Pro/MECHANICA® Wildfire™ 4.0

Heat Transfer Coefficients & Thermal Contact Resistance

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Convection

- Convective Heat Transfer Rate Equation (Newton's Law of Cooling)

$$q = \frac{Q}{A} = h(T_s - T_\infty)$$

  - Where q = Heat Flux (W/m^2)
  - Q= Heat Transfer Rate (W)
  - T_s is Temperature at Surface of Solid
  - T_∞ is the Bulk Fluid Temperature
  - h is the Heat Transfer Coefficient, or Film Coefficient ($Wm^{-2}K^{-1}$)

Heat Transfer Coefficients

- You can calculate 'h' using the following

$$h = \frac{K}{L} Nu$$

where Nu is the Nusselt Number,
K is the Conductivity of the Fluid and
L is the Characteristic Length

- For Forced Convection

From 'Introduction to Heat Transfer', by Incropera & De Witt

Laminar Flow

$$Nu = 0.664 \, \mathrm{Re}^{1/2} \, \mathrm{Pr}^{1/3}$$

Turbulent Flow

$$Nu = 0.0296 \, \mathrm{Re}^{4/5} \, \mathrm{Pr}^{1/3}$$

- Turbulent Flow - Alternative Method from PTC 'How To'

$$Nu = (0.037 \, \mathrm{Re}^{0.8} \, \mathrm{Pr})/(1 + 2.443 \, \mathrm{Re}^{-0.1} \, (\mathrm{Pr}^{0.6667} - 1))$$

Where Re is the Reynolds No.
(Ratio of Inertia Forces over Viscous Forces)

$$\mathrm{Re} = \frac{VL}{\nu}$$

Pr is the Prandtl No.
(Ratio of Momentum to Thermal Diffusivity)

$$\mathrm{Pr} = \frac{\nu \rho C_p}{K}$$

Where V = Velocity of Moving Fluid, ν=Fluid Kinematic Viscosity

g is the acceleration due to gravity, Cp = Specific Heat

ρ = Density

Heat Transfer Coefficients

- You can calculate 'h' using the following

$$h = \frac{K}{L} Nu$$

where Nu is the Nusselt Number,
K is the Conductivity of the Fluid and
L is the Characteristic Length

- For Free Convection (Vertical Plate)

Laminar Flow

$$Nu = \frac{4}{3}\left(\frac{Gr}{4}\right)^{1/4} g(\Pr)$$

where

$$g(\Pr) = \frac{0.75 \Pr^{1/2}}{\left(0.609 + 1.221 \Pr^{1/2} + 1.238 \Pr\right)^{1/4}}$$

Turbulent Flow

$$Nu = 0.1(Gr.\Pr)^{1/3}$$

Gr is the Grashof No.

(Ratio of Buoyancy Forces to Viscous Forces)

$$Gr = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2}$$

Pr is the Prandtl No.

(Ratio of Momentum to Thermal Diffusivity)

$$\Pr = \frac{\nu\rho C_p}{K}$$

Where V = Velocity of Moving Fluid,
ν=Fluid Kinematic Viscosity

g is the acceleration due to gravity
β is Volumetric Thermal Expansion Coefficient

ρ = Density
Cp = Specific Heat

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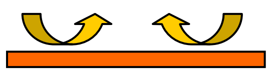
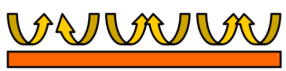
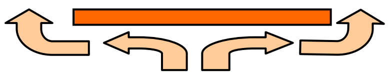
Heat Transfer Coefficients

- You can calculate 'h' using the following

$$h = \frac{K}{L} Nu$$

where Nu is the Nusselt Number,
K is the Conductivity of the Fluid and
L is the Characteristic Length

- For Free Convection (Horizontal Plate)

Laminar Flow	Turbulent Flow	'Trapped' Flow	
			Where Ra is the Rayleigh No.
$Nu = 0.54 Ra^{1/4}$	$Nu = 0.15 Ra^{1/3}$	$Nu = 0.27 Ra^{1/4}$	$Ra = (Gr.\Pr)$
Ra<1e7	Ra>1e7		

Gr is the Grashof No.
(Ratio of Buoyancy Forces to Viscous Forces)

$$Gr = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2}$$

Pr is the Prandtl No.
(Ratio of Momentum to Thermal Diffusivity)

$$\Pr = \frac{\nu\rho C_p}{K}$$

Where V = Velocity of Moving Fluid, g is the acceleration due to gravity, ρ = Density

ν=Fluid Kinematic Viscosity, β is Volumetric Thermal Expansion Coefficient, Cp = Specific Heat

Typical Values of 'h'

Process	h (W/(m^{2}K))	h (mW/(mm^{2}K))
Free Convection		
Gases	2-25	0.002-0.025
Liquids	50-1000	0.050-1.0
Forced Convection		
Gases	25-250	0.025-0.250
Liquids	50-20000	0.050-20.0
Phase Change		
Boiling/Condensation	2500-100000	2.5-100.0

Thermal Resistance

- Analogous to Electrical Resistance
  - Conductive Thermal Resistance

$$R = \frac{1}{KA}$$

  - Convective Thermal Resistance

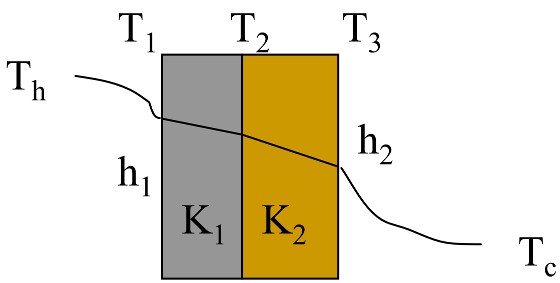
$$R = \frac{1}{hA}$$

  - Radiative Thermal resistance

$$R = \frac{1}{h_r A}$$

- Can be combined in series or parallel to get overall Thermal Resistance

Multiple Materials



- Know Overall Temp Drop from Hot Fluid to Cold Fluid T_h - T_c
- Calculate Thermal Resistances and hence Total Thermal Resistance, R_t
- Therefore Overall Heat Transfer Coeff, U =1/R_t
- Therefore calculate Heat Transfer Rate/Unit Area. (Flux), q
- Heat Flux is Constant through system, therefore calculate temperature drop across each resistance ΔT=qR
- Thus find temps at each surface (Assumed same at internal surface)

Hot Fluid Temp, Th	923
Cold Fluid Temp, Tc	615
Heat Transfer Coeff, h1	0.055
Heat Transfer Coeff, h2	0.019
Thermal Resistance, R1 = 1/h1	18.1818
Thermal Resistance, R4 = 1/h2	52.63158
Thickness, t1	0.254
Thickness, t2	0.5
Conductivity, K1	12.4
Conductivity, K2	12.4
Thermal Resistance, R2 = t1/K1	0.0205
Thermal Resistance, R3 = t2/K2	0.0403
Total Thermal Resistance, Rt= R1+R2+R3+R4	70.8742
Overall Heat Transfer Coeff, U =1/Rt	
= 1/(1/h1+t1/K1+t2/K2+1/h2)	0.01411
Overall Temperature drop DT = Th – Tc	308
Heat Transfer rate for unit area, qa=q/A = ΔT/Rt	4.345728
Temp Drop ΔT1 = qa x R1	79.01323
Temp Drop ΔT2 = qa x R2	0.089017
Temp Drop ΔT3 = qa x R3	0.175231
Temp Drop ΔT4 = qa x R4	228.7225
Check Temperature Drop	308
Calculated Skin Temp, T1 = Th-ΔT1	844
Calculated Skin Temp, T3 = Tc+ΔT3	843.7
Calculated Interface Temp, T2 = T1-ΔT2	843.9

Contact Resistance

- Previously assumed that if solids are touching, they are in perfect contact, i.e. No temp drop across the contact. In practice this may not be true. Some typical values are given below.
- Contact Resistance, R_o
  - Where h_o = interfacial conductance

$$R_o = \frac{1}{h_o A}$$

Interface	Interfacial Conductance, h_o (W/m^2K)
Ceramic to Ceramic	500-3000
Ceramic to Metals	1500-8500
Aluminium to Aluminium	2200-12000
Copper to Copper	10000-25000

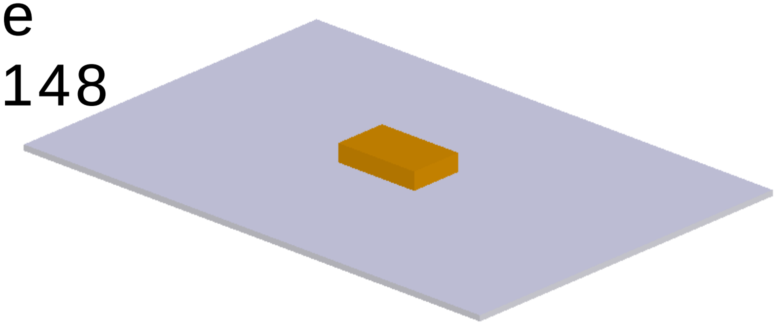
- Mechanica cannot model contact resistance directly in WF3, but it is in WF4
- Work around is to introduce another layer, thickness t with conductivity, K, set to give desired contact resistance.

$$K = \frac{t}{R_o}$$

- Or to alter the thermal conductivities of the materials to take into account contact resistance at the boundaries.

Chip on PCB

- Model – Simple Chip on PCB
  - Assign PCB material to the board Isotropic K = 0.2 N/(sec C)
  - SiliconChip material to the Chip part. Isotropic, K = 148 N/(sec C)
  - Create surface region on board under chip
  - Make measures at points top & bottom of board & chip



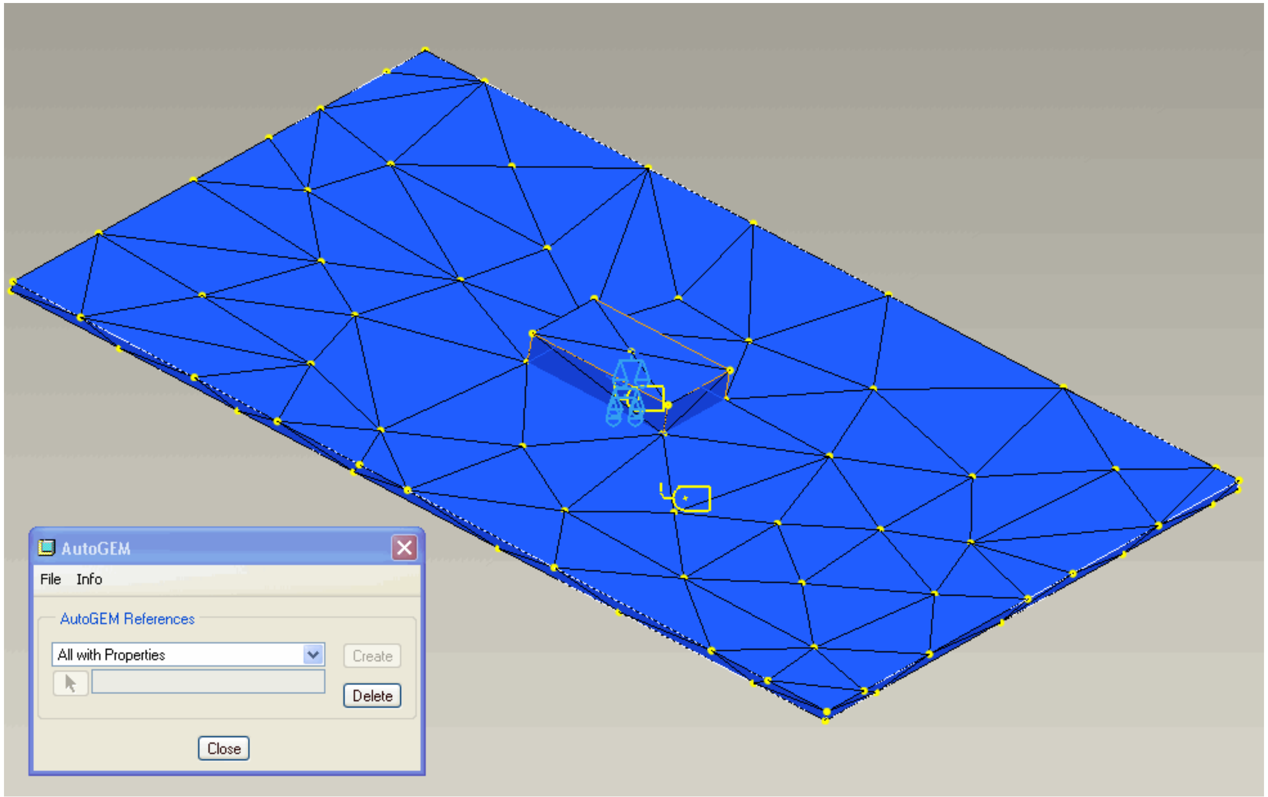
Chip on PCB

- Estimated Heat Transfer Coefficients
  - Use HeatTransferCoefficients.xls to calculate estimate h-values
  - Assume Natural (Free) Convection

Surface	L1	L2	L	Est Temp	Rayleigh No	Orientation	Flow	H mW/mm2-K
Top of Chip	.025	0.015	0.004	80	2.8e2	Hor.	Laminar	0.013
Chip Long Side	.025	.005	.002	80	1.8e1	Vert.	Laminar	0.016
Chip Short Side	.015	.005	.002	80	1.8e1	Vert.	Laminar	0.016
PCB Top	.150	.100	.030	50	2.4e4	Hor	Laminar	0.007
PCB Btm	.150	.100	.030	50	2.4e4	Hor	Trapped	0.0035

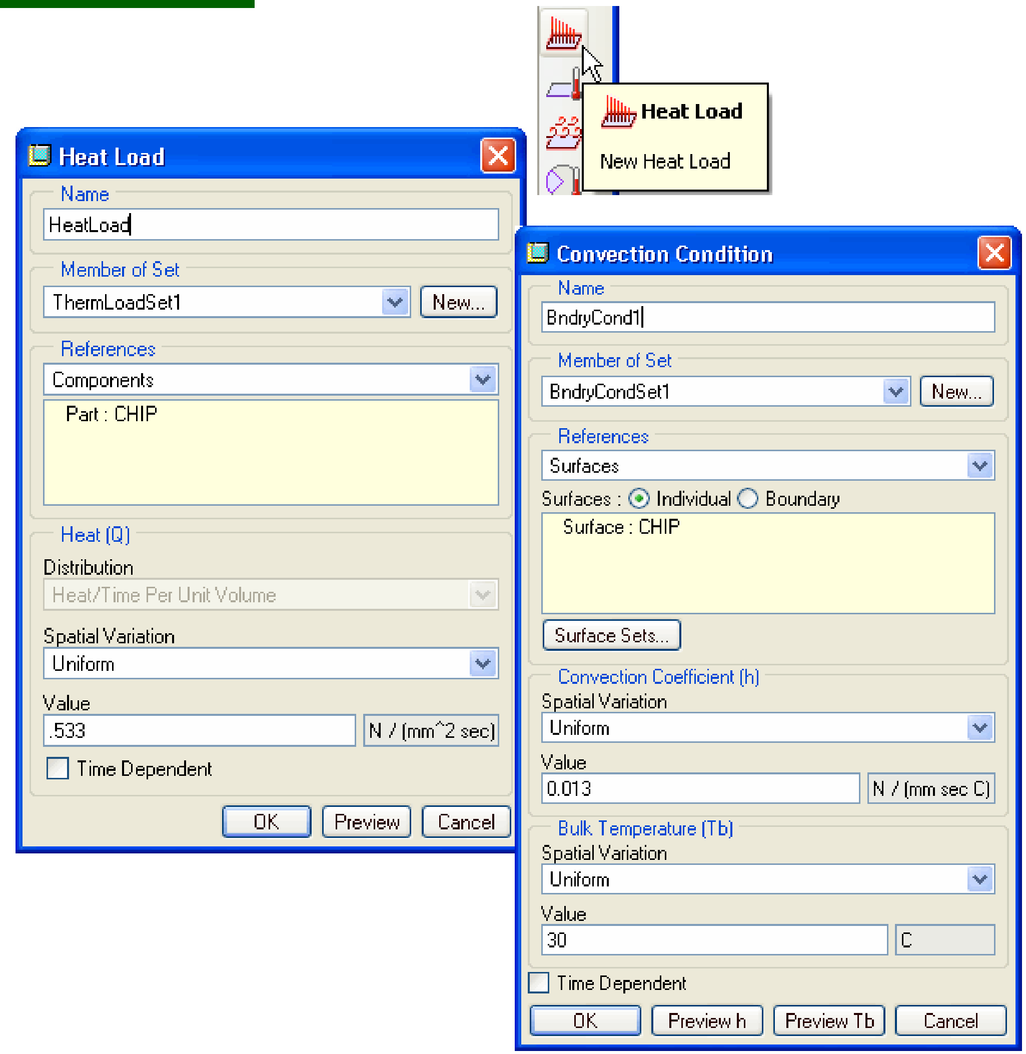
Chip on PCB

- Mesh the assembly (All solids)



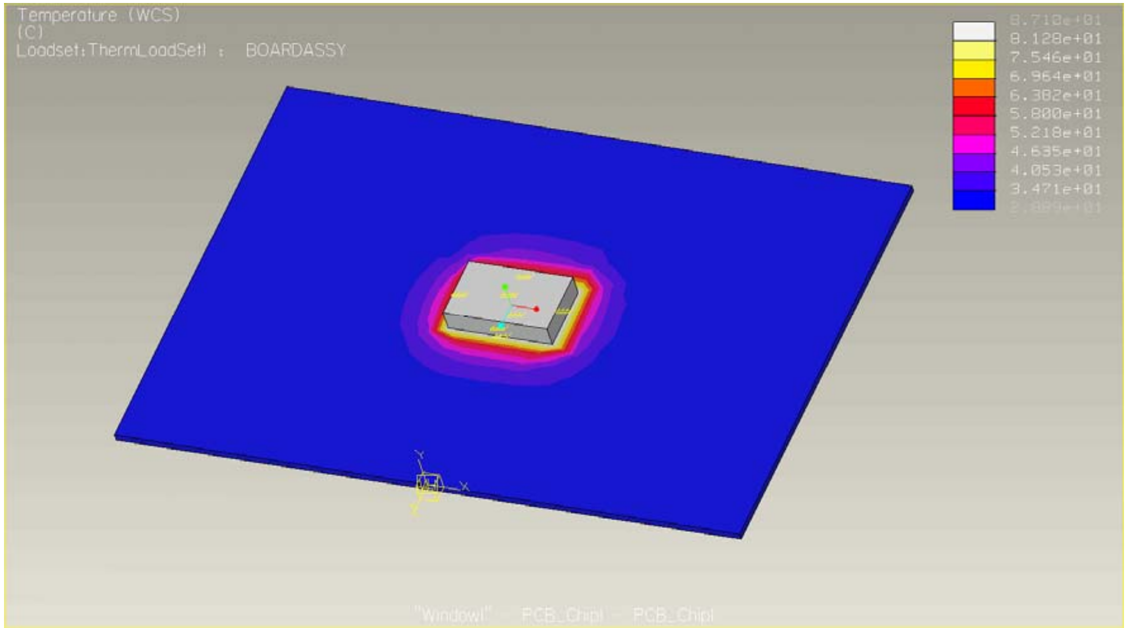
Chip on PCB

- Apply a Volume heat load to the chip component, of 0.533 mW/mm^3 (or $N/(mm^2s)$)
- Note Volume=1875 mm^3, so Total Q = 1W
- Apply boundary conditions
- No Thermal Interface, so perfect Contact
- Set up and run a Steady State Thermal analysis called ‘PCB_Chip1’



Chip on PCB

- Review Results PCB_Chip1 - Max Temp = 87.1 ^{o}C

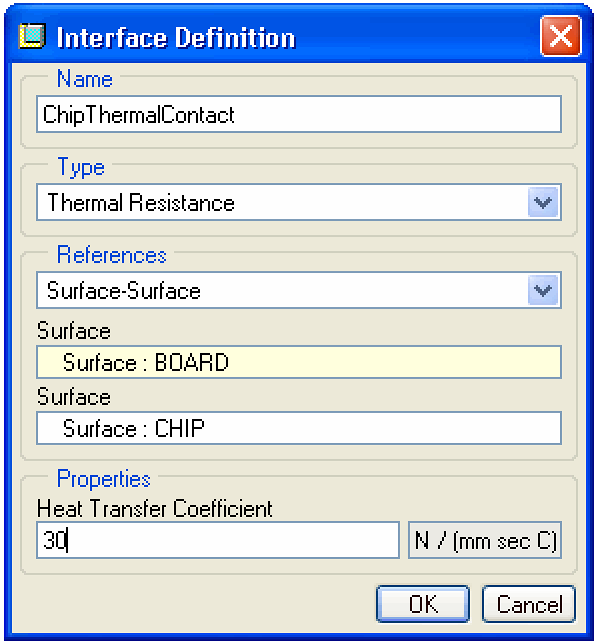


Temp Btm of Board	Temp Top of Board	Temp Btm of Chip	Temp Top of Chip
85.7	87.1	87.1	87.1

Chip on PCB

Add Thermal Contact Interface

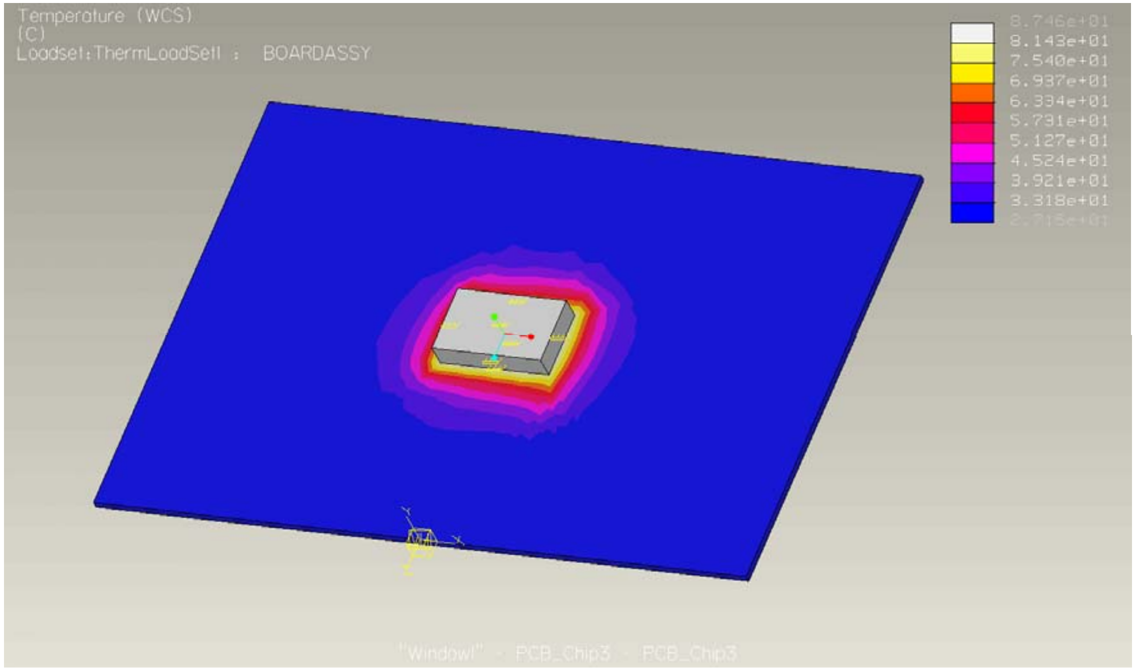
- From Incropera & DeWitt, Contact Resistance, R_0 for Silicon Chip to Aluminium, with a 0.02mm Epoxy Interface is between 20e-4 & 90e-4 m^2-K/W for a unit area.
- Therefore, as $h_0 = 1/R_0$, h_0 is between 11000 & 50000 W/m^2-K, say 30,000 W/m^2-K, which is 30 mW/mm^2-K or N/(mm sec C)
- Re-Mesh
- Run a Steady State Thermal analysis called 'PCB_Chip3'



Chip on PCB

- Review Results PCB_Chip3 - Max Temp = 87.5 ^oC

H_o = 30



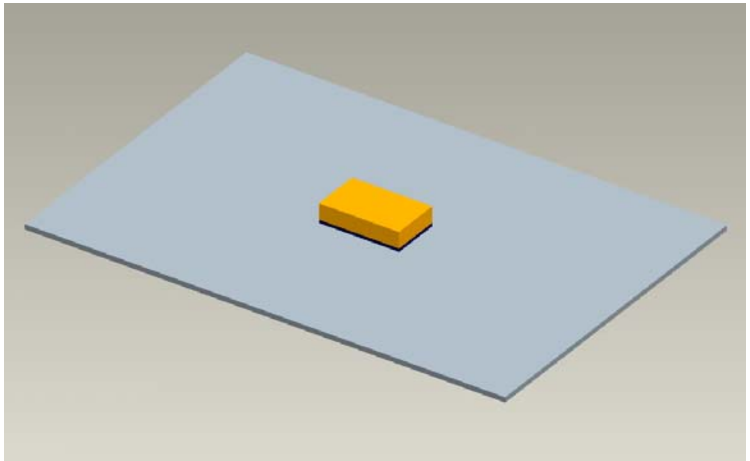
Temp Btm of Board	Temp Top of Board	Temp Btm of Chip	Temp Top of Chip
80.5	85.0	84.7	84.7

Chip on PCB

- Compare with 'Old-Fashioned' Method
  - Add component 'Contact Layer' to represent contact resistance
  - Thickness = 1mm
  - Calculate conductivity K, to give desired contact resistance of 33.3e-4 m^2-k/W (33.3e-2 mm^2-k/W), (ho = 30 W/mm2-K) mm.

$$K = \frac{t}{R_o}$$

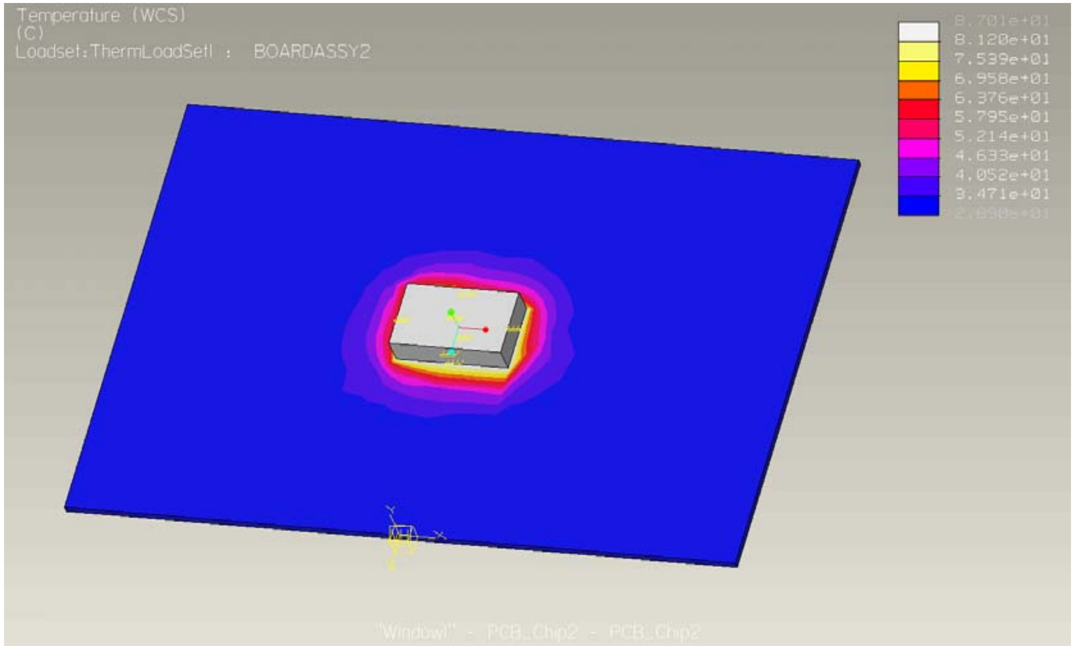
  - K= 30 N/(sec C) (W/mm-K)



Chip on PCB

- Review Results PCB_Chip2 - Max Temp = 87.0 ^oC

Old Method Extra Layer



Temp Btm of Board	Temp Top of Board	Temp Btm of Chip	Temp Top of Chip
85.9	87.0	87.0	87.0

Chip on PCB

- Repeat with Different Contact Resistances
- Summary of Results (all SPA)

h_o mW/mm^2-K	Max Temp	Temp Btm of Board	Temp Top of Board	Temp Btm of Chip	Temp Top of Chip
Bonded Perfect Contact	87.1	85.7	87.1	87.1	87.1
30	87.5	80.5	85.0	84.7	84.7
200	87.1	80.4	84.5	84.4	84.4
1	88.4	80.5	88.4	87.7	87.7
.001	116.0	38.8	38.8	116.0	116.0
Old Method Extra Layer	87.0	85.9	87.0	87.0	87.0
Adiabatic Interface	118.7	30	30	118.7	118.7