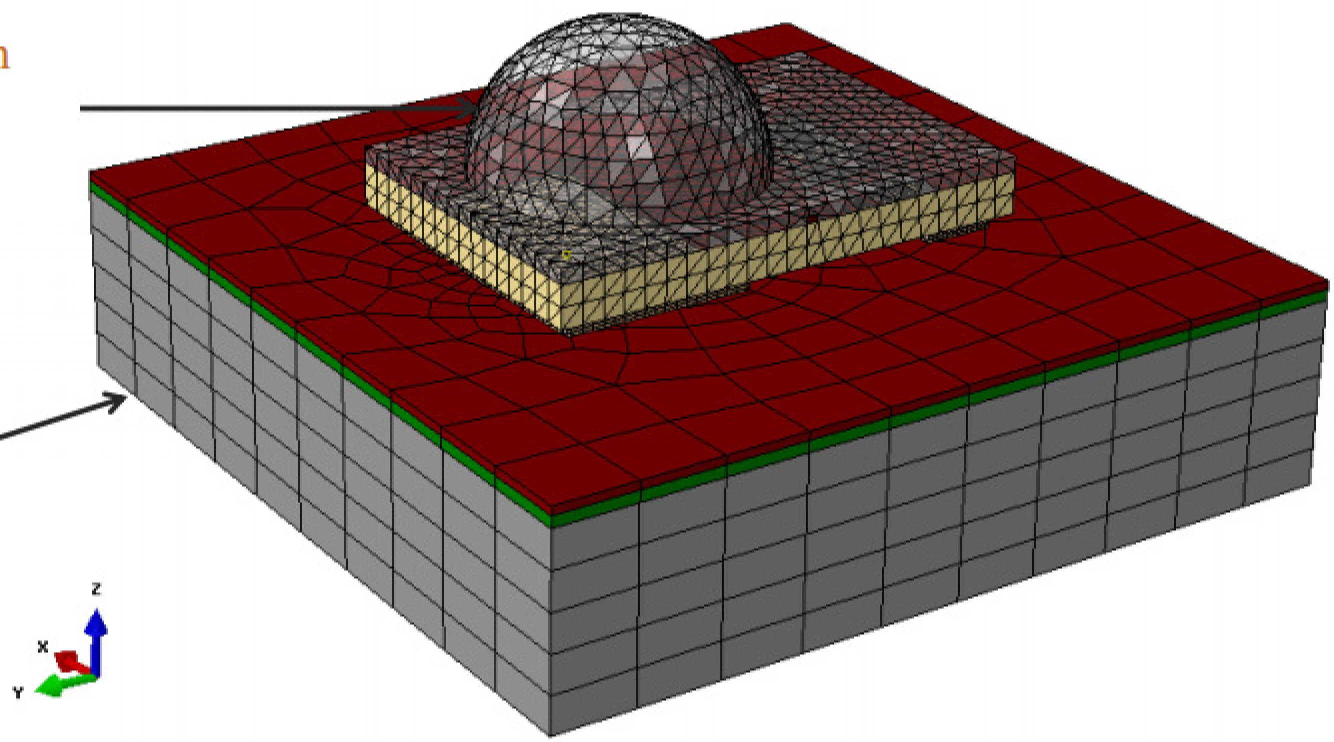
Meshed Model

Tetrahedron
Elements
C3D4



Hexagonal
Brick Elements
C3D8R

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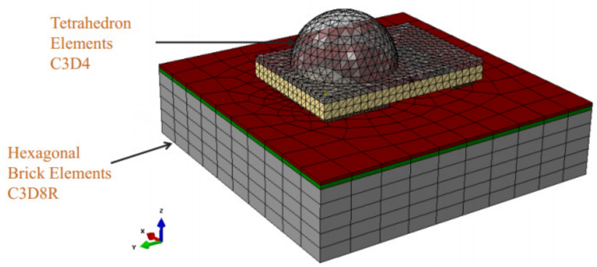
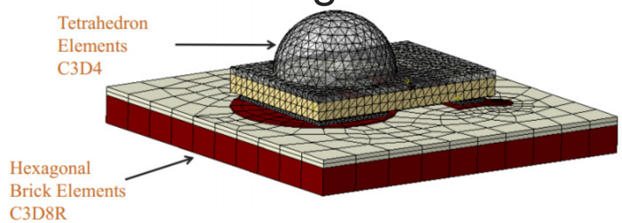
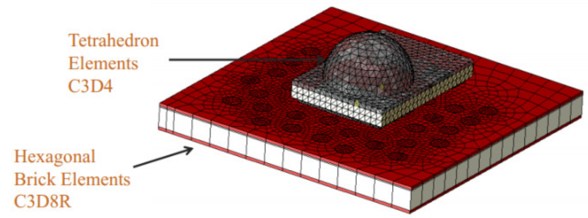
Meshed Models

IMS Laird Board

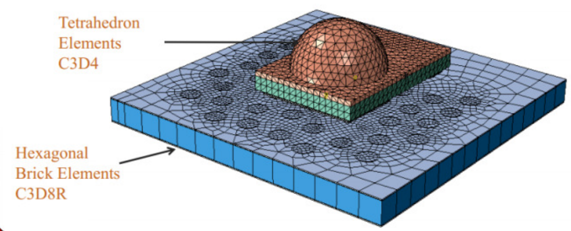


IMS Bridge Semiconductor

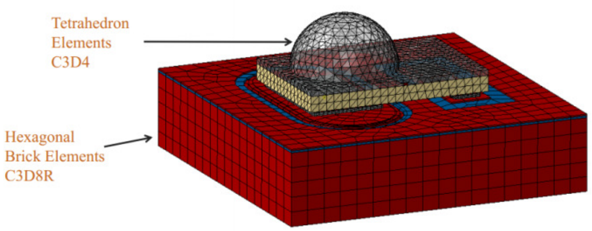




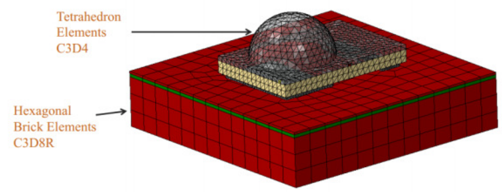
FR4-Hitachi



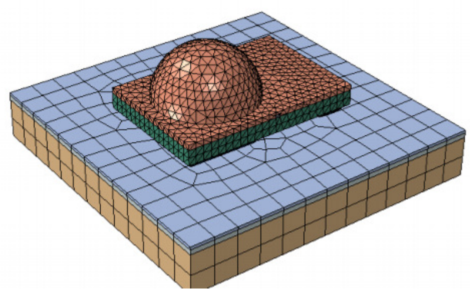
IMS Bree



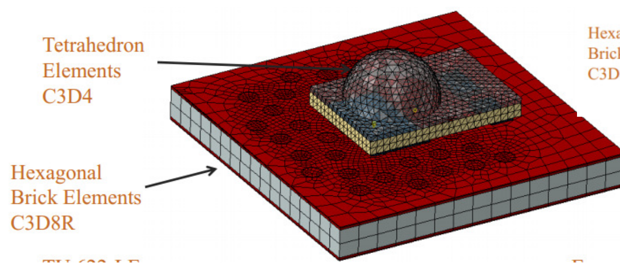
IMS Berquist



FR4-E&E



IMS Nippatsu



FR4-Multek

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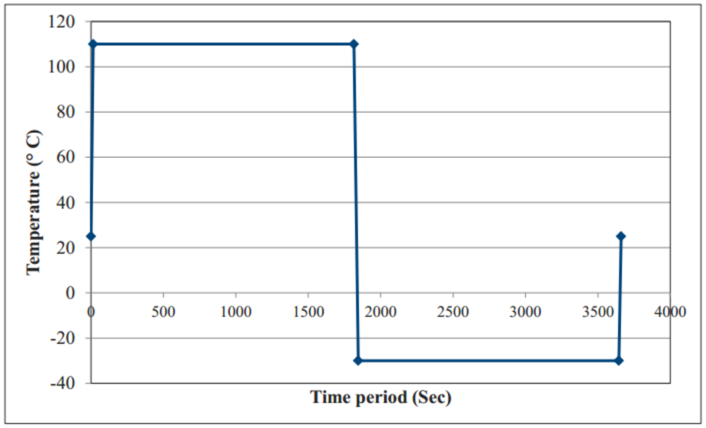
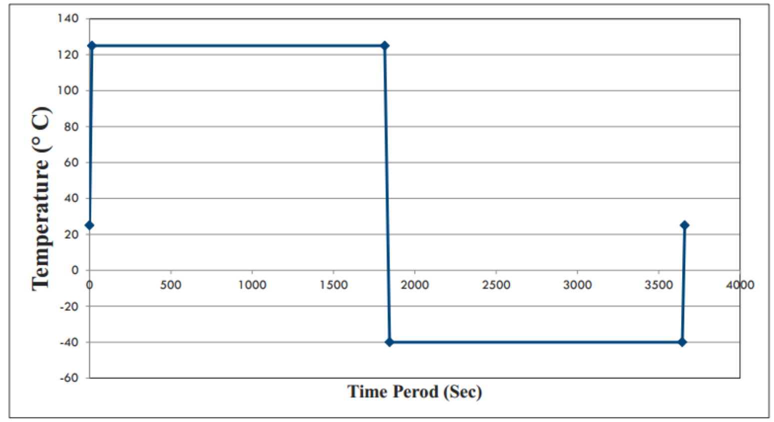
Different Temp Cycles



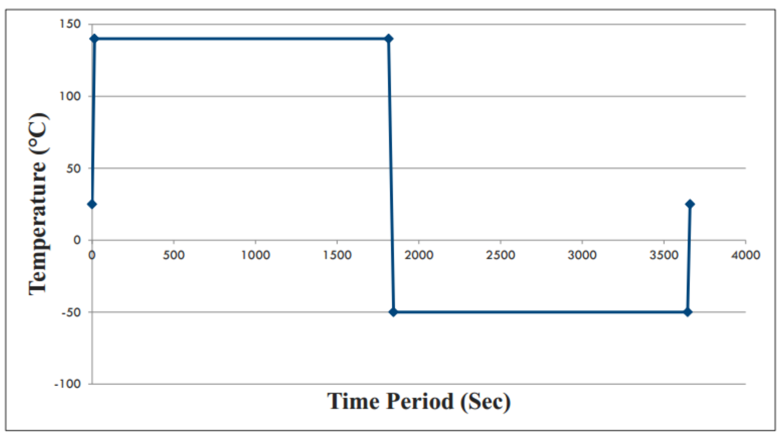
30 Minutes Dwell
30 sec Ramp

-30 to +110C



30 Minutes Dwell
30 sec Ramp

-40 to +125C



30 Minutes Dwell
30 sec Ramp

-50 to +145C

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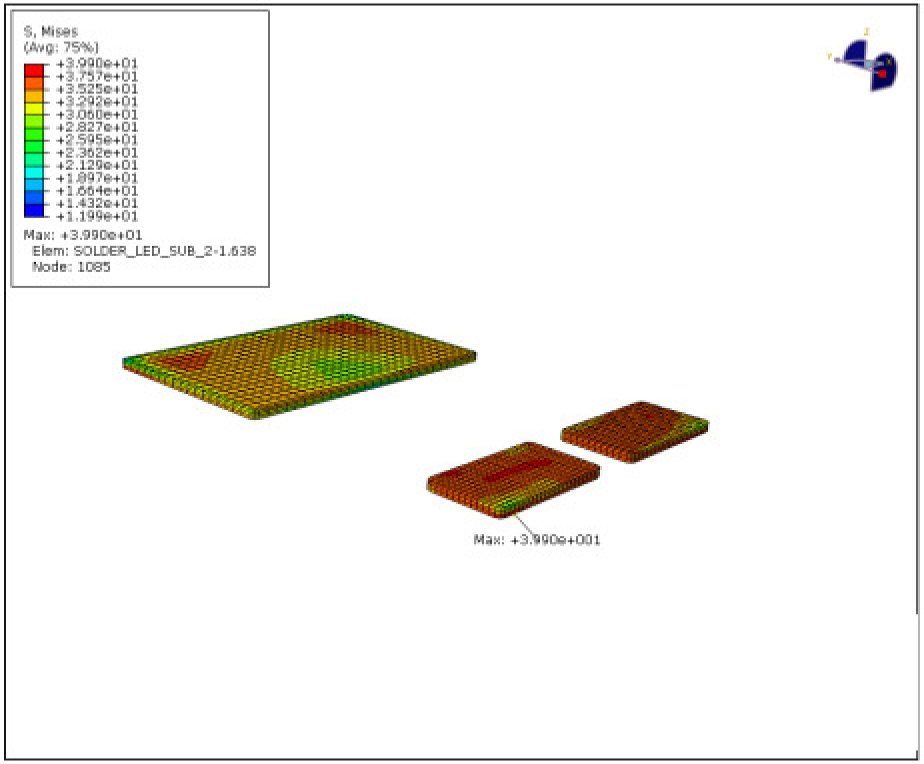
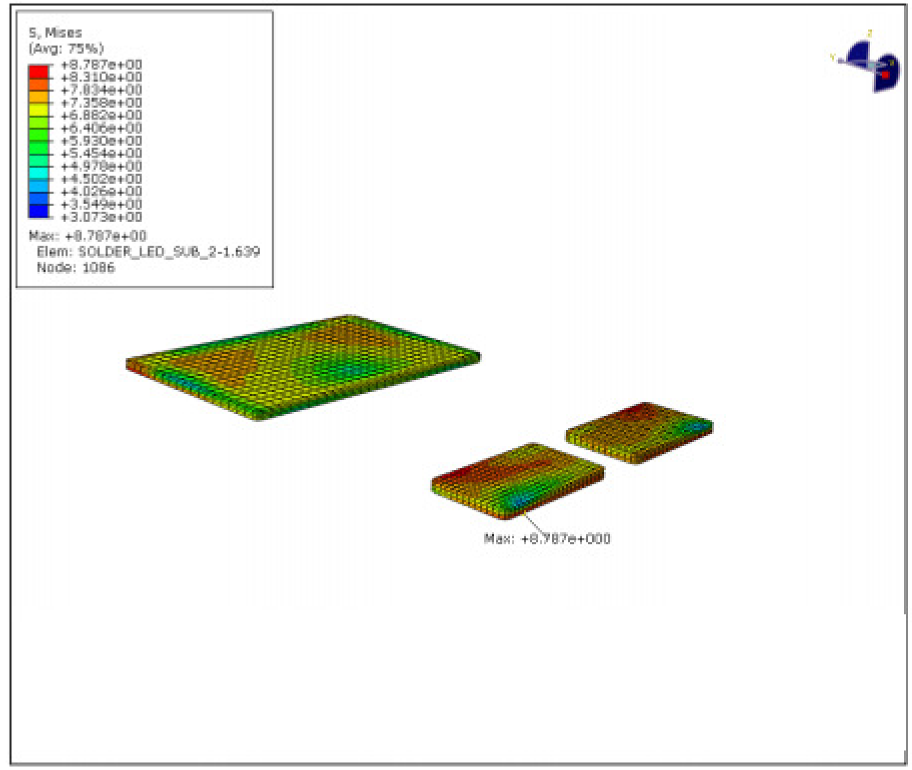
Von Mises Stresses (Function of Temp cycle)



Von Mises Contour Plot
End of Cold Dwell



Von Mises Contour Plot
End of Hot Dwell

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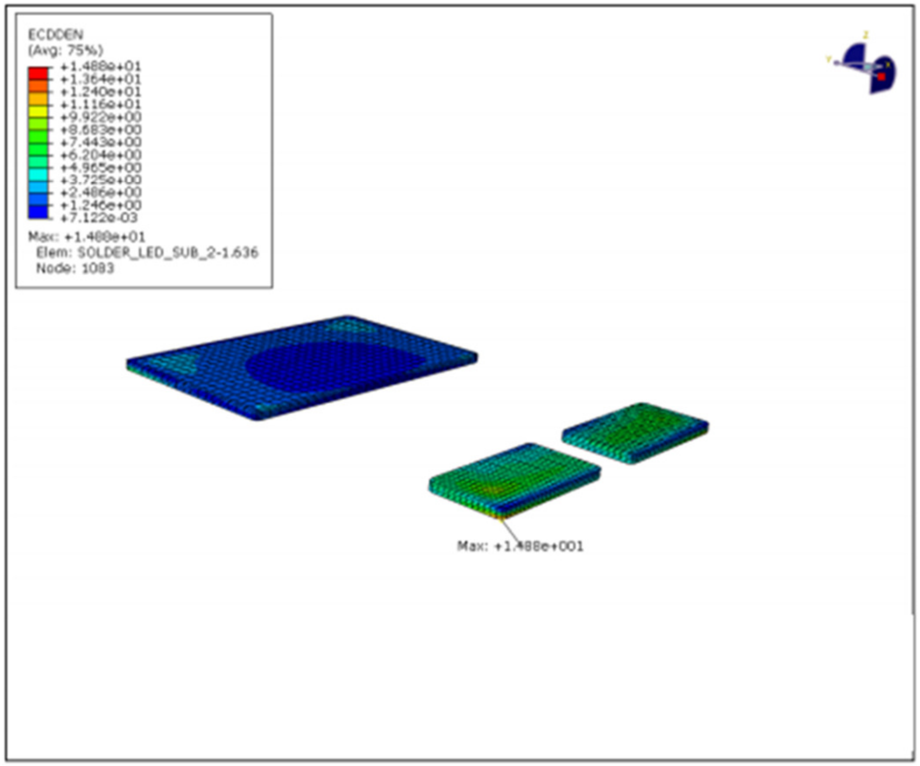
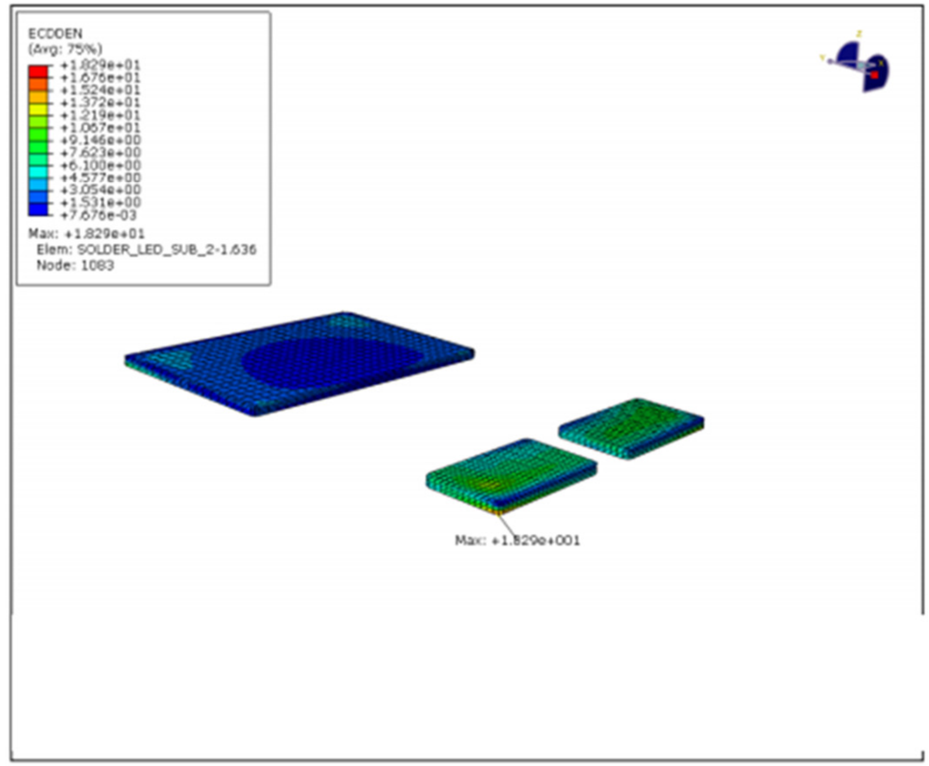
Creep Strain Energy Density

Were generated for each temperature cycle



Strain Energy Density Contour Plot
End of Cold Dwell



Strain Energy Density Contour Plot
End of Hot Dwell

Temp cycle 1

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Validation Approach

- General Illumination (outdoor lighting). If used in light/timer activated (street lamps)
  - 1 cycle per day = 17,277 (temperature change of 80C, 20 to 100C) would be 47 years
  - 2 cycles per day, 24 years
- As the number of cycles per day increases then the time to failure decreases accordingly.
- 20 to 100C is pretty severe for anything but automotive, which has lower rated life expectations than those noted above.

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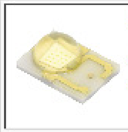
HR13

Philips Tool for Demonstrating Reliability Characteristics

Philips Rebel LED Thermal Mechanical Fatigue Calculator



This program calculates the life of the Philips Rebel LED solder joints under thermal cycling. Initially the form contains typical values for each entry. Clicking on the compute button at the bottom of the form will display the corresponding results.

LED Model: LUXEON Rebel
Solder Alloy: Sn3.0Ag0.5Cu
Solder joint height: 75 [microns]

Substrate

Type : Bergquist IMS
Surface Copper Thickness: 2 [ounce]

Environmental Conditions

LED thermal pad temperature: 140 [°C]
Power on time: 30 [minutes]
Power off temperature: -50 [°C]
Power off time: 30 [minutes]

Output: Compute

Stress: [MPa]
Strain range:
Strain Energy: [MPa]
Characteristic Life: cycles to failure
Time to Failure: years

Probability of Failure, Cycles

0.1%	1.0%	10%	20%	40%	80%	100%

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Slide 30

HR13 Let's agree on showing a relevant example i.e. street light....
Hechfellner, Rudolf, 1/27/2013

Summary

- Constructed LUXEON Rebel LED model with 12 different substrates.
- Thermo-Mechanical Analysis was conducted for 9 substrates for three different thermo-mechanical environments using SAC405 solder alloy.
- Results from FEA analysis show good correlation with experimental data. Experimental results appear to support FEA analysis.

- **A tool was developed for use in predicting the solder joint reliability of Philips LUXEON Rebel LEDs on a variety of substrates to facilitate their customers ability to select the most viable approach for their particular application.**

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Thanks

Greg Caswell
DfR Solutions
443-834-9284
gcaswell@dfrsolutions.com

Rudi Hechfellner
Philips Lumileds
408-964-2644
Rudi.hechfellner@philips.com

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