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reliability designed, reliability delivered

Using Physics and Industry Best Practices to Predict the Lifetime of LED Power Supplies

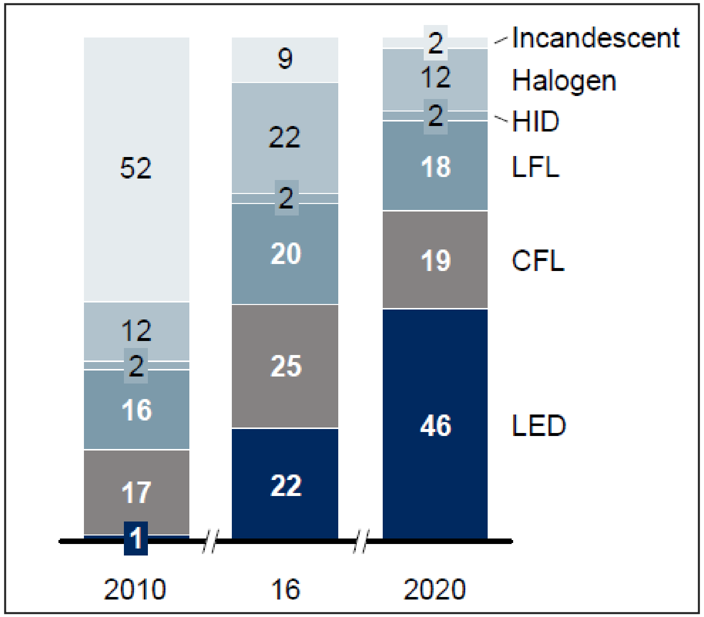
Craig Hillman, PhD

February 8, 2012 APEC Orlando, FL

Motivation

Lighting the Way: Perspectives on LEDs and the Global Lighting Market, McKinsey Consulting, July 2011

- There is strong anticipation that LEDs will dominate general lighting in near future
- This penetration can not be taken for granted
  - High upfront costs will require strong demonstration of ROI
  - Poor reliability will slow acceptance!



Light source market share by units

- Experience of compact fluorescent light (CFL) is an important lesson learned

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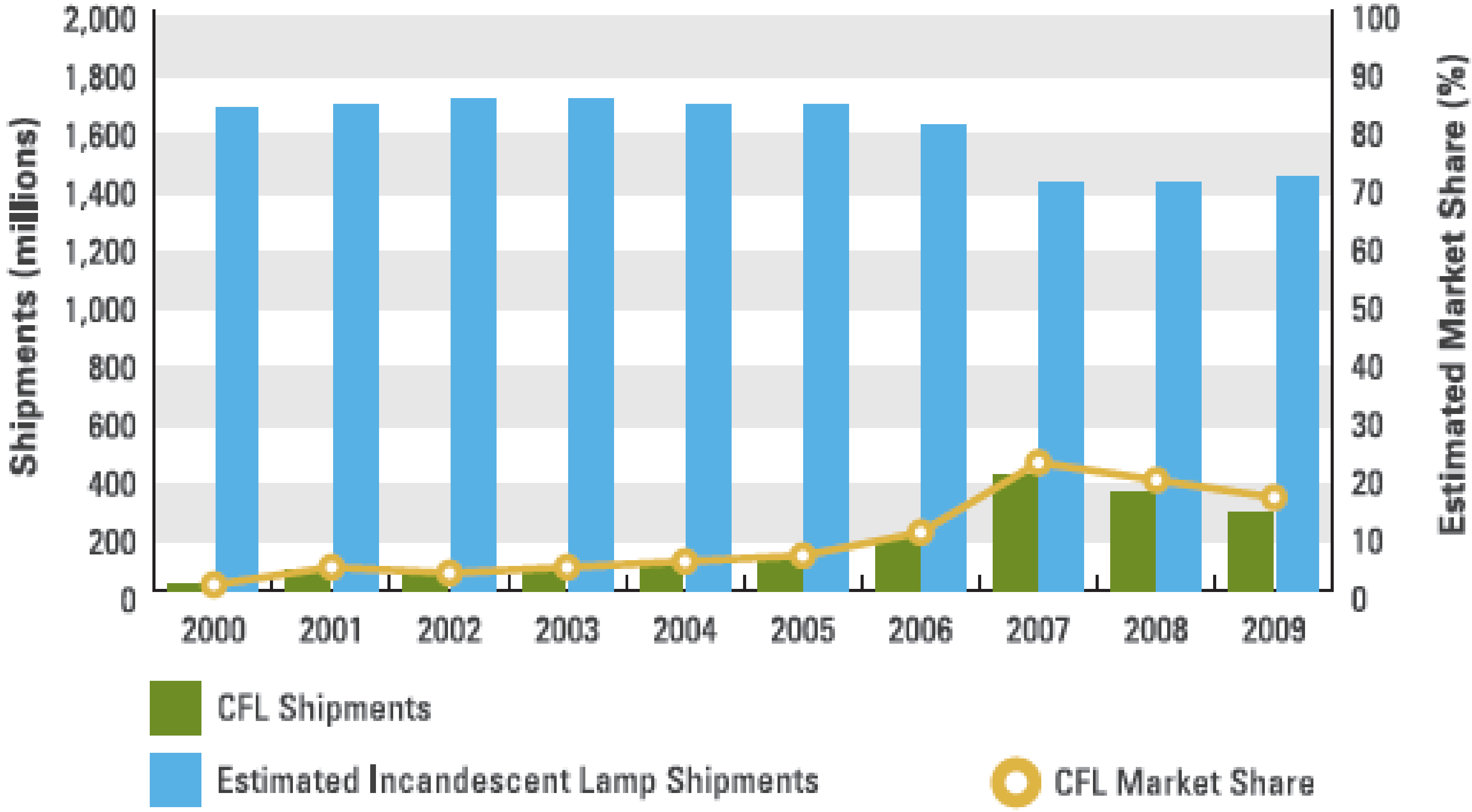
Market Share of CFLs is Dropping! Why?



CFL Market Profile: Data Trends and Market Insights, US Dept. of Energy, September 2010

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CFL Market Share: Perceived Reliability

- Prof. Siminovitch of UC – Davis has identified three (3) areas of dissatisfaction
  - Color quality
  - Dimming
  - Product longevity
- Numerous other websites / blogs have reported issues with CFL reliability

green.blogs.nytimes.com/2009/01/27/why-efficient-light-bulbs-fail-to-thrive/, Jan. 27, 2009, New York Times

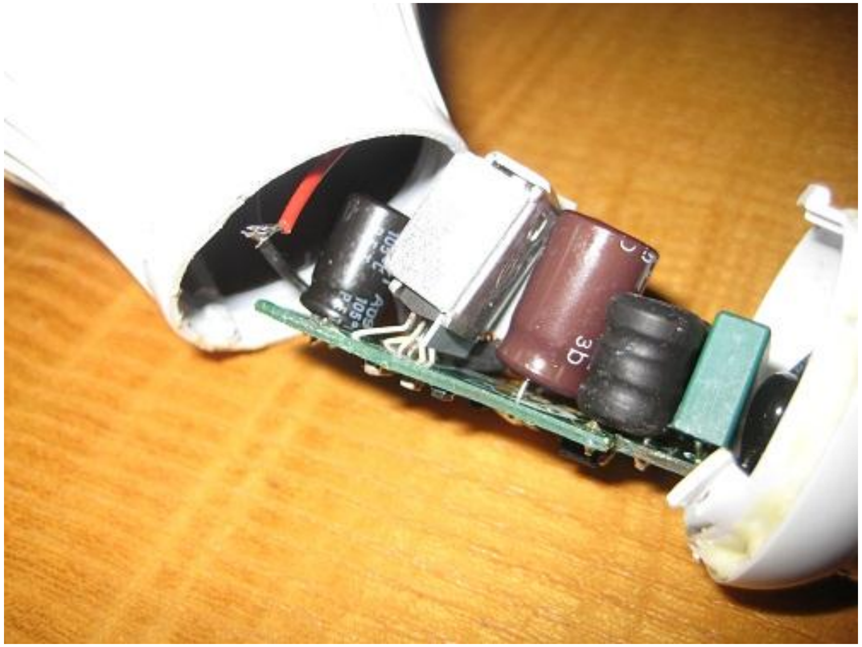
- Rensselaer Polytechnic Institute (RPI) found early failure rates of CFLs between 2 to 13 percent
  - Returns higher in thermally challenging environments (reflectors, high switching)
  - Indications that power supplies play a major role in failures

Will LED Light Bulbs Best Your CFLs and Incandescents?, Popular Mechanics, August 4, 2010, http://www.popularmechanics.com/science/environment/will-led-light-bulbs-best-cfls-and-incandescents

LED Lighting and Reliability

- Similar complaints about LED bulbs are starting to increase
- As with CFLs, power supplies seem to be a major driver for failure

http://www.edn.com/blog/PowerSource/41566-Here_s_one_LED_light_that_didn_t_make_it_to_50_000_hrs.php?cid=EDNToday_20120120



- At $20-$40 per bulb, LEDs will be even more sensitive to a perceived lack of reliability

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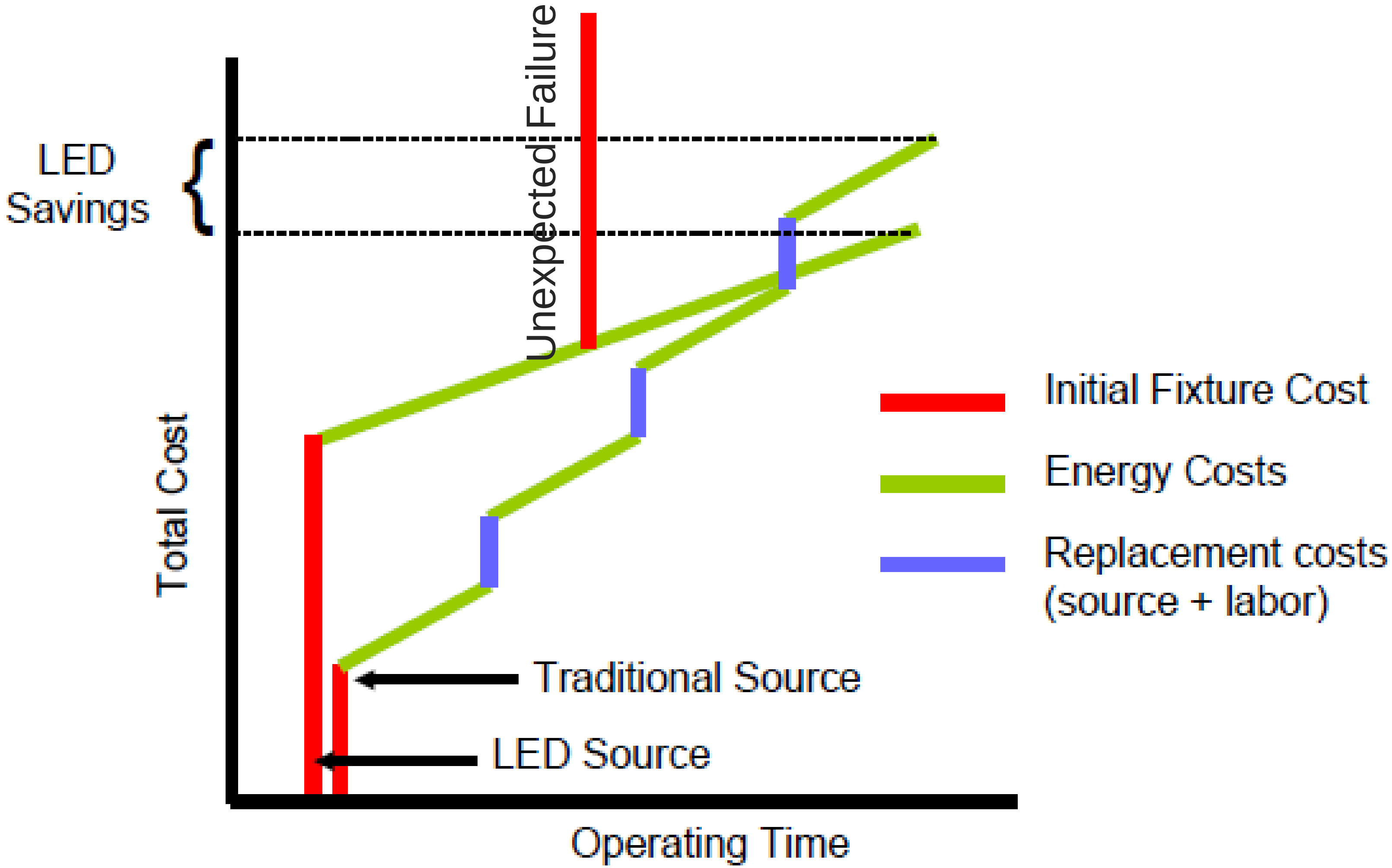

100,000 Hour Lifetimes And Other LED Fairytales, John Curran, 2008 Lightfair

Best Practices – Electronic Reliability

- **Establish reliability goal**
- **Quantify the use environment (includes thermal analysis and assessment)**
- Component stress analysis
- Perform failure mode effects analysis (FMEA)
  - Identifies CTQs and tolerances
  - Allows for development of comprehensive control plans with suppliers (SPC with Ppk's)
- Design for manufacture (DfM) and Design for Reliability (DfR)
  - Involve contract manufacturers in DfM
- Supplier qualification
  - Product cleanliness
- Design verification
  - Step stress tests to define design margins
- **Physics of failure (PoF) life prediction model**
- Perform the applicable product qualification tests
  - Accelerated life test (ALT) to validate the life prediction model
  - Temperature-Humidity-Bias (THB) tests to check for contaminants
  - Mechanical loading (Vibration, Mechanical Shock)

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Reliability Goals

- Identify and document two 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
  - MTBF or MTTF calculation should be primarily an administrative or marketing exercise (response to customer demands)

Reliability Goals (MTBF/MTTF)

- The use of MTBF/MTTF introduces an extensive amount of confusion for the non-reliability professional
  - The consumer believes 25,000 hour lifetime means nothing will fail for 25,000 hours (How Long Did You Say That Bulb Would Last?, Eric Taub, Feb. 11, 2009, New York Times)

- If the average bulb is only used 2 hours per day, the consumer would assume no failures for 34 years
  - Electrolytic capacitors can not last much beyond 15 years

- Any lifetime prediction needs to be a combination of bulb and power supply performance

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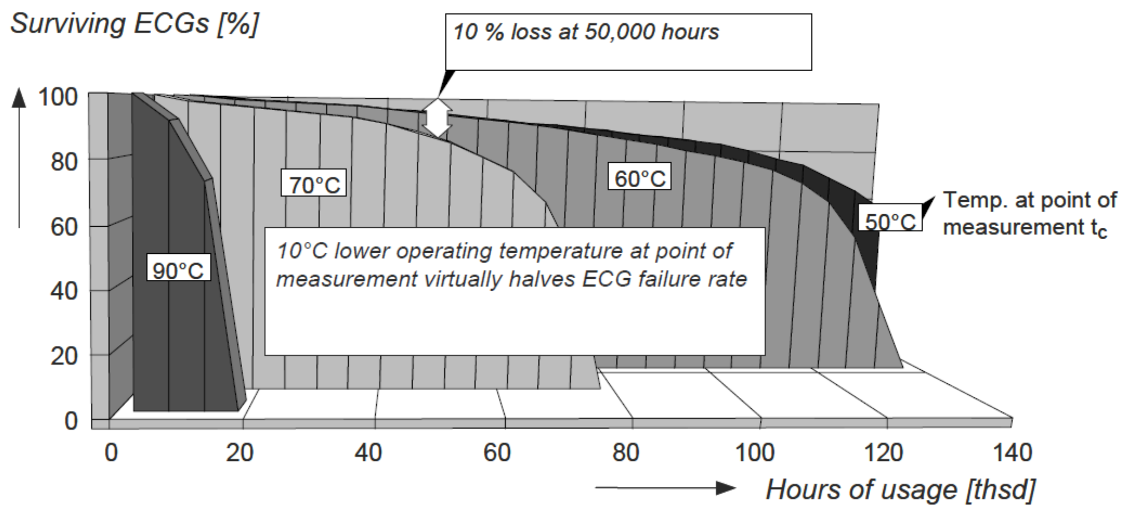
Reliability Goals (survey of ballast manufacturers)

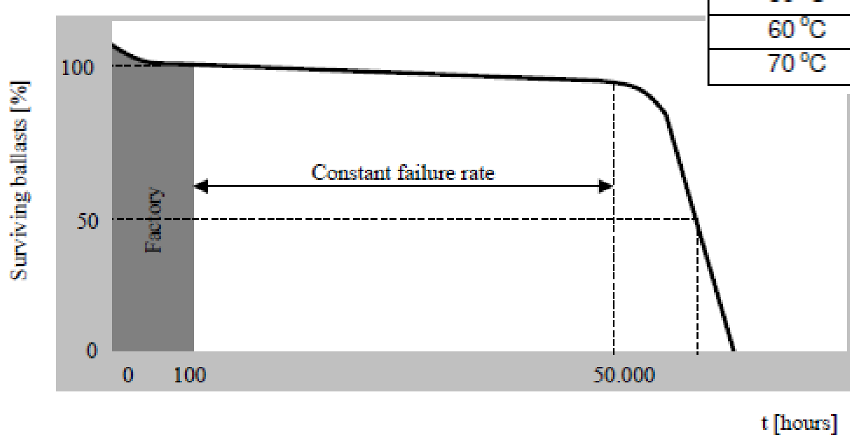
Company	Product	Failure Rate (per 1k hours)	Lifetime (hours)	MTBF (hours)
Nedap	Luxon	0.1%	87,600	400k
HEP		0.2% (50C)		
Tridonic	ATCO	0.2%	50,000 (B10)	
Lightwave				1M
Osram	ECG	0.2%	50,000 (B10, tc)	
Philips		0.2%	50,000 (B10, 65C)	
Vossloh	ELX	0.2%	50,000	
EZ-TRON			7,000 (B10)	37-89k
Universal				26-61k
UC Berkeley	Field	0.04 – 0.08%		
Asian Electronics Limited	Field	0.02%		

MTBF not a common reliability metric

Failure Curves (Philips, Osram)



Temperature	Failure rate at 8 Years	Failure rate at 12 Years	Failure Rate at 20 Years
50 °C	3%	5.5%	10.75%
60 °C	3%	5.5%	13.75%
70 °C	5.5%	13.75%	100%



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Reliability Goals (Recommendations)

- Understand what 50,000 hour lifetime means
  - For many ballast OEMs, this is B10 at some temperature
  - This is based on 0.2% failure rate every 1k hours
    [AFR of 1.75% (17,500ppm)]
  - This can be derived through calculations or testing
    (requires a MTBF of 57 years)
  - This is a marketing activity
- Track field performance
  - Achievable goal is 0.05% failure rate every 1k hours [AFR of 5000ppm]
- Ensure no wearout of the ballast before 50,000 operational hours

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Understand the Use Environment

- Different applications will have different ambient conditions and different usage profiles
  - Residential Lighting
  - Commercial Lighting
  - Industrial Lighting
  - Which market are you serving?

- A critical step is to identify 'realistic worst-case' for each environmental stressor
  - The automotive world typically talks of meeting the needs of 95% or 98% of their customers
  - Go beyond the spec…how are customers really using the product?

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Environment (Ambient Temperature)

- The majority of residential/commercial installations will see relatively stable macro-ambient temperatures
  - 25C ± 5C

- Outdoor lighting and industrial lighting will experience diurnal cycling
  - Realistic worst-case: Phoenix, AZ

<u>Remember</u>: The ballast is degrading even if not powered on!

Month	Cycles/Year	Ramp	Dwell	Max. Temp (^oC)	Min. Temp. (^oC)
Dec.+Jan.+Feb.	90	6 hrs	6 hrs	20	5
March + Nov.	60	6 hrs	6 hrs	25	10
April + Oct.	60	6 hrs	6 hrs	30	15
May + Sept.	60	6 hrs	6 hrs	35	20
Jun.+Jul.+Aug.	90	6 hrs	6 hrs	40	25

Environment (Power Cycling)

- Power is a crucial aspect of the LED Lighting environment
  - Both in terms of magnitude, duration, and cycling
- Magnitude
  - Temperature rise due to operation can vary depending upon lighting category
  - Recessed tends to experience temperatures higher than open
- Duration
  - Residential average is 2 hrs/day; room average ranges from 1 to 4 hrs/day
  - Many lifetime specifications assume 8 hrs/day
  - Commercial/industrial can reach 24 hrs/day
- On-Off Cycles
  - This is relatively poorly defined, but can be quite critical
  - Can range from 1/day to more than 20/day (motion sensors)

Environments

- Vibration / Mechanical Shock
  - Only during transportation
- Relative Humidity
  - Critical environment for bathroom and outdoor installations
- Corrosive Gases
  - Potential for outdoor installations in South/East Asia
- Electrical
  - Potentially critical in industrial applications

Ballast Lifetimes

- Ballasts are unable to meet lifetime typically due to
  - Voltage transients
  - Elevated temperature
  - Solder joint fatigue

- For voltage transients, GE recommends testing based on ANSI/IEEE C62.41.2-2002
  - 6kV / 500A / 100kHz Category B Ring Wave test
  - 500 surges

Ballast Survival When Exposed To Commonly Found Transient Voltages
IEEE Industry Applications Conference

Elevated Temperature

- What components will wearout when exposed to constant or cyclic temperature?
  - Electrolytic capacitors
  - Film capacitors
  - Ceramic capacitors
  - Optocouplers
  - Integrated Circuits
    - Not relevant for technology in LED Power Supplies
  - Solder joints

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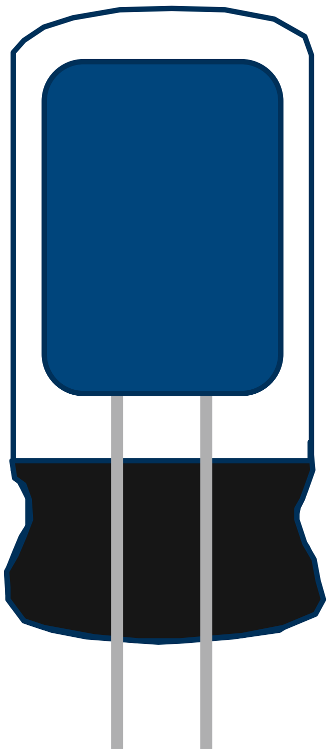
Electrolytic Capacitors

- 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!)

$$L_x = L_o \times 2^{(To-Tx)/10}$$

  - However, there are variations from manufacturer to manufacturer



Capacitor Lifetime Calculations (Nichicon)

- Lr is rated lifetime
- Tr is rated temperature
- T is ambient temperature
- Ir is rated ripple current
- I is actual ripple current
- Δtr is the temperature rise due to rated ripple current
- Δt is the temperature rise due to actual ripple current
- α and K are coefficients

$$L = L_r \times 2^{\frac{T_r - T}{10}} \times \frac{1}{B_n}$$

Miniature w/o ripple

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

$$L = L_r \times 2^{\frac{T_r - T}{10}} \times 2^{\alpha\, 1 - \left(\frac{I_r}{I}\right)^2 \times 2^{-\left(\frac{T_r - T}{30}\right)}}$$

Miniature w/ ripple

$$L = L_r \times 2^{\frac{T_r - T}{10}} \times 2^{1 - \frac{\Delta t_r \times \left(\frac{I_r}{I}\right)^2}{K}}$$

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Capacitor Lifetime Calculations (Nippon Chemi-Con)

- Lr is rated lifetime
- Tr is rated temperature
- T is ambient temperature
- Ir is rated ripple current
- I is actual ripple current
- Δtr is the temperature rise due to rated ripple current
- Δt is the temperature rise due to actual ripple current
- A and Kv are coefficients

$$L = L_r \times 2^{\frac{T_r - T}{10}} \times 2^{-\frac{\Delta t}{5}}$$

Miniature w/o ripple

$$L = L_r \times 2^{\frac{T_r - T}{10}} \times 2^{\frac{\Delta t_r - \Delta t}{5}}$$

Miniature w/ ripple

$$L = L_r \times 2^{\frac{(T_r + 5) - (T - 25)}{10}} \times 2^{\frac{25 - \Delta t}{A}} \times Kv$$

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Capacitor Lifetime Calculations (Rubycon)

- Lr is rated lifetime
- Tr is rated temperature
- T is ambient temperature
- Ir is rated ripple current
- I is actual ripple current
- Δtr is the temperature rise due to rated ripple current
- Δt is the temperature rise due to actual ripple current
- Vr is rated voltage
- V is actual voltage
- A and Kv are coefficients

$$L = L_r \times 2^{\frac{T_r - T}{10}} \times 2^{\frac{\Delta t_r}{(10 - 0.25\Delta t_r)} - \frac{\Delta t}{(10 - 0.25\Delta t)}}$$

Miniature

$$L = L_r \times 2^{\frac{T_r - T}{10}} \times 2^{\frac{\Delta t_r}{10} - \frac{\Delta t}{10}} \times \left(\frac{V_r}{V}\right)^{2.5}$$

Large can

Capacitor Lifetime Calculations (Panasonic/Sanyo)

- Lr is rated lifetime
- Tr is rated temperature
- Ta is core temperature
- Ir is rated ripple current
- I is actual ripple current
- Δtr is the temperature rise due to rated ripple current
- Δt is the temperature rise due to actual ripple current
- Vr is rated voltage
- V is actual voltage
- A and Kv are coefficients

$$L = L_r \times 2^{\frac{T_r - T_a}{10}}$$

All

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E-Cap Life Prediction

- Major problem: Like all limited life components, predictions are extrapolated from manufacturers' ratings
  - The basis of these ratings, lifetime and temperature, is not always clear

- Issues
  - Failure definition can vary
  - Lifetime can be with or without ripple current
  - Probability of failure after lifetime is never defined (test to zero failures)
  - Different approaches to extend lifetime
    - Large volume of electrolyte
    - Higher boiling point electrolyte / lower vapor pressure
    - Better seal
    - Ability to operate at lower electrolyte volumes
  - Degradation of seal due to temperature or temperature cycling is never addressed

E-Cap Life Prediction (cont.)

- A better approach would be to establish a physics-based equation derived from
  - Electrolyte boiling point
  - Volume of electrolyte
  - Critical volume
  - Evaporation rate
  - Embrittlement rate of rubber/plastic stopper

- Unfortunately, most capacitor manufacturers consider this information ‘proprietary’

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DC Film Capacitor Lifetime Prediction

- Unfortunately, film capacitor life prediction suffers from the same limitations as electrolytic capacitor
  - Specifically, a dependence on manufacturer's ratings instead of true design/material information

- Additional problems
  - Different dielectric materials (IEC 60384)
    - Polyethylene – Terephthalate (-2, 11, 19), Polycarbonate (-6, 12), Polystyrene (-7), Polypropylene (-13, 16), Polyphenylene Sulfide (-20), Polyethylene – Naphthalate (-23)
  - Broad variation in life model parameters
  - Different test parameters used to identify lifetime
  - Different definitions of lifetime

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Life Model Parameters

$$L = L_r \times 2^{\frac{T_r - T}{10}} \times \left(\frac{V_r}{V}\right)^7$$

Emerson Network Power

$$L = L_r \times T_f \times \left(\frac{V_r}{V}\right)^9$$

Faratronic

$$L = L_r \times 2^{\frac{T_r - T}{10}} \times \left(\frac{V_r \times F}{V}\right)^8$$

Cornell Dublier

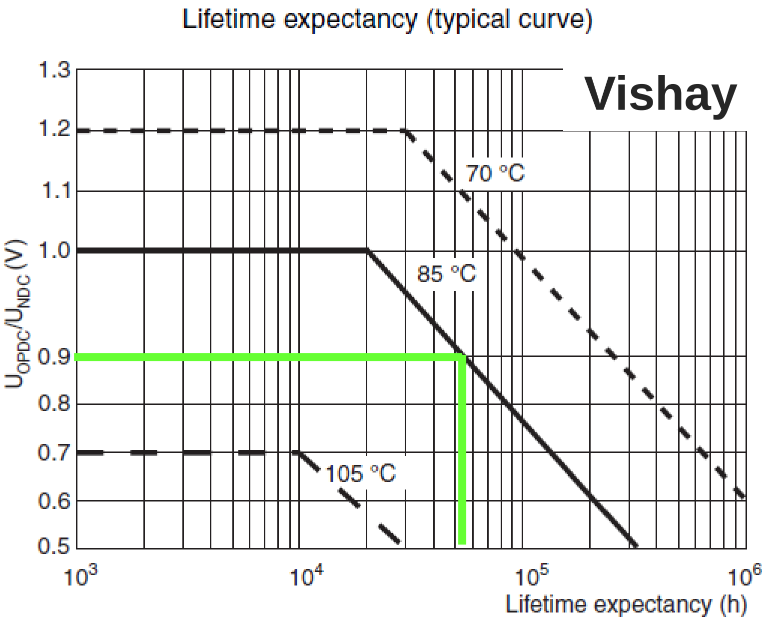
Conversion factor(temperature)	
Temperature	Conversion factor
<=40	1
55	2.3
70	5.2
85	12
100	33
110	77
120	206
125	346

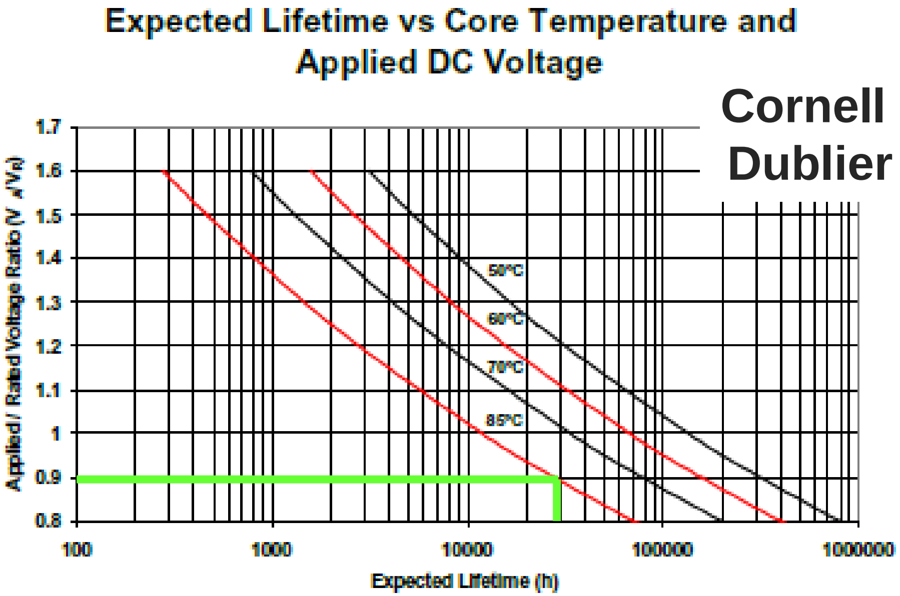
Other Issues

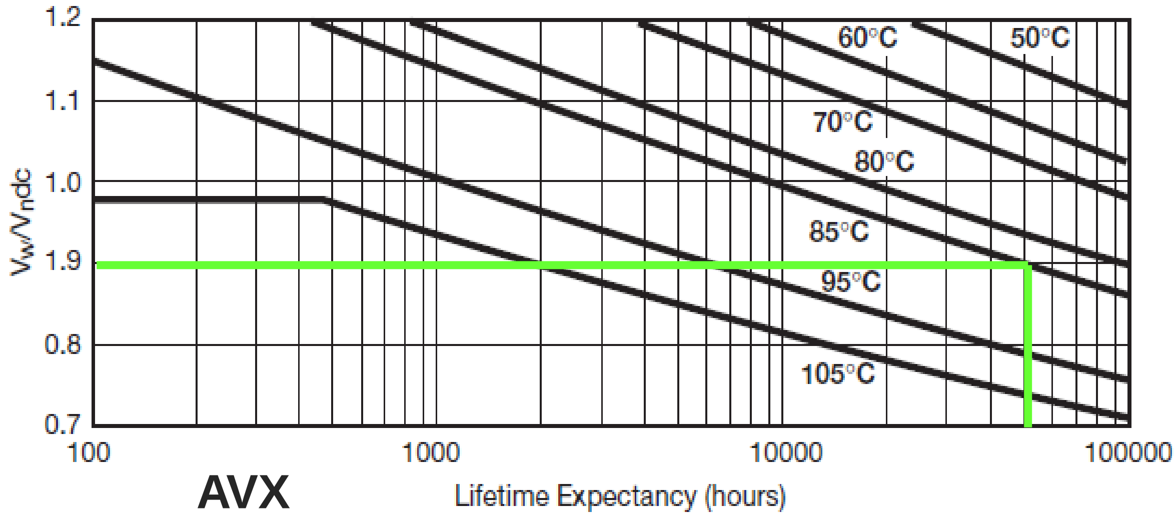
- Test Condition
  - IEC 60384-16 Electrical Endurance
    - Rated Temp.; Voltage: 1.25Vr, Duration: 1K to 2K hrs
  - Other Versions
    - Above Rated Temp.; Voltage: 1.25Vr, Duration: 2K hrs
    - Temp: 85C; Voltage: 1.1Vr; Duration: 1000 hrs
    - Temp: 85C; Voltage: 1Vr; Duration: 5000 hrs

- Lifetime Definition
  - The best suppliers provide a clear differentiation between failure rate and lifetime

RELIABILITY
Operational life > 300,000 h
Failure rate < 5 FIT (40°C and 0.5 x U_R)







- 105C Rated, Polypropylene Film
  - 85C, 0.9Vr
    - Vishay: 55K hrs
    - Cornell: 30K hrs
    - AVX: 50K hrs

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Ceramic Capacitor Lifetime Prediction

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

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

- 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 (8.62×10^{-5} eV/K)
- Lifetime may be limited for extended value capacitors
  - Sub-2 micron dielectric thickness
  - Greater than 350 layers (increased failure opportunity)

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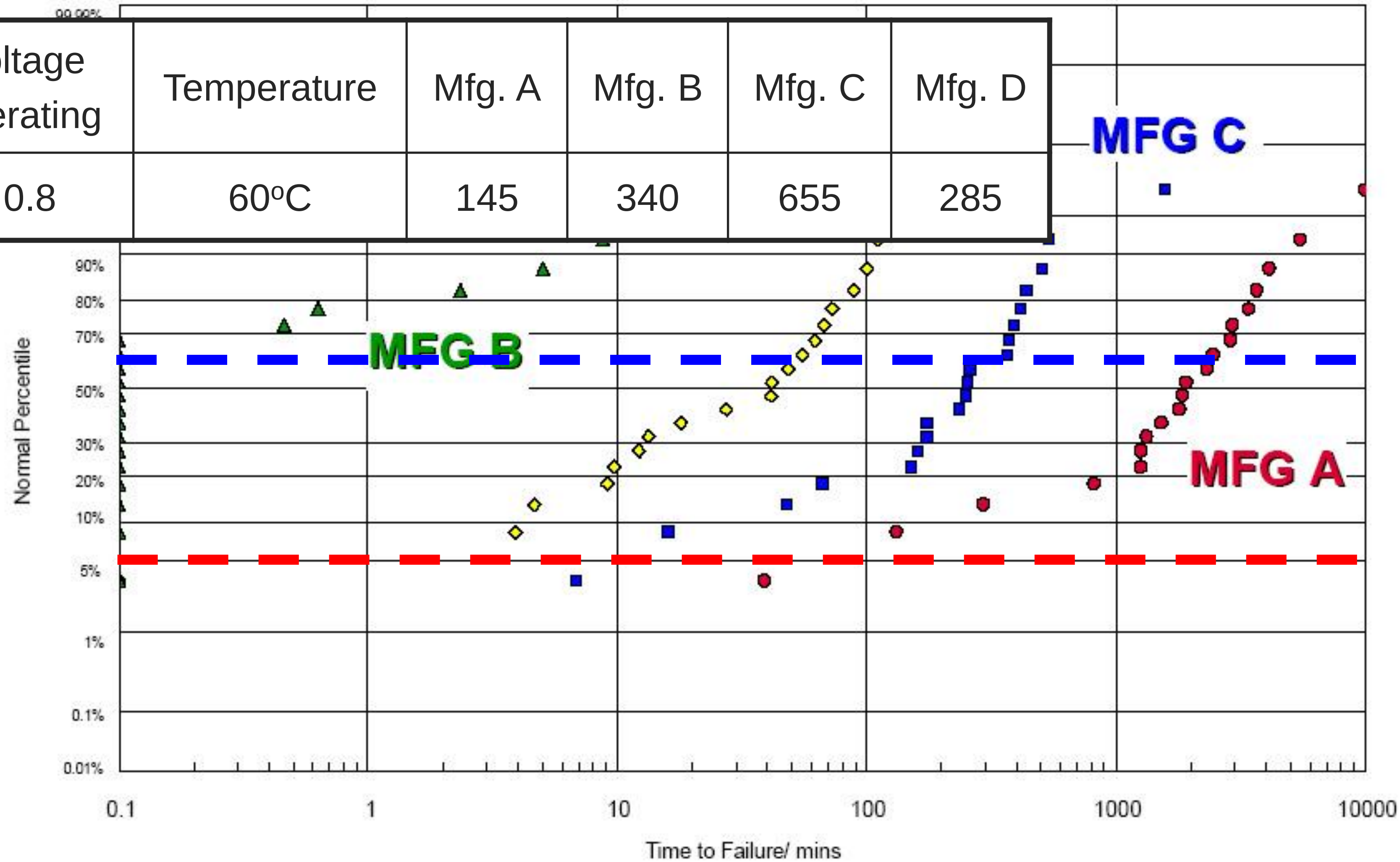
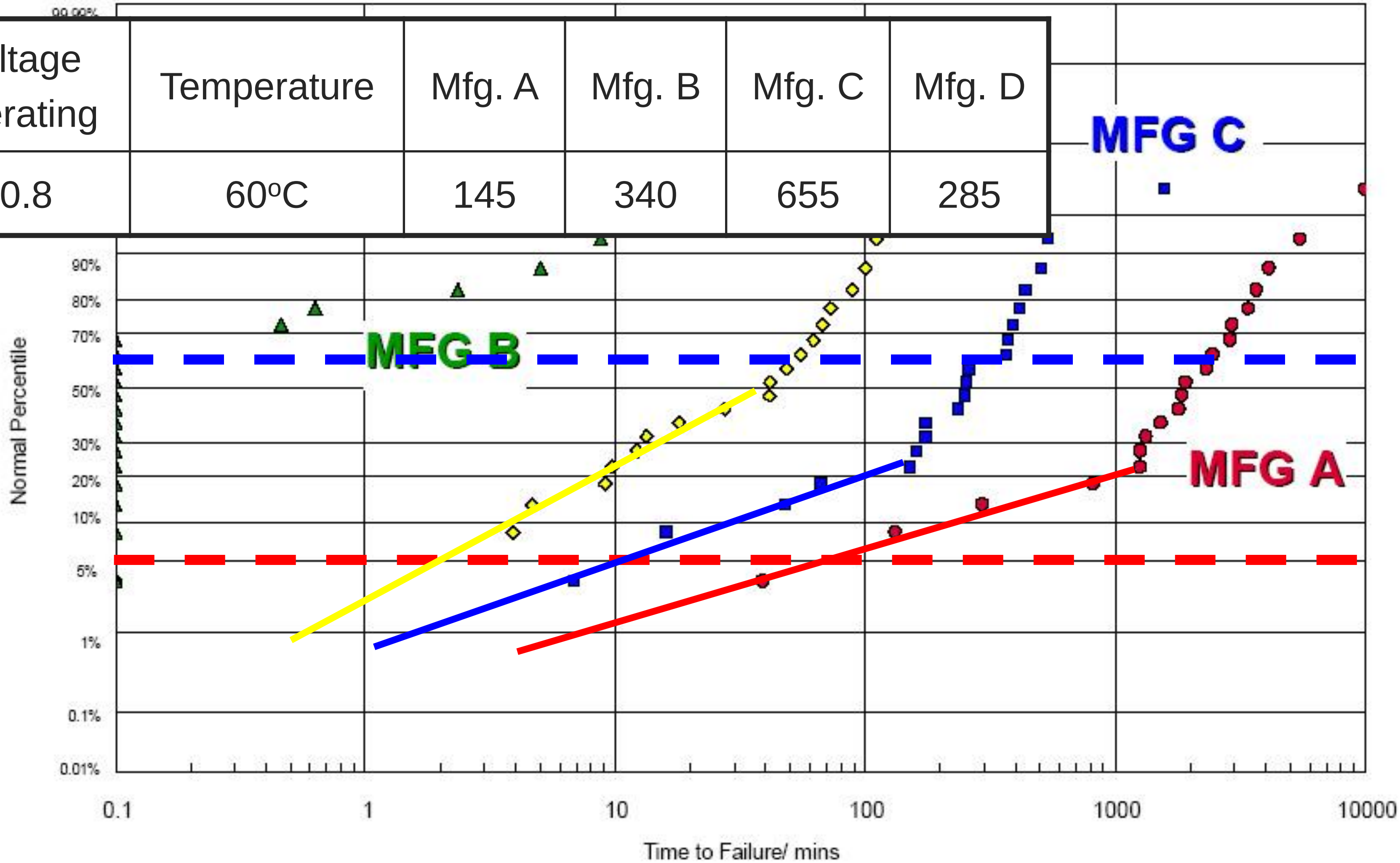
Voltage Derating	Temperature	Mfg. A	Mfg. B	Mfg. C	Mfg. D
0.8	60^{o}C	145	340	655	285



- Difference between MTTF and $t_{5\%}$ is a factor of 40
  - For a design with 20 ceramic capacitors, all product could fail within 3 - 15 yrs

Randall, et. al., CARTS 2003

Voltage Derating	Temperature	Mfg. A	Mfg. B	Mfg. C	Mfg. D
0.8	60ºC	145	340	655	285



- Extrapolation can result in a factor of 250 difference between MTTF and $t_{1\%}$
  - 1% failure rate in less than 10 years in benign conditions (0.5 derating, 45ºC)

Randall, et. al., CARTS 2003

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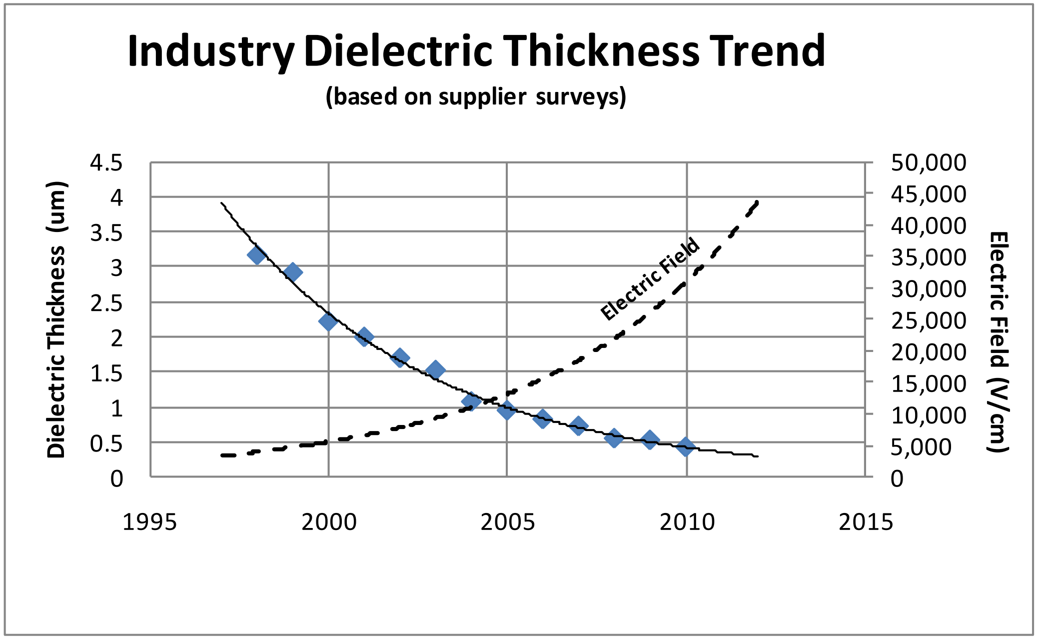
Ceramic Capacitor Wearout (cont.)

- When to be concerned?
  - Dielectric thickness less than 2 - 3 microns
  - Approx. 2 - 10 µF/mm^3



- Case size/capacitance guide
  - X7R
    - 0402 > 0.05 µF; 0603 > 0.2 µF; 0805 > 1 µF; 1206 > 5.6 µF
  - X5R/Y5V
    - 0402 > 0.5 µF; 0603 > 2 µF; 0805 > 5.6 µF; 1206 > 16 µF

Inconsistency in Parameters (Different Failure Mechanisms)

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

Temperature (K)	383	418	433	433	433
Temperature (C)	110	145	160	160	160
Voltage	18.9	12.6	37.8	37.8	37.8
Capacitor	0603/10uF/6.3V	0603/10uF/6.3V	0603/10uF/6.3V	0805/22uF/6.3V	1206/47uF/6.3V
HALT Life (minutes)	192	15	0.75	23	4
Model	Time to Failure at 38C and 3.3V (years)				
DfR	16	4	8	250	43
Panasonic	2	0	1	18	3
Murata	35	17	84	2,561	445
Venkel	273	355	2,698	82,739	14,389
Intel	8,279	2,512	66,723	2,046,184	355,858
Kemet-A	32,155	4,142	404,915	12,417,401	2,159,548
Kemet-B	3,132	2,321	19,234	589,845	102,582
0603 / DfR	6,482	1,997	47,067	1,443,400	251,026

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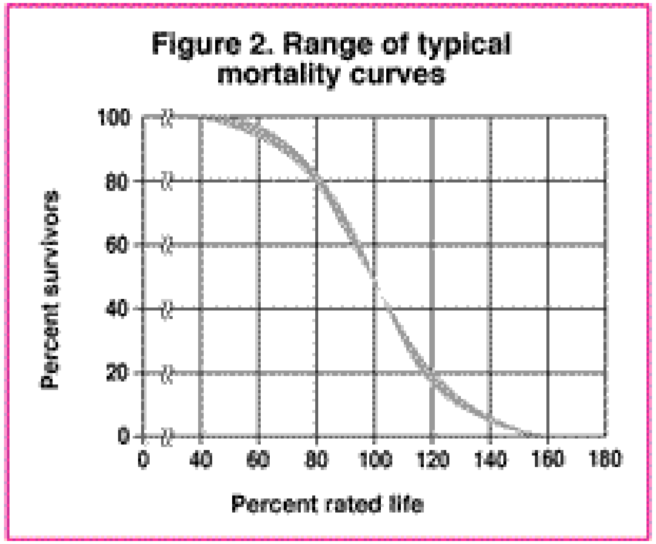
Optocoupler

- Most Optocoupler LEDs are rated to 50,000 hours at ambient temps and rated forward current
  - This is MTTF lifetime
  - Time to 5% failure can be half the time
- Failure definition typically 50% reduction in brightness
  - This needs to be related back to circuit requirements, like CTR
- Assume worst-case parameters
  - n=1.5; Ea=0.7eV



$$t_2 = t_0\left(\frac{I_2}{I_0}\right)^{-n}$$

n = 1.5 to 2

$$t = ce^{Ea/kT}$$

Ea = 0.5 to 0.7eV

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Optocoupler Lifetime (Example)

Days/ Year	Hrs/ Day	Total Hrs/ Year	Temp (oC)	Temp (K)	Forward Current	Rated Current	Current AF (n=1.5)	Temp AF (Ea=0.7eV)	Total AF		
90	12	1080	40	313	6.3	50	22.36	0.27	6.05	302731	37841
180	12	2160	50	323	6.3	50	22.36	0.12	2.71	135548	33887
90	12	1080	55	328	6.3	47	20.38	0.08	1.68	84194	10524
90	12	1080	60	333	6.3	44	18.46	0.06	1.05	52579	6572
90	12	1080	70	343	6.3	38	14.81	0.03	0.41	20722	2590
180	12	2160	75	348	6.3	35	13.09	0.02	0.26	13034	3258
		8640									94674 Hrs
											10.8 Yrs

Note 1: 11 years is MTBF; B10 is likely closer to 5 years

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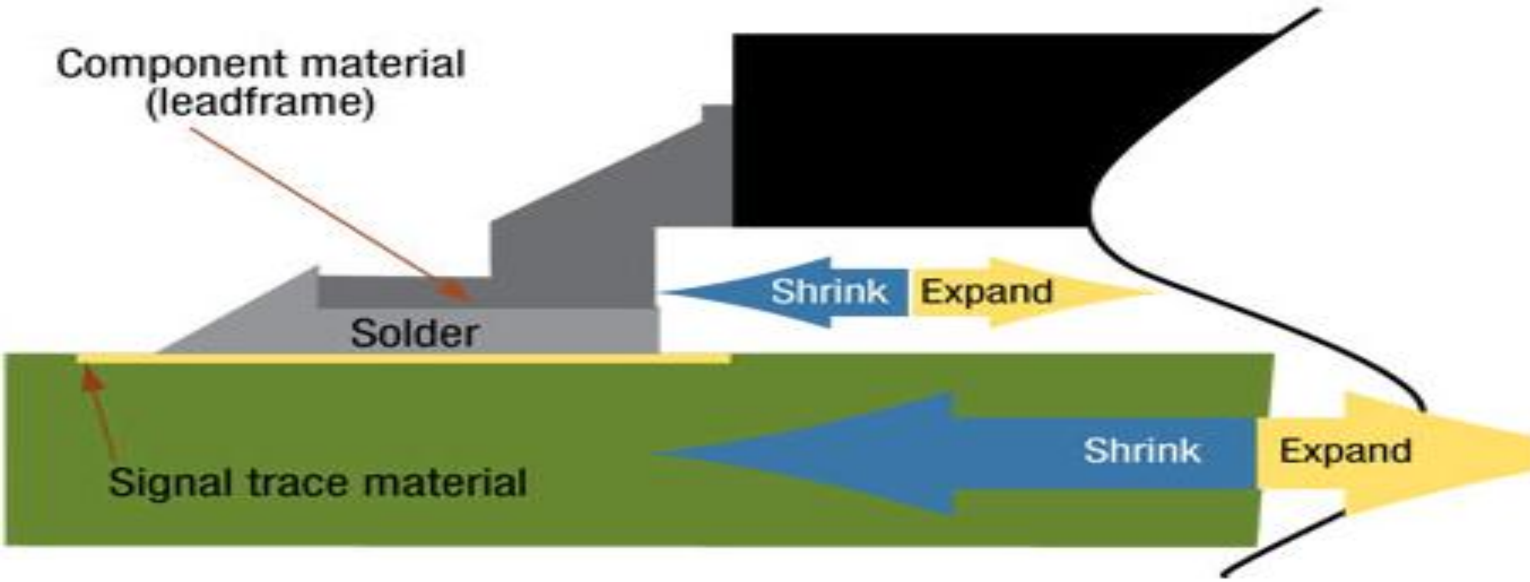
Introduction to Solder Joint Fatigue

- 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)



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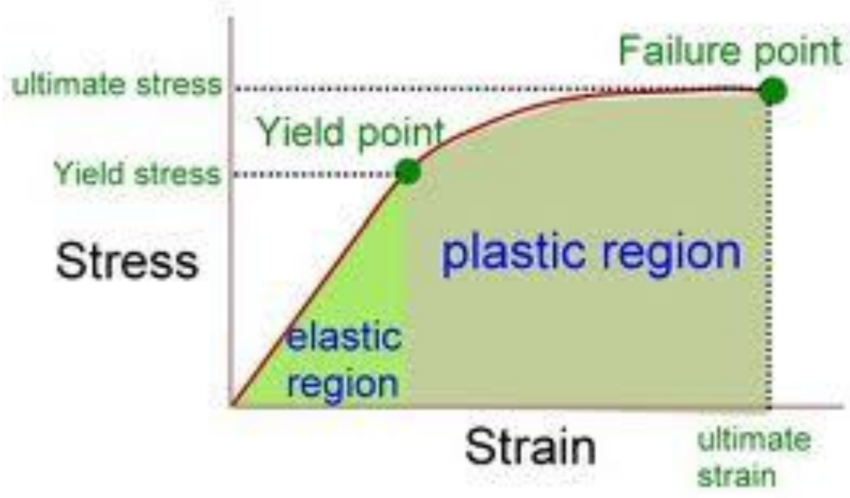
Introduction (cont.)

- 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



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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**, α is coefficient of thermal expansion (**CTE)**, ΔT is temperature cycle, h is **solder joint height**

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PoF Example – SAC Model (cont.)

- 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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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 (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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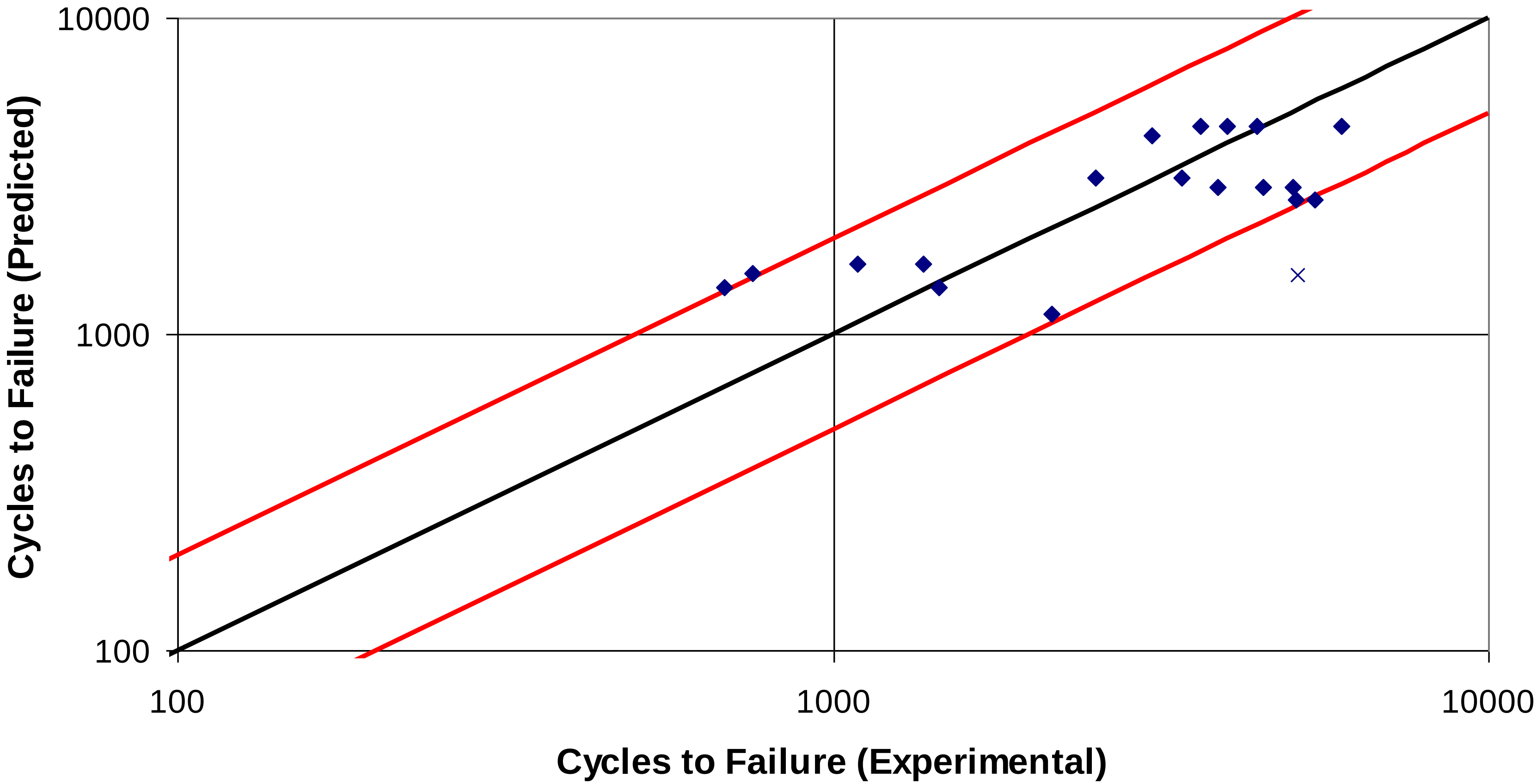
Validation – Chip Resistors



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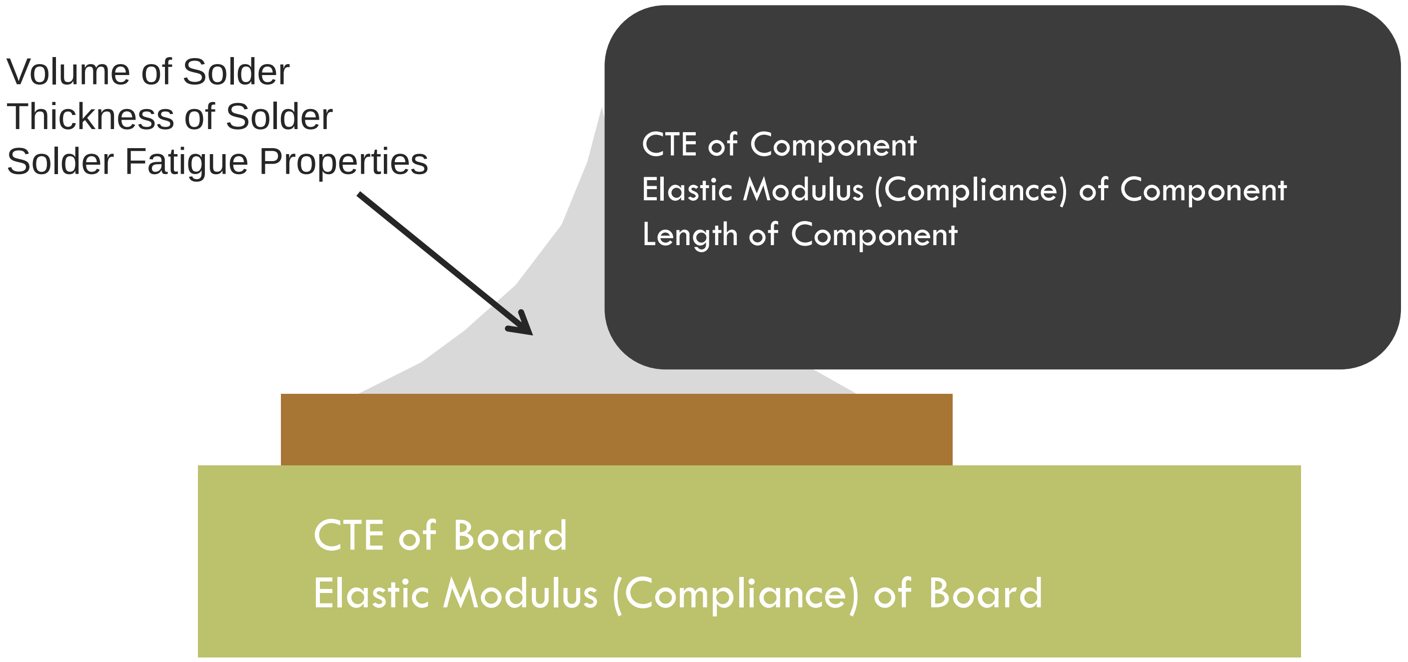
Drivers for Solder Joint Fatigue

- Knowing the mechanism and the models, we can start to identify critical drivers for solder joint fatigue



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

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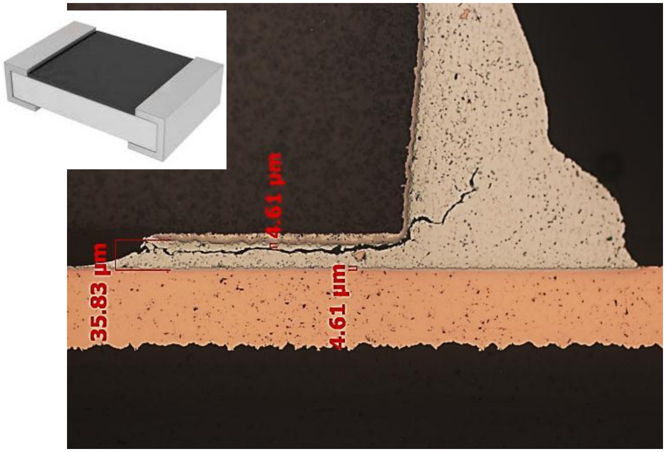
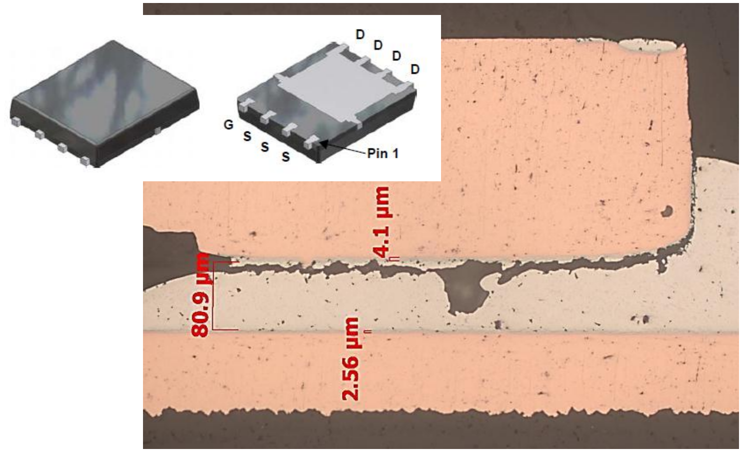
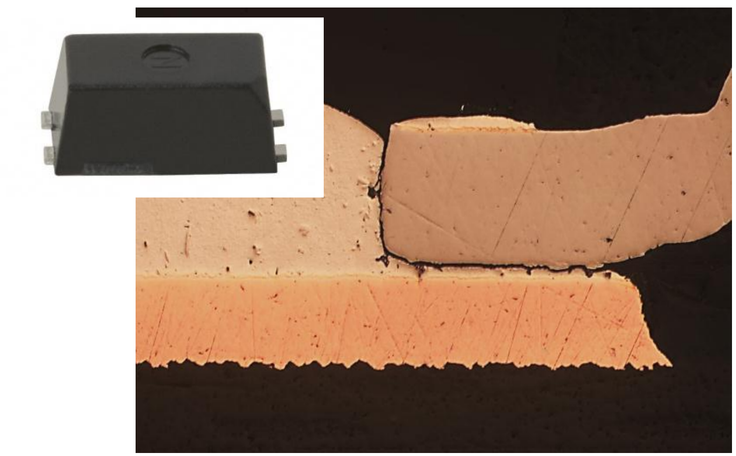
Avoiding Solder Joint Failures



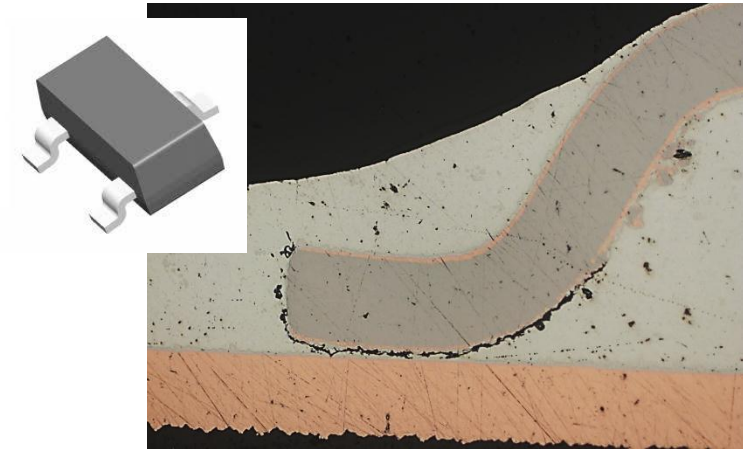
Chip Resistor



QFN



SOT Alloy 42



SOT Alloy 42

Conclusion

- Knowledge is key
  - Reliability goals, environment, components, design
- Current system of component ratings introduces risk into predicting long-term reliability
  - Especially in low-cost, long-life systems (like LED lighting!)
- Need to move towards a physics-based approach for reliability prediction
  - Resources/time minimal with today's modeling/simulation tools

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