MINISTÉRIO DA CIÊNCIA E TECNOLOGIA
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

PCB Effective Thermal Conductivity for Spacecraft Electronic Boxes Thermal Analysis and Design

Rafael Lopes Costa, Valeri Vlassov
rafael.costa@inpe.br, valeri.vlassov@inpe.br
Brazilian National Institute for Space Research (INPE), São José dos Campos-SP, Brazil

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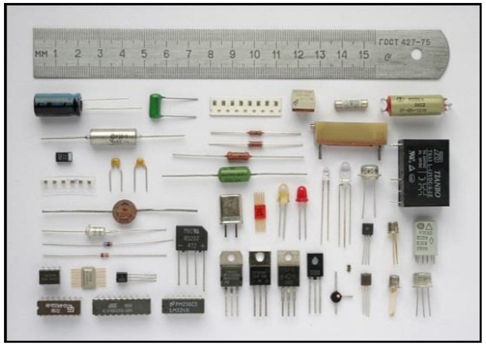
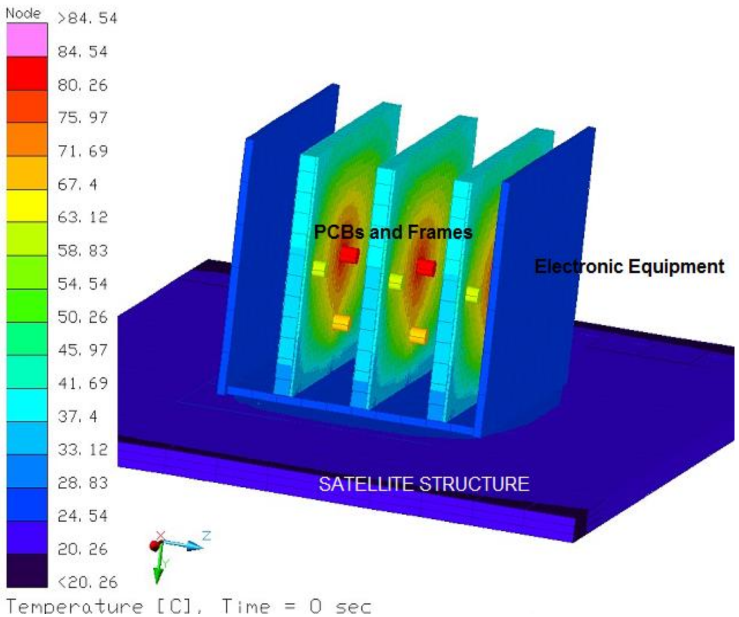
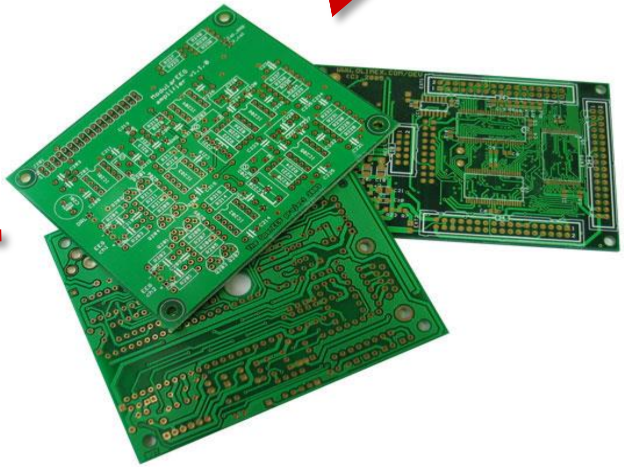
The problem

Electronic components are mounted over Printed Circuit Boards (PCB) which are fixed to built-in frames in the the electronic box thermally connected to the satellite structure (normally honeycomb sandwich panels).



Electronic components

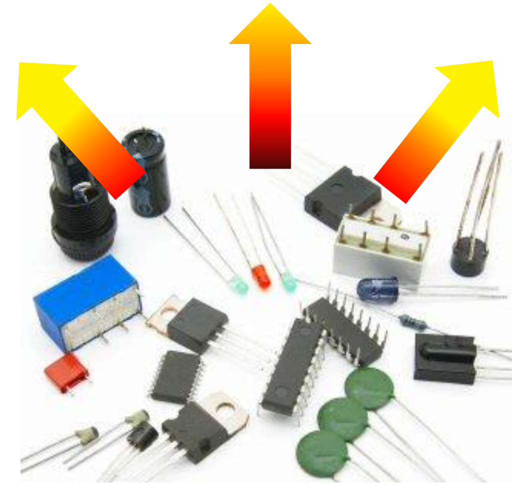




Printed Circuit Boards - PCBs

The problem

Electronic components **generate heat** while operating, which must be dissipated to avoid overheating.



The **components reliability is directly related to its operational temperature**. Thus, thermal analysis and design of electronics shall be accurate for hot conditions. The operational temperature limits should never be exceeded.

$$MTF = Ae^{\left(-\frac{E_a}{kT}\right)}$$

mean time to failure

For **Space applications**, **conduction along the PCB** is the only way to spread the heat from the small areas where the components are mounted, once there is no pressurized air to apply convection based cooling technics.

The effective thermal conductivity (k_{eff})

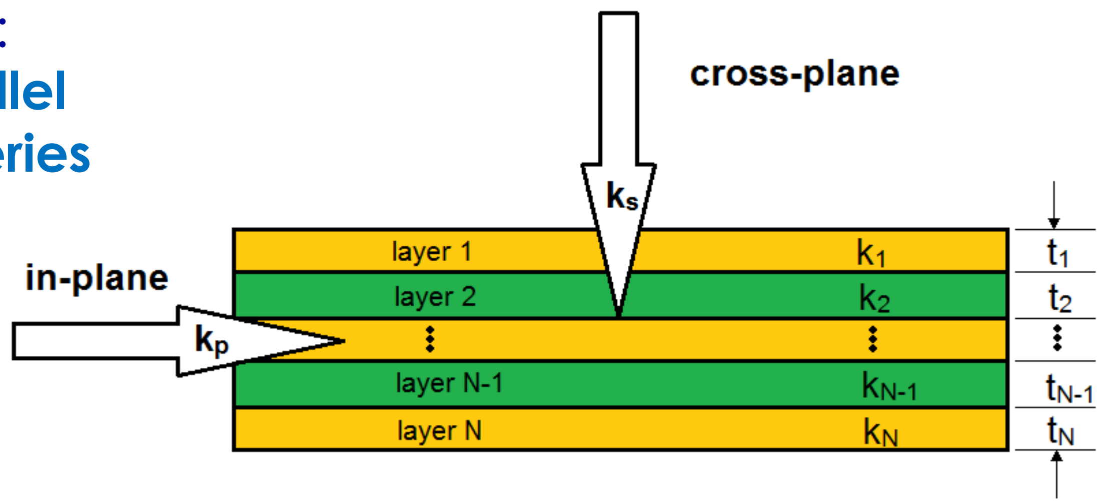
PCBs are basically made of **FR4 (k~0.25 W/mK)** and **copper (k=398 W/mK) lines**. Therefore, the analysis of the thermal conduction is not a trivial task.

In this context, the thermal analysis of the conduction along the PCB is simplified by the use of **effective thermal conductivity (k_{eff})**. Such parameter considers that a single value of thermal conductivity could be applied to a single layer plate (isotropic) and present a similar thermal behavior that a multilayer board does.

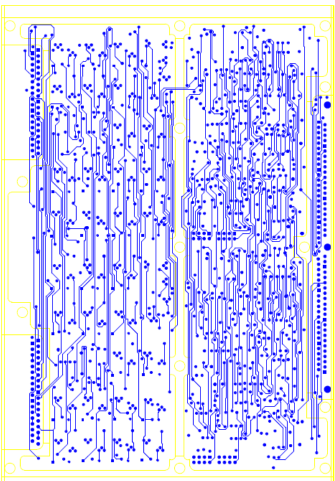
There are some simplified methods used to determine the canonical thermal conductivities:

k_p: in-plane, or **in parallel**

k_s: cross-plane, or **in series**



Canonical simplified analytical methods to calculate the effective thermal conductivities



parallel

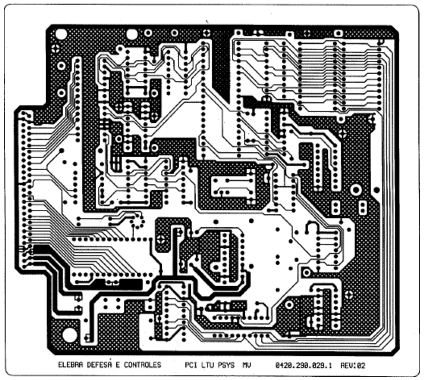
$$k_p = \frac{\sum_{i=1}^{N} k_i f_{ai} t_i}{\sum_{i=1}^{N} t_i}$$

In-plane conductivity

series

$$k_s = \frac{\sum_{i=1}^{N} t_i}{\sum_{i=1}^{N} \frac{t_i}{f_{ai} k_i}}$$

Cross-plane conductivity



Where $\mathbf{f_{ai}}$ is the copper covering percentage factor of the layer (for the FR4 layers, f_{ai} is 1)

Canonical means

$$\bar{k}_{ma} = \frac{(k_s + k_p)}{2}$$

Arithmetic Mean

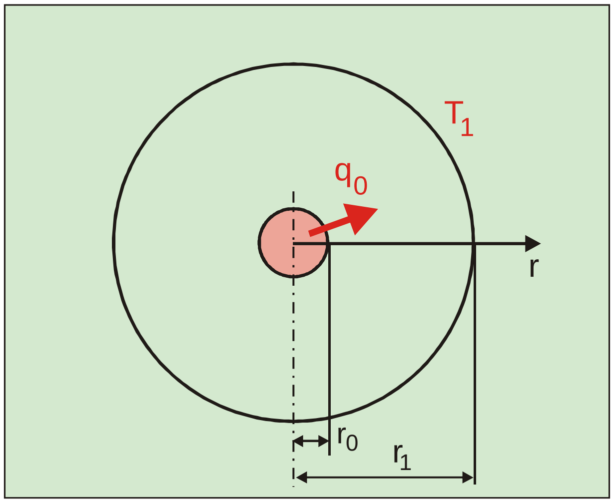
$$\bar{k}_{mg} = \sqrt{k_s k_p}$$

Geometric Mean

$$\bar{k}_{mh} = \frac{2 k_s k_p}{(k_s + k_p)}$$

Harmonic Mean

Effective thermal conductivity uncertainty effect



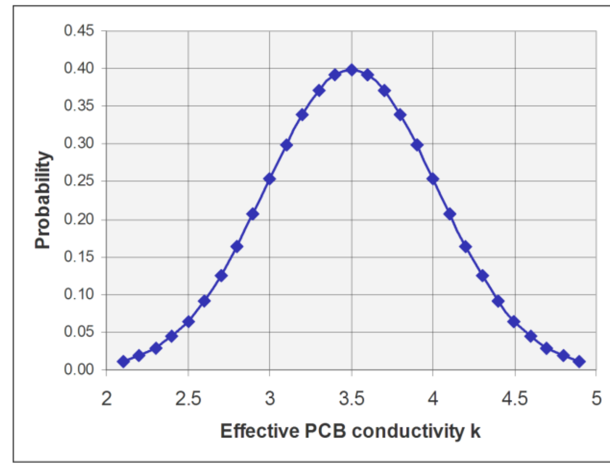
$$T(r) = T_0 + \frac{Q}{4\pi k\delta}\left(1 - \left(\frac{r}{r_0}\right)^2\right)$$

$$0 \le r \le r_0$$

$$T(r) = T_1 + \frac{Q}{2\pi k\delta} Ln\left(\frac{r_1}{r}\right)$$

$$r_0 \le r \le r_1$$

$$p(k) = \frac{e^{-\frac{(k-\bar{k})^2}{2(\Delta k)^2}}}{\sqrt{2\pi}}$$



Average temperature at the component mount area

$$\bar{T}_b = T_1 + \frac{Q}{8\pi k\delta}\left(1 + 4Ln\left(\frac{r_1}{r_0}\right)\right)$$

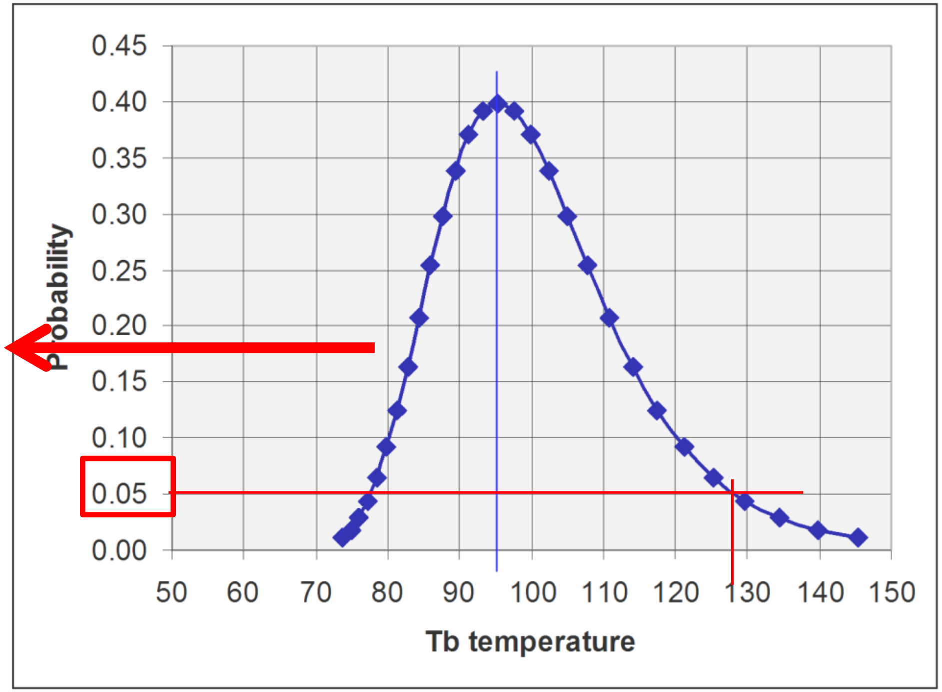
We assume that k_{eff} of PCB has an uncertainty with normal distribution. Thus, k on the denominator causes the undesirable distortion of T_b the distribution

Effective thermal conductivity uncertainty effect (exemple)

Example:
Q= 1 W, δ = 1.6 mm, k= 3.5 W/m/K, r_0= 5 mm, r_1= 50 mm, T_1= 20 °C

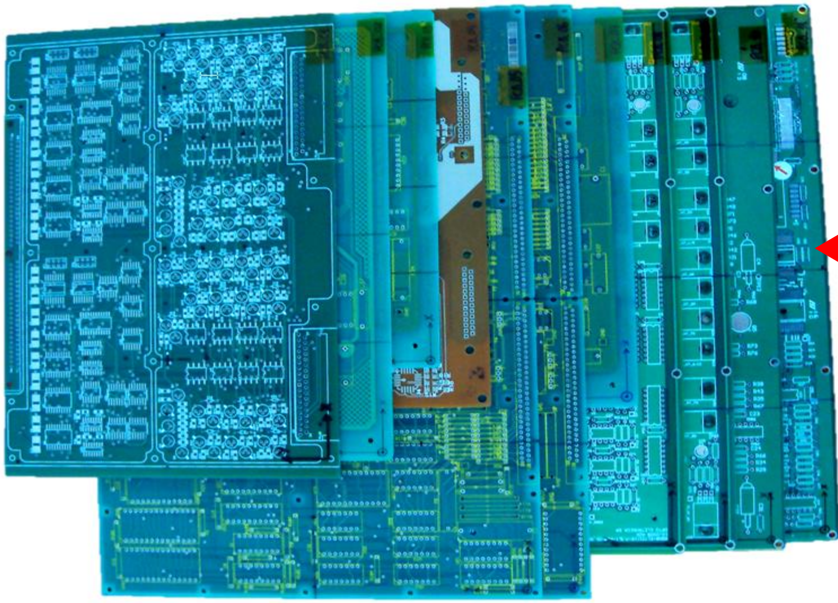
Assuming a "small" k deviation of ±15% may cause T_b temperature deviation up to 32.3 °C from average value of 95.2 °C, in the 0.95 confidence interval.

k on the denominator causes the **undesirable** distortion



Conclusion: It is very important to know the uncertainty range of PCB k_{eff}!

Canonical effective conductivities – PCB samples



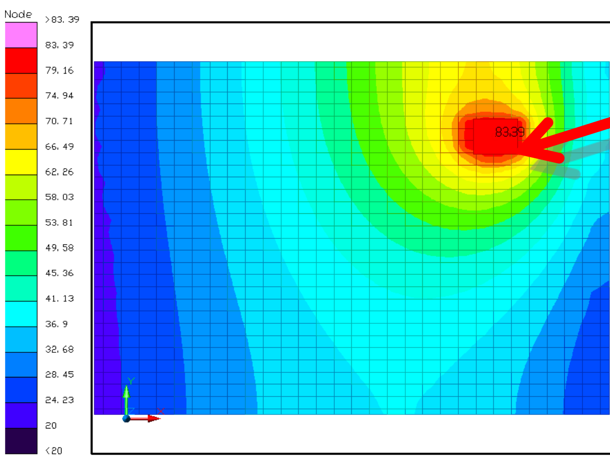
11 real satellite PCB samples
(2 and 6 copper layers)

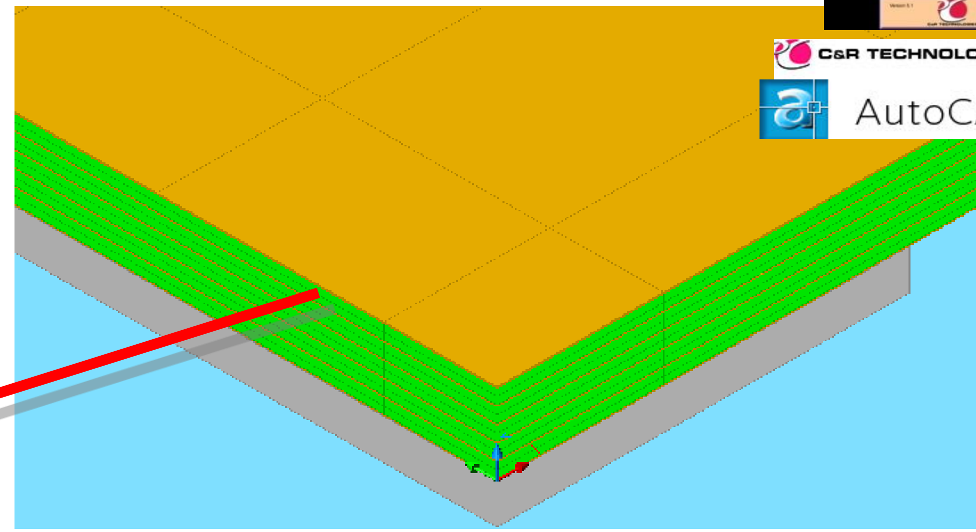
Isotropic k_{eff}

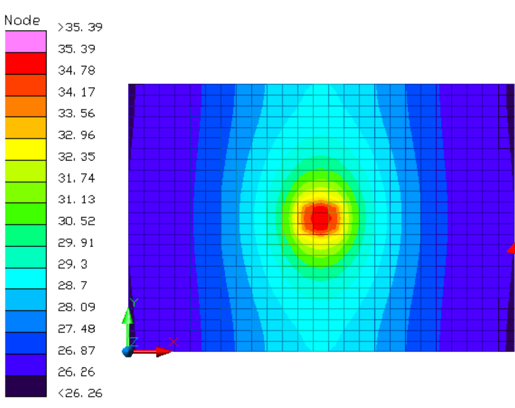
Board sample	Number of layers	k_p (W/mK)	k_s (W/mK)	Arithmetic Mean (W/mK)	Geometric Mean (W/mK)	Harmonic Mean (W/mK)
PCB_01	6	15.23	0.22	7.73	1.84	0.44
PCB_02	2	5.16	0.21	2.59	1.03	0.40
PCB_03	2	5.16	0.21	2.59	1.03	0.40
PCB_04	6	64.96	0.33	32.64	4.63	0.66
PCB_05	6	21.09	0.23	10.66	2.20	0.46
PCB_06	6	21.87	0.23	11.05	2.24	0.46
PCB_07	2	4.18	0.21	2.20	0.93	0.39
PCB_08	6	16.97	0.21	8.59	1.91	0.42
PCB_09	6	16.66	0.21	8.44	1.89	0.42
PCB_10	6	23.73	0.22	11.97	2.26	0.43
PCB_11	6	32.37	0.22	16.29	2.64	0.43

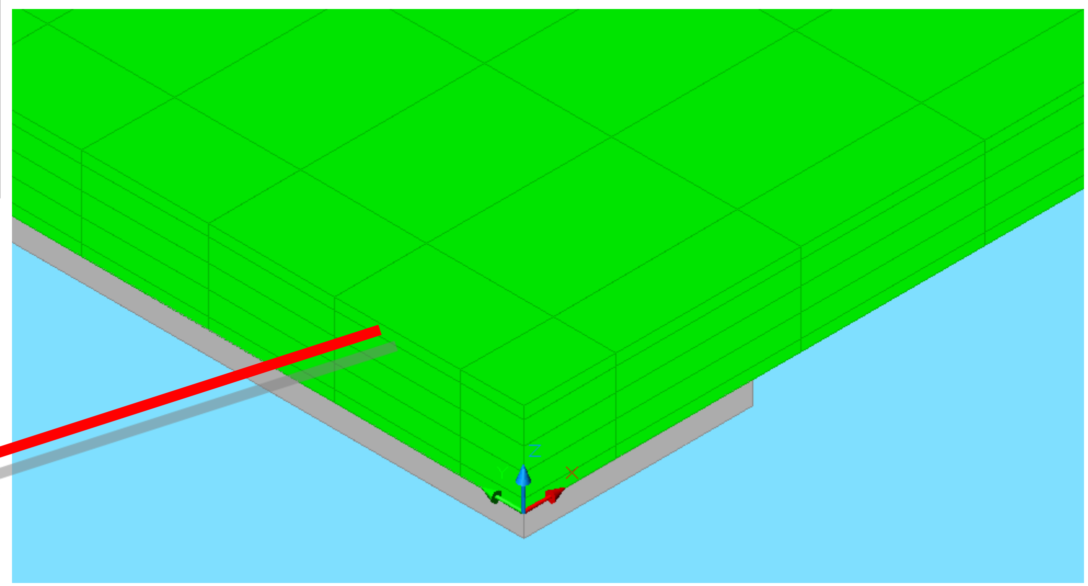
Thermal Desktop® TMM

- **Detailed model** (multilayer)
- **Simplified isotropic model** (k_{eff})
- **Simplified anisotropic model** (k_p and k_s)



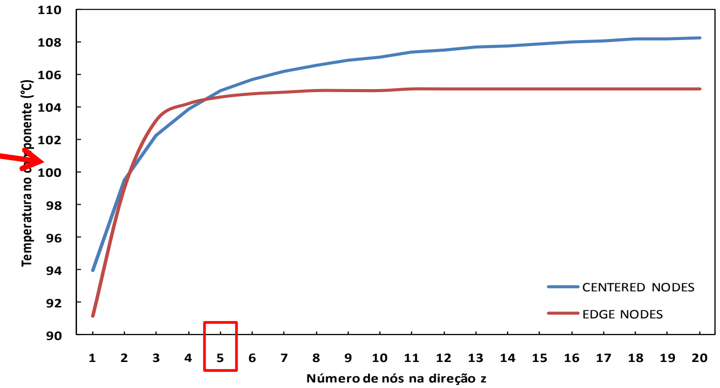




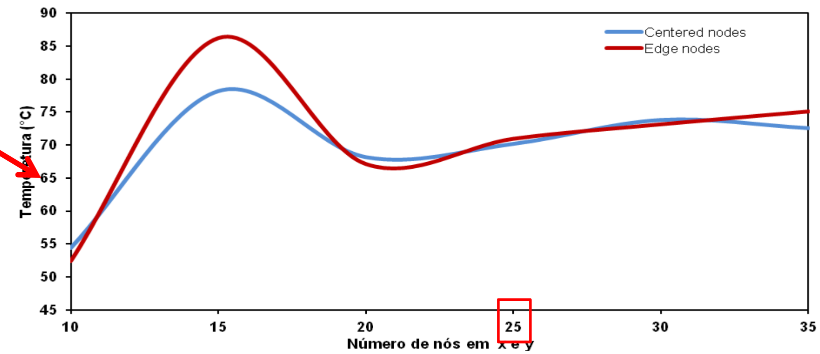


Numerical mesh investigation (TMM)

- Nodes in z (cross-plane)



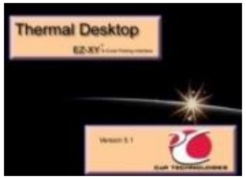
- Nodes in xy (in-plane)



- Parâmetros numéricos adicionais

- Component size influence:
  Uncertainty of ±3.2%

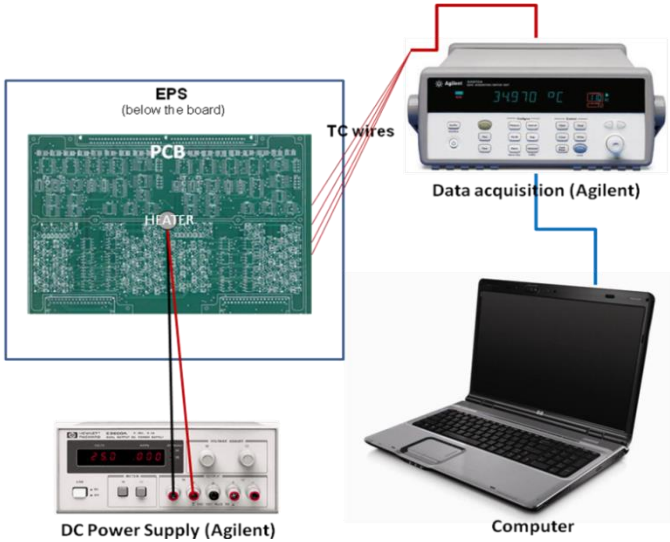
Position	Size1 (W/mK)	Size2 (W/mK)	Size 3 (W/mK)	Deviation(%)
1	7.73	7.36	7.36	2.84
2	8.26	7.98	8.02	1.87
3	7.70	7.33	7.33	2.82
4	7.96	7.49	7.21	5.00
5	8.28	8.00	7.81	2.92
6	7.86	7.44	7.19	4.56
7	7.91	7.47	7.22	4.64
8	8.40	8.05	7.87	3.33
9	7.85	7.43	7.20	4.40
10	8.11	7.83	7.67	2.79
11	8.15	8.01	7.84	1.92
12	8.10	7.82	7.66	2.82
13	8.15	8.01	7.84	1.94

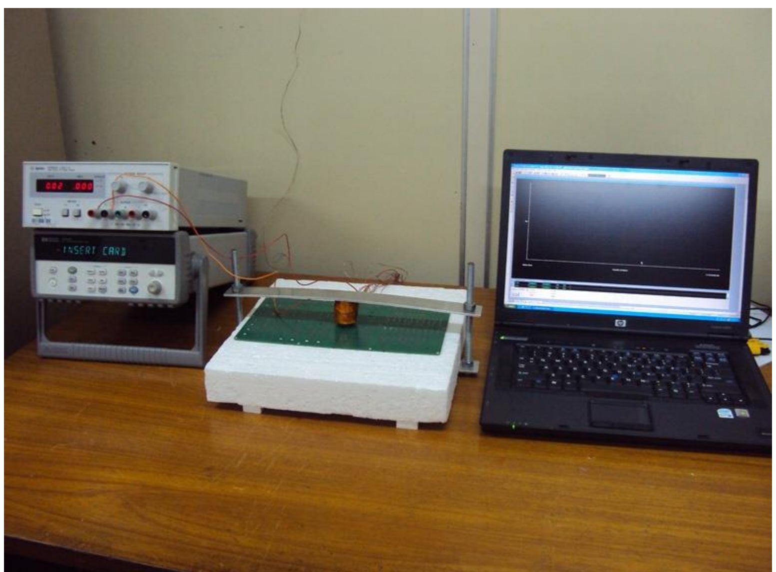


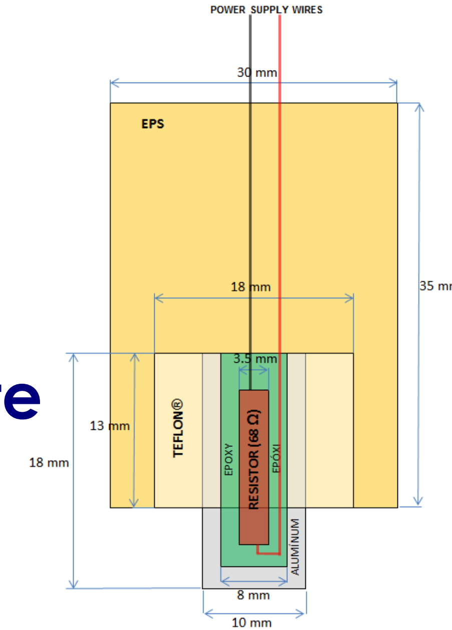
C&R TECHNOLOGIES

AutoCAD

Natural convection test – steady state

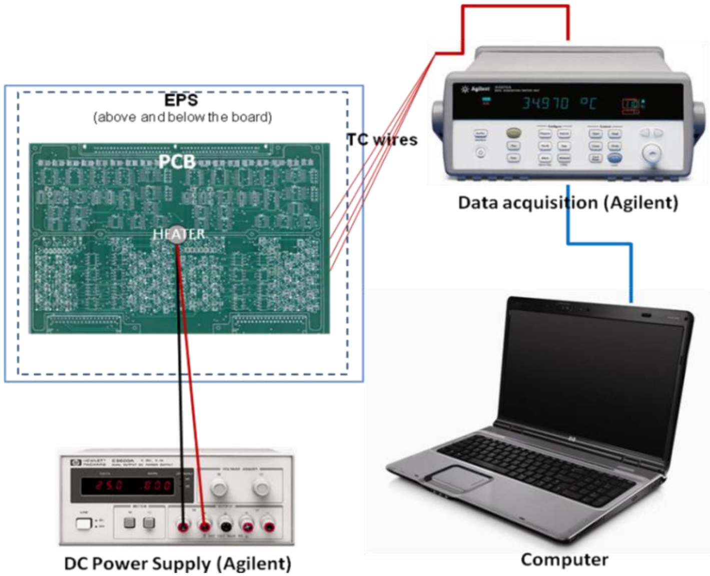


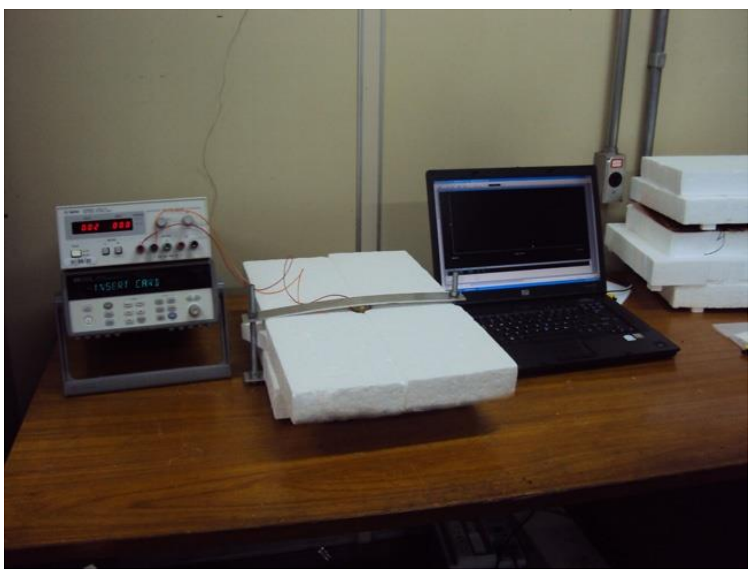


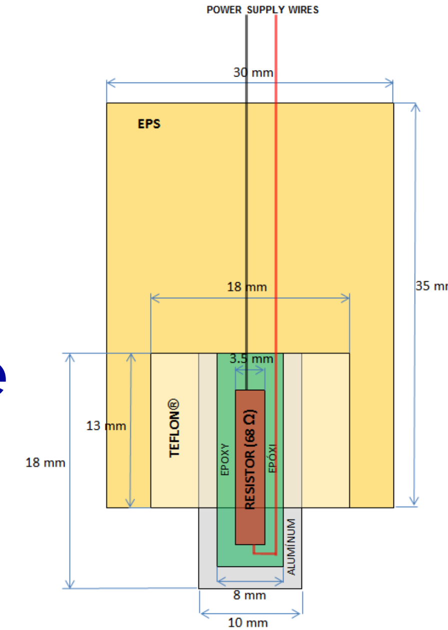


- **Easy to execute**
- Long-running
- Convection heat transfer uncertainties
- Thermal coupling between heater/PCB/EPS uncertainties
- Effective emissivity of the PCB uncertainty

Insulated test – transient

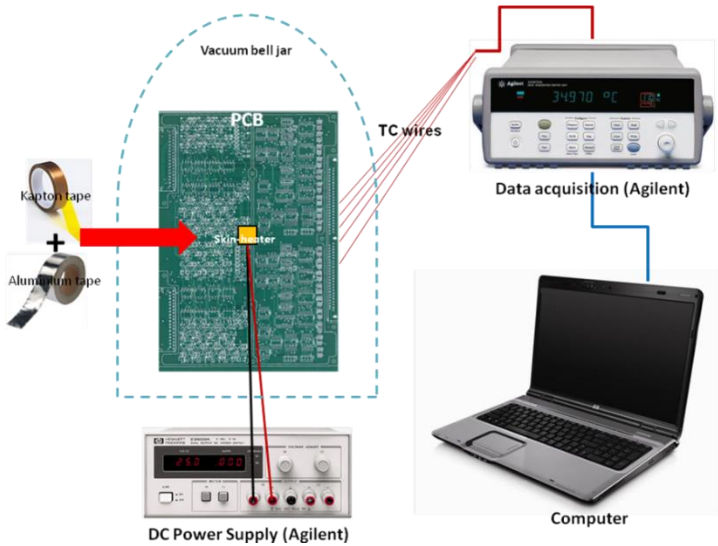




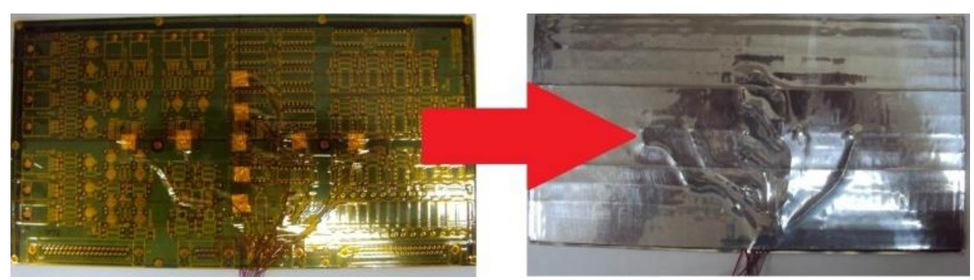


- **Easy to execute**
- **Fast-running**
- EPS convection coefficient uncertainty
- Thermal resistance between heater/PCB/EPS uncertainties

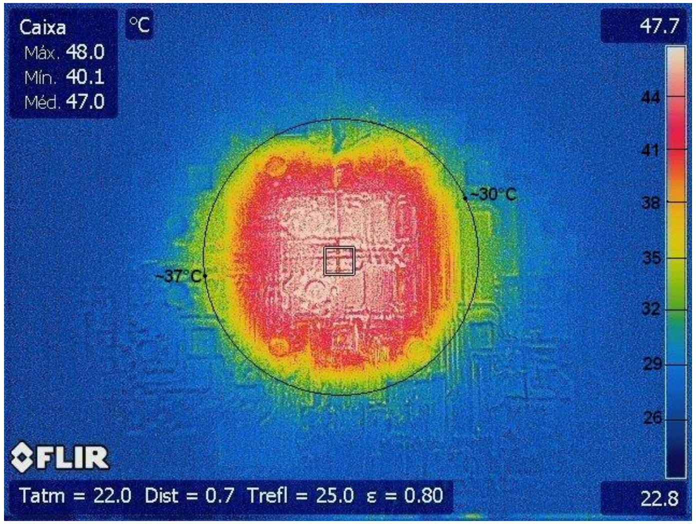
Vacuum test – steady state VALIDATION



- **No convection**
- It takes time to prepare the setup
- Uncertainties on thermal contacts
- If MLI blanket is used, all its uncertainties shall be considered



IR Imaging VALIDATION



Non-homogeneous distribution of copper lines

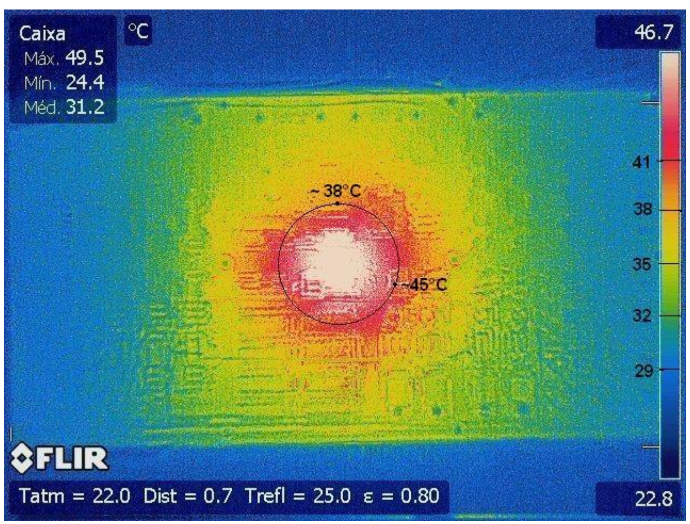
37°C – k_{eff}= 2 W/m°C
30°C – k_{eff}= 4 W/m°C

Deviation= ±55%

Deviation observed from other methods

±37.1%

±39.8%



45°C – k_{eff}= 11 W/m°C
38°C – k_{eff}= 18 W/m°C

Deviation= ±24%

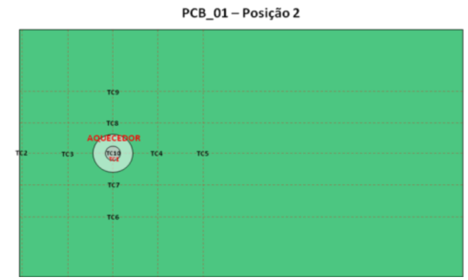
Test types

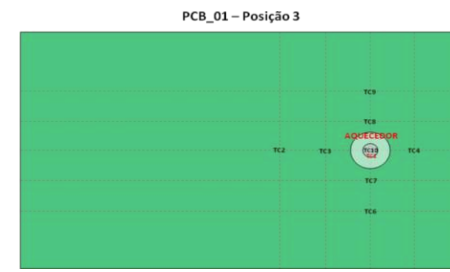
- **TRANSIENT with convection:**
All 11 PCBs, 3 different positions
(33 tests)

- **STEADY STATE with convection:**
All 11 PCBs, 1 position (center)
(11 tests)

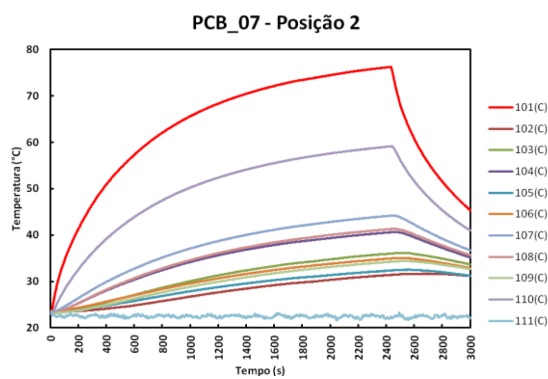
- **TRANSIENT in vacuum:**
Only for PCB_08 – validation
(4 tests)

- **IR IMAGING:**
Only for PCB_08 and PCB_12 – validation
(2 tests)

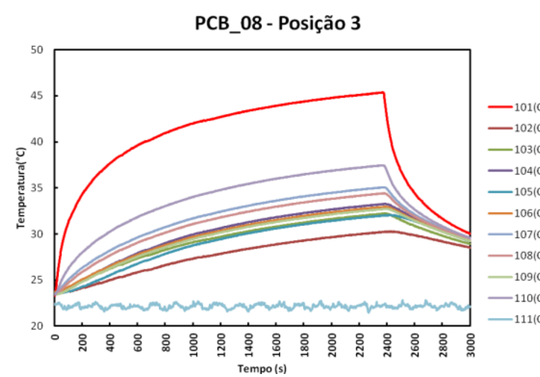




Typical curves for the transient tests



2-layers PCB

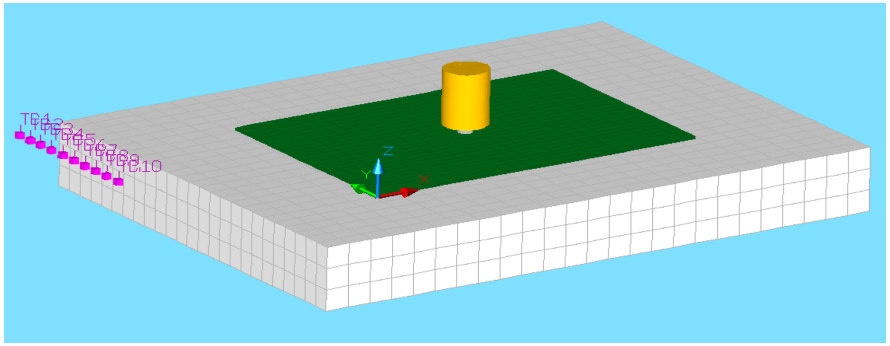


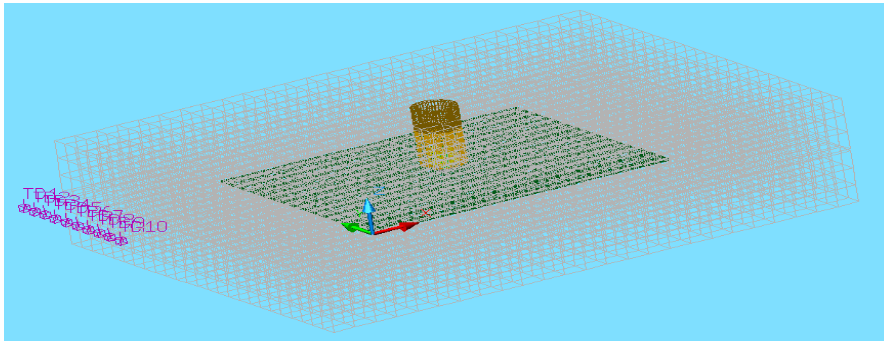
6-layers PCB

Adjustment Procedure

Steady State
(22 TMMs)

Transient
(66 TMMs)





$$\min_{k_{eff}} \delta T = \sqrt{\frac{1}{N_{TC}}\sum_{i=1}^{N_{TP}}(T_{x,i}-T_{m,i})^2}$$

$$\min_{k_{p,eff},k_{s,eff}} \delta T = \sqrt{\frac{1}{N_{TC}}\sum_{i=1}^{N_{TC}}(T_{x,i}-T_{m,i})^2}$$

$$\min_{k_{eff}} \delta T = \sqrt{\frac{1}{N_{\tau}}\frac{1}{N_{TC}}\sum_{j=1}^{N_{\tau}}\sum_{i=1}^{N_{TC}}(T_{x,i}(\tau_0+j\Delta\tau)-T_{m,i}(\tau_0+j\Delta\tau))^2}$$

$$\min_{k_{p,eff},k_{s,eff}} \delta T = \sqrt{\frac{1}{N_{\tau}}\frac{1}{N_{TC}}\sum_{j=1}^{N_{\tau}}\sum_{i=1}^{N_{TC}}(T_{x,i}(\tau_0+j\Delta\tau)-T_{m,i}(\tau_0+j\Delta\tau))^2}$$

Adjustment RESULTS

PCB_01

ANISOTROPIC			
TRANSIENT	**$k_{p,eff}$ (W/m°C)**	**$k_{s,eff}$ (W/m°C)**	**ΔT (°C)**
Position 1	5.9	0.30	2.7
Position 2	7.5	0.30	1.4
Position 3	6.5	0.30	1.8
STEADY STATE	**$k_{p,eff}$ (W/m°C)**	**$k_{s,eff}$ (W/m°C)**	**ΔT (°C)**
Position 1	5.6	0.40	1.2

ISOTROPIC		
TRANSIENT	**k_{eff} (W/m°C)**	**ΔT (°C)**
Position 1	3.9	2.6
Position 2	5.7	1.4
Position 3	5.5	1.9
STEADY STATE	**k_{eff} (W/m°C)**	**ΔT (°C)**
Position 1	5.4	2.6

AVERAGES: μ_{keff} = 5.1 W/m°C $\mu_{kp,eff}$ = 6.4 W/m°C $\mu_{ks,eff}$ = 0.33 W/m°C

PCB_02

ANISOTROPIC			
TRANSIENT	**$k_{p,eff}$ (W/m°C)**	**$k_{s,eff}$ (W/m°C)**	**ΔT (°C)**
Position 1	1.3	0.70	2.4
Position 2	1.9	0.30	2.3
Position 3	2.0	0.30	1.7
STEADY STATE	**$k_{p,eff}$ (W/m°C)**	**$k_{s,eff}$ (W/m°C)**	**ΔT (°C)**
Position 1	2.3	0.30	1.3

ISOTROPIC		
TRANSIENT	**k_{eff} (W/m°C)**	**ΔT (°C)**
Position 1	3.2	2.2
Position 2	1.2	3.0
Position 3	1.9	1.6
STEADY STATE	**k_{eff} (W/m°C)**	**ΔT (°C)**
Position 1	2.3	1.7

AVERAGES : μ_{keff} = 2.2 W/m°C $\mu_{kp,eff}$ = 1.9 W/m°C $\mu_{ks,eff}$ = 0.40 W/m°C

Adjustment RESULTS

PCB	μ_{keff} (W/m°C)	$2\sigma_{keff}$ (W/m°C)	Deviation $2\sigma_{keff}$ (%)	$\mu_{kp,eff}$ (W/m°C)	$2\sigma_{kp,eff}$ (W/m°C)	Deviation $2\sigma_{kp,eff}$ (%)	$\mu_{ks,eff}$ (W/m°C)	$2\ \sigma_{ks,eff}$ (W/m°C)	Deviation$2\sigma_{ks,eff}$ (%)
PCB_01	5.1	1.6	31.4	6.4	1.6	25.0	0.33	0.10	30.3
PCB_02	2.2	1.6	72.7	1.9	0.8	42.1	0.40	0.40	100.0
PCB_03	1.4	0.2	14.3	1.7	0.4	23.5	0.23	0.06	26.1
PCB_04	7.7	0.6	7.8	14.3	2.4	16.8	0.23	0.10	43.5
PCB_05	6.2	2.0	32.3	8.6	3.8	44.2	0.26	0.18	69.2
PCB_06	6.9	3.0	43.5	8.9	3.6	40.4	0.30	0.08	26.7
PCB_07	2.8	3.0	107.1	2.1	0.8	38.1	0.26	0.12	46.2
PCB_08	10.0	4.2	42.0	13.0	4.0	30.8	0.25	0.14	56.0
PCB_09	8.8	2.6	29.5	12.0	3.6	30.0	0.23	0.06	26.1
PCB_10	9.7	2.4	24.7	11.6	4.2	36.2	0.25	0.08	32.0
PCB_11	13.4	0.4	3.0	18.9	1.8	9.5	0.23	0.06	26.1
	Average Δk_{eff}		±37.1%	Average $k_{p,eff}$		±30.6%	Average $k_{s,eff}$		±43.8%

DEVIATIONS: due to irregular distribution of conductive paths and holes

Proposed correlation for $k_{p,eff}$ with normally-distributed factor ξ

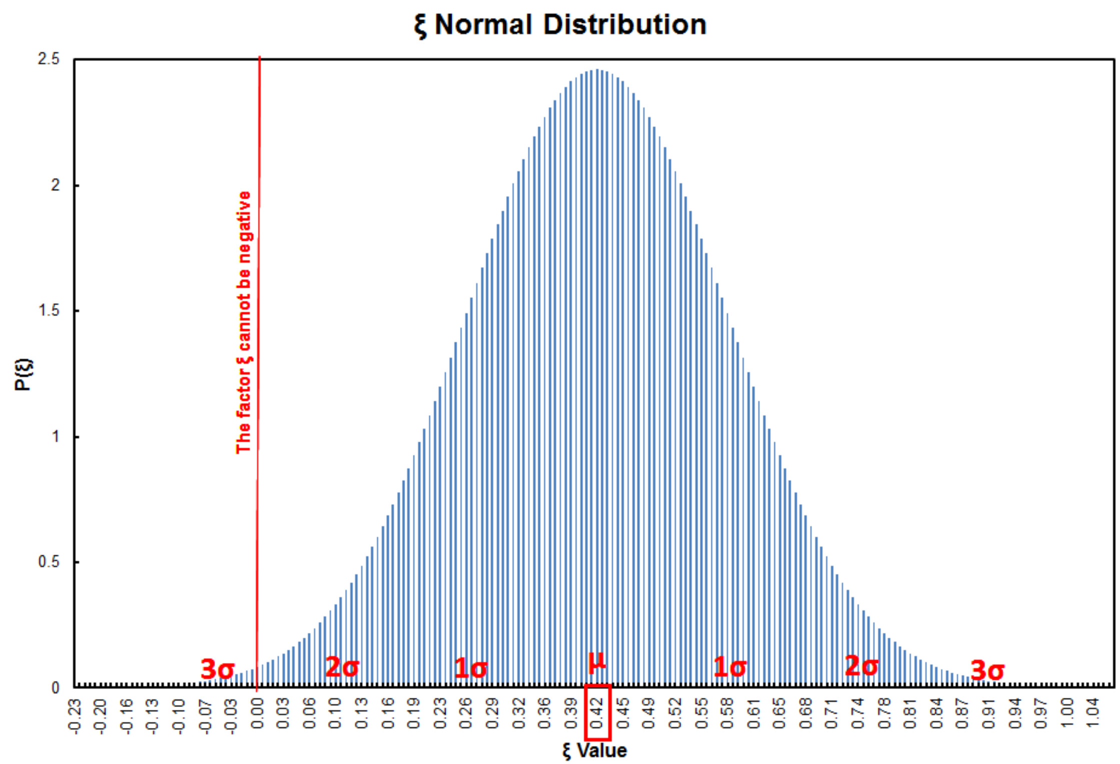
$$k_{p,eff} = \frac{\sum\limits_{i=J[1]} k_{FR4} t_i + \xi \sum\limits_{i=J[2]} f_{ai} k_{Cu} t_i}{\sum\limits_{i=1}^{N} t_i}$$

where:

N – number of layers
t_i – thickness of each layer
J[1] – FR4 layers set
J[2] – Cu layers set

$\xi_{ave} = 0.42$
$\xi_{min} = 0.10\ (-\,2\sigma)$
$\xi_{max} = 0.74\ (+\,2\sigma)$

$\sigma_\xi = 0.16$



Proposed correlation for $k_{s,eff}$ with normally-distributed factor ξ

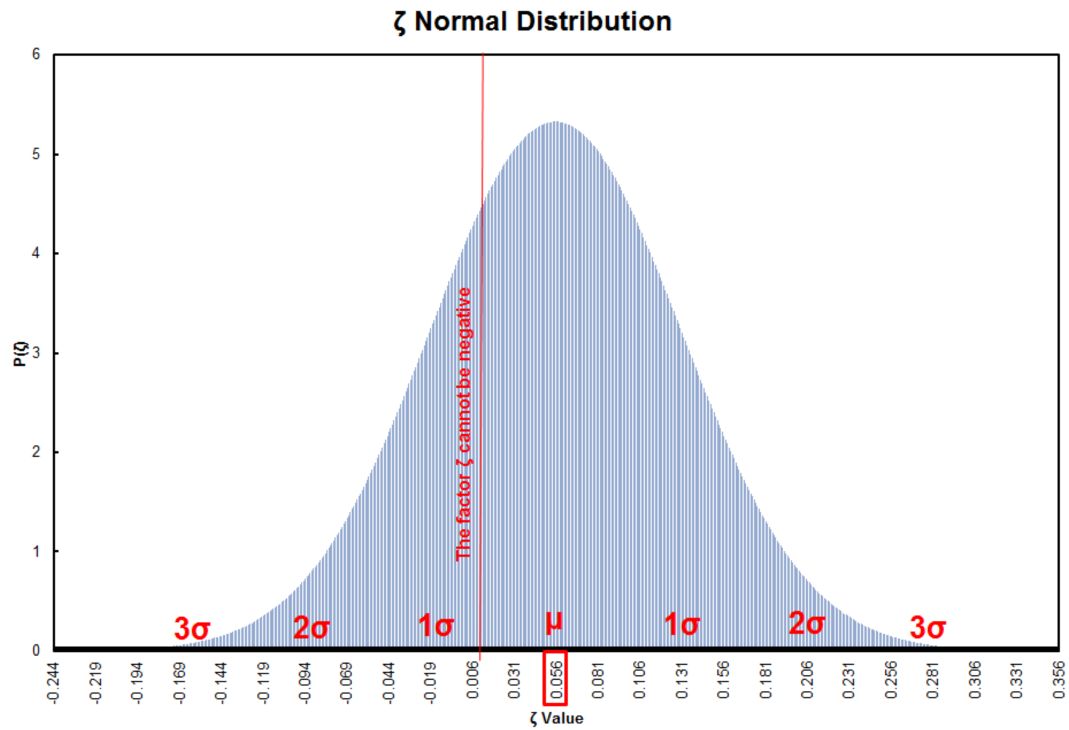
$$k_{s,eff} = (1-\zeta f_h)\frac{\sum_{i=1}^{N} t_i}{\sum_{i=1}^{N} \frac{t_i}{f_{ai} k_i}} + \zeta f_h k_{Cu}$$

$\zeta_{ave} = 0.056$

$\zeta_{min} = 0\ (-2\sigma)$

$\zeta_{max} = 0.206\ (+2\sigma)$

$\sigma_\zeta = 0.075$



Isotropic k_{eff} model: Weighted Arithmetic Mean (MAP)

$$k_{eff} = \alpha k_{p,eff} + \beta k_{s,eff}$$

Set	α	B
2 layers	0.89	0.11
6 layers	0.73	0.27
All	0.74	0.26

$$k_{eff} = 0.74 k_{p,eff} + 0.26 k_{s,eff}$$

Isotropic k_{eff} model: Weighted Geometric Mean (MGP)

$$k_{eff} = k_{p,eff}^{\alpha} k_{s,eff}^{\beta}$$

Set	α	β
2 layers	0.94	0.06
6 layers	0.92	0.08
All	0.92	0.08

$$k_{eff} = k_{p,eff}^{0.92} k_{s,eff}^{0.08}$$

Isotropic k_{eff} model: Weighted Harmonic Mean (MHP)

$$k_{eff} = \frac{1}{\dfrac{\alpha}{k_{p,eff}} + \dfrac{\beta}{k_{s,eff}}}$$

Set	α	β
2 layers	0.98	0.02
6 layers	0.99	0.01
All	0.99	0.01

$$k_{eff} = \frac{1}{\dfrac{0.99}{k_{p,eff}} + \dfrac{0.01}{k_{s,eff}}}$$

The mean choice

Set	Average deviations from k_{eff} (%)		
	MAP	**MGP**	**MHP**
All	15.76	14.34	14.51
2 layers	11.84	12.64	14.63
6 layers	14.65	14.08	14.13
Average	**14.08%**	**13.69%**	**14.42%**

The best weighted mean: **Weighted Geometric Mean** (MGP)

Small deviation between the means (± 2.5%)

Comparative example:

PCB_11				
Simplified Canonical Method				
k_p (W/m°C)	k_s (W/m°C)	k_{eff} MA (W/m°C)	k_{eff} MG (W/m°C)	k_{eff} MH (W/m°C)
32.37	0.22	16.29	2.64	0.43
Weighted Means Method				
$k_{p,eff}$ (W/m°C)	$k_{s,eff}$ (W/m°C)	k_{eff} MAP (W/m°C)	k_{eff} MGP (W/m°C)	k_{eff} MHP (W/m°C)
13.69	0.29	10.21	10.07	9.40

Practical guide – ANISOTROPIC model

Necessary data:

- FR4 thermal conductivity – k_{FR4} [W/(mK)]
- Copper thermal conductivity – k_{Cu} [W/(mK)]
- PCB total area - A_{PCB} [m^2]
- Total PCB thickness - t_{PCB} [m]
- Thickness of each copper layer – $t_{Cu,i}$ [m]
- Total thickness of all FR4 layers – t_{FR4} [m]
- Copper traces coverage factor for each conductive layer - $f_{a,i}$
- Through holes metalized area factor – f_h

In-plane effective thermal conductivity ($k_{p,eff}$)

$$k_{p,eff} = \frac{k_{FR4} t_{FR4} + 0.42\left(\sum_{i=J[2]} f_{ai} k_{Cu} t_{Cu,i}\right)}{t_{PCB}}$$

$$k_{p,eff}^{\min} = \frac{k_{FR4} t_{FR4} + 0.10\left(\sum_{i=J[2]} f_{ai} k_{Cu} t_{Cu,i}\right)}{t_{PCB}}$$

Cross-plane effective thermal conductivity ($k_{s,eff}$)

$$k_{s,eff} = (1 - 0.056 f_h)\frac{t_{PCB}}{\left(\frac{t_{FR4}}{k_{FR4}} + \sum_{i=J[2]}^{N} \frac{t_{Cu,i}}{f_{ai} k_{Cu}}\right)} + 0.056 f_h k_{Cu}$$

$$k_{s,eff}^{\min} = \frac{t_{PCB}}{\left(\frac{t_{FR4}}{k_{FR4}} + \sum_{i=J[2]}^{N} \frac{t_{Cu,i}}{f_{ai} k_{Cu}}\right)}$$

Practical guide – ISOTROPIC model

Isotropic thermal conductivity from $k_{p,eff}$ e $k_{s,eff}$

$$k_{eff} = (k_{p,eff})^{0.92} \cdot (k_{s,eff})^{0.08}$$

$$k_{eff}^{min} = \boxed{0.935}(k_{p,eff}^{min})^{0.92} \cdot (k_{s,eff}^{min})^{0.08}$$

Uncertainty due to the frames on the edges (typical configuration)

Effective thermal conductivities for electronics thermal design

- **Operational temperature limits** → $k_{p,eff}^{min}$ $k_{s,eff}^{min}$ k_{eff}^{min}
- **Derated operational temperature limits** → $k_{p,eff}$ $k_{s,eff}$ k_{eff}

CONCLUSIONS

- 2 types of tests , 2 validation tests

- Correlations with introduced normally-distributed factors to calculate $k_{p,eff}$ e $k_{s,eff}$ with uncertainty margins

- We believe the results are applicable for other PCBs of typical satellite platforms, once the introduced factors represent the layout variety of conductive paths, based on statistic of 11 different PCBs

- These factors are dimensionless, they have established normal distribution, and do not depend on PCB parameters such as number of layers, percent of copper coverage of each layer and number of metallized crossing holes

- Isotropic model - Better approximation of k_{eff} from $k_{p,eff}$ and $k_{s,eff}$: MGP

- Uncertainty (2σ) due to conductive paths irregularity
    - k_{eff} – ±37.1%
    - $k_{p,eff}$ – ±30.6%
    - $k_{s,eff}$ – ±43.8%

- Practical approach on how to use the correlations for electronics thermal design