Lead Free

From the Perspective of A Printed Circuit Manufacturer

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Environmental Concerns

- Human exposure
- Contamination of drinking water
- Contamination of landfills
- 4% of landfill is electronic waste
- Short life span of electronics increases the rate of fill in landfills

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Lead Free Issues

- 1% of lead used is in electronics
- Easy to ban or restrict
- No long term data on the reliability of alternatives
- Lack of infrastructure or standards
- Higher cost for alternatives

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What Is Driving Lead Free

- Environmental interests
- Business and marketing interests
- European legislation
  - WEEE (waste of electrical and electronic equipment 2002/96/EWG)
  - RoHS (restriction of hazardous substances 2002/95/EWG)
- Other legislation pending

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WEEE 2002/96/EWG Defined

- Regulates disposal and recycling of electronic waste
- Producers are responsible for waste and financing its collection
- Users should be allowed to recycle products free of charge

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RoHS 2002/95/EWG Defined

- Compliments WEEE 2002/96/EWG
- As of July 1th 2006 products put to market shall not exceed specified limits on specific substances
- Restricts the following substances…
  - Cadmium (Cd)
  - Hexa-valent Chromium (Cr^{6+})
  - Lead (Pb)
  - Mercury (Hg)
  - Polybrominated biphenyls (PBB)
  - Polybrominated biphenylethers (PBBE or PBDE)

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RoHS Specified Limits*

Substance	By weight	By mg/kg	By ppm
Cadmium (Cd)	0.01 %	100 mg/kg	100 ppm
Lead (Pb)	0.1 %	1000 mg/kg	1000 ppm
Mercury (Hg)	0.1 %	1000 mg/kg	1000 ppm
Hexa-valent Chromium (Cr^{6+})	0.1 %	1000 mg/kg	1000 ppm
PBB, PBBE or PBDE	0.1 %	1000 mg/kg	1000 ppm

***By weight in homogeneous materials of electrical and electronic equipment**

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Homogeneous Material

- Homogeneous material in RoHS terms means a component or material that cannot be mechanically disjointed into different materials by unscrewing, cutting, crushing, grinding, abrasive processes and similar procedures.
- RoHS homogeneous material is defined as the component or material to be measured for maximum allowable concentration values of the restricted substances determined by EU RoSH regulations.

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Homogeneous Material

- Homogeneous is defined as "of uniform composition throughout". If this definition is finalized, a semiconductor may not be classified as homogeneous, as it is composed of different homogeneous elements such as lead, silicon, gold, frames, wires, etc. which must individually comply with the requirements of the RoHS Directive. These values are subject to EC Environment Council ratification.

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Who Must Comply With RoHS?

- The producer manufactures and sells electrical and electronic equipment under his own brand. The producer resells under his own brand equipment produced by other suppliers. A reseller is not regarded as a producer if the brand of the actual producer appears on the equipment or imports or exports electrical and electronic equipment on a professional basis into a Member State.

Who Must Comply With RoHS?

- When production is sub-contracted to a contract manufacturing (CEM) organization, it is not likely the CEM will hold producer responsibility if the brand name of the original equipment manufacturer (OEM) appears on the product. The OEM would be responsible as their brand name appears on the finished equipment.

Equipment Within the Scope of ROHS

- Large household appliances
- Small household appliances
- IT and telecommunications equipment
- Consumer equipment
- Lighting equipment
- Electrical and electronic tools
- Toys, leisure and sports equipment
- Automatic dispensers
- Batteries and Accumulators
- Medical devices (with the exception of all implanted and infected products) & Monitoring and control instruments are being addressed separately by the European Commission. Currently studies are being conducted after which proposals for implications will be reviewed.

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RoHS Exemptions

- RoHS does not apply to spare parts for the repair of Electrical and Electronic Equipment (EEE) placed on the market before 1 July 2006.
- RoHS does not apply to replacement components that expand the capacity of and/or upgrade EEE placed on the market before 1 July 2006.

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RoHS Exemptions

- Mercury (Hg)
  - In compact fluorescent lamps not exceeding 5 mg per lamp.
  - In straight fluorescent lamps for general purposes not exceeding:
    - Halophosphate 10mg
    - Triphosphate with normal lifetime 5mg
    - Triphosphate with long lifetime 8mg
  - In straight fluorescent lamps for special purposes
  - In other lamps not specifically mentioned in the Annex to the RoHS Directive

RoHS Exemptions

- **Lead:**
  - In glass of CRTs, electronic components and fluorescent tubes
  - As an alloying element in steel containing up to 0.35% lead by weight, aluminium containing up to 0.4% lead
  - As a copper alloy containing up to 4% lead by weight
  - In high melting temperature type solders (eg tin-lead solder alloys containing more than 85% lead)
  - In solders for servers, storage and storage array systems (exemption granted until 2010)
  - In solders for network infrastructure equipment for switching, signalling, transmission as well as network management for telecommunication
  - In electronic ceramic parts (e.g. piezo-electronic devices)

RoHS Exemptions

- **Cadmium plating** except for applications banned under Directive 91/338/EEC (1) amending Directive 76/769/EEC (2) relating to restrictions on the marketing and use of certain dangerous substances and preparations.
- **Hexavalent chromium** as an anti-corrosion of the carbon steel cooling system in absorption refrigerators.

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Are They Serious?

- Enforcement for RoHS varies from EU member state to member state.
- The Reuters news organization reported back on December 5, 2001 that the sale of 1.3 million Sony PlayStation One game consoles was blocked due to health and environmental concerns. The Dutch Government barred the game consoles and 800,000 accessories from entry into the Netherlands. The cables in the units contained too much cadmium. This move forced Sony to replace the peripheral cables on their units.

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How Does RoHS Impact PCBs?

- Specified Polybrominated PBB, PBBE and PBDE materials have not been used as fire retardants in PCBs for decades – No Effect
- Specify white or black nomenclature inks only. Other color inks use restricted substances as coloring agents

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How Does RoHS Impact PCBs?

- Lead-Free is the result of RoHS
  - RoHS restricts the use of lead
  - Eutectic solders consisting of tin/lead are not allowed
  - A suitable alternate final finishes must be specified by the PCB purchaser
  - Lead-Free solders require higher assembly temperatures for greater amounts of time
  - Materials must be capable of withstanding higher temperatures

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How Much Higher?

- Today's Tin Lead Alloy melts at 183°C with typical peak reflow temperatures of 215 -220°C
- SnAgCu (SAC) lead free alloy melts at 217°C with peak reflow temperatures of 235-260°C
- SN100CL melts at 227°C with peak reflow temperatures of 245-270°C

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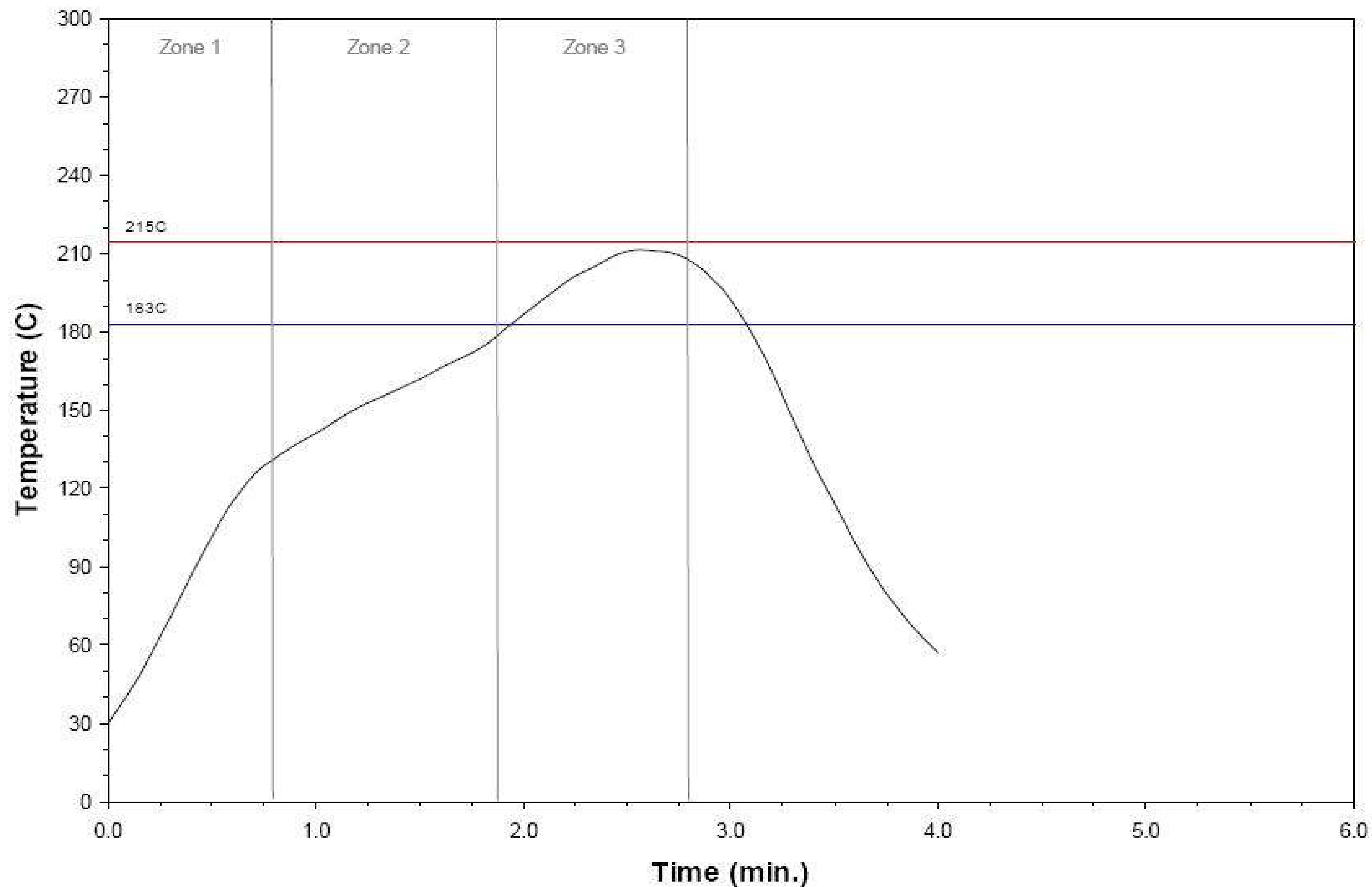
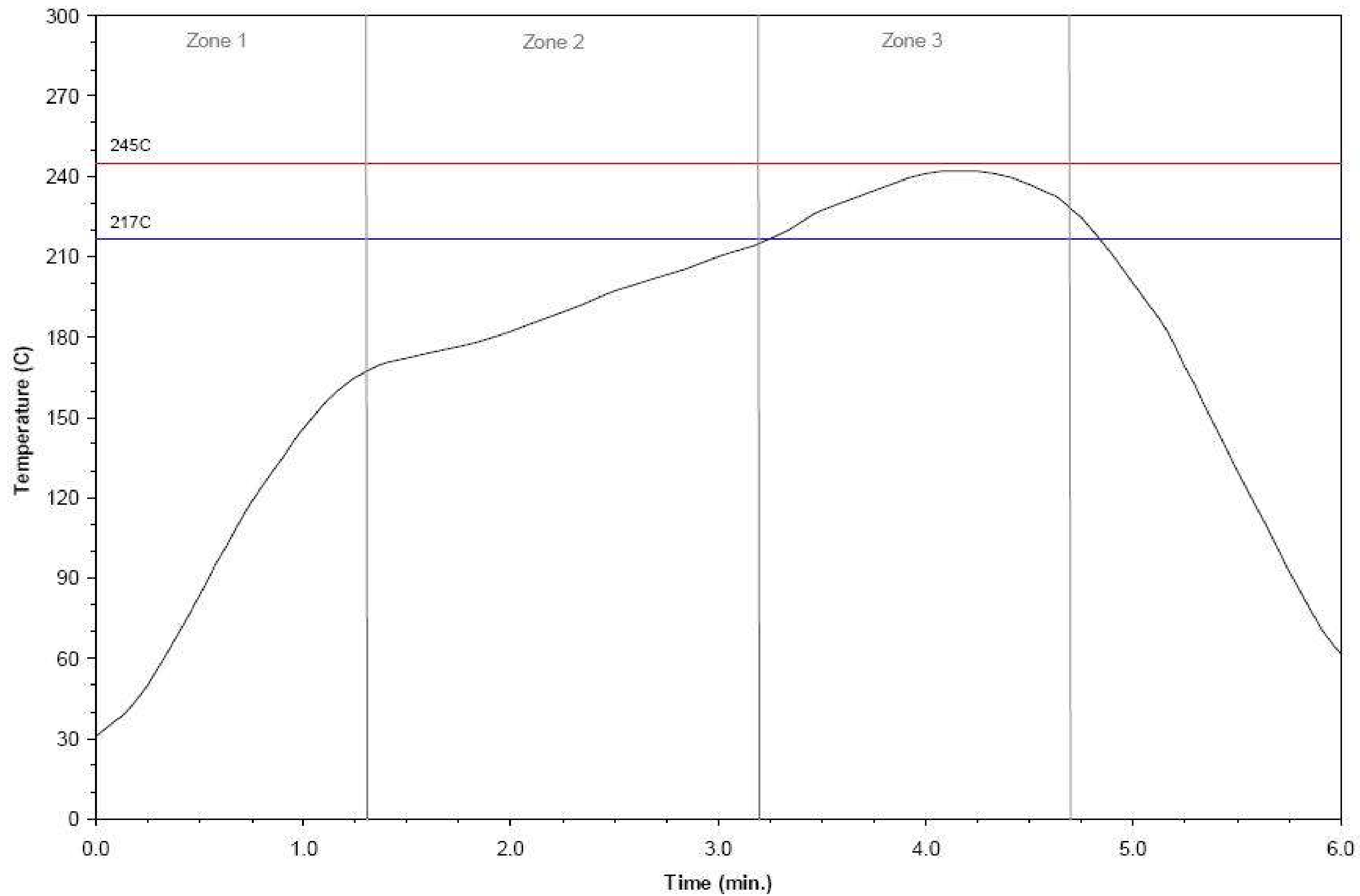
How Much Higher?



Eutectic Reflow Profile

* Reference IPC

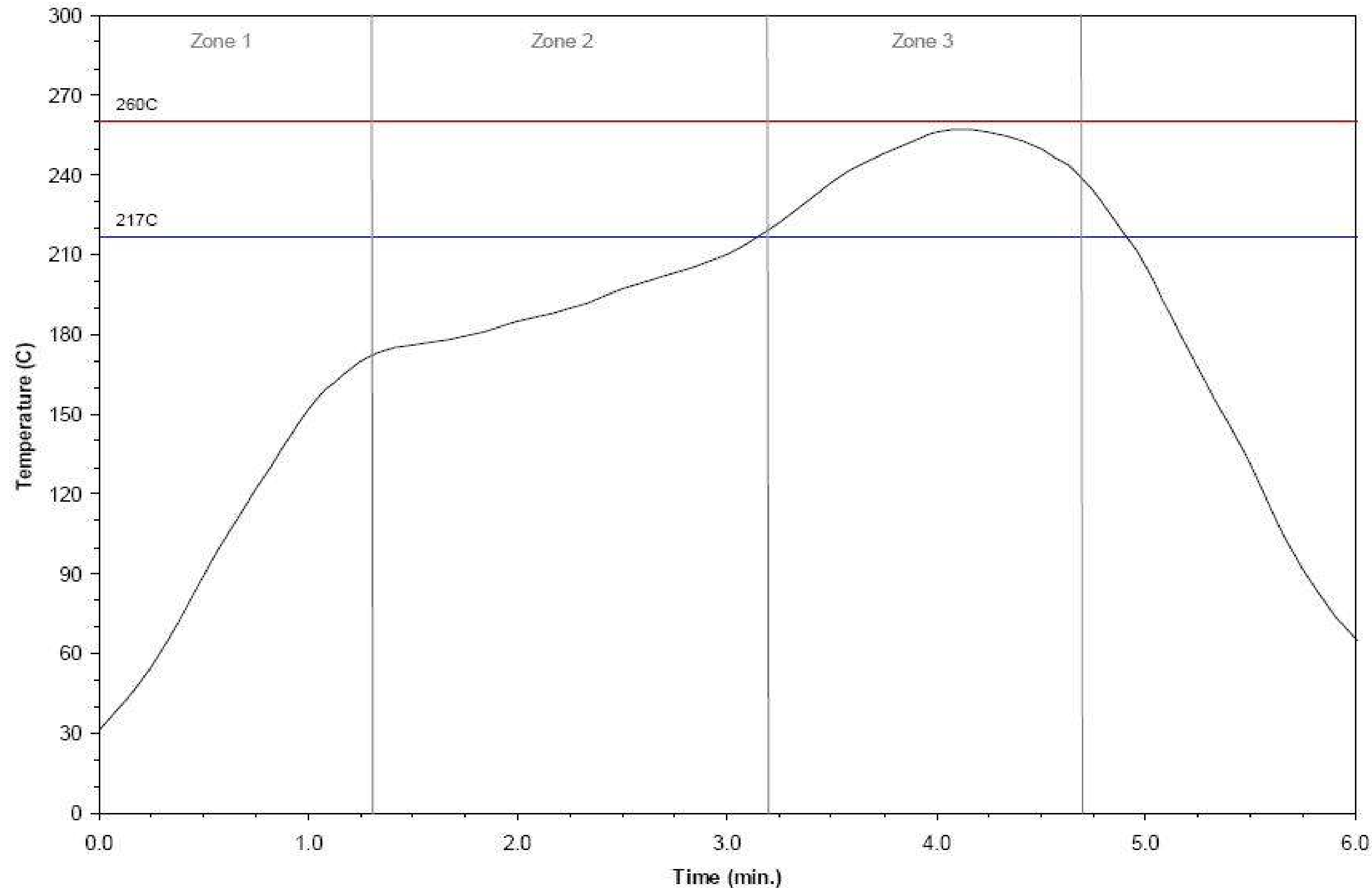
How Much Higher?



245°C Reflow Profile

* Reference IPC

How Much Higher?



260°C Reflow Profile

* Reference IPC

How Much Higher?

- Lead-free process require 60 to 90 seconds above alloy melting point
- 20-30°C above alloy melting point to ensure good wetting
- Profile shall be dependant upon circuit board design (thermal management)
- Complex designs may require pre-baking to raise core temperatures prior to assembly

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RoHS and Lead-free Misconceptions

- All RoHS compliant PCBs are Lead-free assembly compliant – False.
- Lead-free shall not have a cost impact – False.
- Lead-free is a drop in process – False.
- 140°C Tg FR4 is not compatible with Lead-Free assembly – Design Specific

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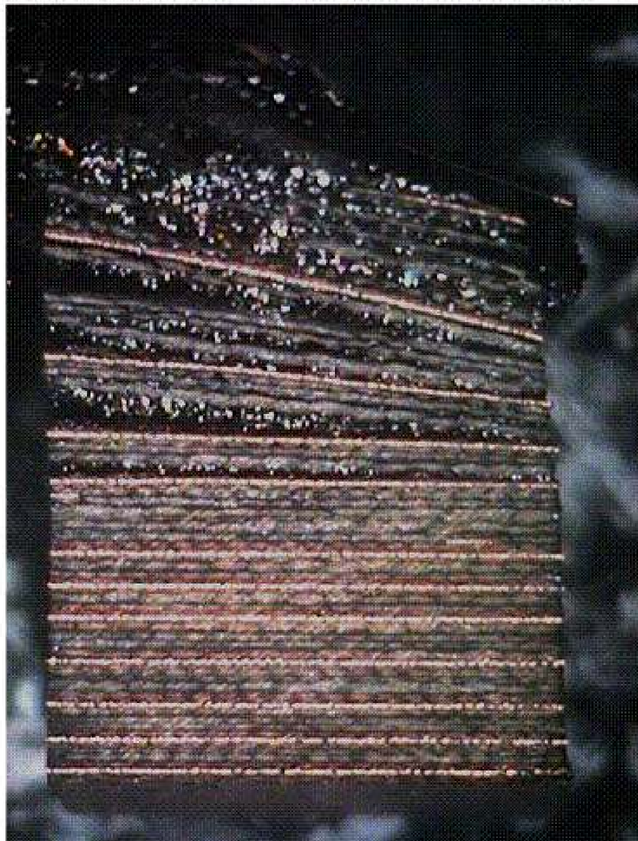
What's The Worst That Could Happen?

40 Layer FR4 PWB
TMA T-260 Sample



- Example of an 8.4mm, 40-layer backplane after T260 testing.
- T260 value was approximately 2 minutes.

What's The Worst That Could Happen?

This manufacturer switched to a 175°C Tg FR-4
to "avoid problems" with Pb-free assembly

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Why Can't We Use Standard FR4?

- Material properties must be understood in order to make a decision.
- Properties that require explanation
  - Glass Transition Temperature (Tg)
  - Coefficient of Thermal Expansion (CTE)
  - Decomposition Temperature (Td)
  - T260/T288 Time to Delamination
  - CAF (Conductive Anodonic Filament)

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Glass Transition Temperature (Tg)

- By definition this is the temperature at which a polymer changes from hard and brittle to soft and pliable
- Test Methods (each give slightly different values)
  - Dynamic Mechanical Analysis (DMA)
    - Measures modulus
  - Differential Scanning Calorimetry (DSC)
    - Measures rate of heat absorption
  - Thermal Mechanical Analysis (TMA)
    - Measures expansion rate

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Glass Transition Temperature (Tg)

- Has nothing to do with the fiberglass reinforcement material in the printed circuit board
- Value refers to the resin system when it changes from a hard glassy state to a soft rubbery state
- Critical point in thermal expansion

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Glass Transition Temperature (Tg)

- Below the Tg value the rate of thermal expansion is low
- Above the Tg value the rate of thermal expansion is higher by a factor of up to 10
- The Tg has historically been the designer's gauge for reliability

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Coefficient of Thermal Expansion (CTE)

- By definition this is a material's fractional change in length for a given unit change of temperature
- The common unit of measurement is ppm/°C, parts per million per degree centigrade
- 1 ppm is equivalent to 0.0001% of total observed dimension

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Coefficient of Thermal Expansion (CTE)

- A material rated at 250 ppm /°C would change 0.025% in dimension for every degree change in temperature
- A .100" thick board over a 100°C temperature range there would be a total thickness change of 2.5% which equates to 0.0025"

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Coefficient of Thermal Expansion (CTE)

- The circuit board resin system expands at one rate below the Tg and another rate above the Tg (This is why the Tg value is important)
- High Tg material tend to be more stable
- Low Tg material tend to be less stable

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Coefficient of Thermal Expansion (CTE)

- Glass, copper, nickel and gold all have fixed expansion rates up to their melting points (Copper CTE = 17 ppm/°C)
- Standard FR4 with Tg = 140°C has a CTE = 50 ppm/°C below Tg and CTE = 250 ppm/°C above Tg (both in the Z – axis)

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Coefficient of Thermal Expansion (CTE)

- Lead-Free assembly temperatures on a .100” thick PCB result in approximately .004” difference in Z – axis expansion between copper and FR4
- Increased risk of lifted lands (pads) and hole wall failure due to the difference in expansion

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Decomposition Temperature (Td)

- By definition this is the temperature at which a 5% weight loss occurs by thermal gravimetric analysis (TGA) ASTM D 3850
- Decomposition is the breaking of chemical bonds in the resin system
- A 2% to 3% weight loss of this nature will adversely affect circuit performance
- Damage caused from decomposition is cumulative

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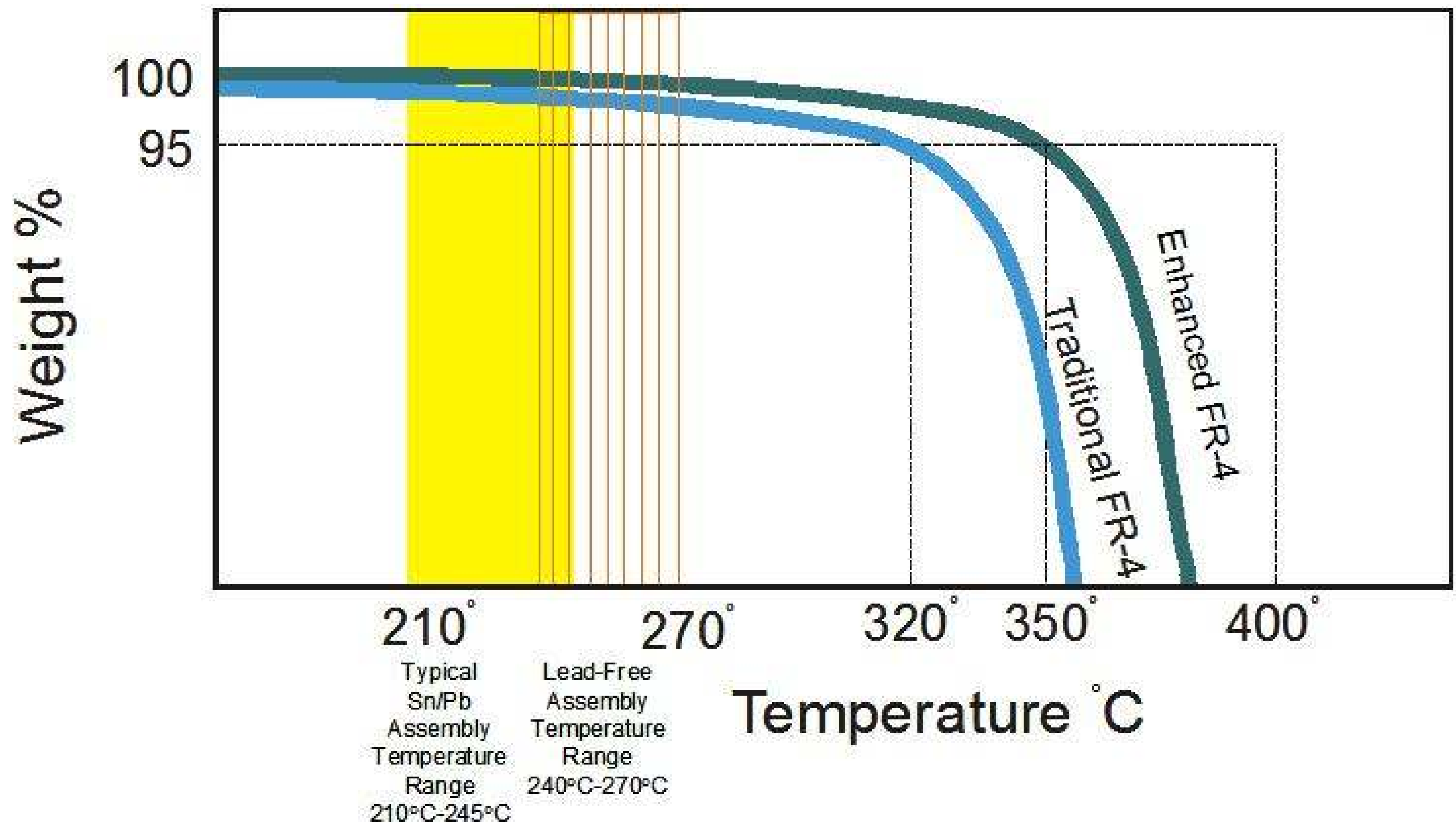
Decomposition Temperature (Td)



* Ref data from Polyclad Laminates

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Decomposition Temperature (Td)

A Comparison of Four Laminate Materials

- LGLD = 140°C T_g/320°C T_d FR-4
- LGHD = 140°C T_g/350°C T_d FR-4
- HGLD = 175°C T_g/310°C T_d FR-4
- HGHD = 175°C T_g/350°C T_d FR-4

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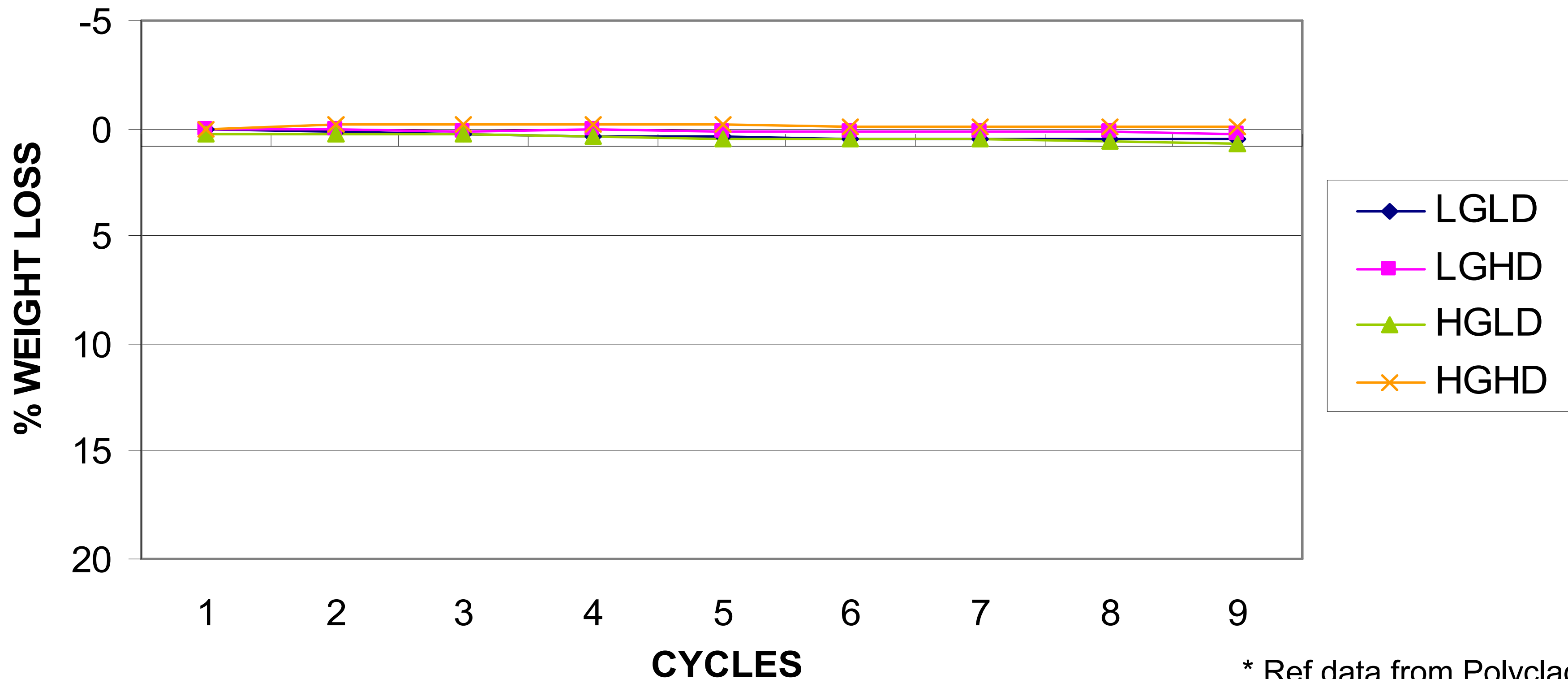
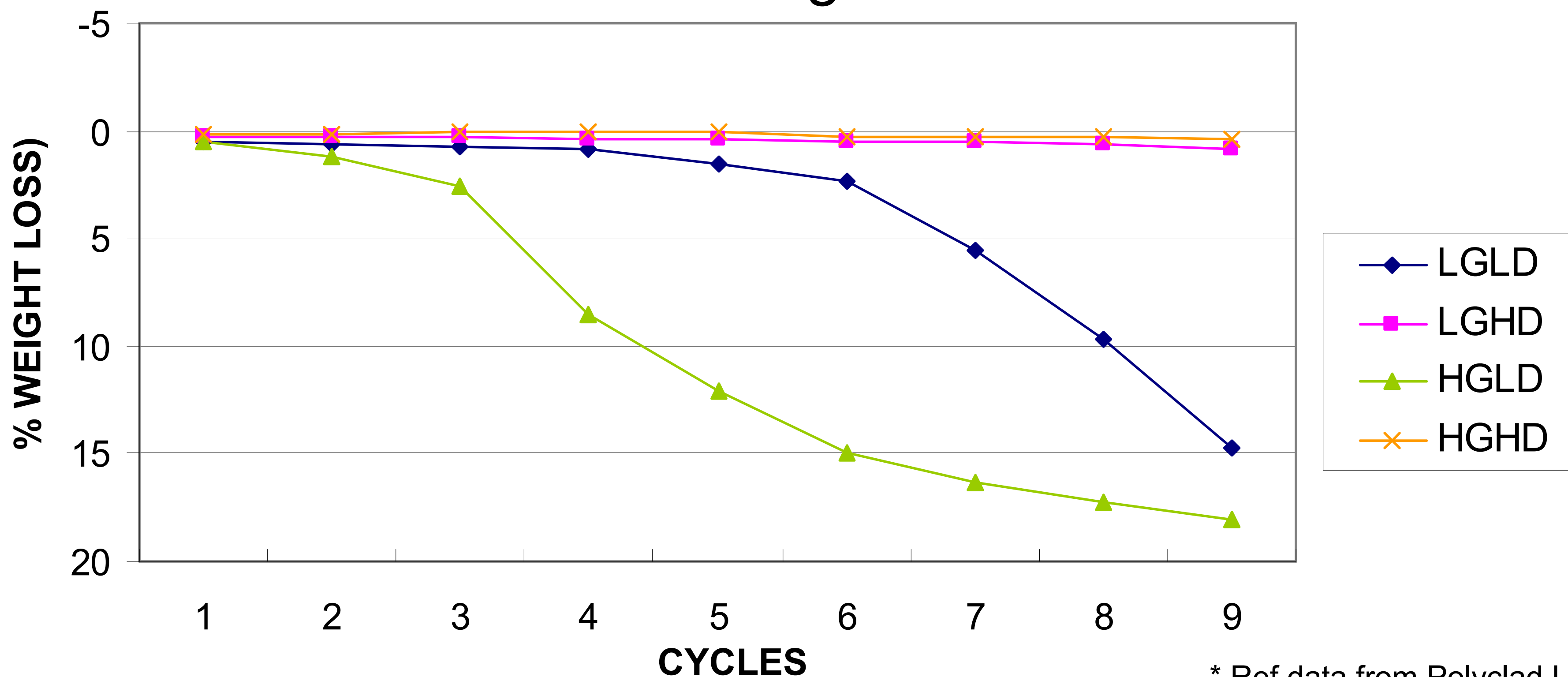
Decomposition Temperature (Td)



* Ref data from Polyclad Laminates

Decomposition Temperature (Td)



* Ref data from Polyclad Laminates

T260/T288 Time to Delamination

- This is a test defined by the IPC under IPC-TM-650 Test Method 2.4.24.1
- A test sample is incrementally raised in temperature 10°C/min to 260°C/288°C and then dwell at 260°C/288°C
- The time in minutes from the start of the dwell time to an event at 260°C/288°C is the time to delamination

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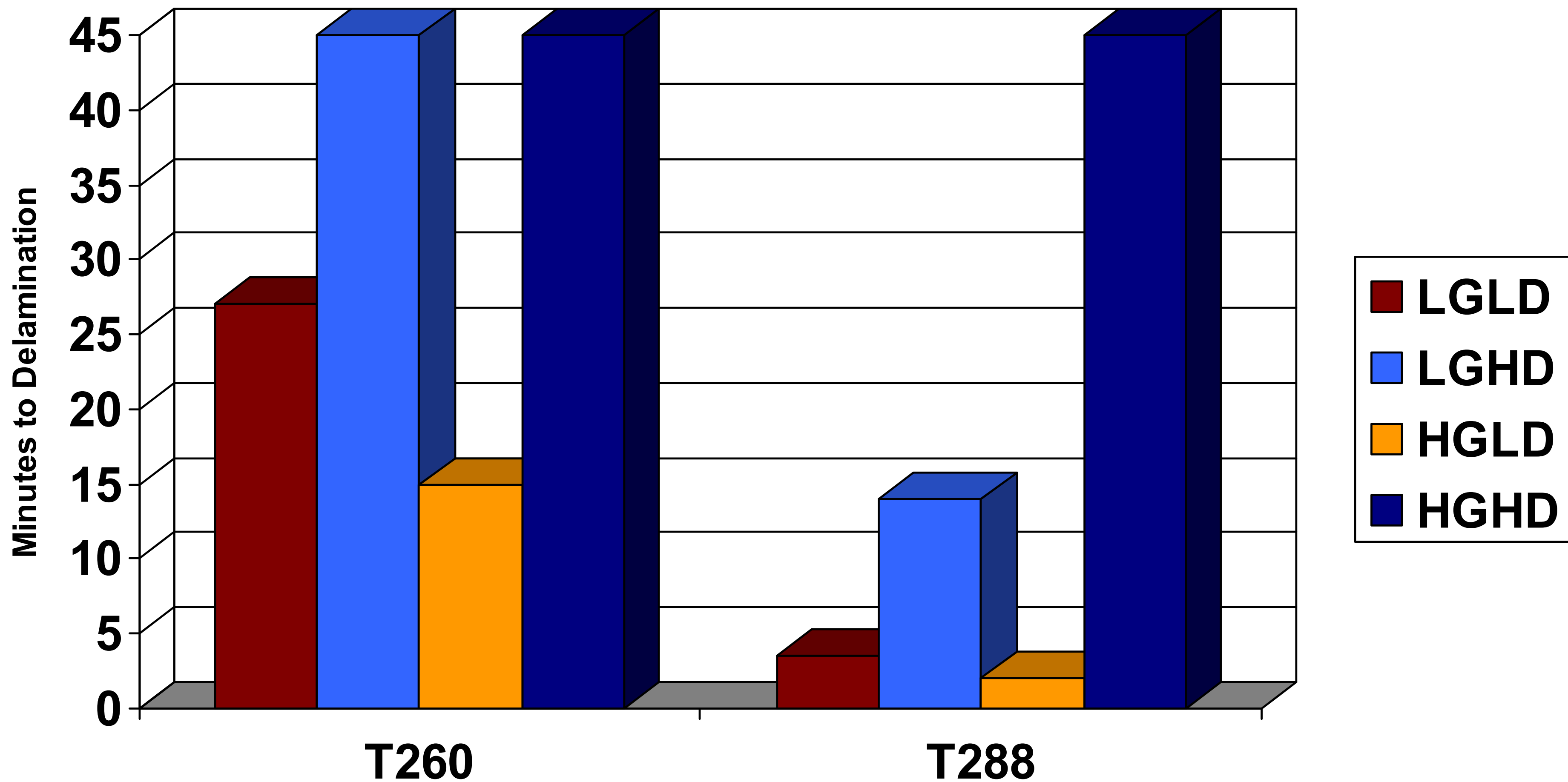
T260/T288 Time to Delamination

- An event is defined as delamination, cracking, moisture release, stress relaxation, decomposition or a sudden movement detected by a calibrated sensor
- Time to delamination has been observed to decrease as the board gets thicker
- Longer T260/T288 times indicate better delamination/measles/blister resistance

T260/T288 Time to Delamination



4-7628 Laminate

* Ref data from Polyclad Laminates

CAF (Conductive Anodonic Filament)

- Bell Labs first identified CAF in 1976
- Field failures were identified in 1980
- CAF is formed as a result of several events

CAF (Conductive Anodonic Filament)

CAF Formation

- As an epoxy resin system is heated there is the possibility that the resin shall separate from the fiberglass reinforcement
- The separation forms an open channel at the resin to fiberglass interface along the length of the fiberglass strand

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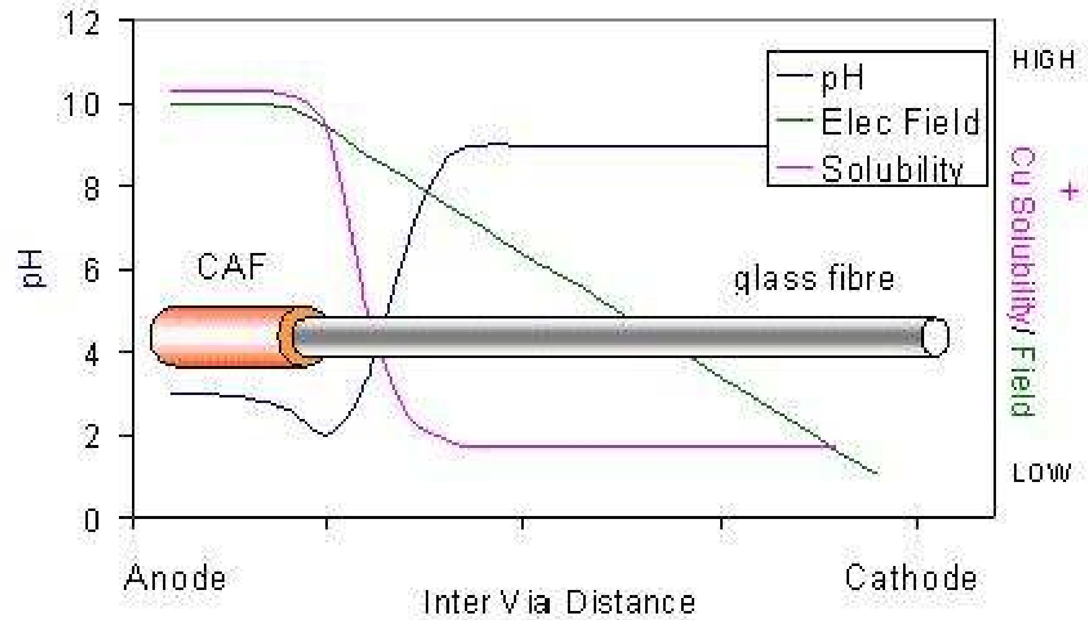
CAF (Conductive Anodonic Filament)

CAF Formation

- When an assembled board is exposed to high humidity the CAF channel fills with water
- The copper corrodes and an electrochemical pathway develops

CAF (Conductive Anodonic Filament)

- The water acts as an electrolyte, the copper circuitry becomes the anode and cathode and the operating voltages act as the driving potential



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CAF (Conductive Anodonic Filament)

- A filament containing copper grows along the channel formed at the epoxy resin and glass interface
- The growing filament ultimately forms a short between two unlike conductors resulting in a field failure

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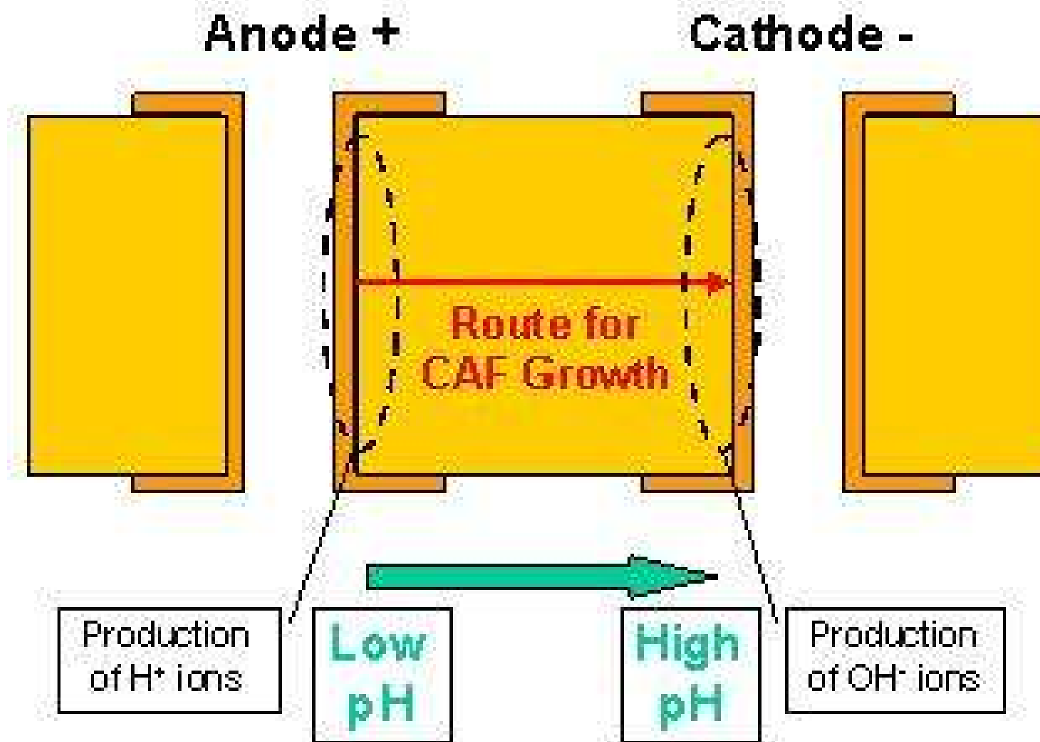
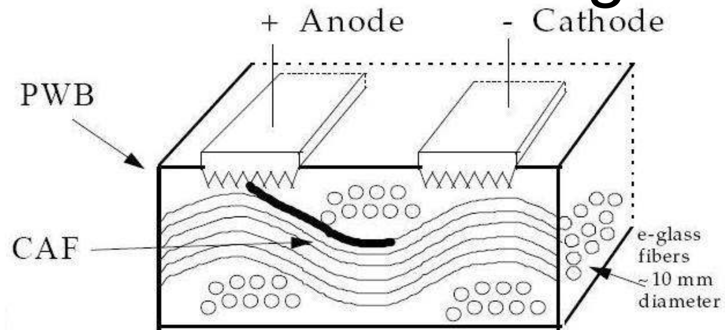
CAF (Conductive Anodonic Filament)

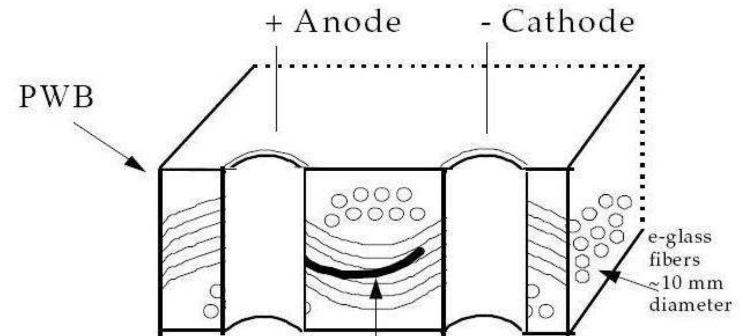
Diagram of CAF Growth

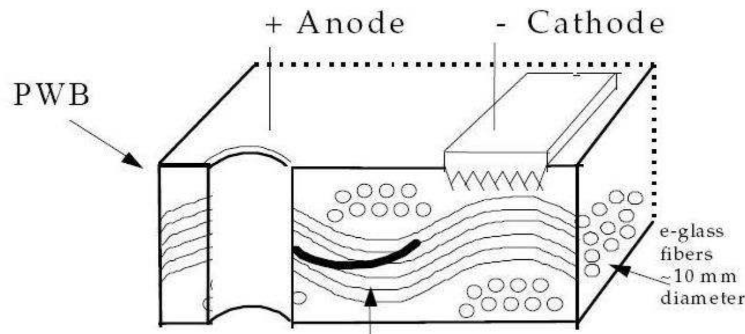


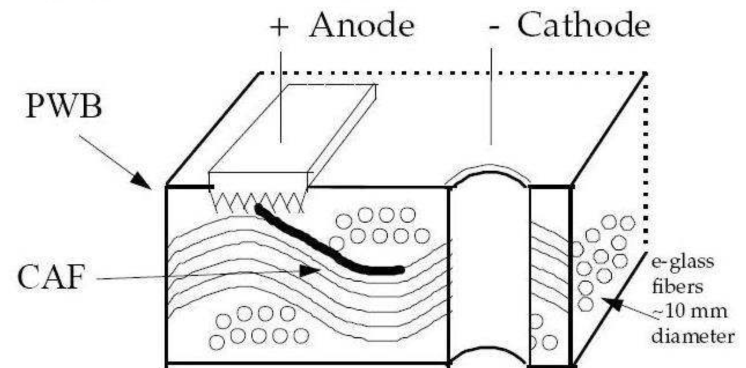
CAF (Conductive Anodonic Filament)

Diagrams of CAF Growth









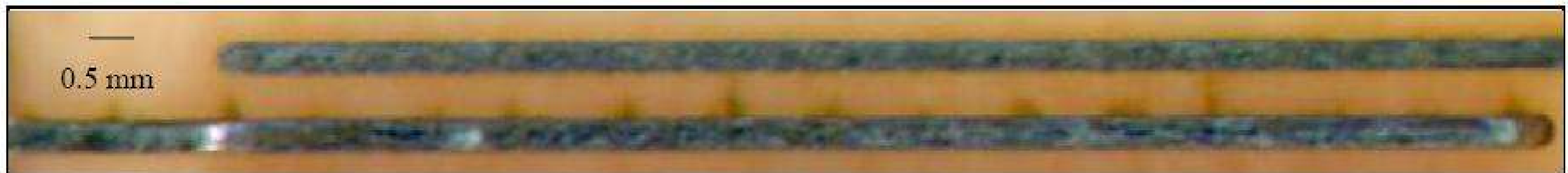
A=Track To Track, B= Hole To Hole, C= Hole To Track, D= Track To Hole

CAF (Conductive Anodonic Filament)

- Formation of CAF viewed through a micro section

CAF (Conductive Anodonic Filament)

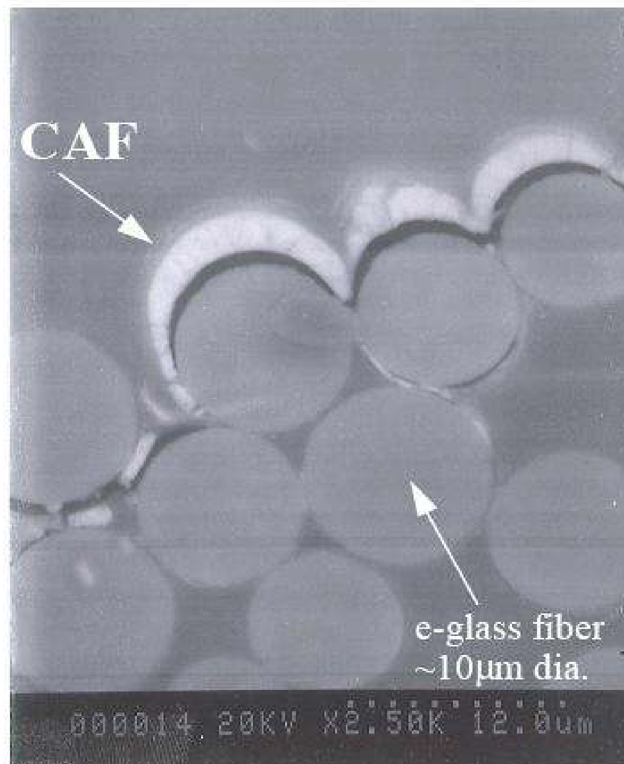
Optical view displaying multiple CAF formations bridging a 0.5 mm gap between anode and cathode on a standard coupon.



CAF (Conductive Anodonic Filament)

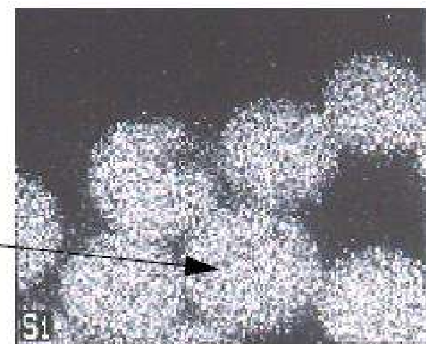
SEM and X-Ray Images on CAF

BSE Image @ 20kV



Cu x-rays

Cl x-rays



Si x-rays

Br x-rays

CAF (Conductive Anodonic Filament)

- CAF is not easily observable
- CAF shall not appear in a printed circuit board until after several months of active use within certain environments
- CAF resistant does not imply immunity to CAF
- Lead-free advertised materials resist CAF growth better than standard FR4

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Verification

- RoHS compliance
  - C of C based on existing paper trail, actual measurements and estimations (IPC-1750 series)
  - Scientific analysis to detect non-conformances by destructive testing
  - Destructive testing for RoHS compliance is costly
  - Testing for metals is $800.00 1st sample / $400.00 each additional sample
  - Testing for plastic/laminate/solder mask is $1,500.00 1st sample / $750.00 each additional sample

* Pricing courtesy of Trace Labs East

Verification

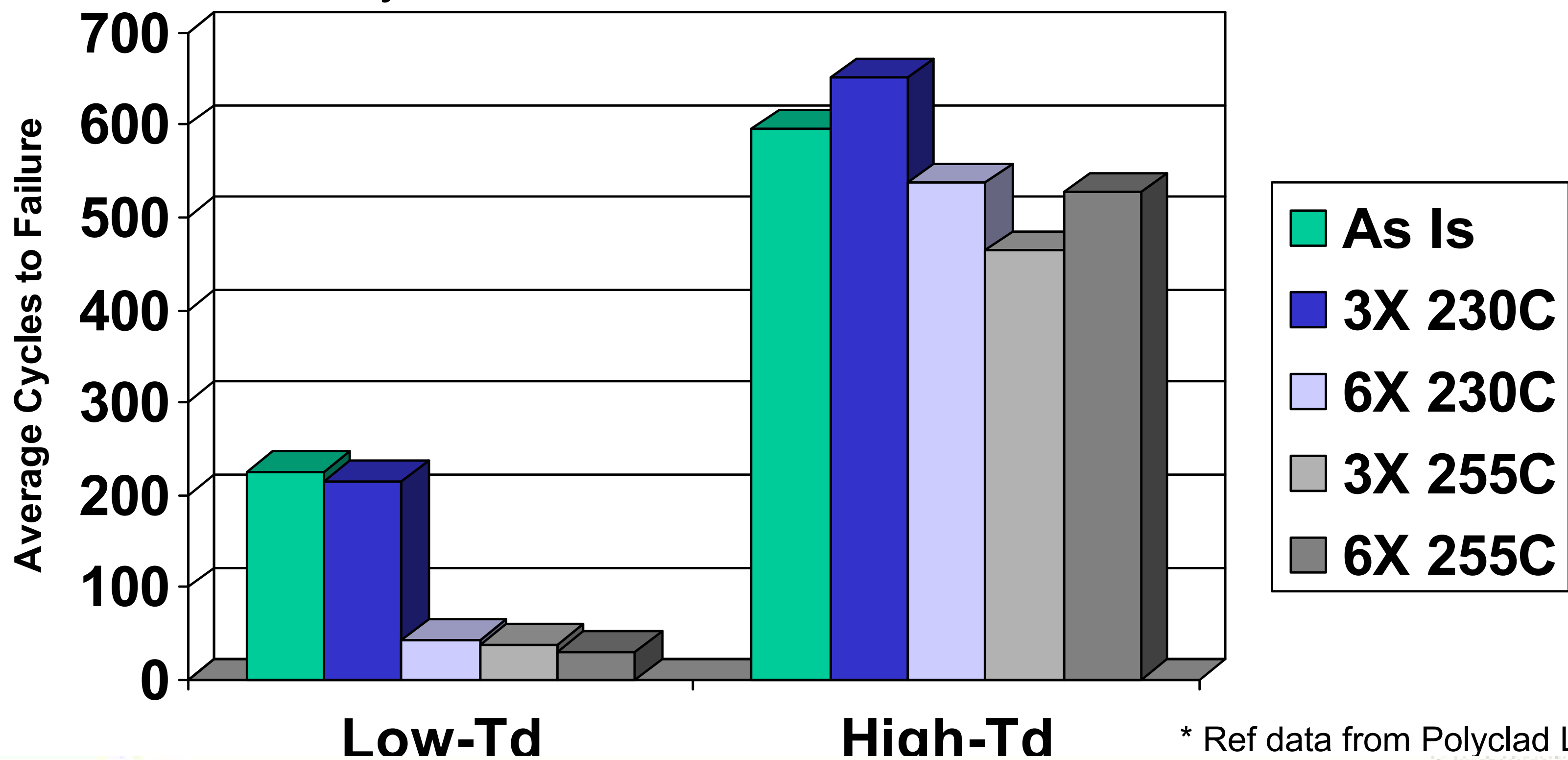
- Lead-free survivability
  - Passing assembled board testing may not be enough
  - High reliability products should be tested
  - Interconnect Stress Testing (IST) to detect latent plated through hole interconnect failures
  - CAF testing to detect latent filament growth
  - IST estimated cost = $3,296.00
  - CAF testing estimated cost = $3,822.00

* Pricing courtesy of Trace Labs East

IST Test Results

Low-T_d vs. High-T_d 175°C Tg Materials
230°C vs. 255°C Preconditioning

14-Layer PCB, 0.120”, 0.012” Diameter PTH



* Ref data from Polyclad Laminates

Recommendations

- Prior to selecting a laminate system consider the following…
  - Cost of components being installed
  - Complexity of the design
  - Is the product to be used for general or high reliability electronics
- The printed circuit board should be considered as the main foundation for the assembly
- Weak foundations crumble under stress
- Strong foundations stand firm

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Recommendations

- The IPC-4101A material specification is being updated to IPC-4101B
- IPC-4101B is expected to be released by years end
- New material data sheets added specifically for Lead-free
  - IPC-4101 /99, /101, /121 and /124

Recommendations

- Fabrication notes until IPC-4101B is released
  - The finished printed circuit board shall be RoHS compliant
  - Base laminate to meet the requirements of IPC-4101A /24 or /26
  - Tg >= 175°C
  - Td >= 330°C
  - T260 >= 30 minutes
  - T288 >= 5 minutes
  - CTE Z-axis expansion (50°C to 260°C) <= 3.5%

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Thank You

The End