Bare Board Material Performance after Pb-free Reflow

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This presentation will review the findings of a HDPUG consortia effort to evaluate 29 different bare board material and stack-up combinations and their associated performance after 6X Pb-free reflows at 260C. Data presented will focus on the air-air thermal cycling results. IST testing and material survivability after Pb-free assembly reflow portions of this testing are also presented. Test board design aspects, manufacturing processes, Weibull analysis and failure analysis data will be presented. The impact of "plated through hole pitch" on laminate integrity and how material properties relate to the results will be discussed.

This presentation was originally presented by Joe Smetana (ALU) at the APEX 2009 conference, and it be presented here again at the request of the mid-west IPC committee.

Bare Board Material Performance after Pb-free Reflow

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HDPUB
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Overview of Project

- Characterize a significant number of Pb-free materials for Pb-free survivability and reliability.
- Evaluate High Layer Count/High Resin Content Effect
  - Four board stackups:
    - 20 layer ~58% and 69%RC, .116/.118 thick
    - 6 layer, .062 thick, 48%RC,
    - 6 layer, .116 thick, 45%RC
- IST as part of test vehicle design for direct comparison of IST to Air to Air
- *Limited CAF PTH-PTH wall test section to specifically to evaluate the results of Pb-Free reflow on CAF performance
  - Limited to .016 **(Actual .021”)** hole wall to hole wall and .010 hole wall to hole wall
- *Evaluate Electrical Performance data and any effect of Pb-Free reflow on materials

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** Not covered in this paper*

Things to be aware of

- All of these materials were claimed by material suppliers to be Pb-free compatible materials
- All materials were processed to material supplier recommendations – with them present.
  - No “fabricator” tweaks (which may improve the process)
- Boards were plated in 2 lots
  - All 20 layer and thick 6 layer is first lot
  - All thin 6 layer in 2^{nd} lot

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Materials Tested

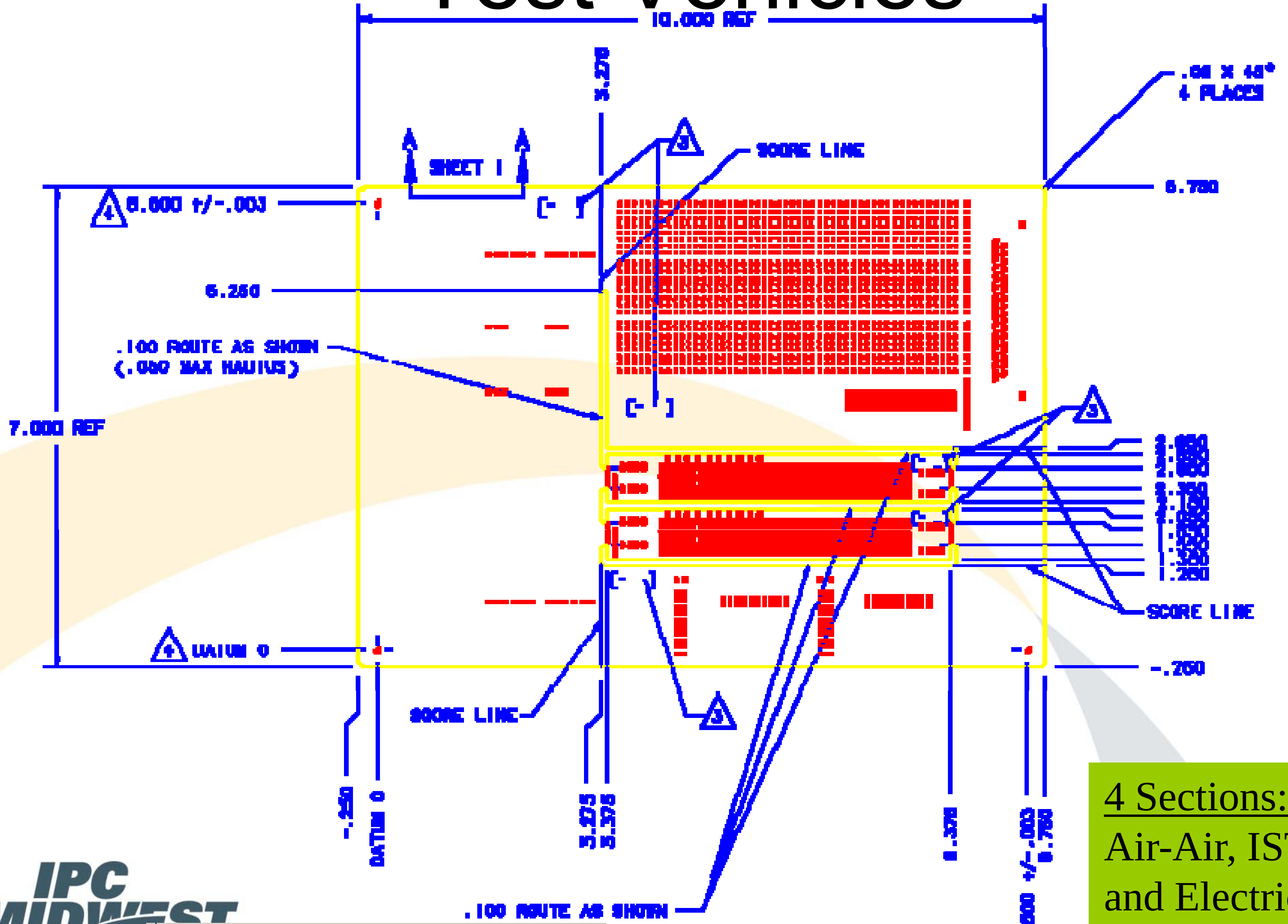
20 Layer Materials and Constructions		
Code	**Material Type**	**Stackup**
A	Baseline Non-Filled Phenolic FR4	Standard
B	Baseline Filled Phenolic FR4	Standard
C	Filled Proprietary Resin FR4	Standard
D	Filled Phenolic FR4	Standard
E	Unfilled Phenolic FR4	Standard
F	Unfilled Phenolic FR4	Standard
G	Filled Phenolic FR4	Standard
H	Unfilled Phenolic FR4	Standard
I	Filled Phenolic FR4	Standard
J	Filled Phenolic FR4	Standard
K	Unfilled Phenolic FR4	Standard
L	Hi-Speed Material	Standard
M	Hi-Speed Material	Standard
N	Hi-Speed Material	Standard
P	Unfilled Phenolic FR4	High Resin
Q	Filled Phenolic FR4	High Resin
R	Unfilled Phenolic FR4	High Resin
S	Filled Phenolic FR4	High Resin

6 Layer Materials and Constructions		
Code	**Material**	**Stackup**
T	Halogen Free FR4, Filled, Dicy, Mid Tg	.062" Thick
U	Halogen Free FR4, Filled, Dicy, Hi Tg	.062" Thick
V	Halogen Free FR4, Filled, Dicy, Hi Tg	.062" Thick
W	Filled Phenolic FR4, Mid Tg	.062" Thick
X	Halogen Free FR4, Filled, Dicy, Mid Tg	.062" Thick
Y	Filled Phenolic FR4, Mid Tg	.062" Thick
Z	Filled Phenolic FR4, Mid Tg	.062" Thick
AA	Filled Phenolic FR4, Mid Tg	.062" Thick
BB	Filled Phenolic FR4, Low Tg	.062" Thick
CC	Unfilled Phenolic FR4, Hi Tg	.116" Thick
DD	Filled Phenolic FR4, Hi Tg	.116" Thick

All 20 layer
High Tg

20 Layer "standard" stackup - .116" thick, 58% Resin Content
20 Layer High Resin stackup - .118" thick, 69% Resin Content
6 Layer .062 thick stackup – 48% Resin Content
6 Layer .116" thick stackup – 45% Resin Content

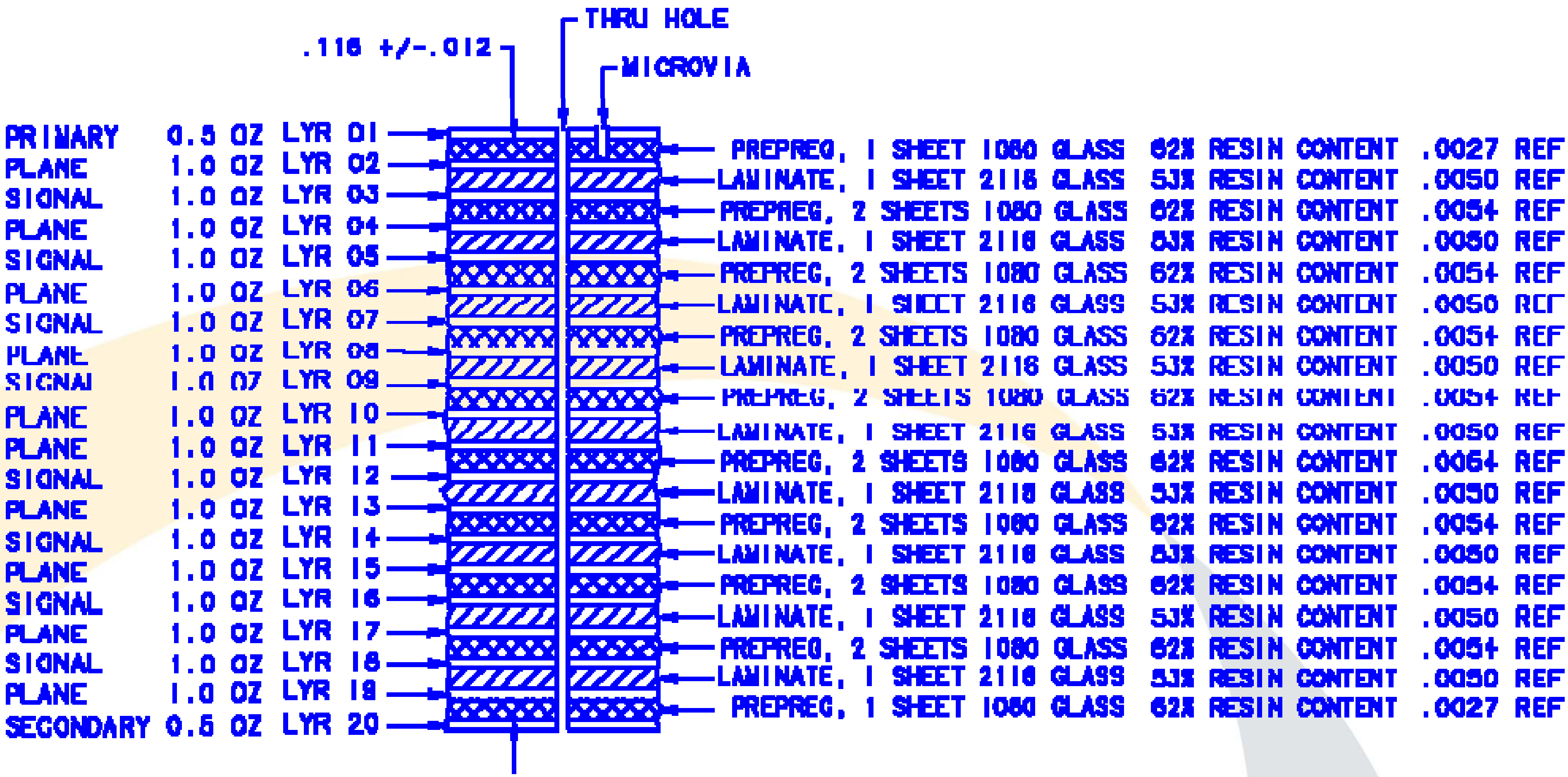
Test Vehicles



4 Sections:

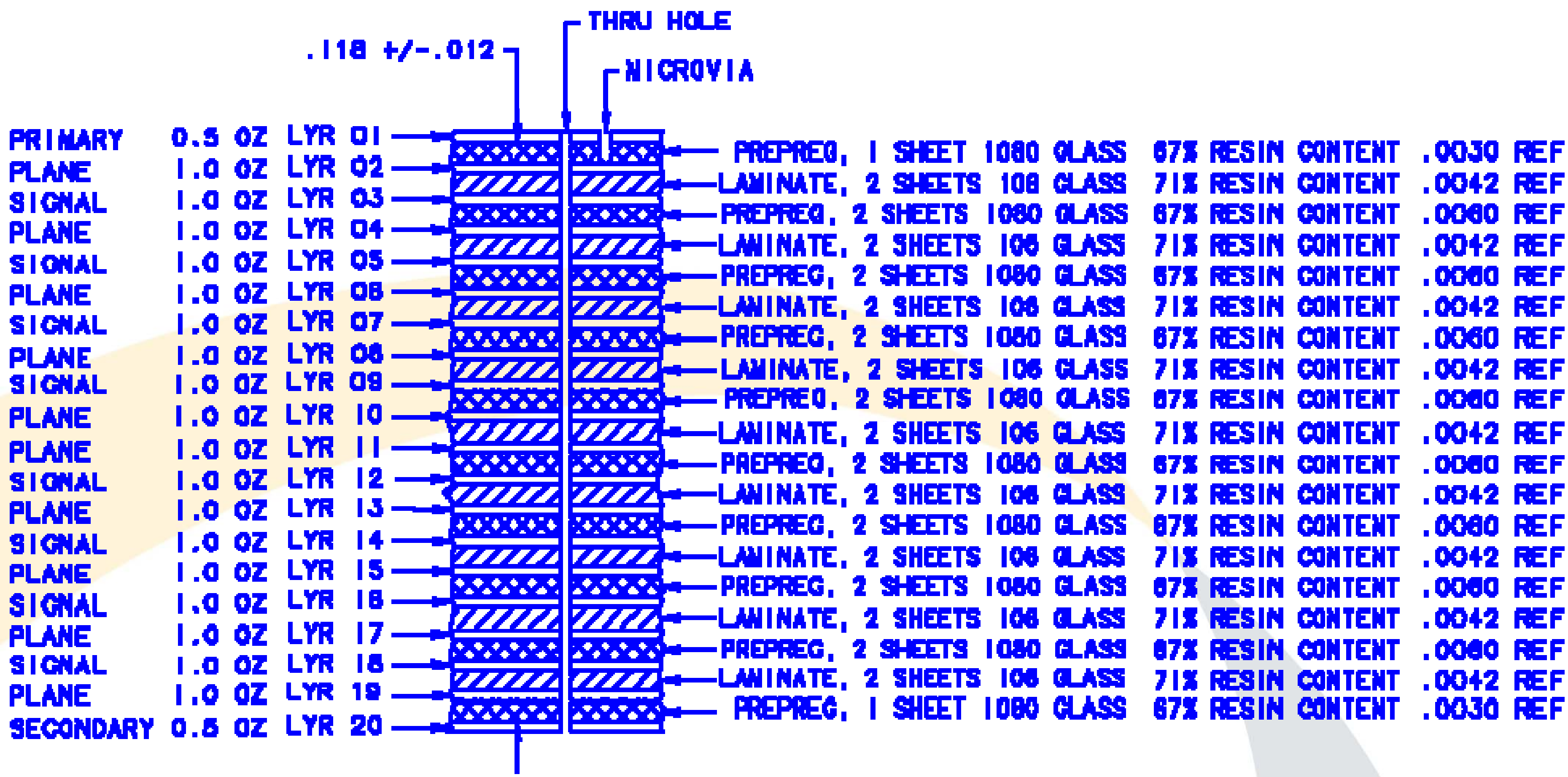
Air-Air, IST, CAF and Electrical

Stackup A, 20 Layer, 58% Resin Content



2 SECTION A–A STACKUP A

Stackup B, 20 Layer, 69% Resin Content



2 SECTION A-A STACKUP B

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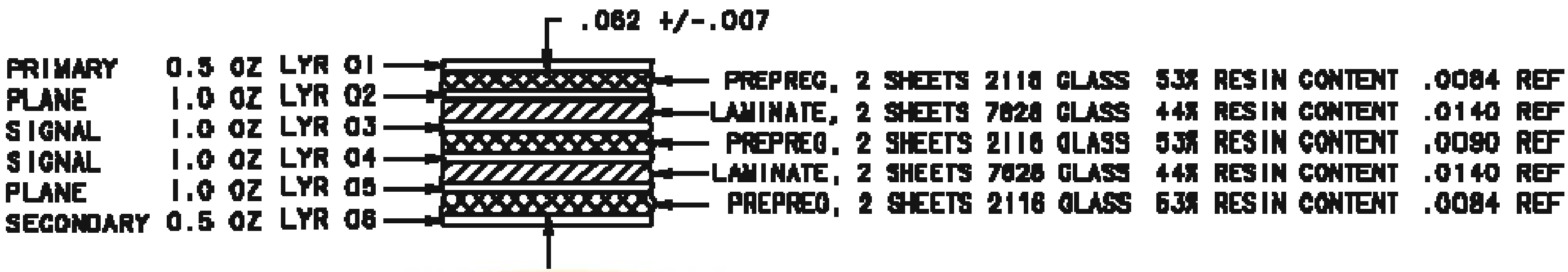
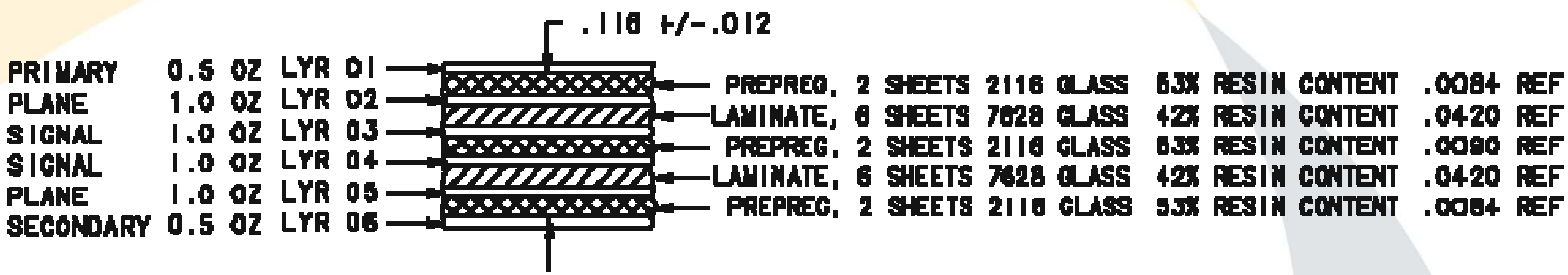
Stackups – 6 layer



2 SECTION A-A STACKUP A
SHEET 2



2 SECTION A-A STACKUP B

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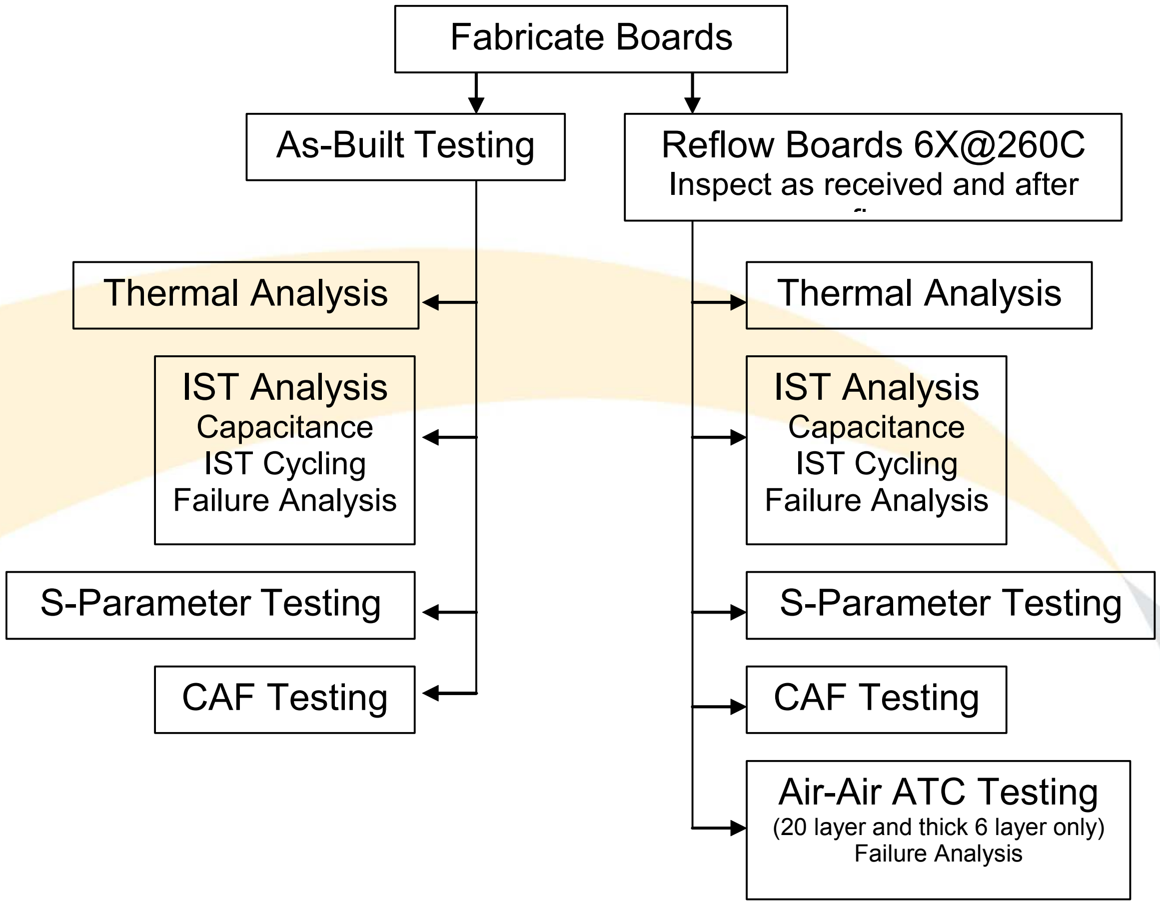
Flow Chart of Testing



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Typical Profile – 6X Reflow

General | Description | Optimization

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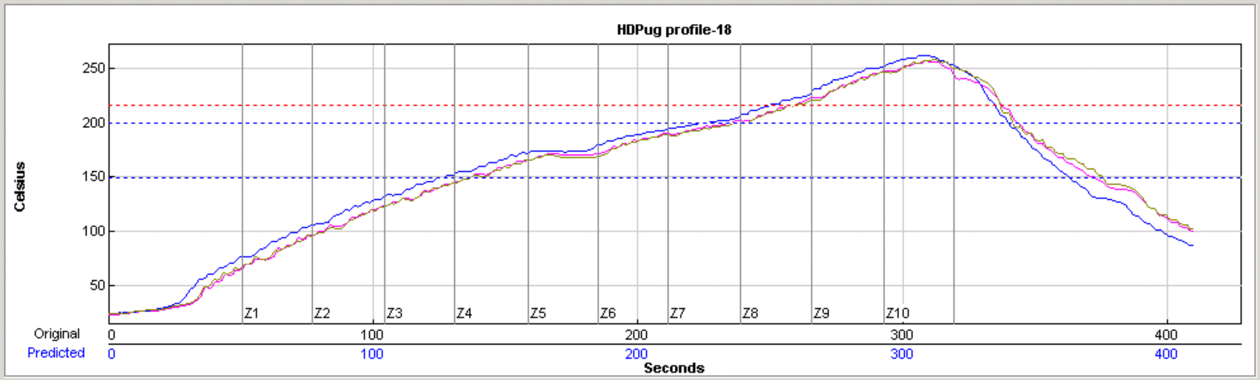
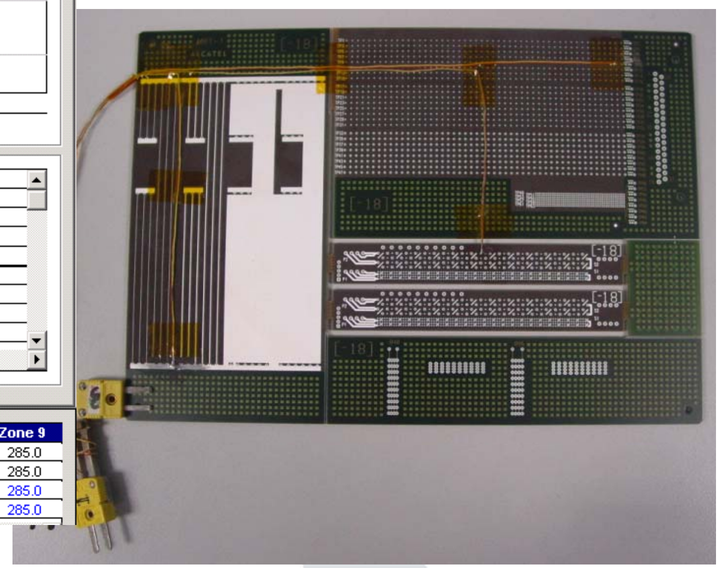


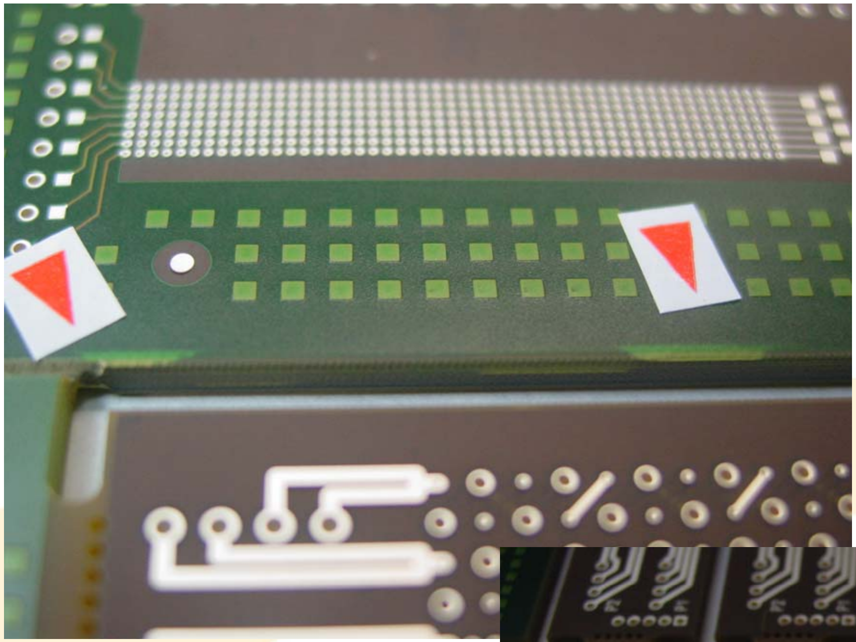
TCs	Max Rising Slope		Soak Time 150-200C		Reflow Time /217C		Peak Temp	
1	1.6	78%	96.5	22%	80.0	34%	257.8	-79%
2	1.6	81%	98.2	27%	84.6	64%	262.7	42%
3	1.6	78%	99.3	31%	77.1	14%	259.0	-51%
Delta	0.07		2.79		7.52		4.84	
P.1	1.6	78%	96.5	22%	80.0	34%	257.8	-79%
P.2	1.6	81%	98.2	27%	84.6	64%	262.7	42%
P.3	1.6	78%	99.3	31%	77.1	14%	259.0	-51%
Delta	0.07		2.79		7.52		4.84	

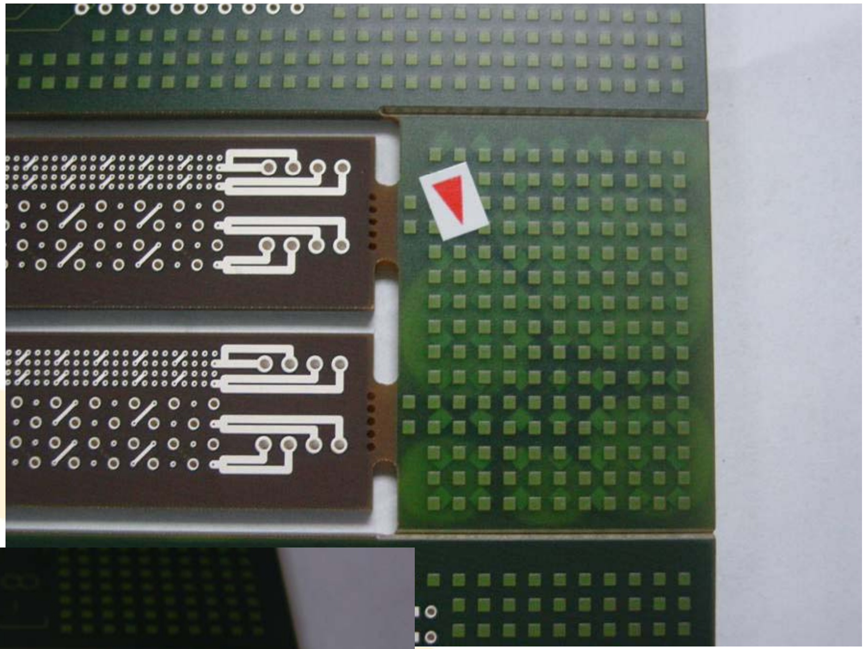
	P.W.I.	inch/min	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9
Original Top	81%	30.0	110.0	135.0	160.0	180.0	200.0	215.0	215.0	250.0	285.0
Original Bottom			110.0	135.0	160.0	180.0	200.0	215.0	215.0	250.0	285.0
Predicted Top	81%	30.0	110.0	135.0	160.0	180.0	200.0	215.0	215.0	250.0	285.0
Predicted Bottom			110.0	135.0	160.0	180.0	200.0	215.0	215.0	250.0	285.0

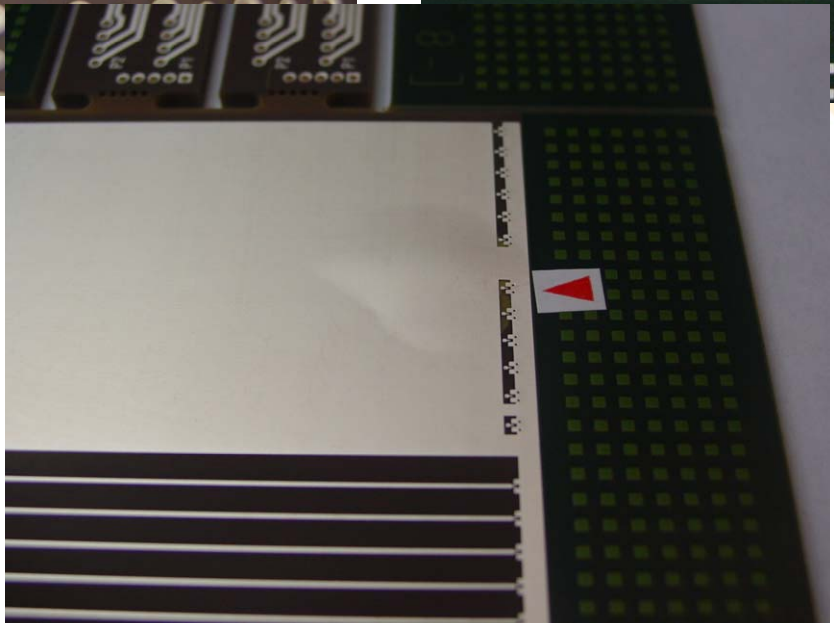


Target 260ºC + 5/-0
Actual achieved (all stackups) 260º+/-3

Some Materials showed Visible Defects after Reflow







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Summary of Visual Inspection

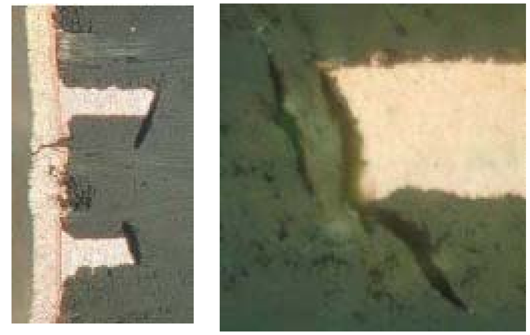
20 Layer Constructions			
Dash Number	Material	Stackup (A=Low Resin Content, B=High Resin Content)	Results
A	Baseline Non-Filled Phenolic FR4	A	Blistering/delamination after 4X reflow. Minor discoloration
B	Baseline Filled Phenolic FR4	A	No defects
C	Filled Proprietary Resin FR4	A	No defects
D	Filled Phenolic FR4	A	No defects other than incoming
E	Unfilled Phenolic FR4	A	Minor blistering/delamination after 5X reflow
F	Unfilled Phenolic FR4	A	Minor blistering/delamination after 5X reflow
G	Filled Phenolic FR4	A	No defects
H	Unfilled Phenolic FR4	A	Major delamination and blistering after only 2X reflow
I	Filled Phenolic FR4	A	No defects
J	Filled Phenolic FR4	A	Minor blistering/delamination after 3X reflow
K	Unfilled Phenolic FR4	A	No defects
L	Hi-Speed Material	A	No defects
M	Hi-Speed Material	A	No defects
N	Hi-Speed Material	A	No defects other than incoming
P	Unfilled Phenolic FR4	B	Minor blistering/delamination after 6X reflow
Q	Filled Phenolic FR4	B	No defects
R	Unfilled Phenolic FR4	B	Major delamination and blistering after 6X reflow
S	Filled Phenolic FR4	B	No defects other than incoming

Summary of Visual Inspection

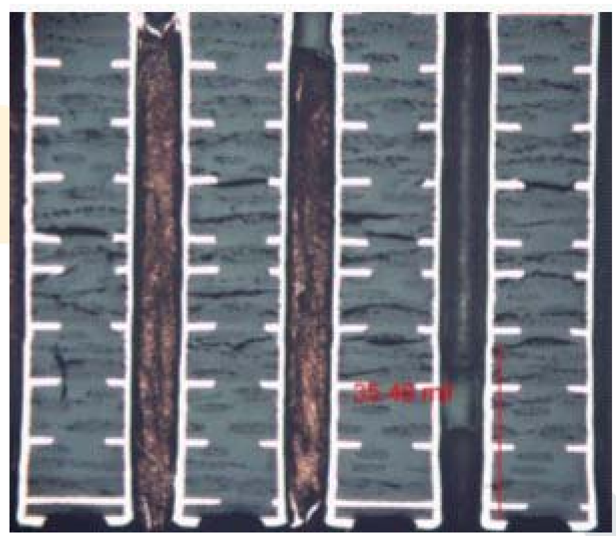
6 Layer Constructions			
Dash Number	**Material**	**Stackup (A=.062" Thick, B=.116" Thick)**	**Results**
T	Halogen Free FR4, Filled, Dicy, Mid Tg	A	No defects
U	Halogen Free FR4, Filled, Dicy, Hi Tg	A	No defects
V	Halogen Free FR4, Filled, Dicy, Hi Tg	A	No defects
W	Filled Phenolic FR4, Mid Tg	A	No defects
X	Halogen Free FR4, Filled, Dicy, Mid Tg	A	No defects
Y	Filled Phenolic FR4, Mid Tg	A	No defects. Discoloration.
Z	Filled Phenolic FR4, Mid Tg	A	No defects. Discoloration.
AA	Filled Phenolic FR4, Mid Tg	A	Severe blistering and delamination after only 1X reflow.
BB	Filled Phenolic FR4, Low Tg	A	No defects. Discoloration.
CC	Unfilled Phenolic FR4, Hi Tg	B	No defects
DD	Filled Phenolic FR4, Hi Tg	B	No defects

Internal Material Degradation

Code	Stackup	Via Pitch		
		0.100 inch	1mm	0.8mm
A	20L Standard	N	L	L
B	20L Standard	N	EC	L
C	20L Standard	N	L	L
D	20L Standard	N	EC	L
E	20L Standard	N	N	L
F	20L Standard	N	EC	L
G	20L Standard	N	EC	L
H	20L Standard	N	L	L
I	20L Standard	N	L	L
J	20L Standard	N	N	L
K	20L Standard	N	L	L
L	20L Standard	L	L	L
M	20L Standard	N	L	L
N	20L Standard	N	N	N
P	20L High Resin	N	L	L
Q	20L High Resin	N	L	L
R	20L High Resin	N	L	L
S	20L High Resin	N	L	L
T	6L .062" Thick	NA	N	L
U	6L .062" Thick	NA	N	N
V	6L .062" Thick	NA	N	N
W	6L .062" Thick	NA	N	EC
X	6L .062" Thick	NA	N	EC
Y	6L .062" Thick	NA	N	N
Z	6L .062" Thick	NA	N	N
AA	6L .062" Thick	NA	N	N
BB	6L .062" Thick	NA	N	EC
CC	6L .116" Thick	N	N	L
DD	6L .116" Thick	N	N	L
Key:				
N	No Internal Defect			
EC	Eyebrow Crack			
L	Longtitudinal Crack			



Eyebrow Cracking



Longitudinal Cracks

Key Messages:

Visual Inspection DOES NOT find these cracks

Via Pitch makes a Big difference

Thickness Makes a Big difference

Resin Content – more to follow

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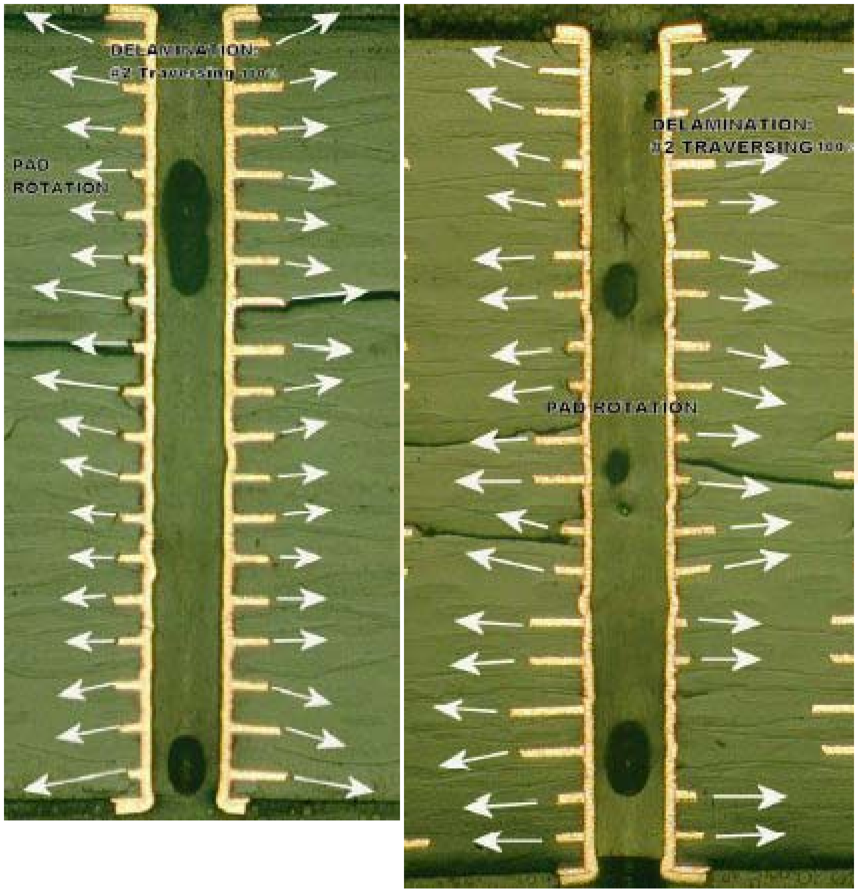
Laminate Integrity Summary



- Performance and Reliability Risks of Internal Delamination/Material Degradation
  - Possible Pathways for CAF
  - Possible Loss of Dielectric Strength
  - Possible Changes in Localized Electrical Properties
  - Reduced Via Integrity
  - False Positive Via Reliability
  - False Positive CAF test performance

Drivers of Reflow-induced Laminate Crack Formation / Propagation

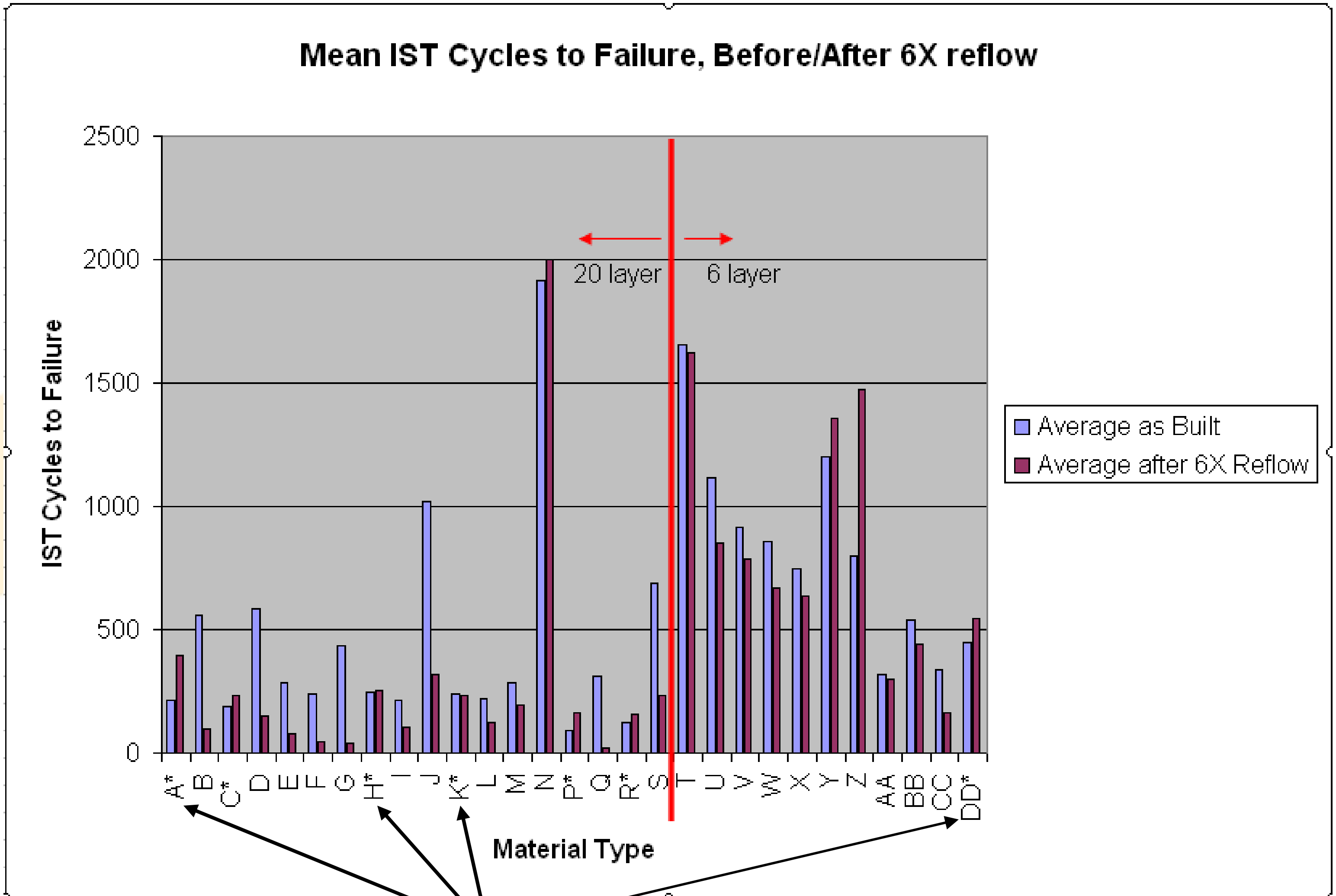
- See the paper for details
  - Moisture/volatiles
  - Micro-fracturing
  - Material Expansion-Stresses
  - Constraints of vias
  - Heat transfer and Moisture Escape paths

STRESS!

Possible Corrective Actions

- Reduction of entrapped moisture within the laminate
- Use of materials with stronger interfaces
- Use of resins with higher fracture toughness
- Also – Use of materials with lower Z-Axis CTE – reduces stresses from expansion

IST Results



* Indicates materials that had indication of delamination in IST cycling (false positives) after reflow

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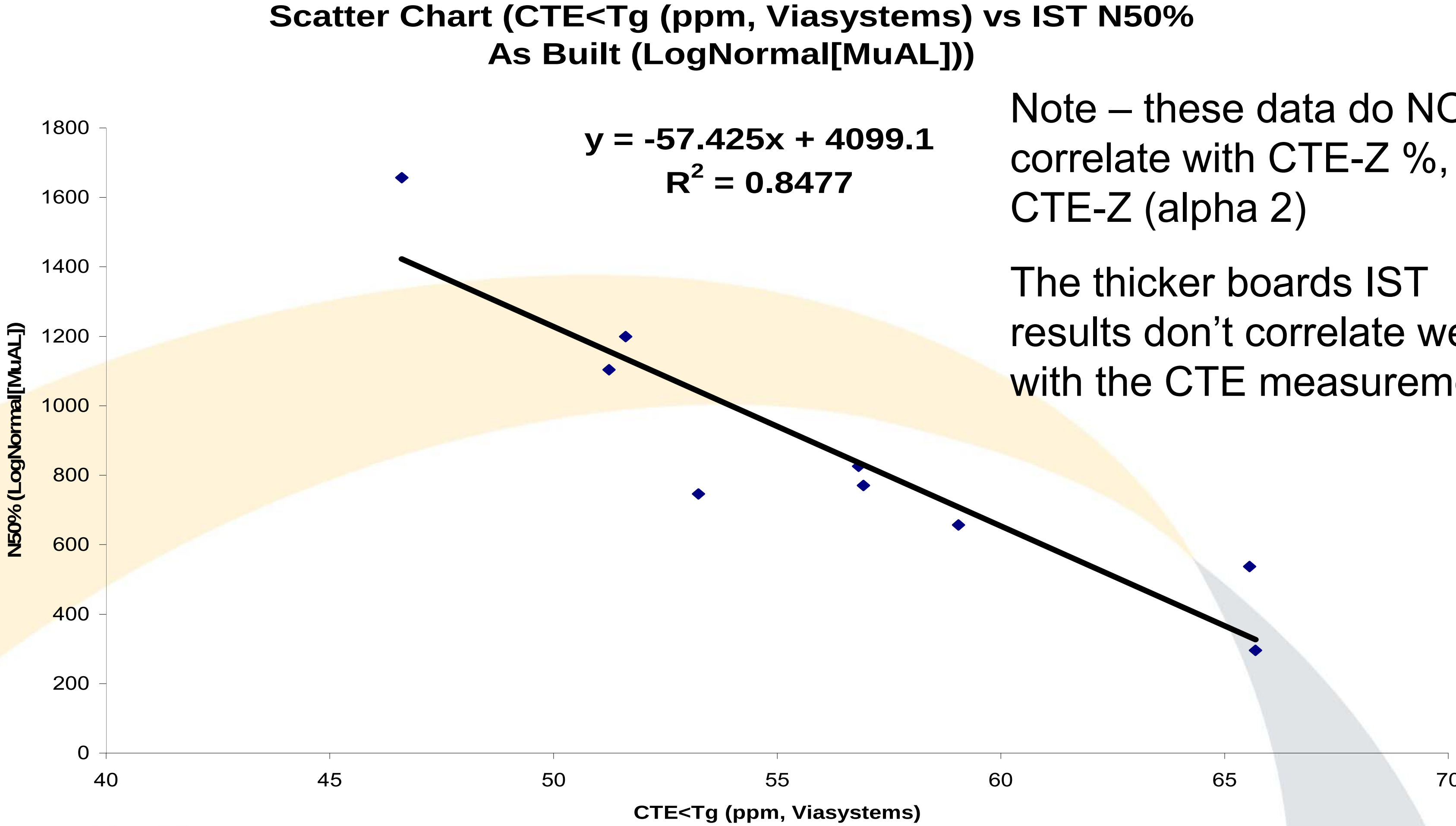
IST Results compared to CTE-Z (alpha 1), as Measured on the boards, 6 layer, .062 constructions only



Note – these data do NOT correlate with CTE-Z %, or CTE-Z (alpha 2)

The thicker boards IST results don't correlate well with the CTE measurements

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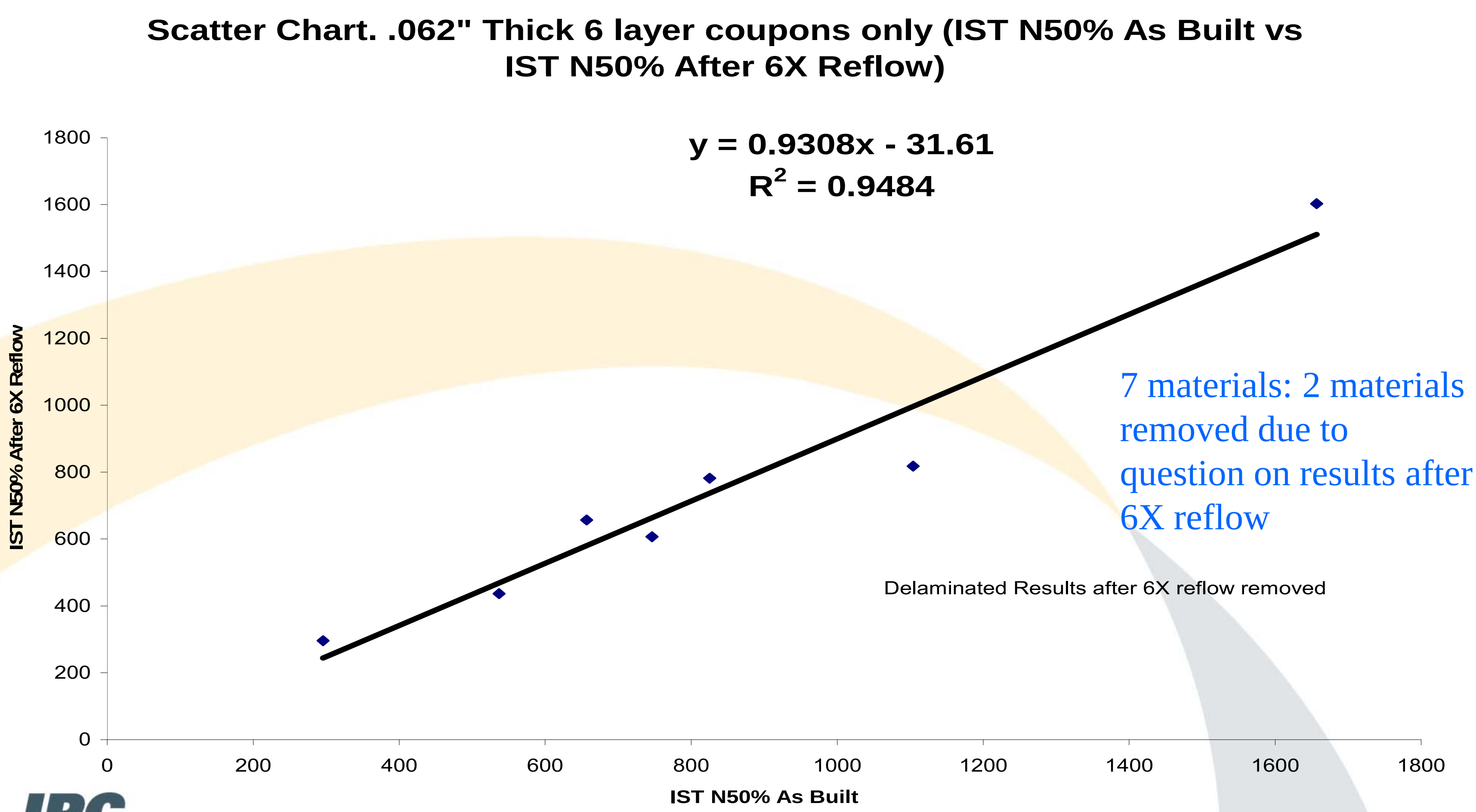
IST Before and After 6X Reflow:
before reflow and after reflow correlate very well



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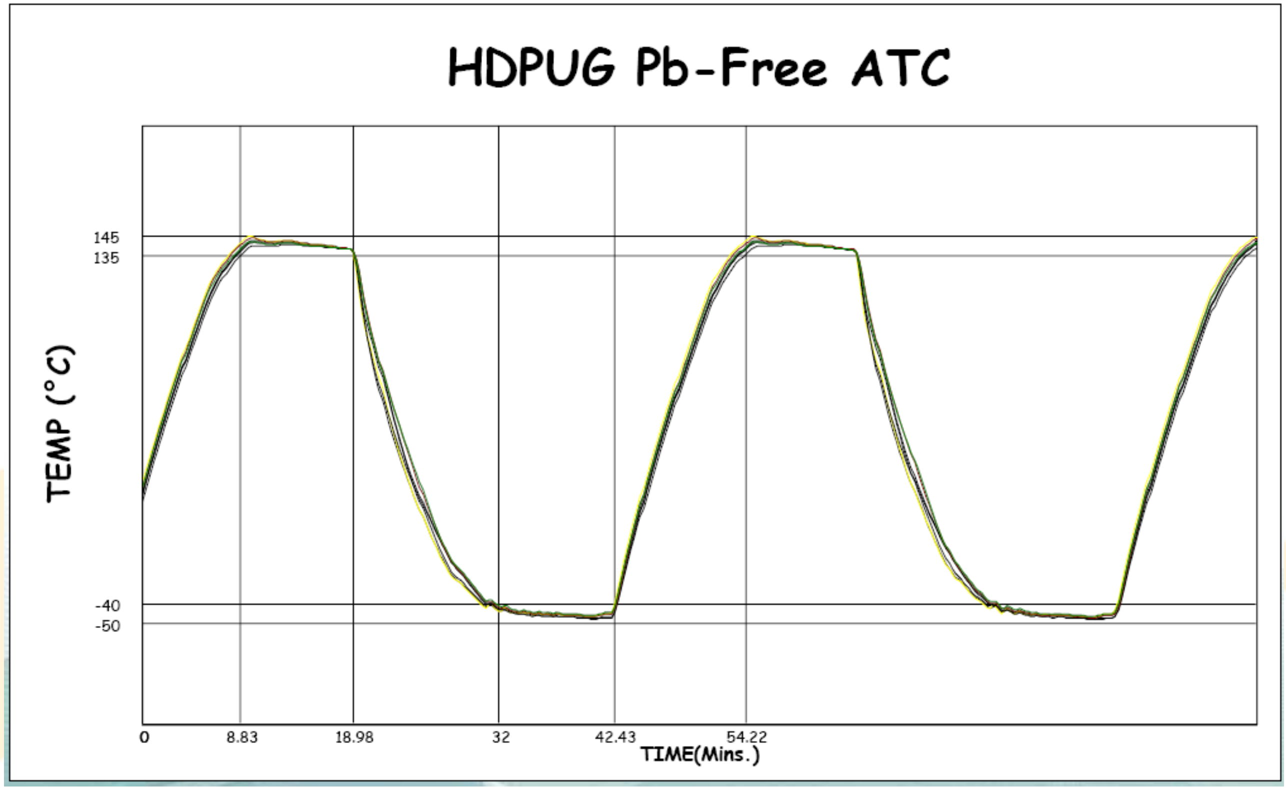
ATC Profile



Max. Temp: 145° C

Min. Temp: -48° C

High Temp Dwell: 10.15 minutes

Low Temp Dwell: 10.43 minutes

High to Low Ramp: 13.02 minutes

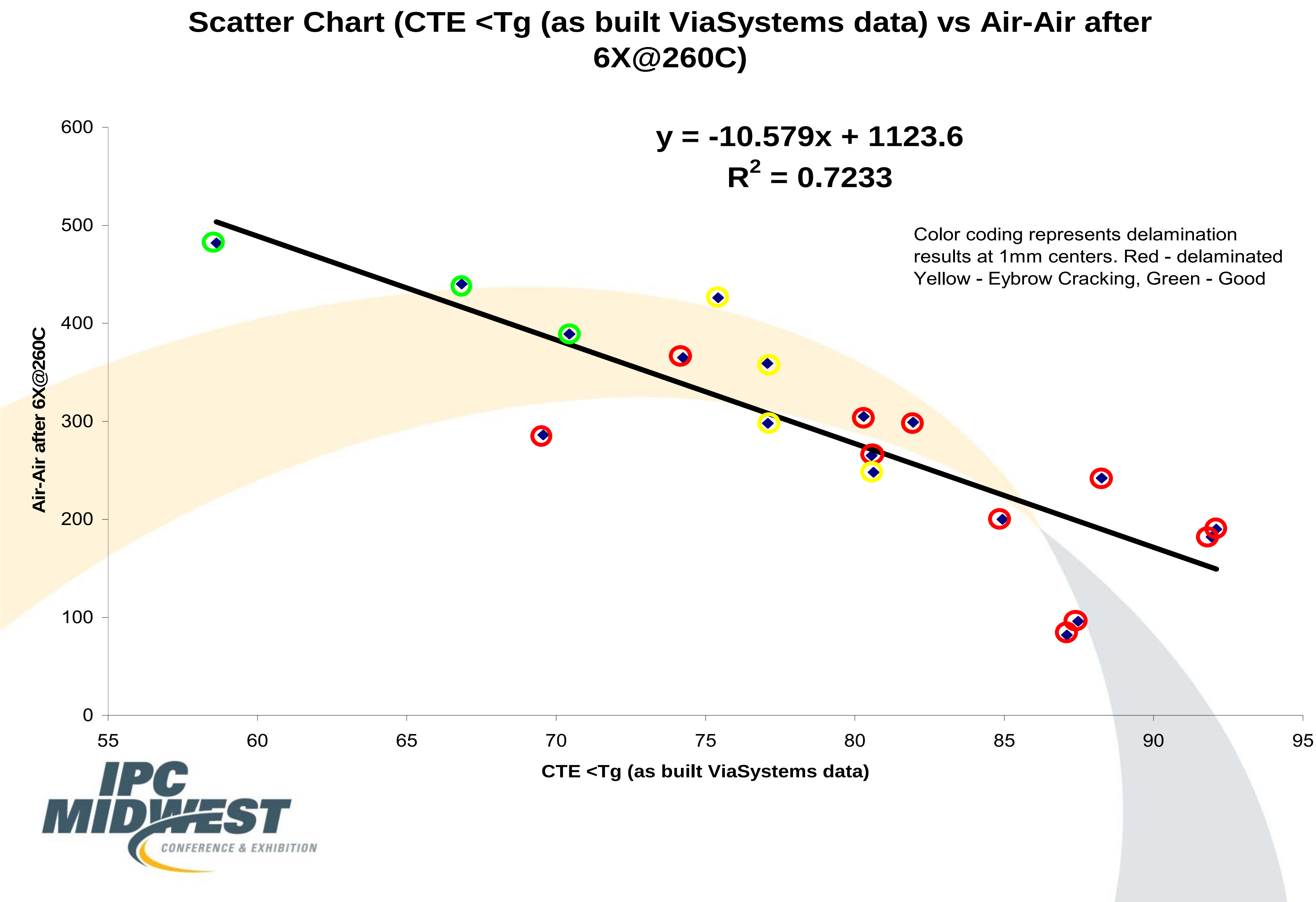
Low to High Ramp: 11.79 minutes

Cycle Rate: 45.39 min / cycle

Frequency: 1.32 cycles / hour

-40 to + 135C Thermal Cycle

ATC results correlated to Actual CTE



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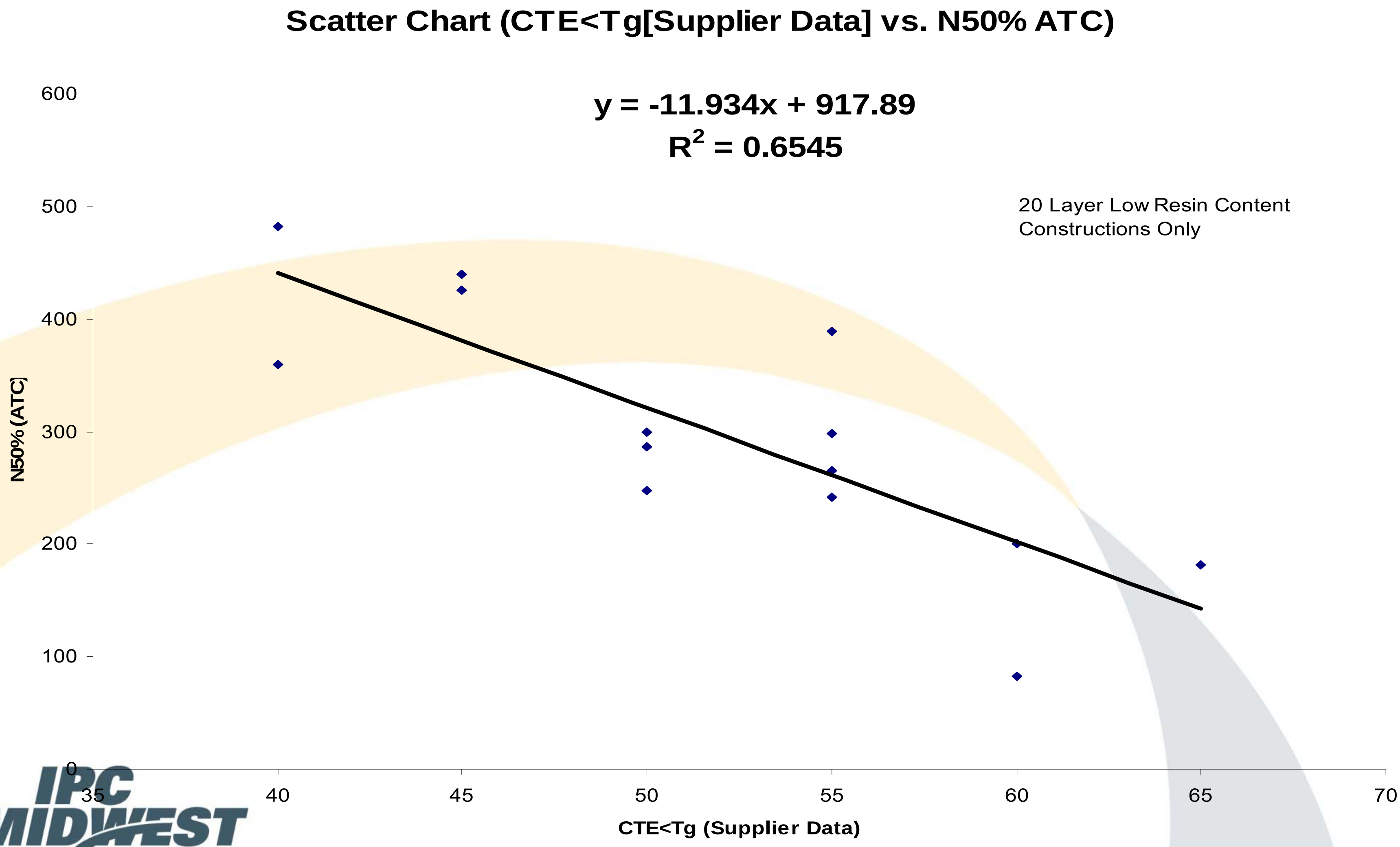
Supplier Data Sheet CTE's don't track so well



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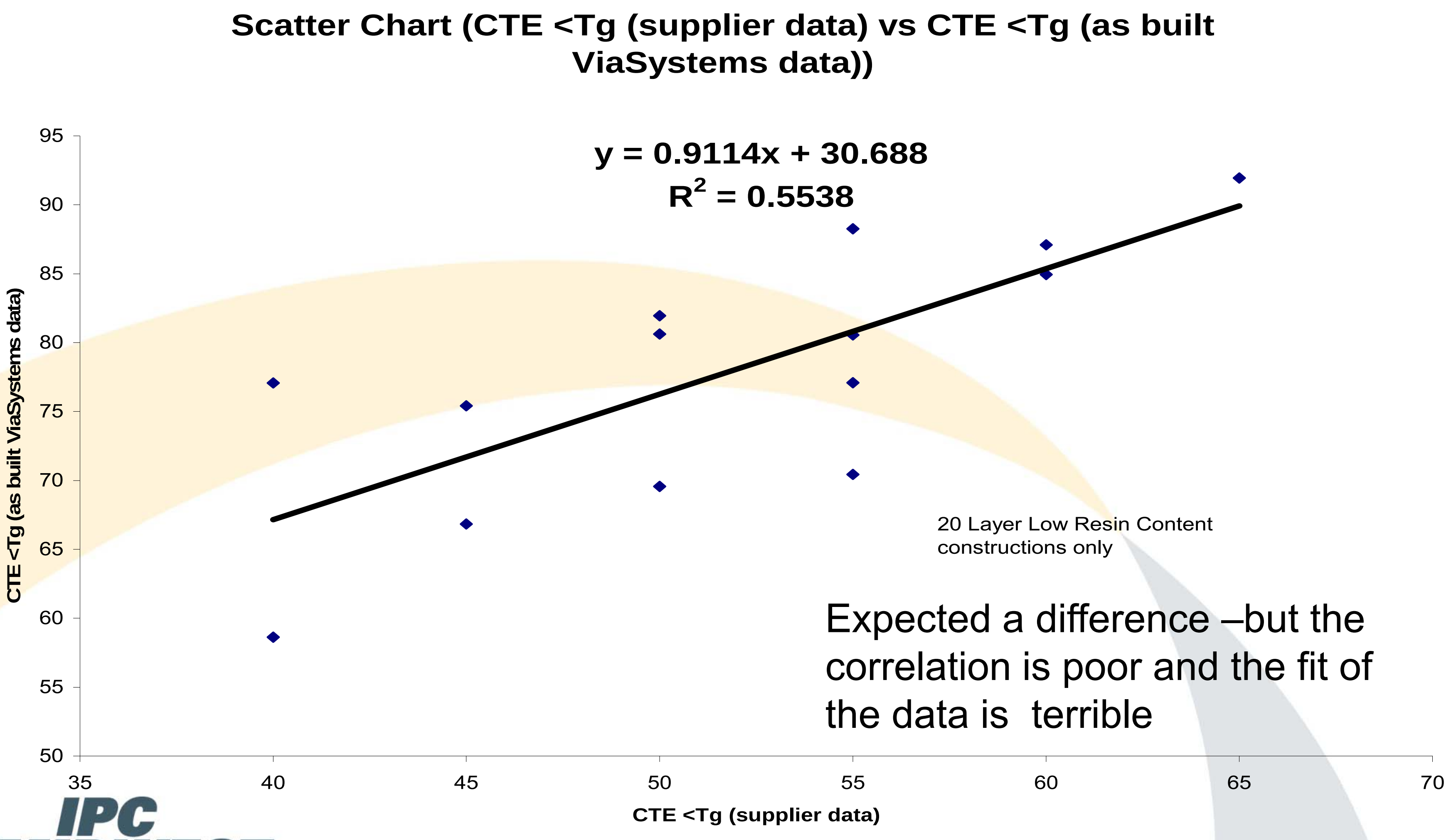
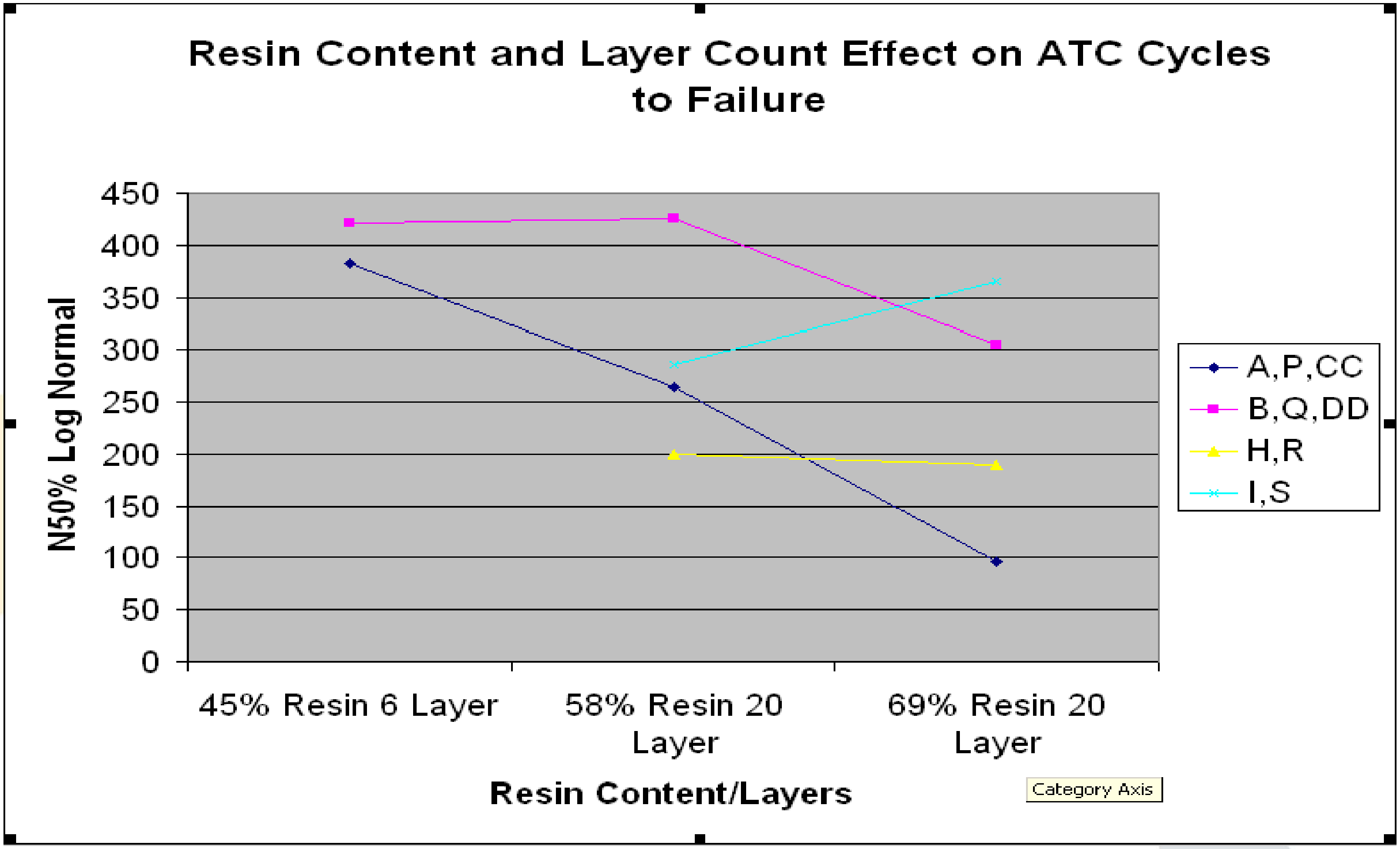
Measured CTE-Z vs. Supplier Data Sheet CTE-Z

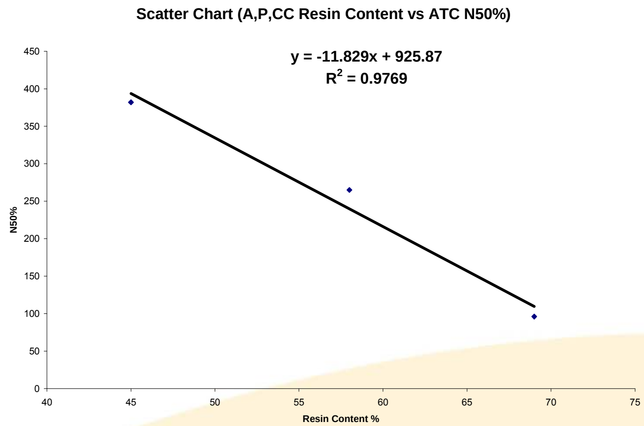


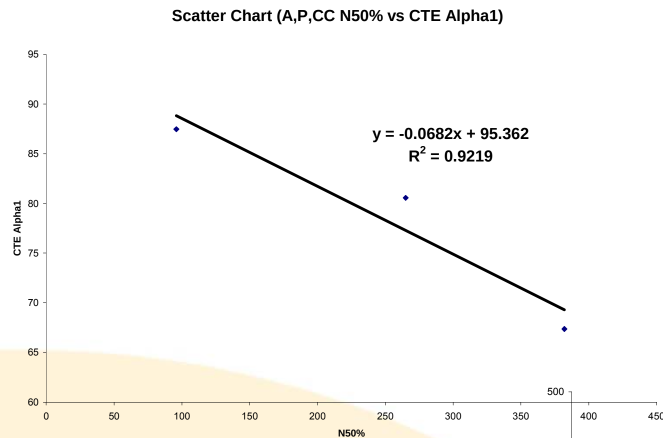
Expected a difference –but the correlation is poor and the fit of the data is terrible

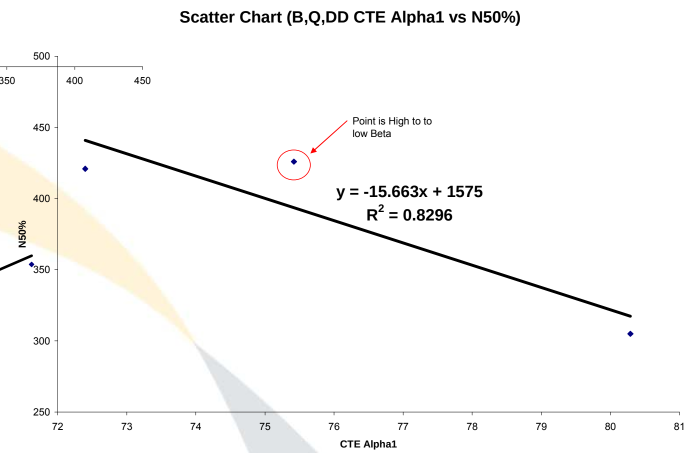
Resin Content and Layer Count Effect on ATC

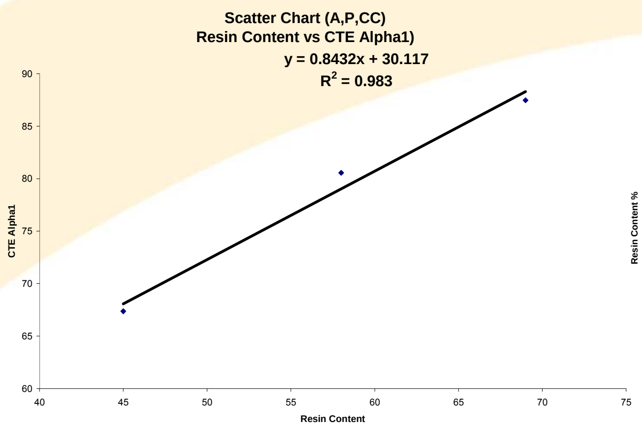


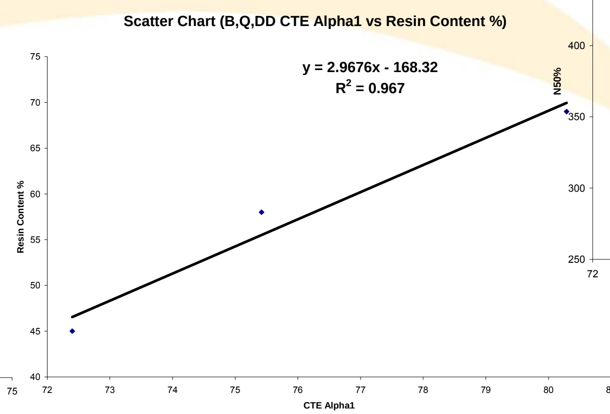
Z-Axis CTE or Layers?







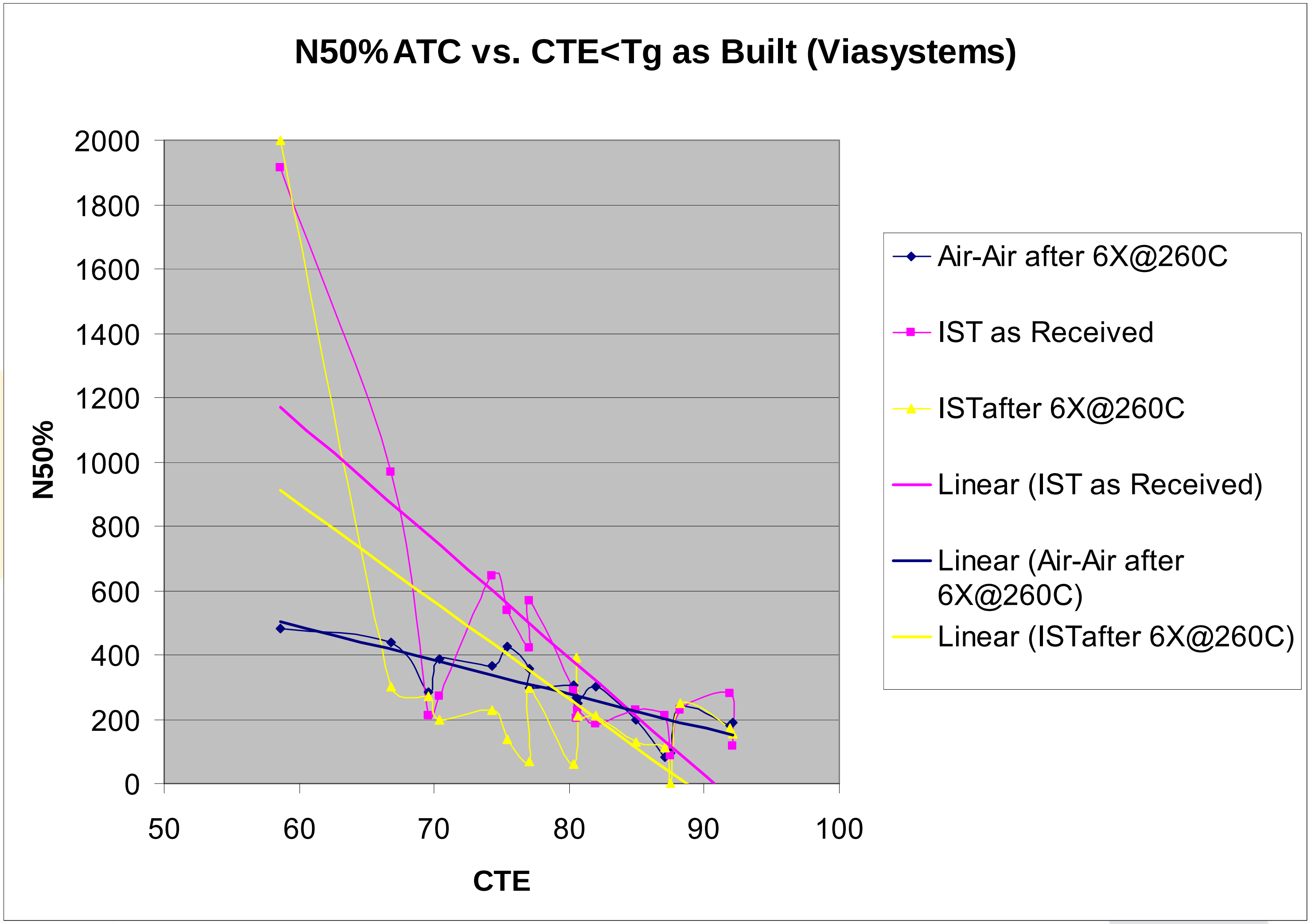




Primary effect is Resin Content – directly linked to Z-CTE

Layer count is a secondary affect

IST and ATC vs. CTE (20L)



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IST vs. ATC – Differences

- First – comparison must be same constructions (graph on previous page is) – these are all 20 layer, 58% RC – but correlation is poor
  - R^2 between the ATC and IST results is only .43 and .47 for as built and after 6X IST respectively (plots not shown), and the fit of the data is poor.
- Potential Causes
  - Design Differences – Highly Unlikely to be the cause
    - ATC – 10 internal pads, IST – 18 internal pads
      - Will affect results – but NOT correlation
    - ATC – Pitch 100 mils, IST – pitch 1mm
      - After eliminating delaminated materials – no major effect expected
  - Test Differences
    - IST – resistive heating of traces and vias, 25-150ºC and fast, ATC – 40 to +135ºC, 45 minute cycle
      - Uniform temperatures in ATC
      - IST heating mostly from traces – in outer 6 (3 top/3 bottom) layers – not likely to be uniform temperatures at extremes - .013" on each side of the .116" thick
      - Explains the slope difference – but NOT the lack of correlation
    - Sensitivity to copper variations/thin copper
      - Both tests are sensitive to this – but IST uses this as part of the resistive heating – as such the is more sensitivity to the copper thickness than ATC (localized heating effect)
      - Combined with sample size (ATC=32, IST=6) – this explains at least part of this
- No ATC done on thin 6 layer – correlation would be expected to be better
- Even if no correlation - IST remains a very valuable tool, and an excellent process control tool.
  - For given construction with good process control IST results will parallel ATC result
  - However - issues noted above make it difficult to use IST to predict long term field reliability performance when this is a critical factor for the application

Failure Analysis – ATC and IST

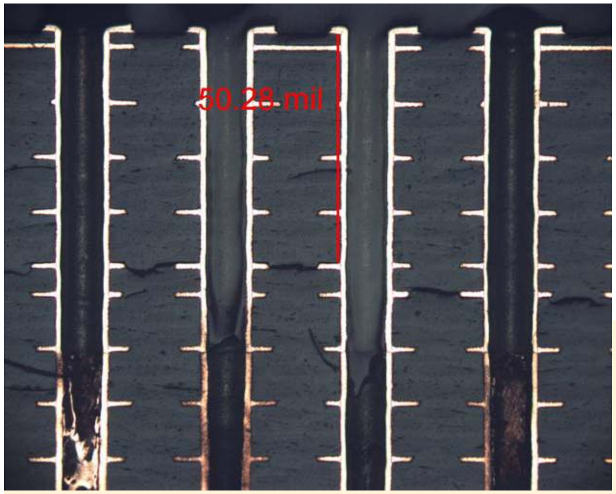
On the 20 layer and thick 6 layer constructions:

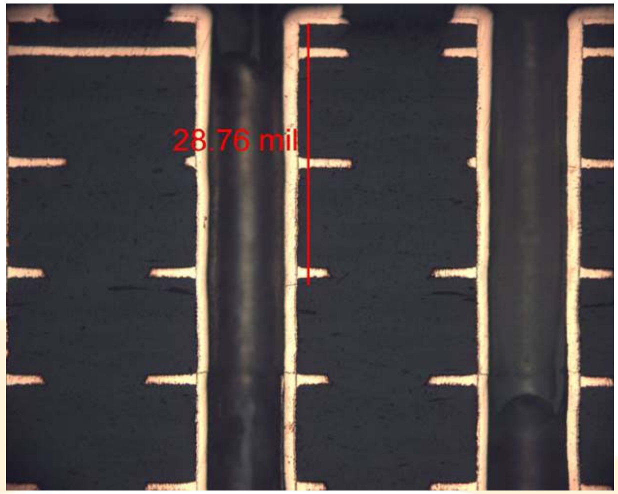
- For the 100 mil pitch samples, only material L has delamination after ATC.
- For the 0.8mm pitch samples, only material N did not delaminate after ATC.
- All failures are barrel cracks. There was no evidence of any interconnect separation or foil cracking in any of the samples.
- At 0.8mm pitch, for all materials except material N, there are multiple copper cracks and delamination.
- The location of the delamination appears not to be relatable and occurs in multiple places.
- For the samples with delamination, the location of the copper barrel cracks appears to be independent of the delamination location, for those samples that have delamination.
- The locations of the cracks in the 100 mil pitch and in the 0.8mm pitch samples may or may not be relatable. Further statistical analysis would be necessary to determine if a relationship exists.
- At 1mm pitch (IST), 11 of the 20 layer constructions delaminated, including all high resin content constructions. An additional 4 of the 20 layer standard resin content constructions had eyebrow cracking. Three materials at 20 layer standard resin content and the 2 thick 6 layer constructions survived at 1mm pitch with no evidence of any material degradation.

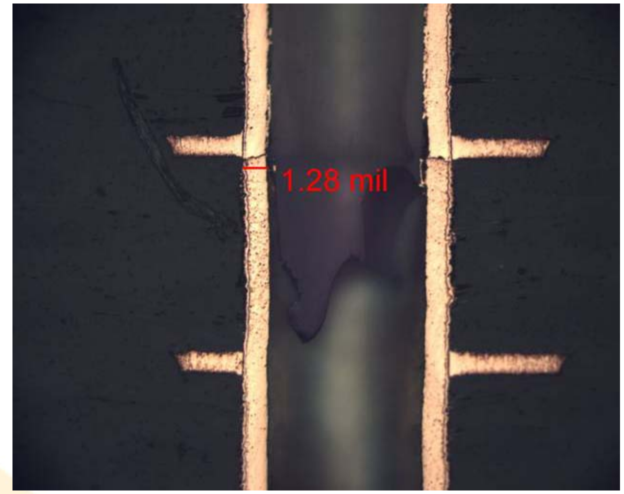
On the thin 6 layer constructions:

- Again, all failures (IST) were barrel cracks
- There was no delamination at 1mm pitch or 100 mil pitch on any of the samples
- At 0.8mm pitch, 1 material, delaminated with no obvious visual blister externally. 1 material, had internal delamination and additionally had blisters visible on the external surfaces of the board.
- 3 materials experienced eyebrow cracking.
- 4 materials did not have any evidence of delamination or material degradation.

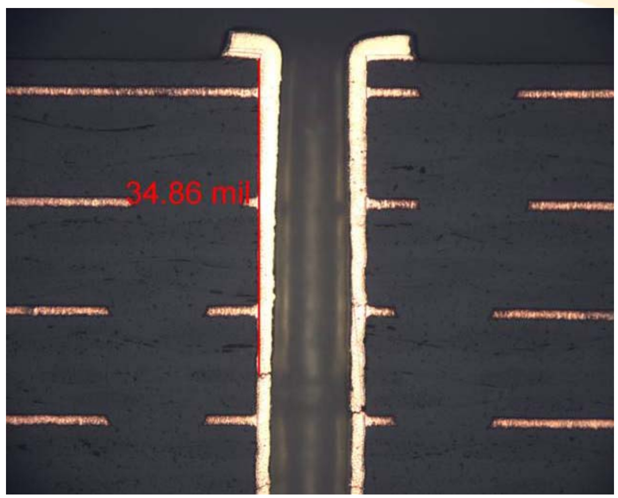
FA – ATC Example (G)

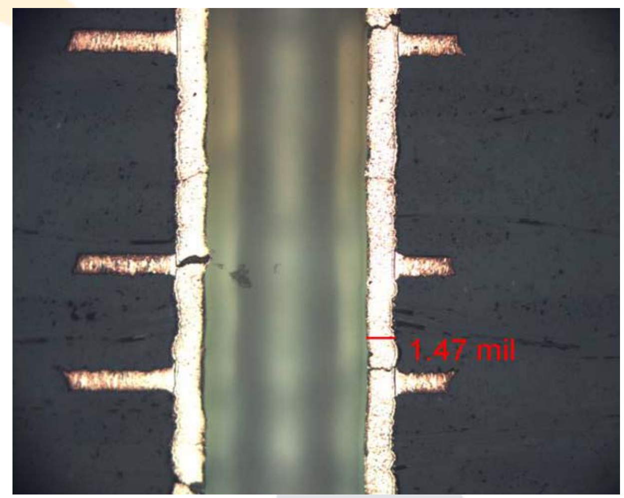




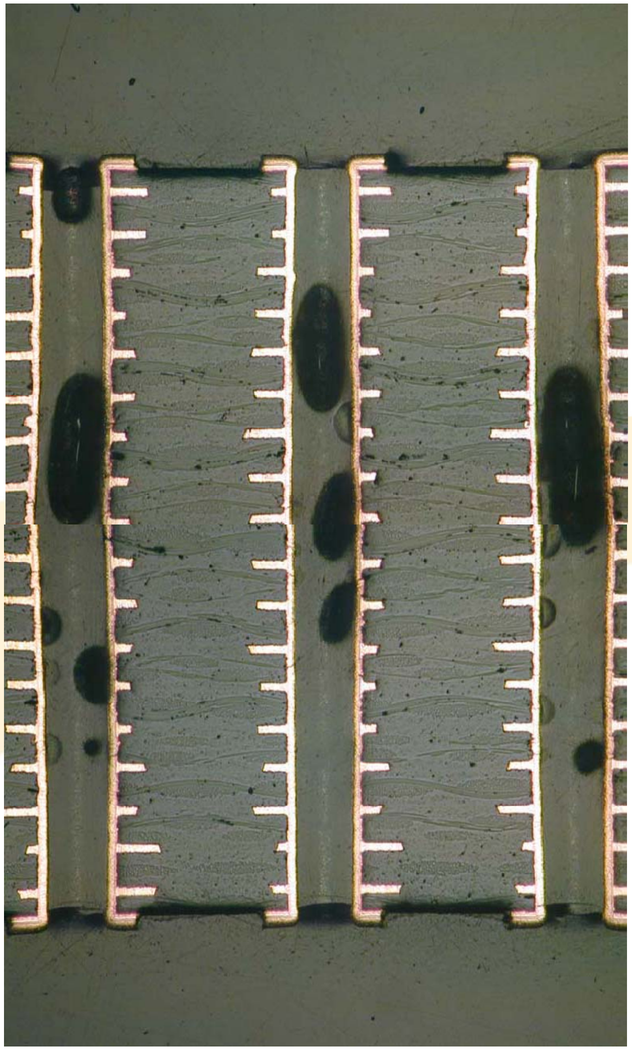


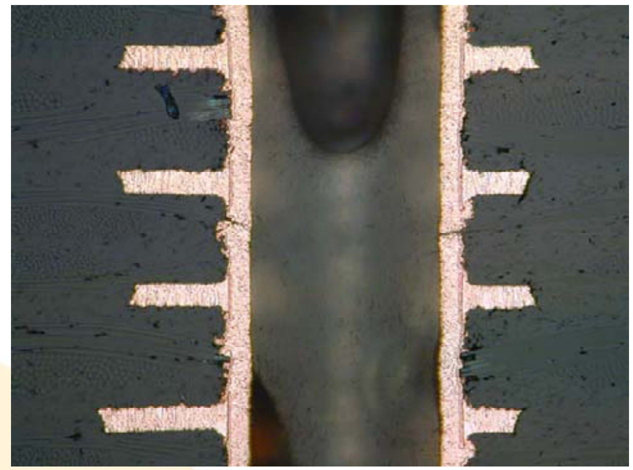
0.8mm pitch (above)
.100” pitch (right)

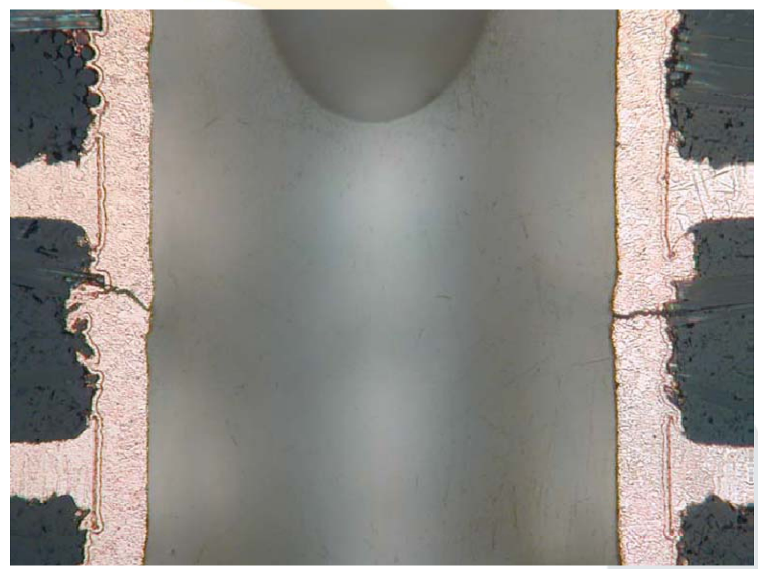




FA – IST As Built Example (G)



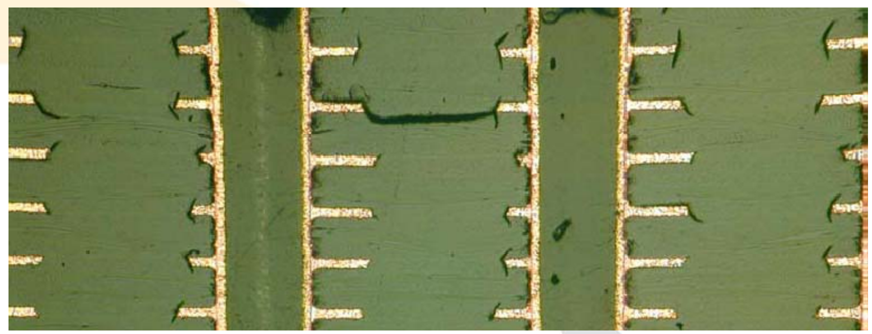




FA for IST after 6X Reflow

- Some materials delaminated at 1.00 mm pitch also
  - Eyebrow cracking also found

Example of Eyebrow Cracking
(D)



Example of Delamination
(I)

Summary (Part 1)

- Understanding, bare board material compatibility with Pb-free assembly and reliability after Pb-free assembly is significantly more complex endeavor than it was for SnPb assembly.
- Board design factors, specifically thickness, resin content, and via pitch play a major role in the assembly survivability and long term reliability.
- Additionally, the complexity of the PCB assembly and the associated required thermal processes and temperatures to achieve proper assembly and rework also play a major role.
- Materials can no longer be specified only by Tg and expected to survive assembly reflow, much less be reliable long term.
- The traditional factors of fabricator quality and plating quality remain as important if not more important than they were with SnPb assembly.
- Specifying other material properties, such at Td, T260, CTE Z, etc. is helpful but also insufficient in specifying materials for Pb-free assembly.
  – A significant issue with this is the lack of correlation between material supplier reported material properties and the actual measured properties of the material on real boards.
  – Improved industry standards are needed to address this issue.
  – As it currently stands, to fully understand the compatibility of materials with Pb-free assembly and their ultimate reliability requires extensive testing, that is time consuming and costly.
- Internal delamination can occur on circuit boards with no visible evidence that it has occurred. Caution by the user is required.

Summary Key Points

- Material supplier claims that a material is Pb-free compatible are insufficient and the material must be evaluated in the application to determine suitability.
- Visual inspection is insufficient to determine material compatibility with Pb-free assembly. At a minimum, crossections are required in the areas of the finest pitch through hole vias to begin to assess the compatibility.
- Thicker boards are more prone to delamination and/or material degradation than thinner boards.
- Moisture content in remaining in materials after fabrication or subsequently absorbed into the laminates likely plays a significant role in assembly Pb-free assembly survivability and associated reliability. Further study is needed in this area.
- The pitch between vias has a major role in Pb-free assembly survivability and ultimately long term reliability. In this testing only one material delaminated at 100 mil centers. Also, on the thick boards, many of the materials delaminated at 1mm centers, and only a single material did not delaminate at 0.8mm pitch. The thinner boards all survived at 1mm pitch centers, but 5 out of 9 materials showed material degradation or delamination at 0.8mm centers.
- High resin content boards have greater Z axis expansion and put more stress on materials.
- CTE–Z (α1) is a driving factor in IST performance and ATC performance and has a significant influence on the ability of materials to survive assembly reflow without delamination and/or material degradation.
- Material supplier reported data on material properties does not translate to material properties on an actual printed circuit board. In the case of CTE-Z, there is not even a good correlation between reported properties and actual properties.
  Industry standards need to address this issue.

Acknowledgements

- This was a massive project that couldn't have been done without a bunch of people supporting this.
- 2 Years worth of work, Thousands of pages of raw data, 200 page formal report, …
- There are MANY people who supported this project – many of who we don't even know their names as they are behind the scenes.

A BIG THANK YOU FOR A VERY SUCCESSFUL PROJECT!

IPC MIDWEST CONFERENCE & EXHIBITION

For More Information

- This project is very extensive and has literally thousands of pages of data associated with it. The complete report is available to HDPUG members*.

*See www.hdpug.org for membership information