The Use of Spreadsheets in Packaging Thermal Calculations

Tutorial
Semitherm-XIV
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Bruce M. Guenin, Ph.D.

Amkor Electronics

Chandler, Arizona

bguen@amkor.com

Outline

Overview

Analytical formulas for 1-D and 2-D heat flow

- Conduction
- Conduction + constant heat transfer coefficient

Package environment

- Representation of test board
- Calculation of heat transfer coefficient

Thermal resistance network

- Numerical solution: non-linear boundary conditions

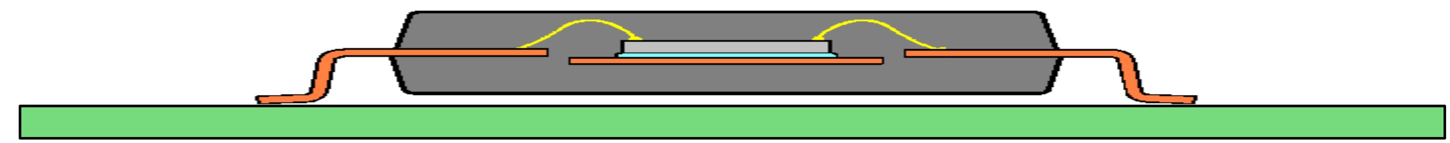
Spreadsheet structure

Case studies

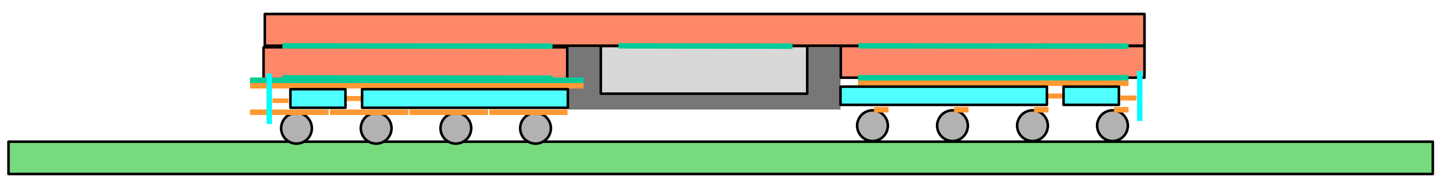
Summary and Conclusions

Examples of Plastic Packages

MQFP



SuperBGA®



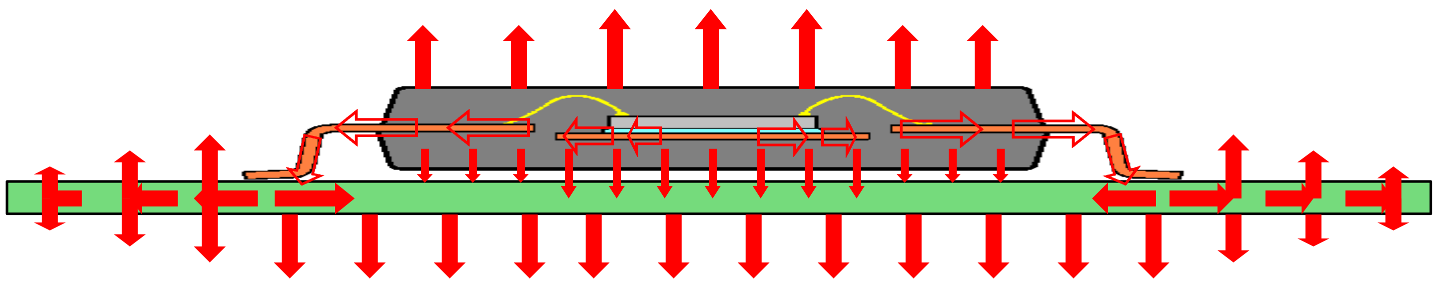
Layered structures

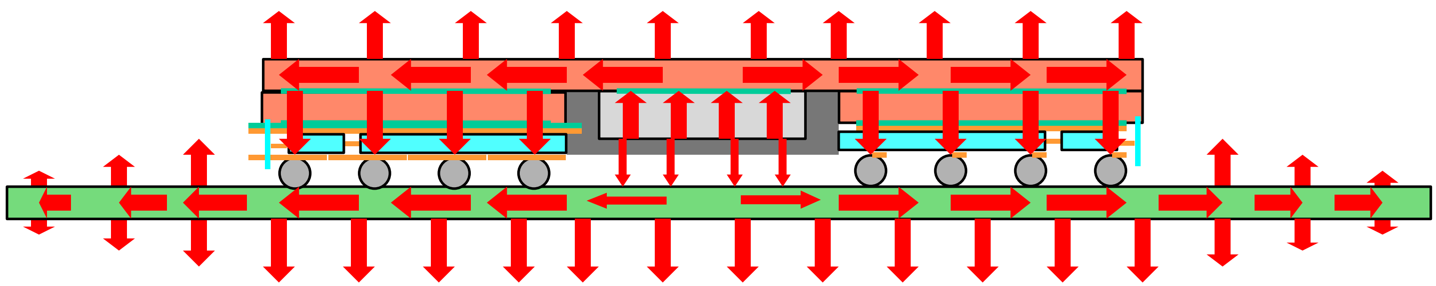
- High conductivity metals
- Low conductivity dielectrics
- Lateral dimensions much greater than thickness

Heat Flow in Plastic Packages

Heat Flow Patterns

- In-plane flow in metals
- Thru-plane flow in dielectrics





Approach to Analytical Modeling

In plastic packages, complicated heat flow patterns can be reduced to a series of heat flow building blocks that can be arranged in a thermal circuit diagram

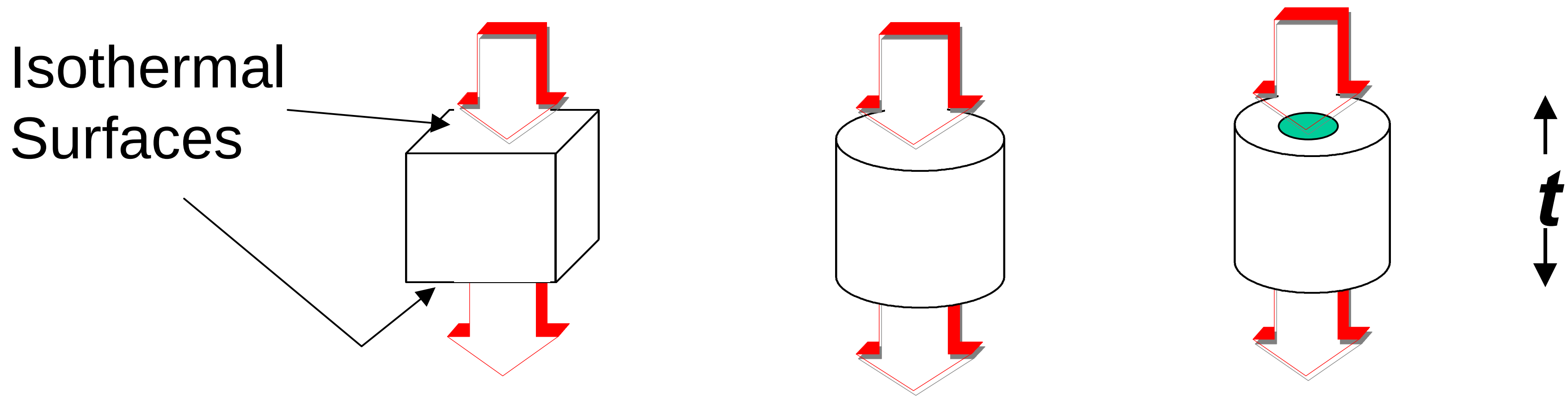
Definition of Thermal Resistance

$$\Theta = \frac{T_A - T_B}{P_{AB}}$$

T_A, T_B = Temperatures of isothermal surfaces

P_{AB} = Total thermal energy flowing between these surfaces per unit time

1-Dimensional Heat Flow



Examples: **Die** / **Die Attach** | **Bond Wire** | **Via**

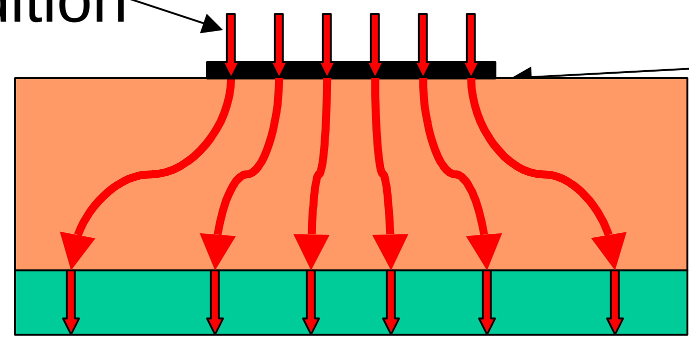
$$\Theta = \frac{t}{\kappa A}$$

Block	$A = L \times W$
Cylinder	$A = \pi r^2$
Hollow Cylinder	$A = \pi \times (r_{Outer}^2 - r_{Inner}^2)$

A = Cross-Sectional Area

κ = Thermal Conductivity

1-Dimensional Heat Flow with Spreading Resistance Correction



$$\Theta_{AB} = \Theta_{SPR} + \Theta_{SPREADER,1-D} + \Theta_0$$

Where:

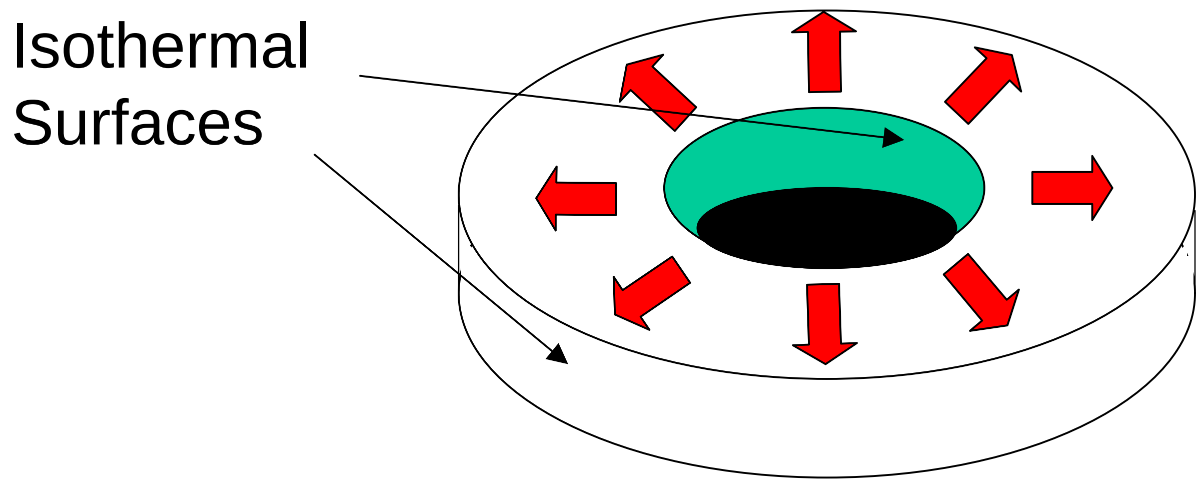
$$\Theta_{SPR} = \frac{\sqrt{A_{SPR}} - \sqrt{A_{SOURCE}}}{k_{SPR}\sqrt{\pi A_{SPR} A_{SOURCE}}} \times \frac{\lambda k_{SPR} A_{SOURCE} \Theta_o + \tanh(\lambda t_{SPR})}{1 + \lambda k_{SPR} A_{SPR} \Theta_o \tanh(\lambda t_{SPR})}$$

Θ_0 = Boundary or Conduction Thermal Resistance, and

$$\lambda = \frac{\pi^{3/2}}{\sqrt{A_{SOURCE}}} + \frac{1}{\sqrt{A_{SPR}}}$$

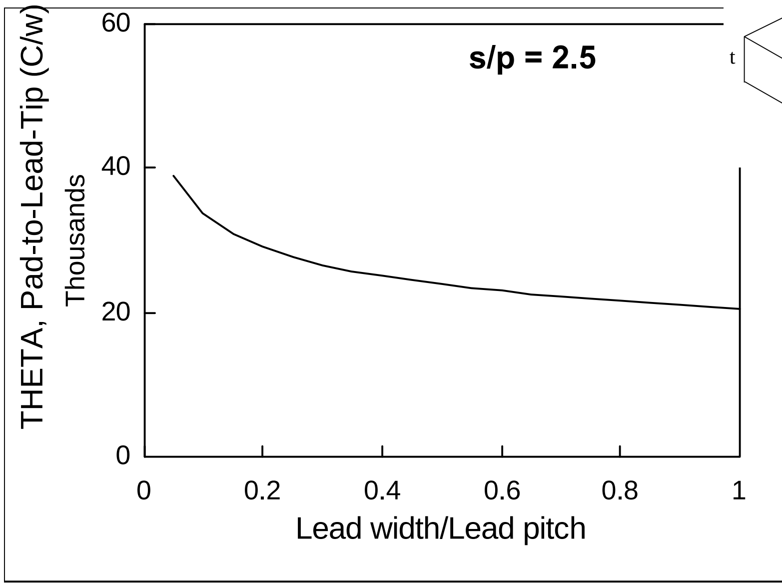
[Ref: Seri Lee, “Calculation Spreading Resistance in Heat Sinks,” Electronics Cooling Magazine, Vol. 4, No. 1 (Jan., 1998), pp. 30 - 33]

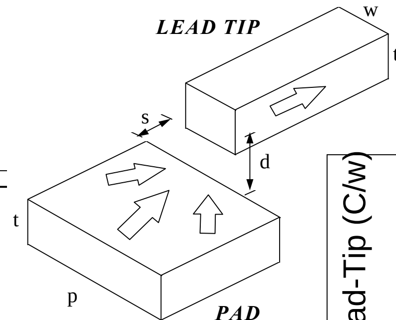
2-Dimensional Heat Flow

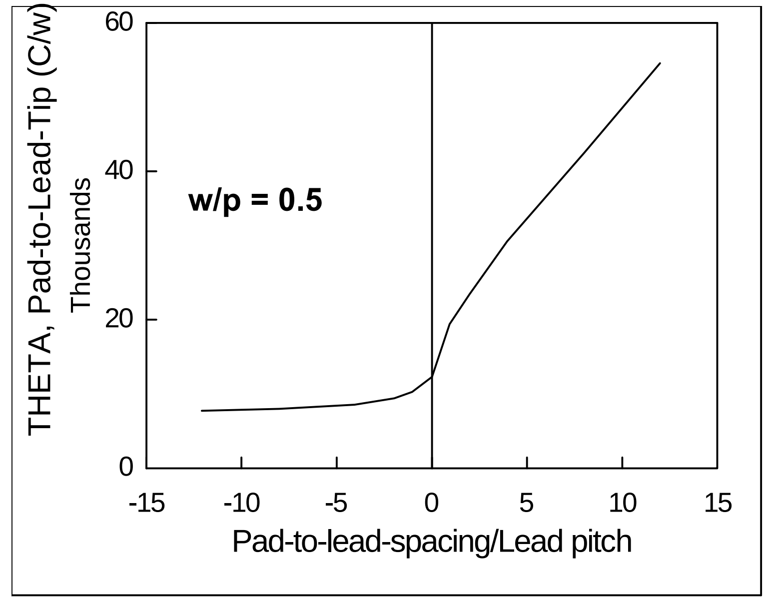


$$\Theta = \frac{1}{2pk\ t} \ln\left(\frac{r_{OUT}}{r_{IN}}\right)$$

FEA Solution: Pad-to-Lead Thermal Resistance







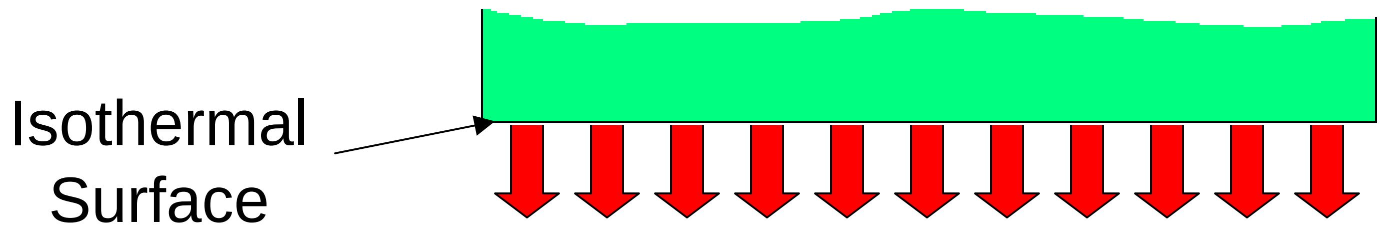
(a) Dependence on w/p

(b) Dependence on s/p

L/F thickness=0.15 mm, d=0.2 mm, p = 0.25,
k(m/c)=0.6 w/m-K, k(L/F)=390 w/m-K

[**Reference** B. S. Lall, B. M. Guenin, R. C. Marrs, and R. J. Molnar, "Parametric FEA Thermal Model for QFP Packages," *Proceedings, SEMI-THERM XII Conference*, March, 1996, pp. 105-110.]

Heat Transfer From Constant Temperature Surface

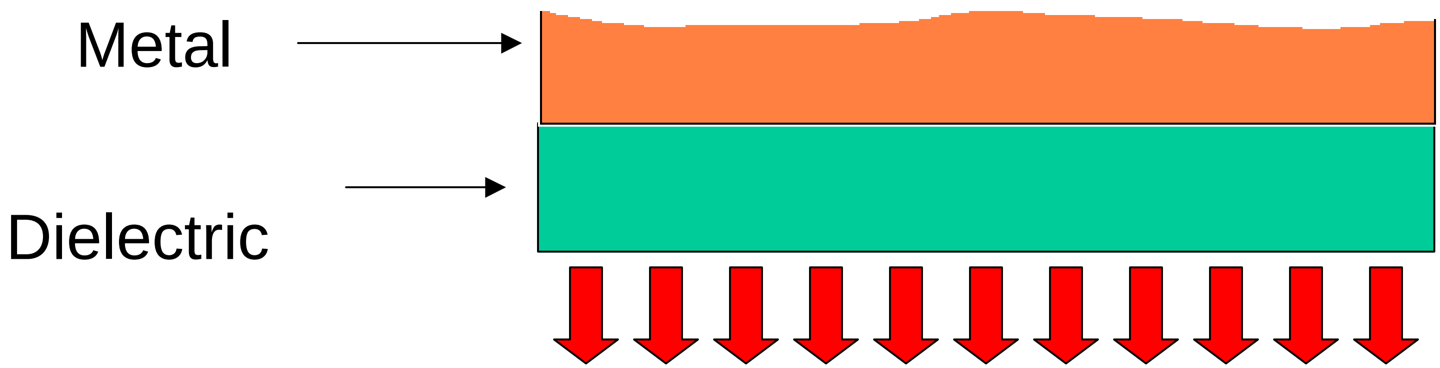


$$\Theta = \frac{1}{hA}$$

h = Heat Transfer Coefficient
A = Surface Area

Heat Transfer to Ambient from Composite: Derating h

Temperature of metal may vary locally

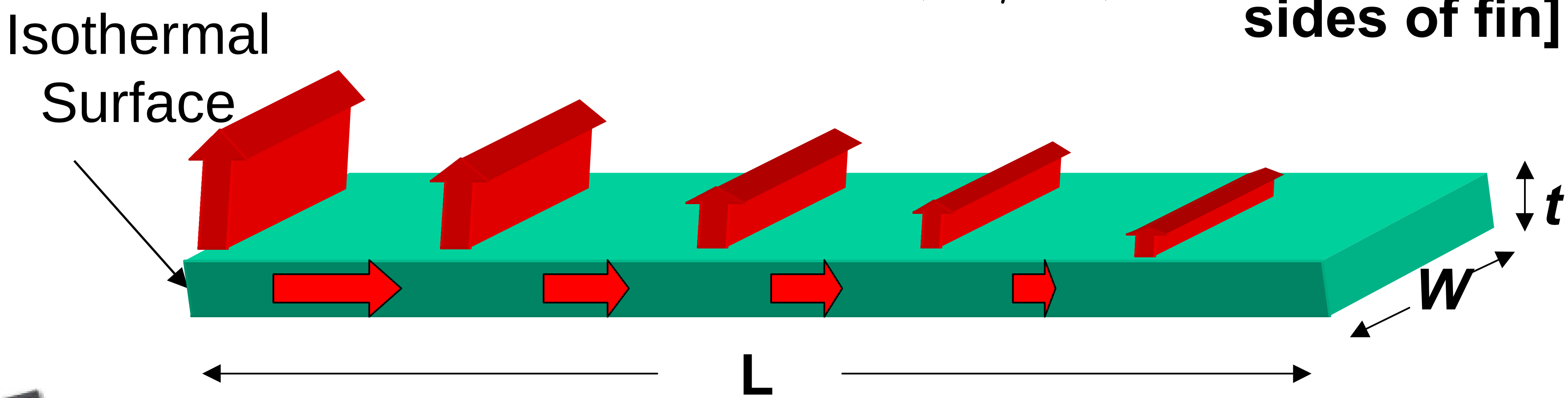


$$h_{EFF} = \frac{h k_{DIELECTRIC}}{k_{DIELECTRIC} + h t_{DIELECTRIC}}$$

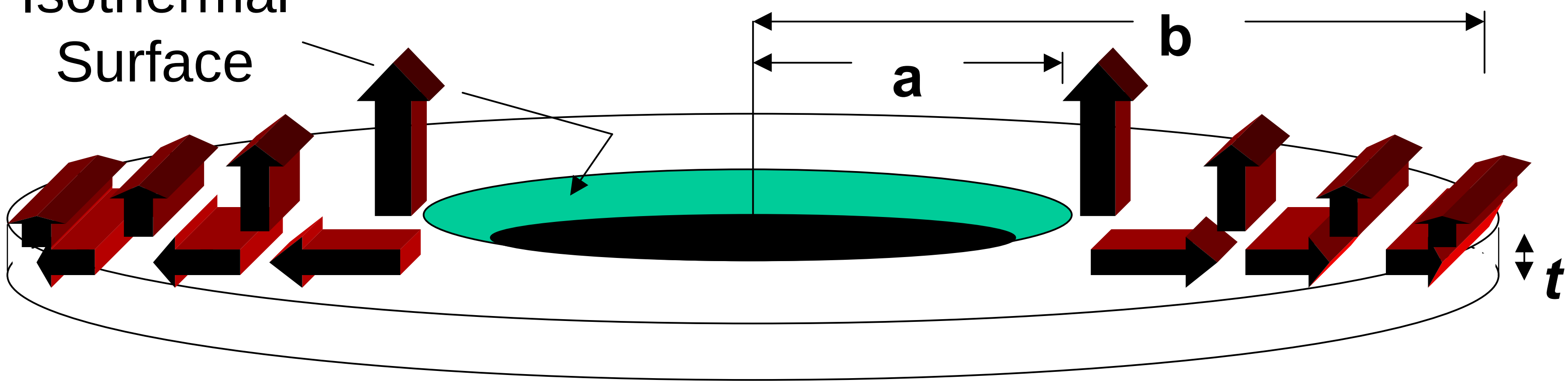
1-D Distributed Conduction/ Convection/Radiation
(Finite Fin)

$$\Theta = \frac{a}{hW} \times \frac{e^{aL} + e^{-aL}}{e^{aL} - e^{-aL}}$$

$$a = (2h/k\,t)^{1/2}$$ **[For h on both sides of fin]**



2-D Distributed Conduction/ Convection/Radiation
(Circular Fin)



$$\Theta = \frac{1}{2\pi a \kappa t \alpha}\left(\frac{K_1(\alpha b)I_0(\alpha a) + I_1(\alpha b)K_0(\alpha a)}{I_1(\alpha a)K_1(\alpha b) - I_1(\alpha b)K_1(\alpha a)}\right)$$

Where $\alpha = (2\,h/\kappa t)^{1/2}$ [For h on both sides of fin]

I_0 I_1 ($K_{0,}$ K_1): modified Bessel functions of the 1st (2nd) kind, order 0 and 1

Reference: B. M. Guenin, R. C. Marrs, and R. J. Molnar, “Analysis of a Thermally Enhanced Ball Grid Array Package,” *IEEE Trans. Comp., Packaging, Manuf. Technol*. - Part A, Vol. 18, No. 4, December 1995, pp. 749-757.

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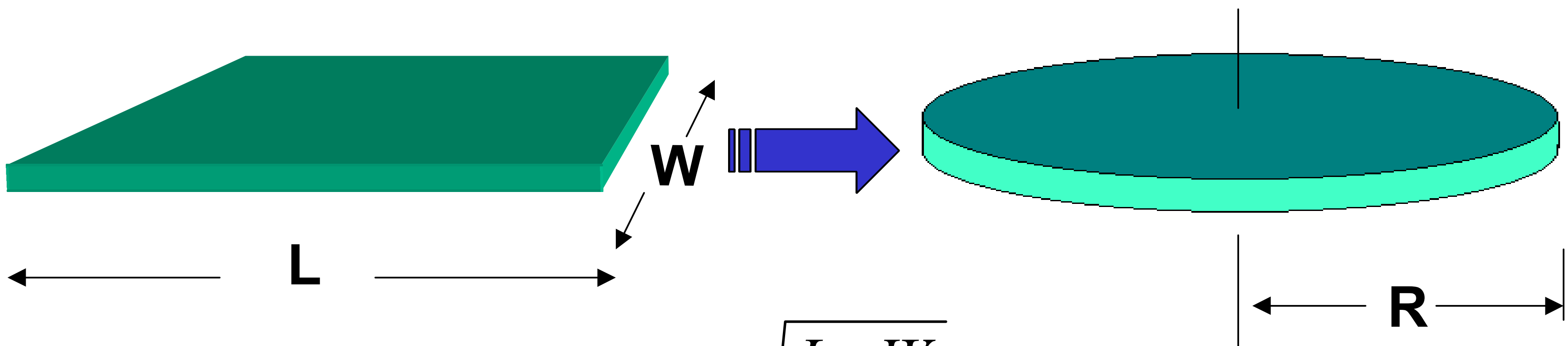
2-D Heat Flow:
Transform Rectangular to Circular Geometry

Transform rectangle into circle

– Equal area and thickness

– 1-D, 2-D, and Circular Fin problems [Ref.]



$$R = \sqrt{\frac{L \times W}{p}}$$

[**Reference:** B. Lall, A. Ortega, and H. Kabir, “Thermal Design Rules for Electronic Components on Conducting Boards in Passively Cooled Enclosures,” *Proceedings, Fourth InterSociety Conference on Thermal Phenomena in Electronic Systems*, May, 1994, pp. 50-61.]

Heat Transfer Coefficient

$$h_T = \left(h_{NC}^3(W,T) + h_{FC}^3(W,V_{AIR})\right)^{1/3} + h_{RAD}(T)$$

h_T = Total Heat Transfer Coefficient

- Predicts heat loss to ambient in industry-standard windtunnel environment
- Deals with natural, mixed, and forced convection regimes
- Includes effect of radiation

References:
1) H. Shaukatullah, M.A. Gaynes, and L.H. White, “A Non-dimensional Correlation for the External Thermal Characteristics of Surface Mount Metal Quad Flat Packs,” *Proceedings of the 4th Intersociety Conference on Thermal Phenomena in Electronic Systems*, 1994, pp. 237-244.
2) B. M. Guenin, A. Chowdhury, R. Groover, and E. J. Derian, “Analysis of Thermally-Enhanced SOIC Packages,” *Proceedings, SEMI-THERM XII Conference*, March, 1996, pp. 1-13.

Heat Transfer Coefficient (Cont.)

$$h_{NC} = 8.66\left(\frac{\Delta T_{Surface\,Air}(^\circ C)}{D_{CHAR}(mm)}\right)^{0.25} W/m^2\,^\circ C$$

$$h_{FC} = 119.9\left(\frac{V_{AIR}(m/s)}{D_{CHAR}(mm)}\right)^{0.5} W/m^2\,^\circ C$$

$$h_{RAD} = 5.67\times10^{-8}\,\mathrm{e}\left(\frac{T_{Surface}{}^4(K^4) - T_{Air}{}^4(K^4)}{T_{Surface}(K) - T_{Air}(K)}\right) W/m^2\,^\circ C$$

Assumes simple, standard package, board configuration

- Single package mounted centrally on test board
- $\mathbf{h_{NC}}$ and $\mathbf{h_{FC}}$ are area averages

h_{NC} assumes horizontal board orientation

D_{CHAR} = Characteristic Dimension

- Set equal to package width in direction of air flow

References:

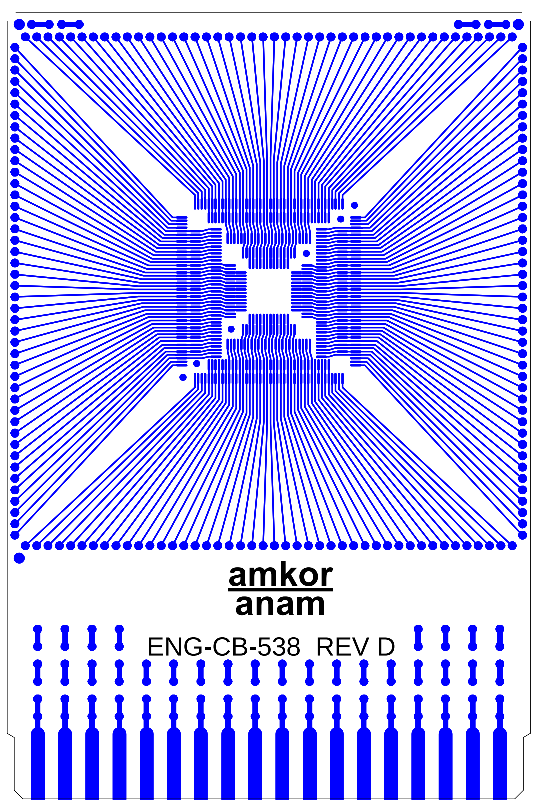
h_{FC}:G.N. Ellison, *Thermal Computations for Electronic Equipment*, Krieger Publishing, Malabar, Florida, 1989.

h_{NC}: B. S. Lall, B. M. Guenin, R. C. Marrs, and R. J. Molnar, "Parametric FEA Thermal Model for QFP Packages," *Proceedings, SEMI-THERM XII Conference*, March, 1996, pp. 105-110.

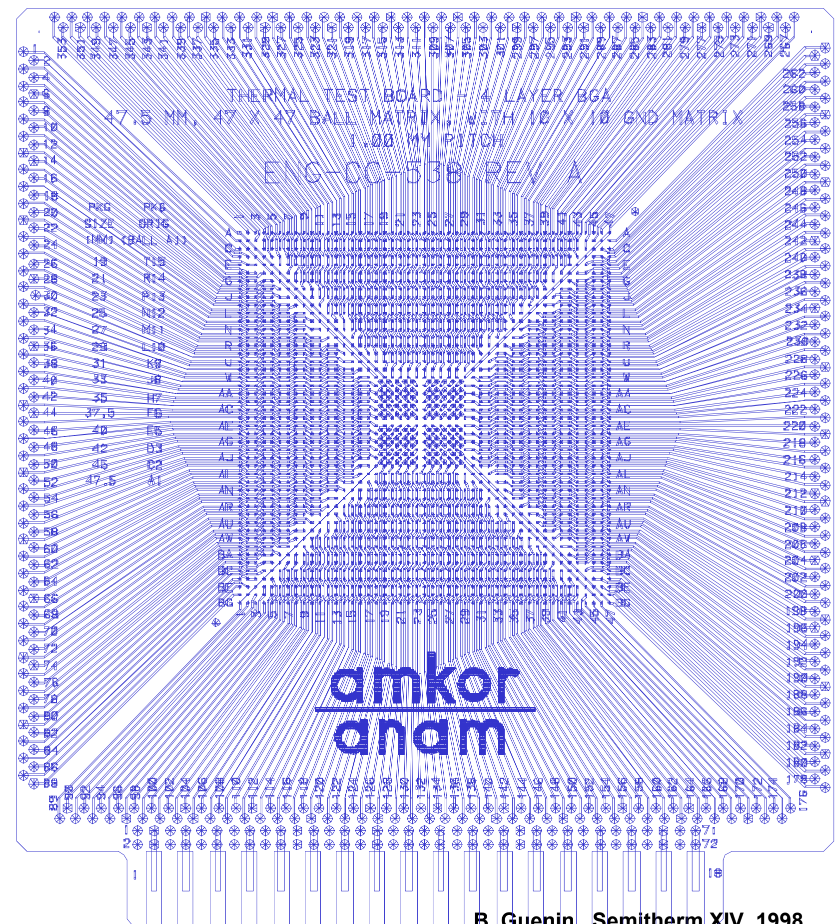
Examples of JEDEC-Standard Thermal Test Boards

Both boards shown are nested designs, to accommodate a variety of package sizes

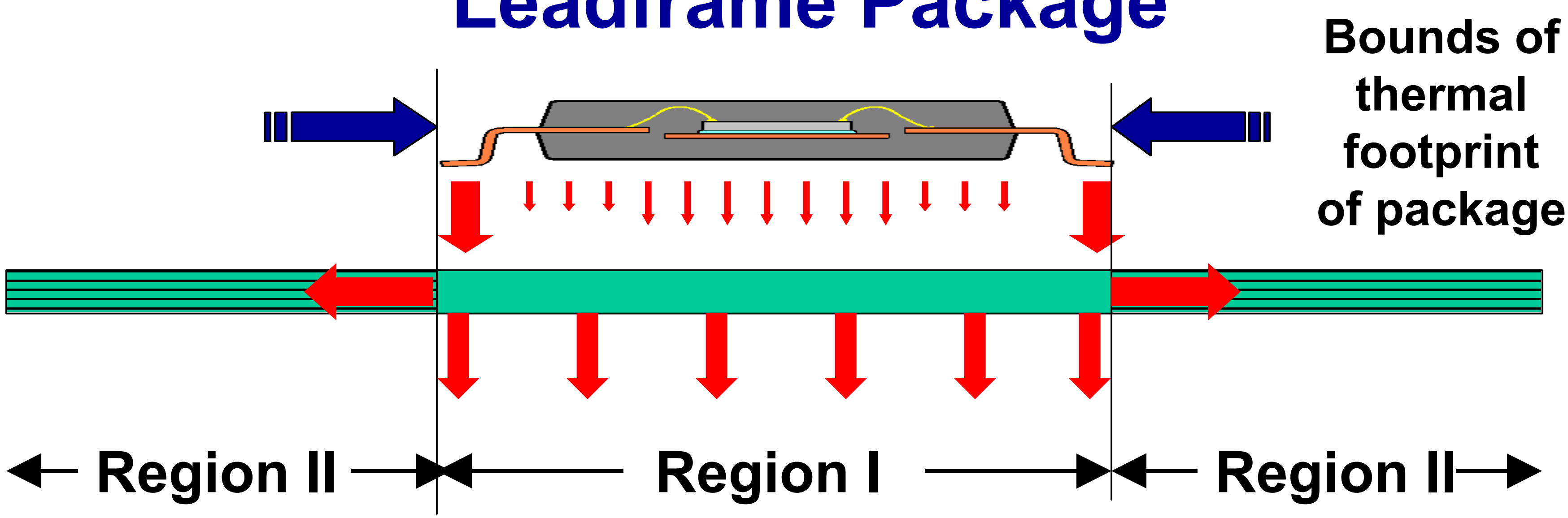
MQFP



BGA



Representation of Test Board:
Leadframe Package



Region I represented as a *Control Volume*

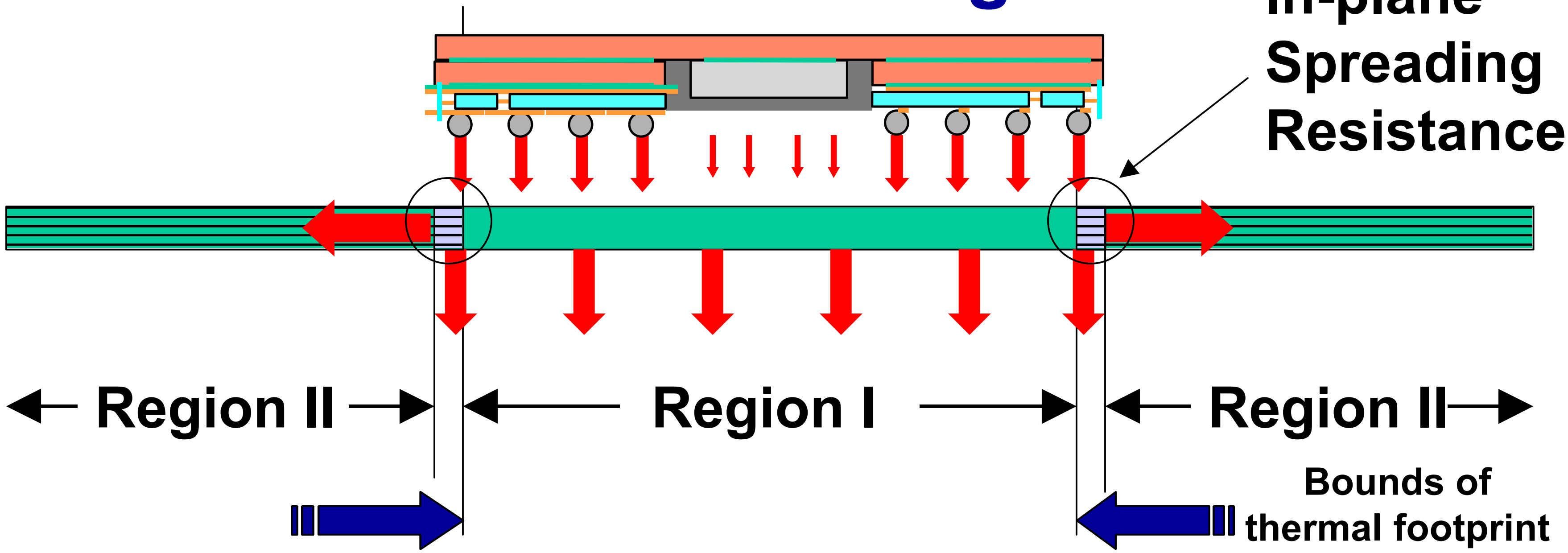
- No internal thermal gradients
- Transmits heat to convective surface under footprint and to Region II

Region II represented as

- A circular fin (for boards containing internal planes
- 4 parallel finite fins (for single-layer test boards)

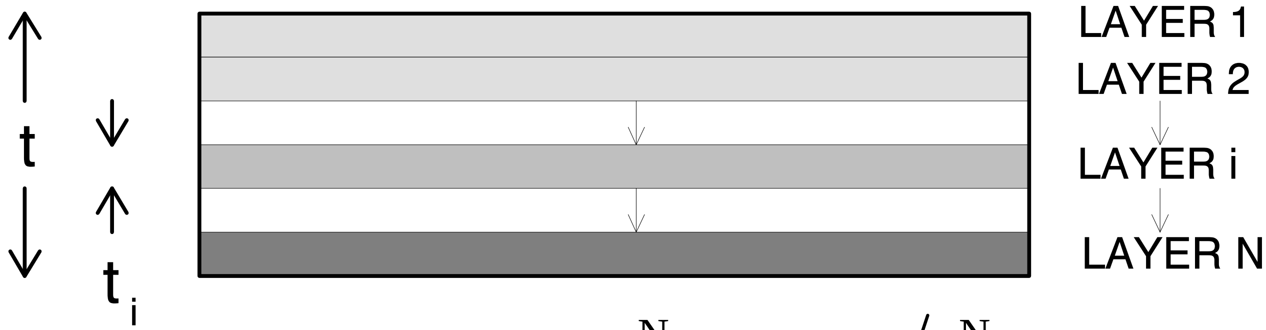
Reference: B. M. Guenin and D. Mahulikar, "Methodology for the Thermal Characterization of the MQUAD® Microelectronic Package," *Proceedings, SEMI-THERM IX Conference*, February, 1993, pp. 176-185.

Representation of Test Board: BGA Package



- Region I bounded by edge of thermal footprint of package
- Region II bounded by edge of package
- When thermal footprint < package width, in in-plane spreading resistance is placed in series with heat flow from Region I to II.
- Functional form of spreading resistance depends on board construction:
  - 2-D circular heat flow (for boards containing internal planes)
  - 4 parallel 1-D heat flow paths (for single-layer test boards)

Calculating Thermal Conductivity of Test Board



$$k_{\text{EFF-IN PLANE}} = \sum_{i=1}^{N} f_i k_i t_i \Bigg/ \sum_{i=1}^{N} t_i$$

f_i is the fractional coverage of copper in layer **i**

κ_i and **t_i** - thermal conductivity and thickness

For application boards, only include planes in calculation [Ref.]

Reference: K. Azar and J.E. Graebner, “Experimental Determination of the Thermal Conductivity of Printed Wiring Boards,” *Proceedings, SEMI-THERM XII Conference*, March, 1996, pp. 169-182.

Definition of a Spreadsheet

Mathematical, financial, engineering software

- Table structure
- Cells can contain
  - Text
  - Numbers
  - Formulas
- Formulas
  - Result is output in cell in which formula is located
  - Inputs come from other cells through linking

C	A	B	C	D	E	F	G	H
1	1-Dimensional Heat Flow Calculation							
2	COMPONENT	MAT'L	WIDTH	LENGTH	THICKNESS	TH.COND	Theta	
3			(mm)	(mm)	(mm)	(w/mm-°C)	(°C/W)	
4	Die	Si	12	12	0.61	0.092	0.91	
5								
6								
7								

+E4/(F4*C4*D4)

Capabilities of Spreadsheets

Advanced mathematical and engineering functions

Macro (programming) languages

Graphing capabilities

Data table formatting

Special Functions in Spreadsheets

Partial Listing (Lotus 5.0 and Excel 97)

- Bessel Functions, Std. And Modified 1st and 2nd Kind
- Beta and Incomplete Beta Function
- Error and Complementary Error Functions
- Gamma and Incomplete Gamma Function
- Exponential Function
- Natural Logarithm
- Common Logarithm (Base 10)
- Trig and Inverse Functions
- Hyperbolic Trig and Inverse Functions
- Complex Variable Analysis
- Statistical Functions

Additional Functions (Excel 97)

- Fast Fourier Transform

Motivation for Analytical Resistor Models

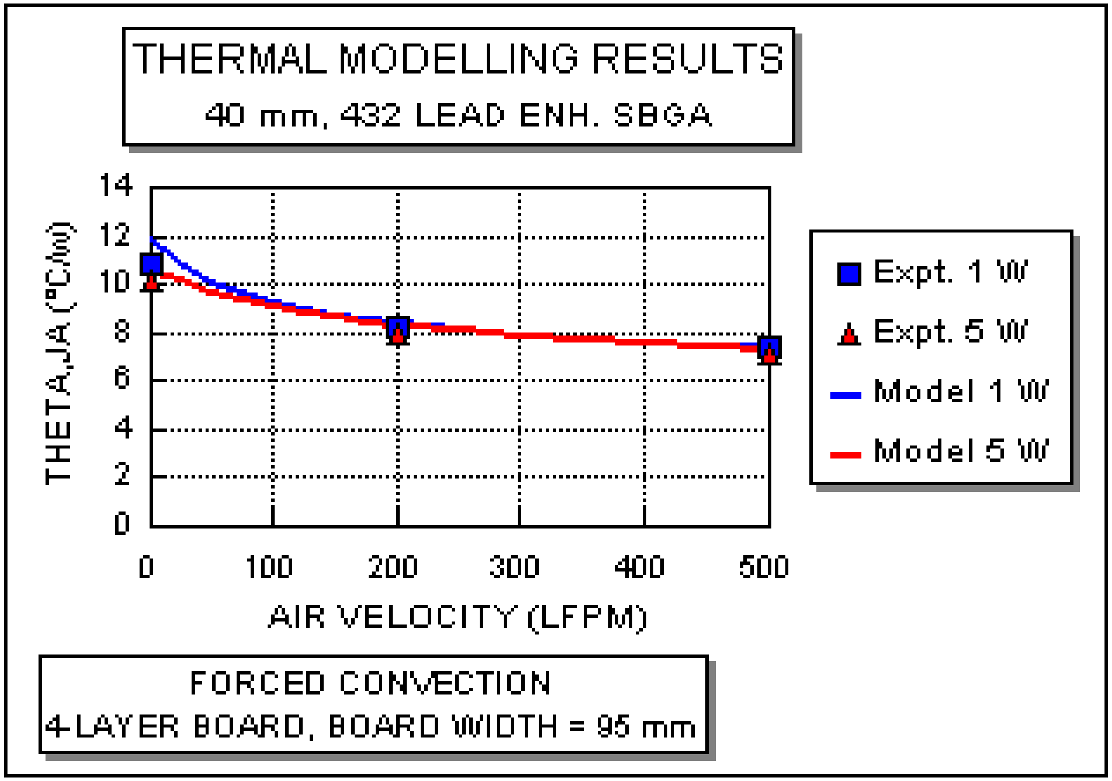
Promotes a high level of insight into how thermal performance of a package is related to its design

– Each package component individually represented in thermal circuit diagram

Can produce accurate, rapid solutions.

Readily incorporates non-linear boundary conditions.

Solution Accuracy

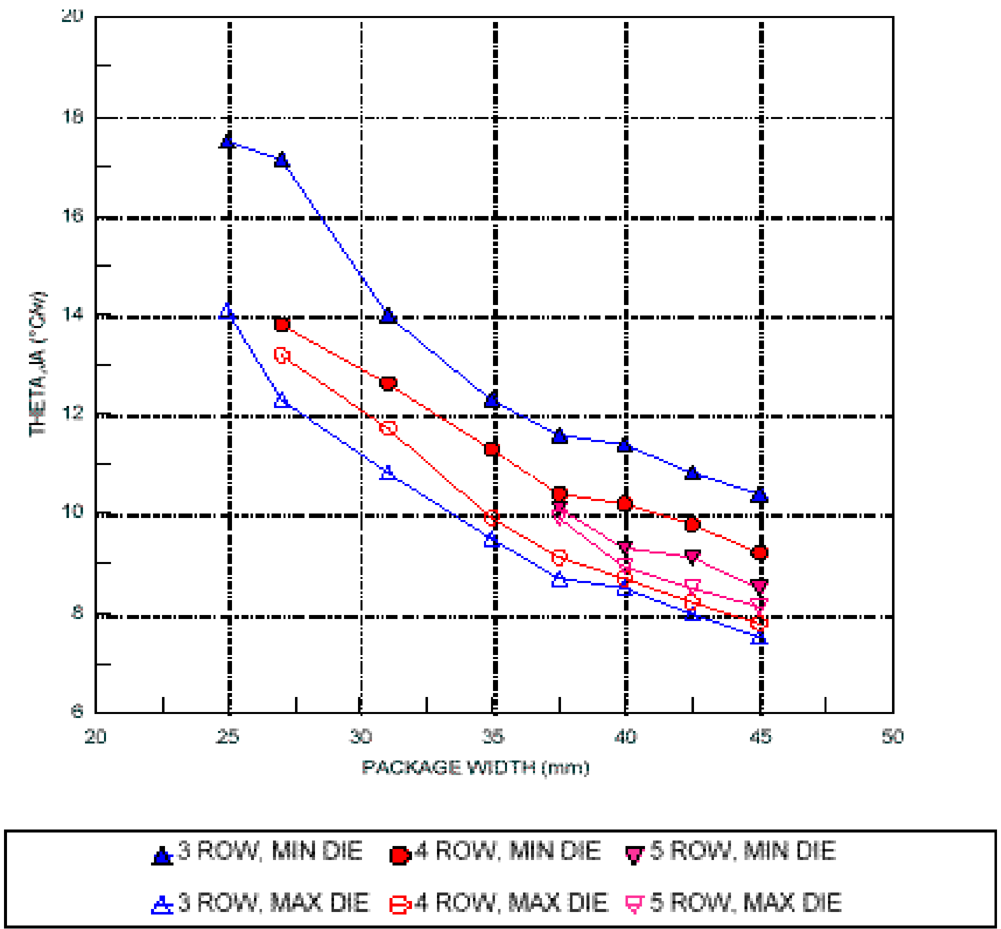


Model Curves

- 15 points each
- 10 sec/point
- Calculation completed in 5 min on 120 MHz Pentium

Accurate solution in natural, mixed, and forced convection regimes

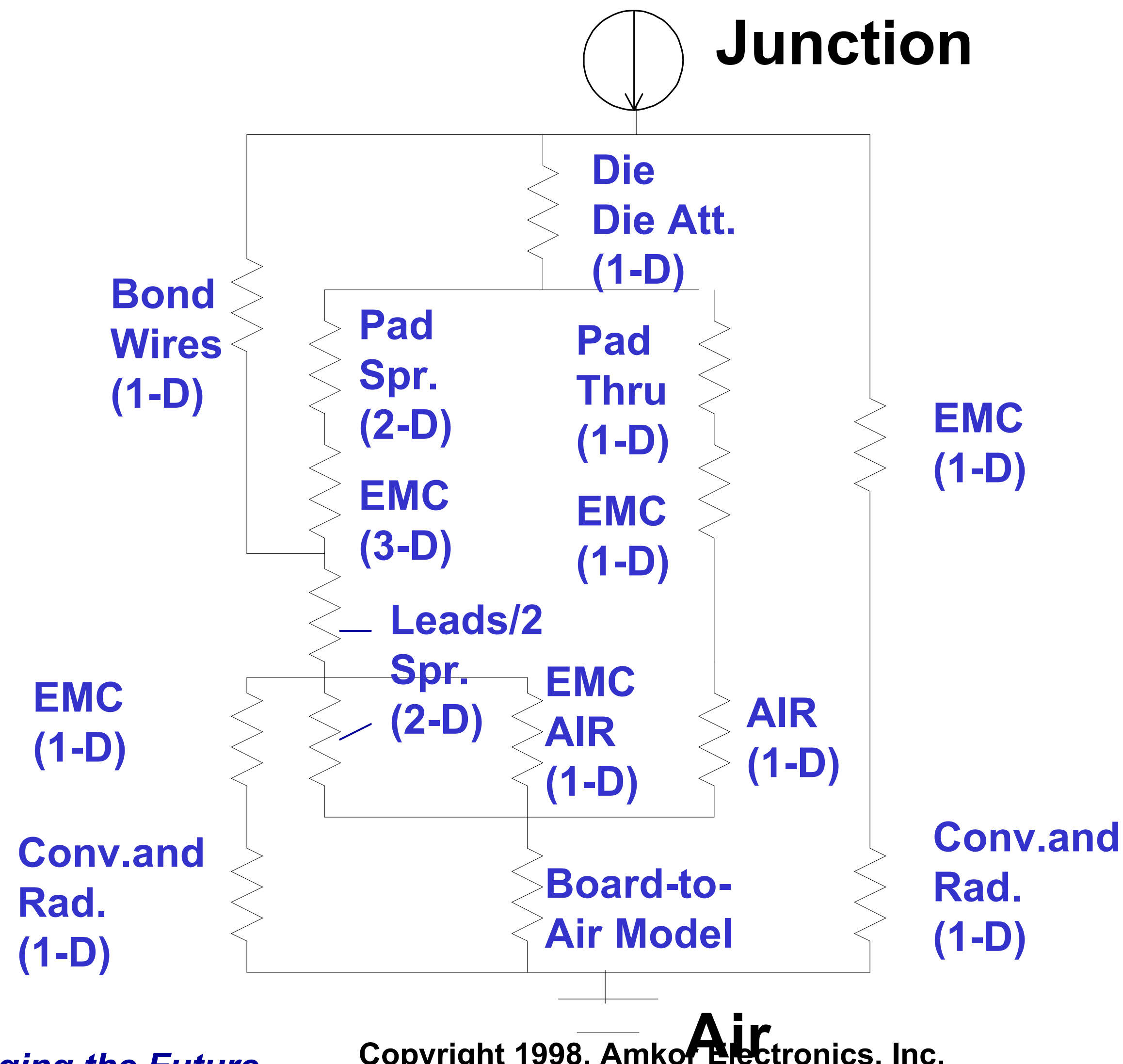
Solution Productivity



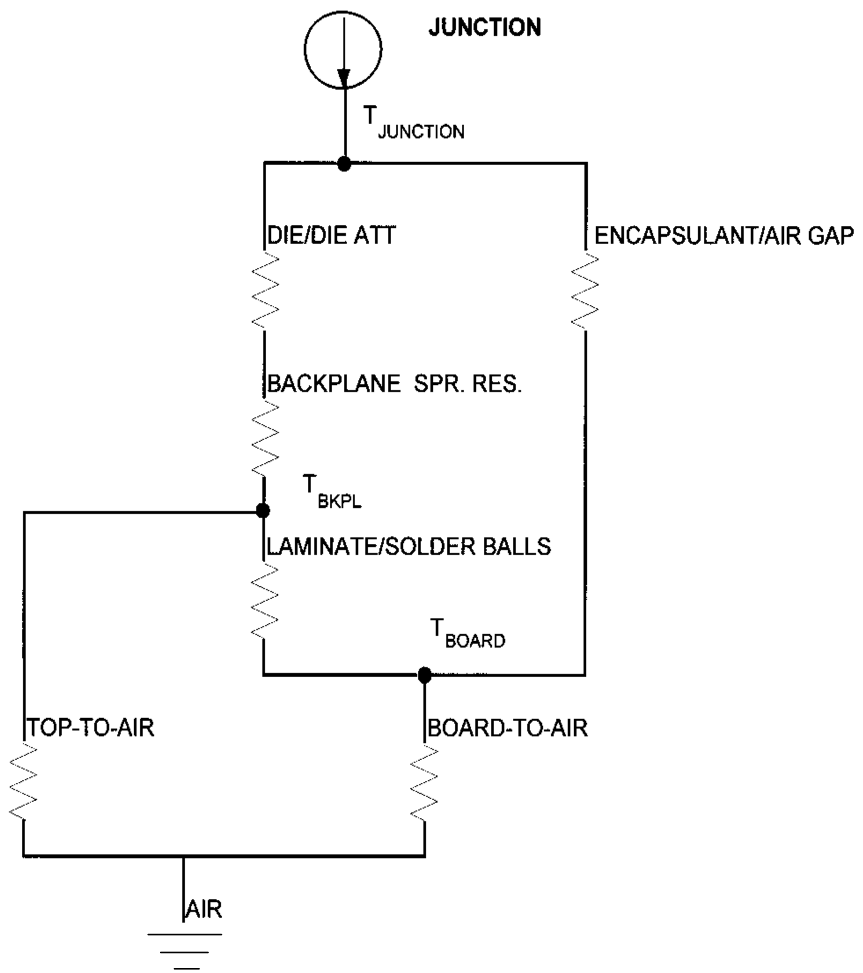
34 SBGA package designs analyzed in under 2 hours

- Natural convection
- ΔT_{JA} = 60°C
- Multilayer test board

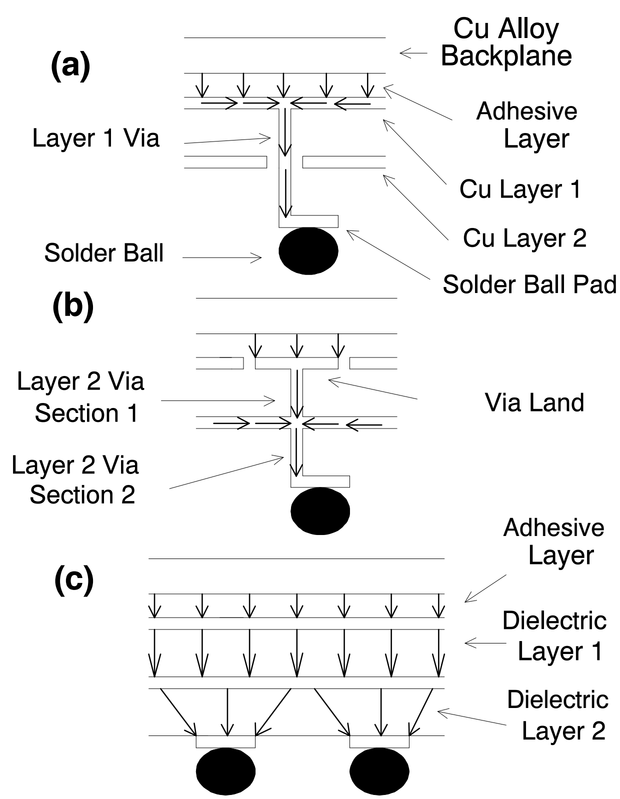
Thermal Circuit Diagram for MQFP Package

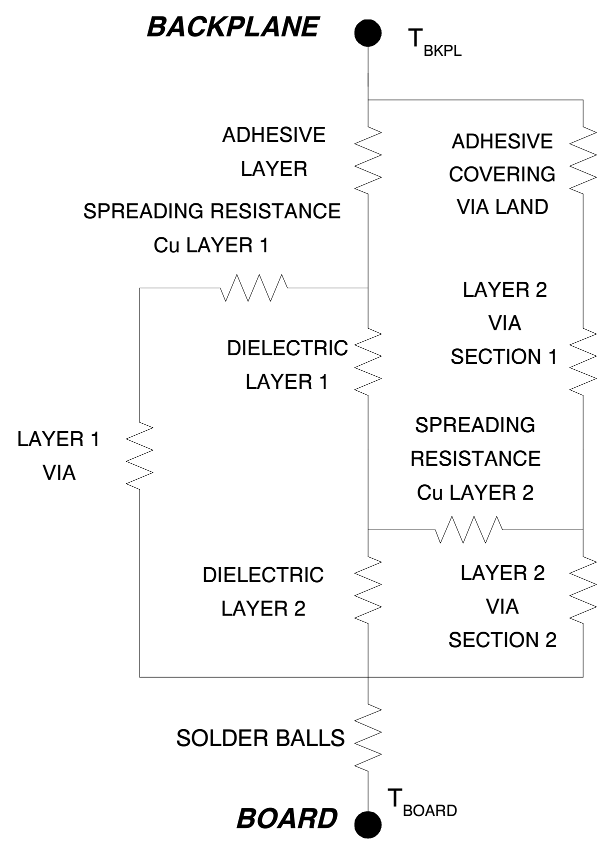


Thermal Resistor Network for SBGA Package



Submodel to Calculate Thermal Resistance of Laminate





Solution of Thermal Resistance Network

Use successive approximations technique to solve for

– Temperatures on all surfaces with temperature-dependent heat transfer coefficients
– Simplify resistance networks by eliminating current loops: solution of equivalent resistors
– Size of thermal footprint of package (PBGA package)

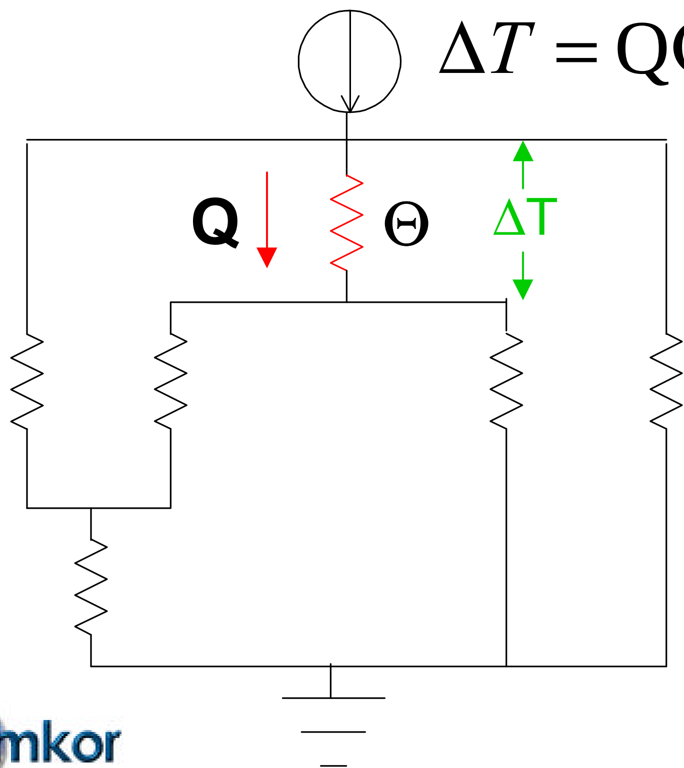
Elimination of Current Loops

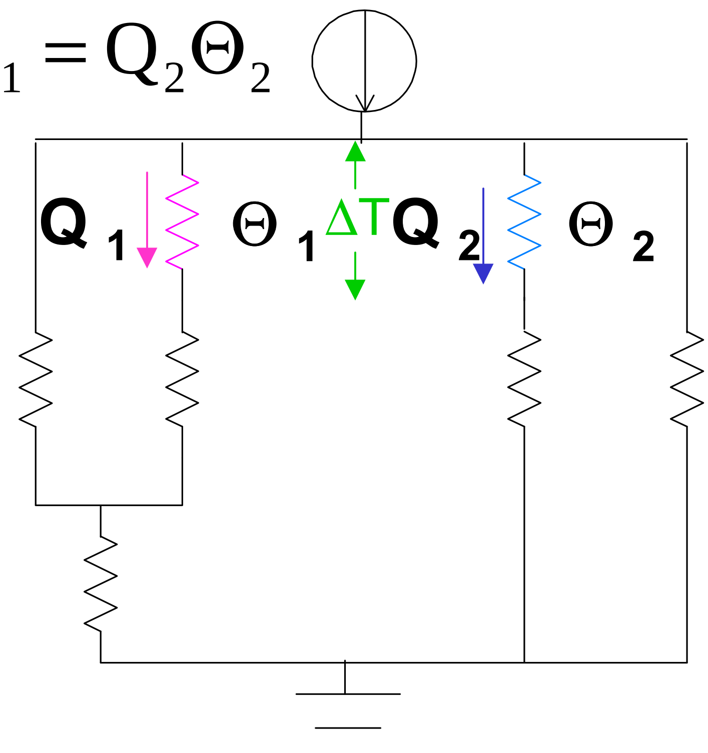
To simplify circuit into simple series and parallel resistor networks

Iterate f until ΔT across R_1 and R_2 is the same as across R

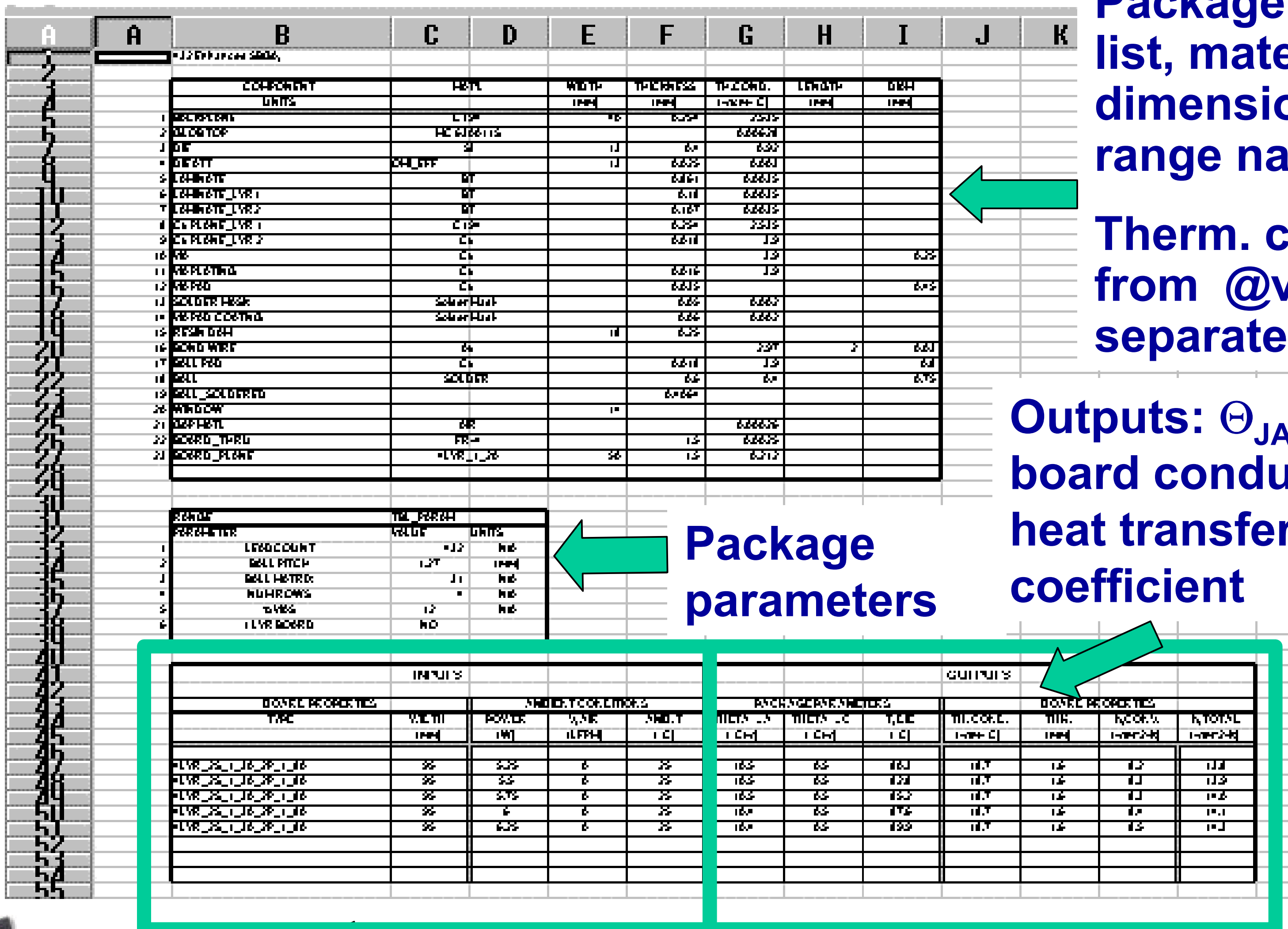
$$Q = Q_1 + Q_2 \qquad Q_1 = f\,Q,\;\; Q_2 = (1-f)Q$$

$$\Delta T = Q\Theta = Q_1\Theta_1 = Q_2\Theta_2$$





Structure of Spreadsheet



Package component list, materials, and dimensions -- given range name:$tbl_inputs

Therm. cond. values from @vlookup link to separate file

Package parameters

Outputs: Θ_{JA}, Θ_{JC}, board conductivity, heat transfer coefficient

Application-specific inputs: board type, power, air velocity,...

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Example of Thermal Resistance Calculation: Circular Fin

	A	B	C	D	E	F	G
1							
2			INPUTS			LOCAL	
3		Components				OUTPUTS	
4		COMPONENT	Type	THICKNESS	TH.COND.		
5				(mm)	(w/mm-°C)		
6		Board	4LYR_1S_1_20_2P_1_100	1.57	2.50E-02		
7							
8		COMPONENT	WIDTH			R,equiv	
9			(mm)			(mm)	
10		Package Body	28			15.80	
11							
12		COMPONENT	WIDTH			R,equiv	
13			(mm)			(mm)	
14		Board	50			28.21	
15							
16		Environmental					
17		h					
18		(W/mm^2-K)					
19		2.00E-05					
20							
21				LOCAL OUTPUTS			
22		Parameter				Value	Units
23		alpha				0.032	
24		K,1(alpha b)*I,0(alpha a) + I,1(alpha b)*K,0(alpha a)				1.22	
25		I,1(alpha a)*K,1(alpha b) - I,1(alpha b)*K,1(alpha a)				-0.63	
26		1/(2 pi a t k alpha)				8.04	(°C/W)
27				GLOBAL OUTPUTS			
28		Theta,board-to-air				15.58	(°C/W)

Value of Width obtained by linking to table on input page thru special function:

@XINDEX($TBL_INPUTS, C12,$B10)

+@BESSELK(F23*F14,1)
*@BESSELI(F23*F10,0)+
@BESSELI(F23*F14,1)*
@BESSELK(F23*F10,0)

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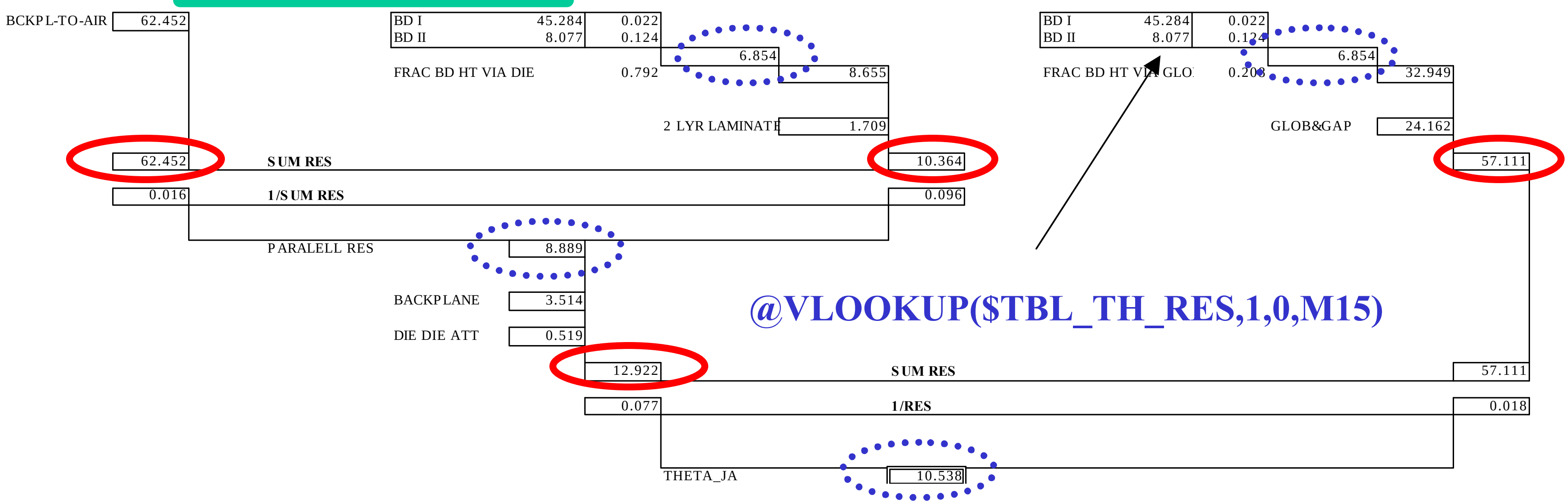
Spreadsheet Solution of Resistance Network

0	LAMINATE	3.64
1	BACKPLANE	3.51
2	WIRES_TRACES	N/A
3	GLOB&GAP	24.16
4	DIE DIE ATT	0.52
5	BD I	45.28
6	BD II	8.08
7	BCKPL-TO-AIR	62.45
8	2 LYR LAMINATE	1.71
	FRAC_HT_BD	0.88

Lookup table linked to solutions of individual resistors, each on separate pages -- named $TBL_TH_RES



= Series Resistor Solution

= Parallel Resistor Solution

Example of Macros to Solve Non-Linear Resistor Network

MACRO: /ITER_LOOP	START	STOP	STEP		COUNTER
{FOR J6,1,50,1,/LOOP}	1	50	1	/LOOP	9

MACRO: /LOOP	START	STOP	STEP		COUNTER
{IF MAX_ERROR<0.1}{RETURN}					
{FOR J11,1,5,1,/ITER_T_DIE}	1	5	1	/ITER_T_DIE	1
{FOR J12,1,5,1,/ITER_T_BOARD}	1	5	1	/ITER_T_BOARD	1
{FOR J13,1,5,1,/ITER_FRAC_DIE}	1	5	1	/ITER_FRAC_DIE	1
{FOR J14,1,5,1,/ITER_FRAC_BD}	1	5	1	/ITER_FRAC_BD	1

MACRO: /ITER_T_DIE			
{LET $T_BKPL_TRIAL,63.1744}	$T_BKPL_'	$DEL_T_BI	25
{CALC}			
{IF 0.0459<0.100}{FORBREAK}		$DEL_T_BI	0.1
{RETURN}			

MACRO: /ITER_T_BOARD			
{LET $T_BOARD_TRIAL,56.7619}	$T_BOARI	$DEL_T_BI	25
{CALC}			
{IF 0.0336<0.100}{FORBREAK}		$DEL_T_BI	0.1
{RETURN}			

MACRO: /ITER_FRAC_DIE			
{LET FRAC_DIE,0.8162}	FRAC_DIE	$DEL_T_J	5000
{CALC}			
{IF 0.2463<0.100}{FORBREAK}		$DEL_T_J	0.1
{RETURN}			

MACRO: /ITER_FRAC_BD			
{LET FRAC_DIE_HT_BD,0.8573}	FRAC_DIE_	$DEL_T_BI	2500
{CALC}			
{IF 0.1156<0.100}{FORBREAK}		$DEL_T_BI	0.1
{RETURN}			

Example of Solved Resistor Network: SBGA® Package

THERMAL RESISTANCE NETWORK FOR 432 LEAD SBGA PACKAGE

PACKAGE PARAMETERS

WIDTH	40	mm
ROW COUNT	4	
BALL PITCH	1.27	mm
BALL MATRIX	31x31	
CAVITY SIZE	14.00	mm
DIE WIDTH	12.70	mm

Bruce M. Guenin, Ph.D.
Amkor Electronics
Advanced Product Development
08-Aug-97

JUNCTION

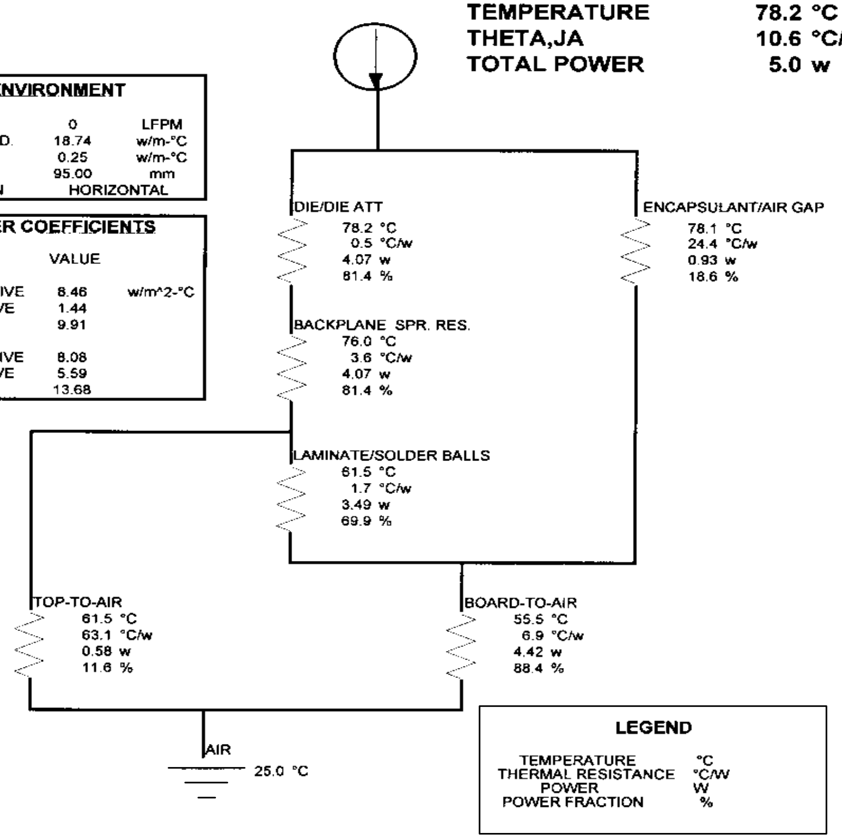
TEMPERATURE	78.2 °C
THETA,JA	10.6 °C/w
TOTAL POWER	5.0 w

PACKAGE ENVIRONMENT

AIR VELOCITY	0	LFPM
IN-PLANE BOARD COND.	18.74	w/m-°C
THRU BOARD COND.	0.25	w/m-°C
BOARD WIDTH	95.00	mm
BOARD ORIENTATION	HORIZONTAL	

HEAT TRANSFER COEFFICIENTS

SURFACE	TYPE	VALUE	
PKG. TOP	CONVECTIVE	8.46	w/m^2-°C
	RADIATIVE	1.44	
	TOTAL	9.91	
BOARD	CONVECTIVE	8.08	
	RADIATIVE	5.59	
	TOTAL	13.68	



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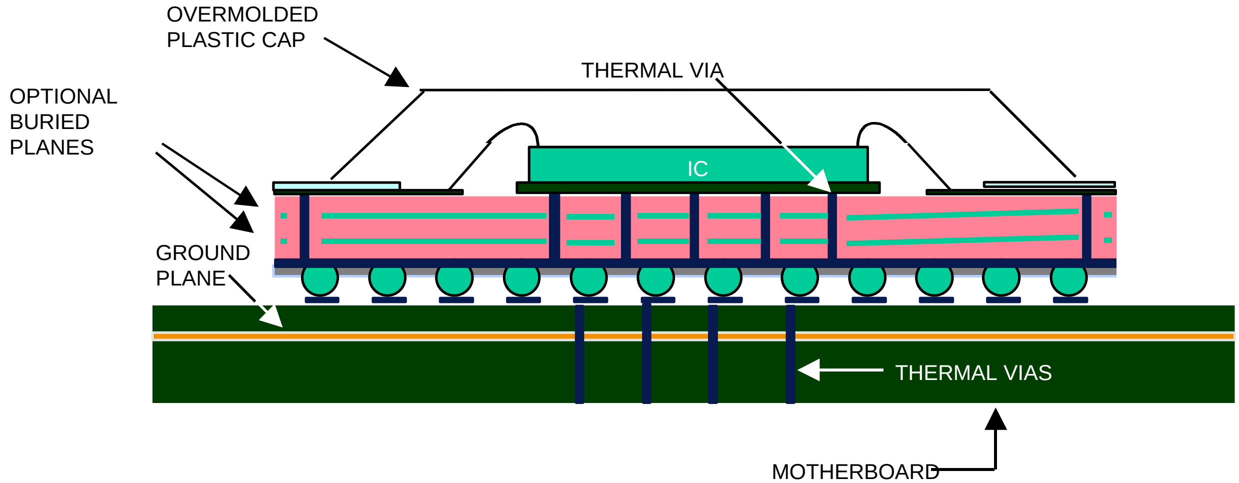
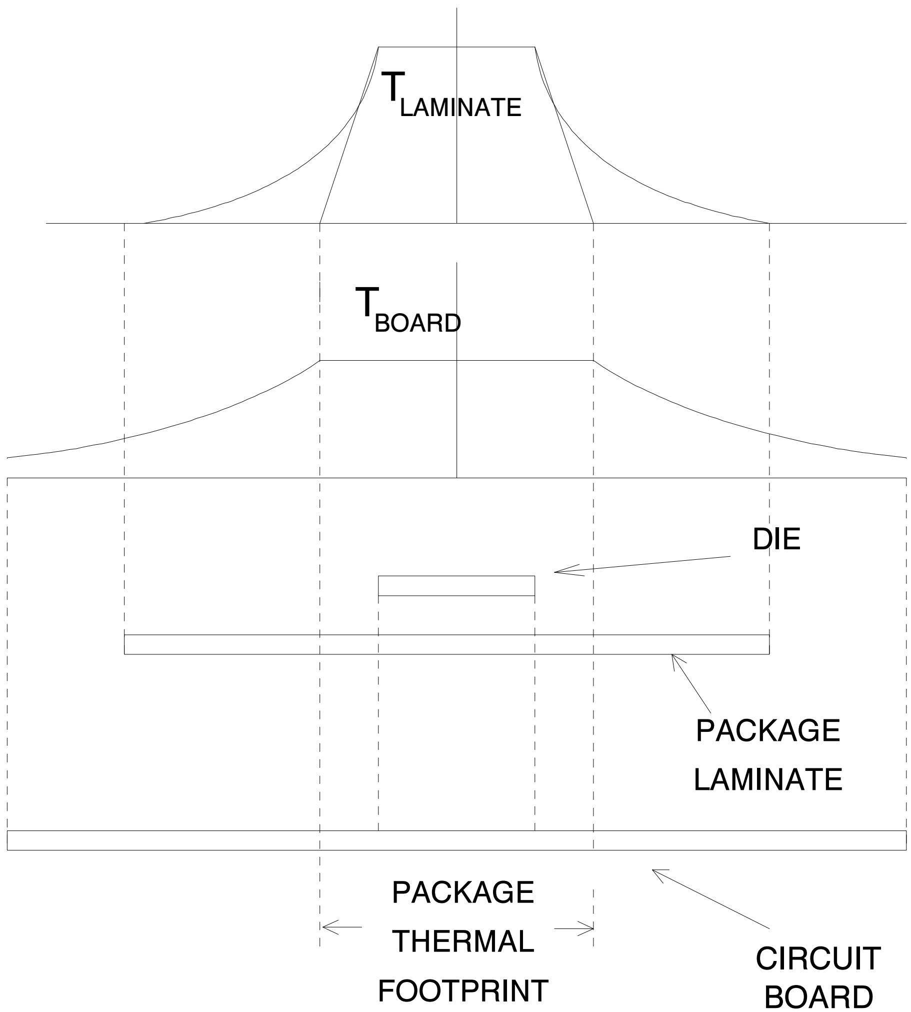
Another Example -- PBGA Package



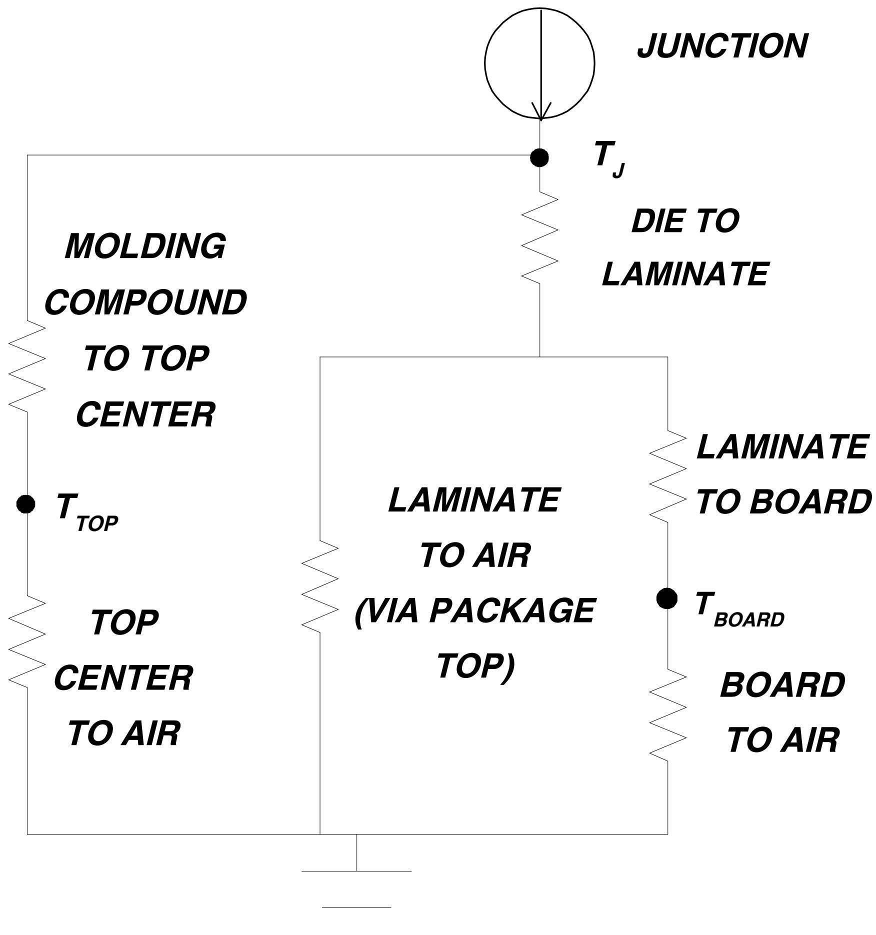
Reference: B. M. Guenin, B. S. Lall, R. J. Molnar, and R. C. Marrs, "A Study of the Thermal Performance of BGA Packages," *Proceedings, International Flip Chip, Ball Grid Array, TAB, and Advanced Packaging Symposium*, February, 1995, pp 37-46.

PBGA Temperature Distribution

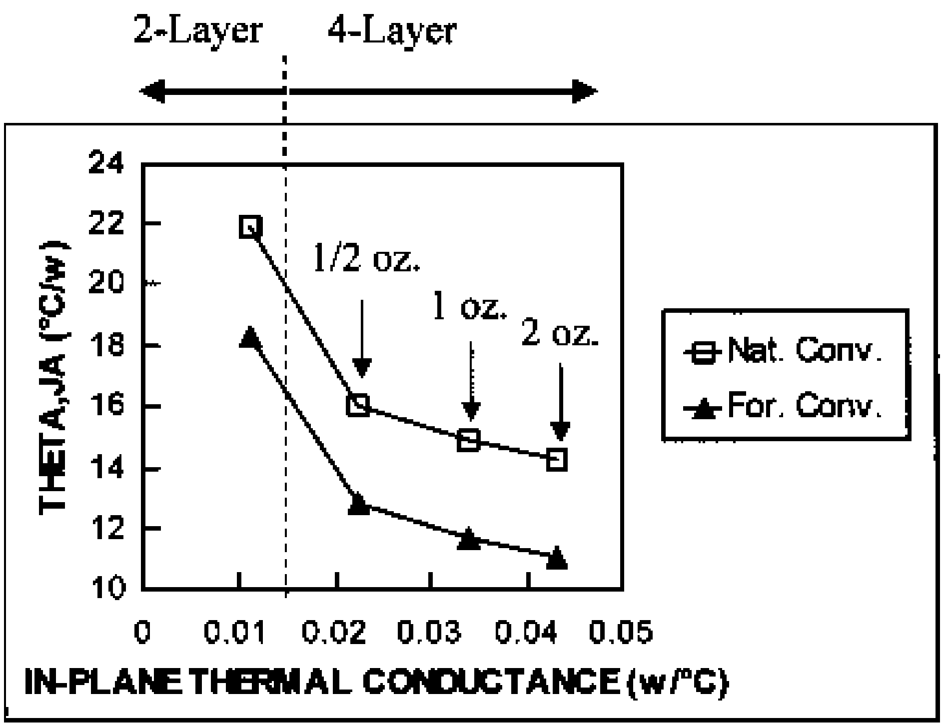


Size of Package Thermal Footprint Determined by Competition Between Heat Spreading and Heat Extraction

Thermal Resistance Network for PBGA Package



Effect of Laminate Metal Content



Model Assumptions:

313 Lead, 35 mm PBGA Pkg.

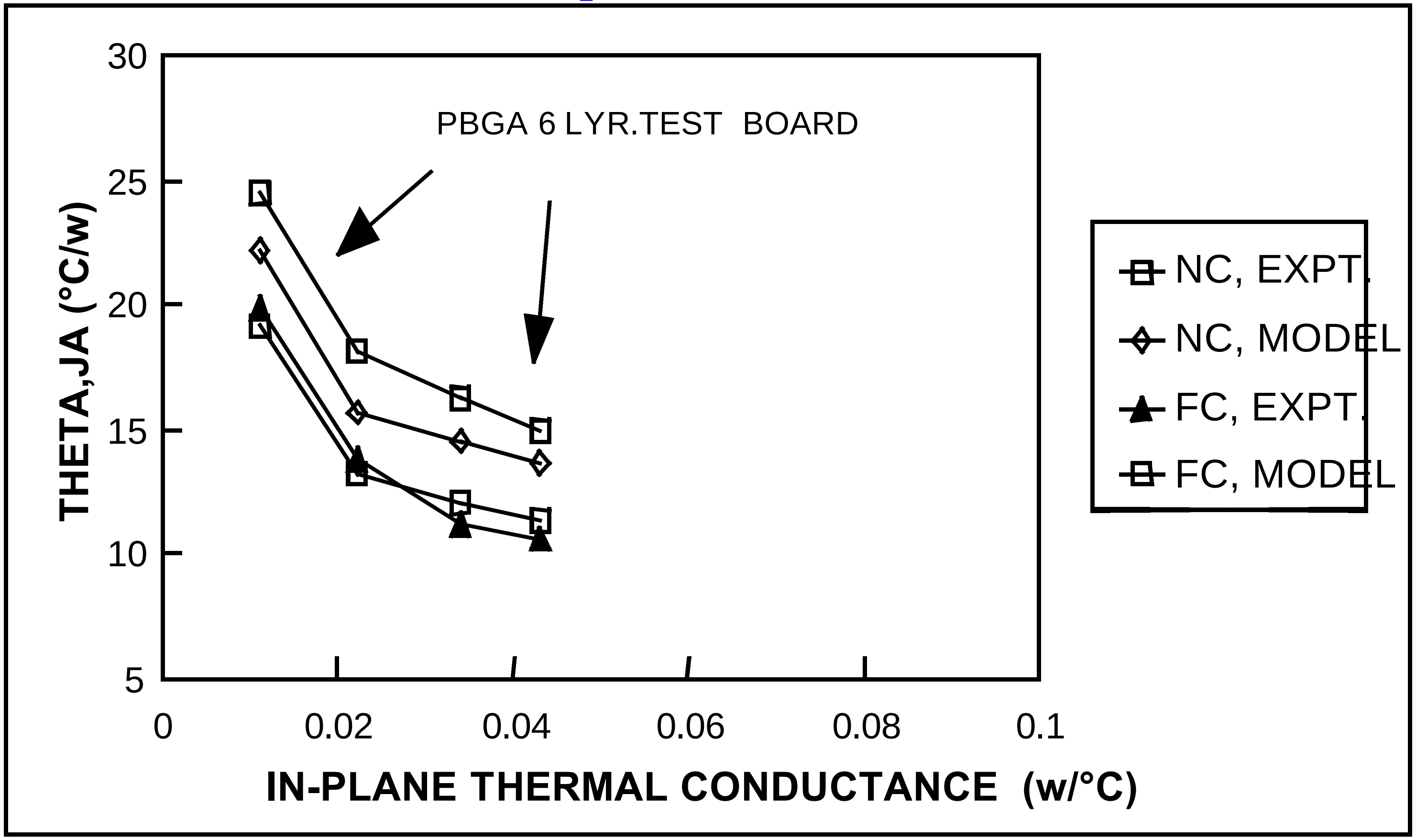
Full Matrix Array

Natural Convection: 4 watt

Forced Convection: 2.5 m/s

6-Layer Board, 80 mm width

PBGA Model -- Comparison with Experiment



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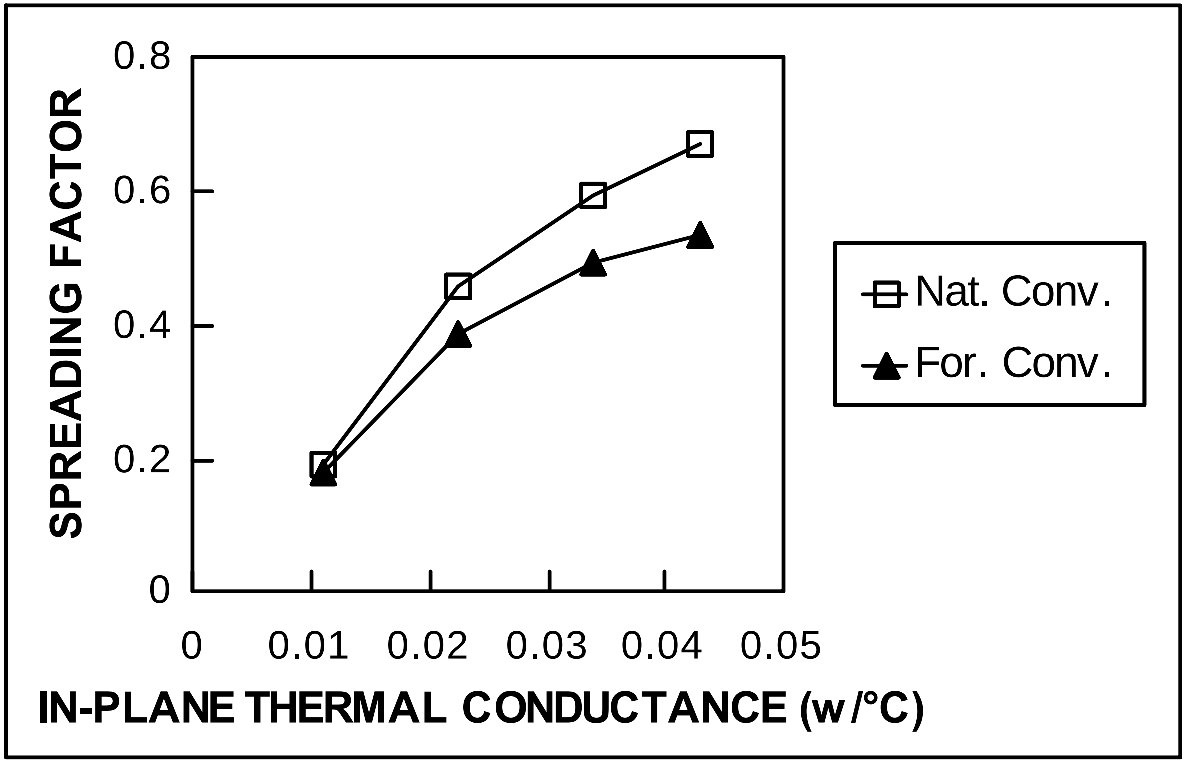
Effect of Laminate Metal Content



Model Assumptions:

313 Lead, 35 mm PBGA Pkg.

Full Matrix Array

Natural Convection: 4 watt

Forced Convection: 2.5 m/s

6-Layer Board, 80 mm width

$$\text{Spreading Factor} = \frac{W_{FOOTPRINT} - W_{DIE}}{W_{PKG} - W_{DIE}}$$

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Tradeoffs in Modeling Approaches

Analytical conduction models can adequately predict package thermal performance in simple configurations.

When a package design follows a fixed format, analytical models can be very efficient, justifying the time to develop.

When there are frequent variations in package design, the use of a finite element analysis code is more practical than an analytical approach.

For complicated configurations, dominated by convective heat transfer, a computational fluid dynamics code is most efficient.

Summary

Conduction in leadframe and BGA plastic packages can be described in terms of simple thermal resistive elements, calculated analytically

Convective and radiative heat transfer in a standard thermal test environment can be accounted for using simple analytical expressions

Resistor networks lend themselves to efficient solution of non-linear problems and to rationalizing the thermal performance of a package

Spreadsheets are efficient tools for solving analytical thermal resistance networks