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Printed Circuit Board (PCB) Thermal Analysis

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Abstract— Because of Complex design and higher demand for Printed Circuit Boards (PCB), thermal design of PCB pose challenges to any heat transfer designer for perfect design. PCB design proceeds on the strength of various assumptions in the predictions of temperatures. Generally, problems were solved for temperatures of a given PCB card without taking all factors into consideration, but the obtained results for those problems are not totally correct. So a forward step was taken by considering all factors to get the correct results. Some of the factors affecting temperature distribution in PCBs are device power dissipations, their distribution in a board, layer-wise thermal conductivity and copper (Cu) spread within a PCB, nature of drill-holes / thermal mass distribution and finally electrical heating effects affecting thermal performance of PCBs. All the above factors bring uncertainty in prediction of temperatures in devices and inferior design generally results in de-lamination of PCB layers. Likewise, Joule Heating phenomenon also impacts the thermal analysis which normally occurs in PCB. Effects of DC drop due to passage of electric current inside Cu-traces, impacts Joule heating effects inside traces of the board and lead to trace level fusing. So in this report the trace level heating was done with different Mechanical computer Aided Engineering (MCAE) software tools by giving the required boundary conditions and results were obtained. The problems were also solved for no-joule heating case and compared.

Keywords—Thermal Conductivity, Joule heating, Trace level Hating.

I. INTRODUCTION

With Complex Design and increasing wattage of devices, the total heat flux from electronic components is steadily increasing. This will result in temperature difference and overheating of the PCBs and respective parts, which effects the electrical performance and safety.

A Printed Circuit Board (PCB) is generally defined as the board where electrical components are connected electrically and supported mechanically by using pads, conductive tracks, and other features engrave from copper sheets overlay onto a non-conductive substrate. The Conductive circuit, which is mainly used in PCB, is copper, even though aluminum, nickel, chrome and other metals are used sometimes. The printed circuit boards are generally made of glass reinforced plastic material with copper traces in place of wires. The board is typically coated with solder mask which is green in color. Fixing of components in position is done by drilling holes through the board, then soldering of components is done after locating them. The copper traces form a circuit by linking the components together.

There are three collection of printed circuit boards, which are generally used: single-sided one, double-sided one, and multi-layered one.

1. *Single Sided Board*: only one surface of dielectric base is placed through conductors.
2. *Double-Sided Board:* both sides of a dielectric base is placed through conductors and plated-through-holes (PTHs) interconnects the layers usually.
3. *Multi-Layer:* 3 or more layers on board are modeled through conductors which are separated by dielectric material and PTH interconnects the layers or pads 4 layer PCB is similar to design of 2 double layered PCBs.

Likewise 6 layer PCB is a similar design of 3 double layered PCB. This modeling of layers is done by placing oxidizing material between double layered PCBs. The type of the board to be produced can be determined by density and structural requirement, and circuitry complexity. Dielectric material normally used is Epoxy.

PCB‟s are rugged, inexpensive and can be highly reliable. The advantage with the PCB‟s which makes the production easy is because of mass manufacturing. PCBs alternatives which are normally used but less compared to actual are Point-to-Point-Construction and Wire-wrap. PCBs manufacturing and assembly can be automated generally but it requires the supplementary design effort to map the circuit. As components are seated and cabled with one single part, erecting circuits with PCBs is faster and cheaper than any other electrifying methods.

When the PC board consists only copper network and without any embedded components, normally that type of board is known as Etched wiring Board or Printed Wiring Board. A board modeled with more computerized components is known as a Printed Circuit Assembly (PCA), PCB Assembly (PCBA) or Printed Circuit Board Assembly.

In previous times PCBs were designed manually by generating a Photo mask on a clear Mylar sheet, generally at two or four times more than the prescribed size. At starting of schematic diagram the Mylar sheet was laid out by component pin pads and then routing was done to traces to connect the pads. Traces were designed with self-adhesive tape. Pre-Printed non-reproducing grids on the surface of Mylar sheet are assisted in Layout. finished photo mask was photo lithographically reproduced onto a photoresist coated on the blank copper-clad boards so that the fabrication of board is done. But Now-a-days the PCB design was made easy through dedicated layout software which helps to do accurate and perfect designs.

Normally the PCB is designed with the following parts:

(1) Components, (2) Pads, (3) Traces, (4) Vias, (5) Top Metal Layer, (6) Bottom Metal Layer.

So there is a need to develop and examine heat transfer processes in greater detail that allow electronic components to be maintained below their failure temperatures. This is due to the increasing demand for the development of more compact, complex and reliable electronic packages. The lifetime of the PCB is reducing day by day due to modern and minute designs so by doing the heat calculation or analysis with different conditions and compared, then the safe design of the PCB is done within the required conditions and temperatures.

II. METHODOLOGY

Theory used to solve a thermal problem requires lot of academic background is required to apply the conditions required for the solution. In this project study, some of the heat transfer basics are used to understand and get through the problems. As we know there are three modes of Heat transfer

(1) Conduction, (2) Convection, and (3) Radiation.

For doing the thermal analysis of PCB the work done in the report depends on conduction process.

In conduction, flow of heat is done by means of interaction between fast moving molecules nearer to the hot end of a body of matter and the slow-going molecules nearer to the cold end. There is a result of successive collisions when a moderate amount of kinetic energy of the speed molecules passes to relaxed molecules, flow of heat is through the body of matter from the hot end to the cold end. Liquids, gases, and solids all conduct heat. Molecules interact less frequently in gases because they are relatively far apart and less conductive compared to liquids and solids. Some electrons in metals are able to move freely and can often interact by collisions so they are best conductors of heat. Due to temperature gradient, the process is defined as a flow of heat. When across a boundary the processes of conduction yield a net flow of energy.

Fourier's law, is stated as the time rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area, at right angles to that gradient, through which the heat flows. This law is stated in two equalized forms: the differential form, in which locally we scrutinize at the fluxes of energy or fluxes of energy .the integral form, in which as a whole we scrutinize at total amount of energy flowing in or out of a body, Ohm's is the electrical analogue of Fourier's law and while Newton's law of cooling is a discrete analog of Fourier's law.

Fourier's Law of thermal conduction differential form shows that the product of thermal conductivity, k, and the negative local temperature gradient, $-\nabla T$ is equal to the local heat flux density, $\overrightarrow{q}$.

The heat flux density is defined as the amount of energy that flows through a unit area per unit time.

$$\overrightarrow{q} = -k\nabla T$$

Where (In SI units)

$\overrightarrow{q}$ is termed as the local heat flux density, W·m−2

k is termed as the material's conductivity, W·m−1·K−1, is termed as the temperature gradient, K·m−1.

∇TFourier's law is applied in its one-dimensional form for many simple applications . In the x-direction,

$$q_x = -k\frac{dT}{dx}$$

Integral form:

By integrating the differential form over the material's total surface, then the integral form of Fourier's law is obtained as:

$$\frac{\partial Q}{\partial t} = -k \oint_S \nabla T \cdot \overrightarrow{dA}$$

Where (In SI units):

- əq/ət is given as the amount of heat transferred per unit time (in W), and
- $\overrightarrow{dA}$ is expressed in an oriented surface area element (in m2)

When the above differential equation is integrated for a homogeneous material of 1-D geometry at constant temperature between two endpoints, gives the equation for heat flow rate as:

$$\frac{\Delta Q}{\Delta t} = -kA\frac{\Delta T}{\Delta x}$$

III. THERMAL SOLVER

In PCB thermal analysis the analysis type normally used to solve is steady state analysis.

It is said that in theory of system, a steady state system has multiple properties that are not changing in time. This means that the partial derivative with respect to time will be zero for those properties p of the system

$$\frac{\partial p}{\partial t} = 0$$

Steady state is almost a normal situation compared to dynamic equilibrium. If a system is said to be in steady state, then the freshly observed behavior of the steady state system will proceed into the future. The probability of repetition of various state will remain constant in stochastic systems. In maximum of the systems, the steady state is not achieved for a time even though the system is started or initiate. This initial situation of the system is often diagnosed as a transient state, start-up or warm-up period.

When two or more reversible processes come at the same rate then the dynamic equilibrium occurs and such a type of system can be said steady state system. There is no rule that a system which is in steady state is always necessary to be in a state of dynamic equilibrium, because there is a chance that some of the theories involved in system are not reversible.

(3)When two solid bodies of any design come in contact to each other, the flow of heat takes place from the hot body to the cold body. With this experience, the temperature profile through the two bodies will be varied. There will be a drop in the temperature at the interface between the contacted surfaces. This phenomenon is result of thermal contact resistance that exists between the contacting surfaces. Thermal contact resistance is defined as the proportion between the average flow of heat across the interface and the temperature drop.

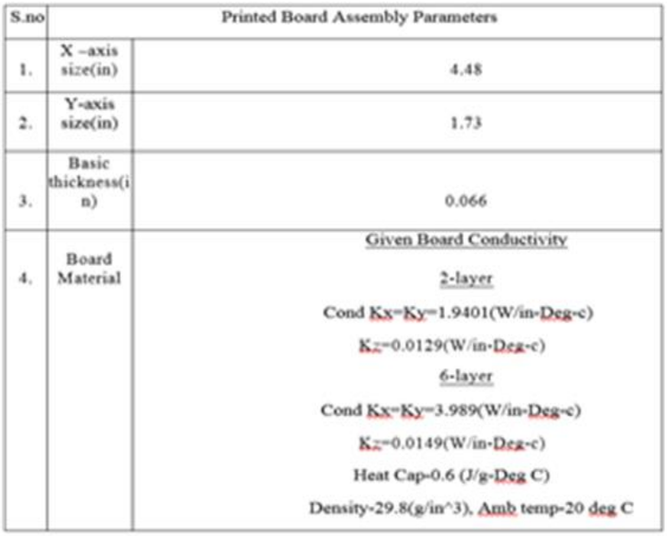
For a plate of thermal, area A, thickness L and conductivity k, The calculated conductance is kA/L, Measured in units W/K (4) By Stefan–Boltzmann law emissivity is the ratio of the thermal radiation from a surface to the radiation from an ideal black surface at the same temperature. The ratio of emissivity alters from 0 to 1. The surface of a black object emanate thermal radiation at the rate of 418 watts per square meter at room temperature. At correspondingly lower rates real objects emit radiation with emissivity's less than 1.

IV. PROBLEM SOLVING FOR NO-JOULE HEATING

A PCB board is taken with 24 number of components having different amount of heat dissipations (W). The prediction of the steady state temperature of a PCB has to be done in the problem. Affects due to various thermal parameters assigned to the components and board are studied and analyzed.

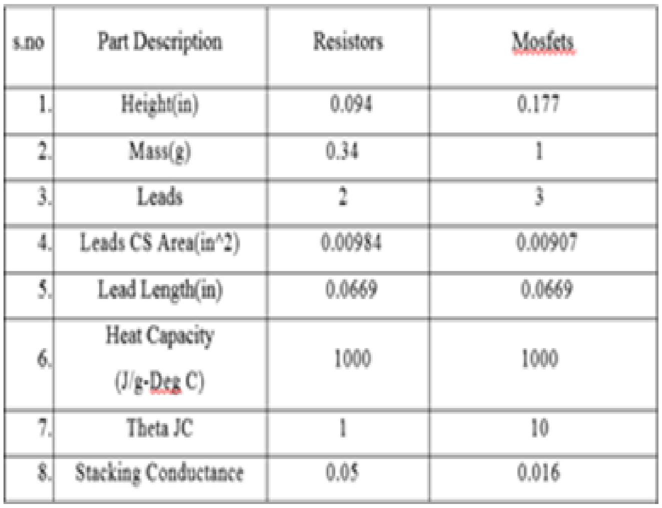
A printed circuit board is taken with 4.8inx4.4in in dimension and 0.066 in thick. An academic problem with total 24 components with a total power dissipation of 8.3 W is assigned and solved. The component and board details are given below. The problem is solved in PC Analyze, TRM and Electro Flo. The problem is solved for both 2-Layer board and 6-Layer board. The ambient temperature taken as 20 degrees.

Board Details:

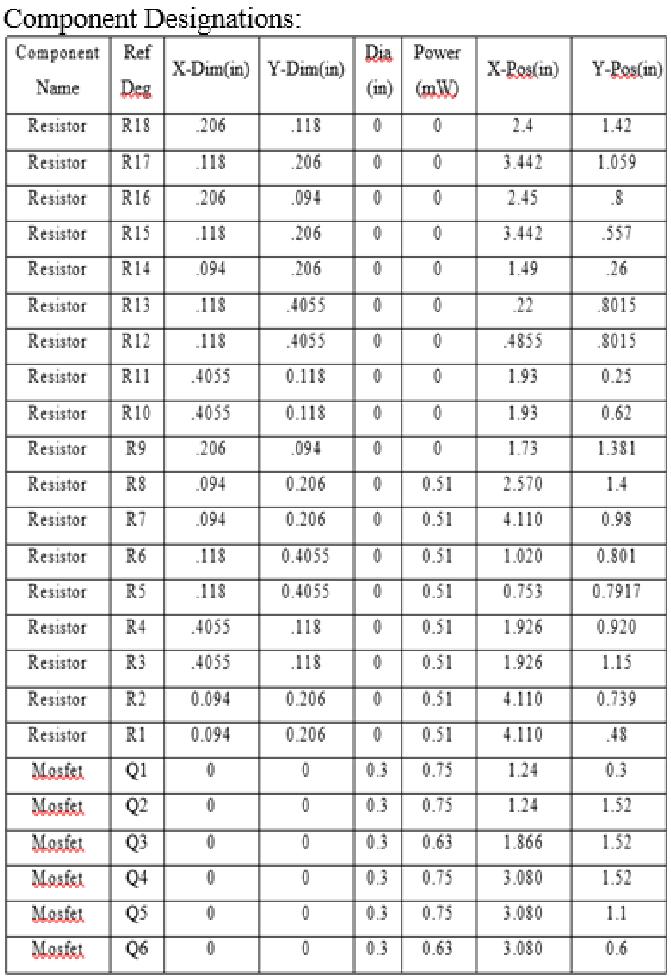


S.no	Printed Board Assembly Parameters	
1.	X –axis size(in)	4.48
2.	Y-axis size(in)	1.73
3.	Basic thickness(in)	0.066
4.	Board Material	Given Board Conductivity 2-layer Cond Kx=Ky=1.9401(W/in-Deg-c) Kz=0.0129(W/in-Deg-c) 6-layer Cond Kx=Ky=3.989(W/in-Deg-c) Kz=0.0149(W/in-Deg-c) Heat Cap-0.6 (J/g-Deg C) Density-29.8(g/in^3), Amb temp-20 deg C

18 Resistors and 6 mosfets are taken



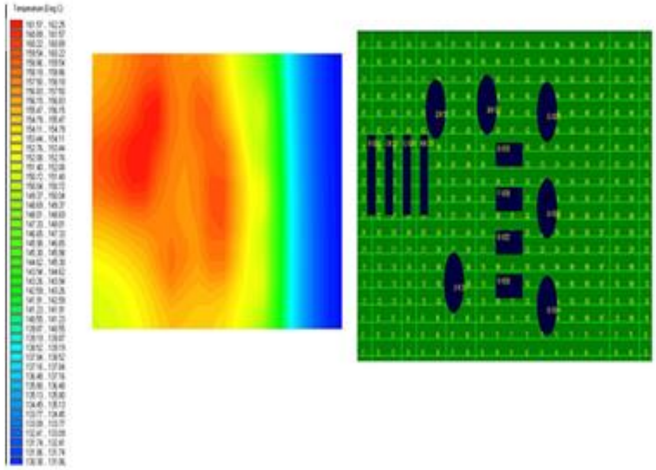
s.no	Part Description	Resistors	Mosfets
1.	Height(in)	0.094	0.177
2.	Mass(g)	0.34	1
3.	Leads	2	3
4.	Leads CS Area(in^2)	0.00984	0.00907
5.	Lead Length(in)	0.0669	0.0669
6.	Heat Capacity (J/g-Deg C)	1000	1000
7.	Theta JC	1	10
8.	Stacking Conductance	0.05	0.016



Component Designations:

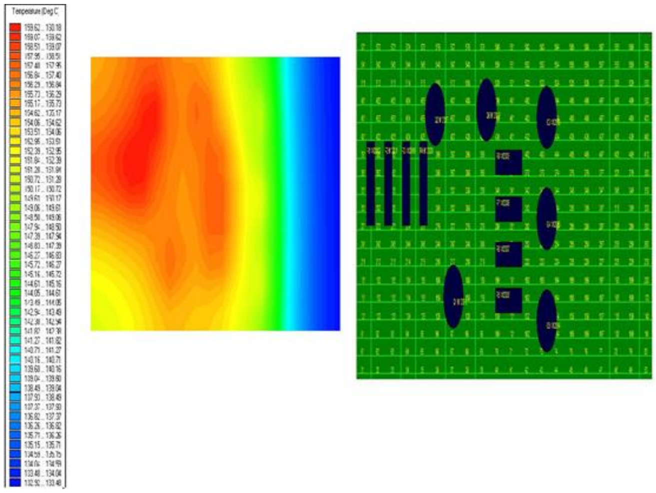
Component Name	Ref Deg	X-Dim(in)	Y-Dim(in)	Dia (in)	Power (mW)	X-Pos(in)	Y-Pos(in)
Resistor	R18	.206	.118	0	0	2.4	1.42
Resistor	R17	.118	.206	0	0	3.442	1.059
Resistor	R16	.206	.094	0	0	2.45	.8
Resistor	R15	.118	.206	0	0	3.442	.557
Resistor	R14	.094	.206	0	0	1.49	.26
Resistor	R13	.118	.4055	0	0	.22	.8015
Resistor	R12	.118	.4055	0	0	.4855	.8015
Resistor	R11	.4055	0.118	0	0	1.93	0.25
Resistor	R10	.4055	0.118	0	0	1.93	0.62
Resistor	R9	.206	.094	0	0	1.73	1.381
Resistor	R8	.094	0.206	0	0.51	2.570	1.4
Resistor	R7	.094	0.206	0	0.51	4.110	0.98
Resistor	R6	.118	0.4055	0	0.51	1.020	0.801
Resistor	R5	.118	0.4055	0	0.51	0.753	0.7917
Resistor	R4	.4055	.118	0	0.51	1.926	0.920
Resistor	R3	.4055	.118	0	0.51	1.926	1.15
Resistor	R2	0.094	0.206	0	0.51	4.110	0.739
Resistor	R1	0.094	0.206	0	0.51	4.110	.48
Mosfet	Q1	0	0	0.3	0.75	1.24	0.3
Mosfet	Q2	0	0	0.3	0.75	1.24	1.52
Mosfet	Q3	0	0	0.3	0.63	1.866	1.52
Mosfet	Q4	0	0	0.3	0.75	3.080	1.52
Mosfet	Q5	0	0	0.3	0.75	3.080	1.1
Mosfet	Q6	0	0	0.3	0.63	3.080	0.6

Final Results for 2-layer board



49.28W/m-k (1.9401W/in-Deg C)

The results are:
Maximum Temperature is 161.57 deg C.
Minimum Temperature is 130.38 deg C.
The Final Results for 6-layer board:



By Taking the Effective Conductivity of the board is: 101.36W/m-k (3.9905W/in-Deg C)

The results are:
Maximum Temperature is 159.62 deg C.
Minimum Temperature is 132.92 deg C

V. PROBLEM SOLVING FOR JOULE HEATING

As discussed in the previous chapters the temperatures of the circuit board depends on various parameters and joule heating is one of them. Joule heating is one of the main parameter which affects the temperature of the board. In the previous chapter problems are solved for no-joule heating and results are obtained. In this chapter the problems are solved for Joule heating case with different boundary conditions.

When the electric current traverse through a conductor then it releases heat and it can also be explained as electric current which flows is transformed into thermal energy. This process is called as Joule Heating. It is given with an expression as the amount of heat released is directly proportional to the square of the current. Such that

$$Q \propto I^2.R.T$$

The simple physics which is behind Joule-heating or self-heating can be explained as.

Consider the metal wire of cross sectional area A and length L in a static electric field, E. An electron which is in the metal wire will involve with several collisions. The average amount of energy adrift to the ions per electron per collision can be identified as follows. The force adjutant on an electron would be: F = -eE,

e is termed as the electron charge. If the mediocre area travelled between collisions is assumed to be x, the average energy loss, can be

$$\mathrm{Uavg} = (-eE).x,$$

Where x = (average electron velocity, v)*(average time between collisions, τ).

Therefore, from above it follows that

$$x = -[\frac{eE\tau}{m}]\tau$$

And

$$\mathrm{Uavg} = \frac{(\mathrm{eE\tau})^2}{\mathrm{m}}$$

Where, m is termed as the mass of the electron.

Therefore the mediocre rate of energy adrift to the ions per unit volume is given by

$$Uavg = \frac{ne^{2\tau}}{m}E^2$$

The power loss, p, is basically the average energy loss per second is given by

$$p = \frac{ne^2\tau}{m}E^2(LA) = \sigma(\rho j)^2(LA)$$

Where, ρ is termed as electrical resistivity and j is termed as current density. Since the electrical conductivity

$$\sigma = (1/\rho),$$

$$P = I^2R$$

The above equation is the electrical power dissipation in a metal wire of resistance R when a current I tides through it. The temperature of the metal connectively is raised when the above electrical energy gets transformed to thermal energy (Joule heat). Hence, for steady current progress in a metal, Joule heating equation can be explained as

$$P = I^2R = IV = \frac{dQ}{dt}$$

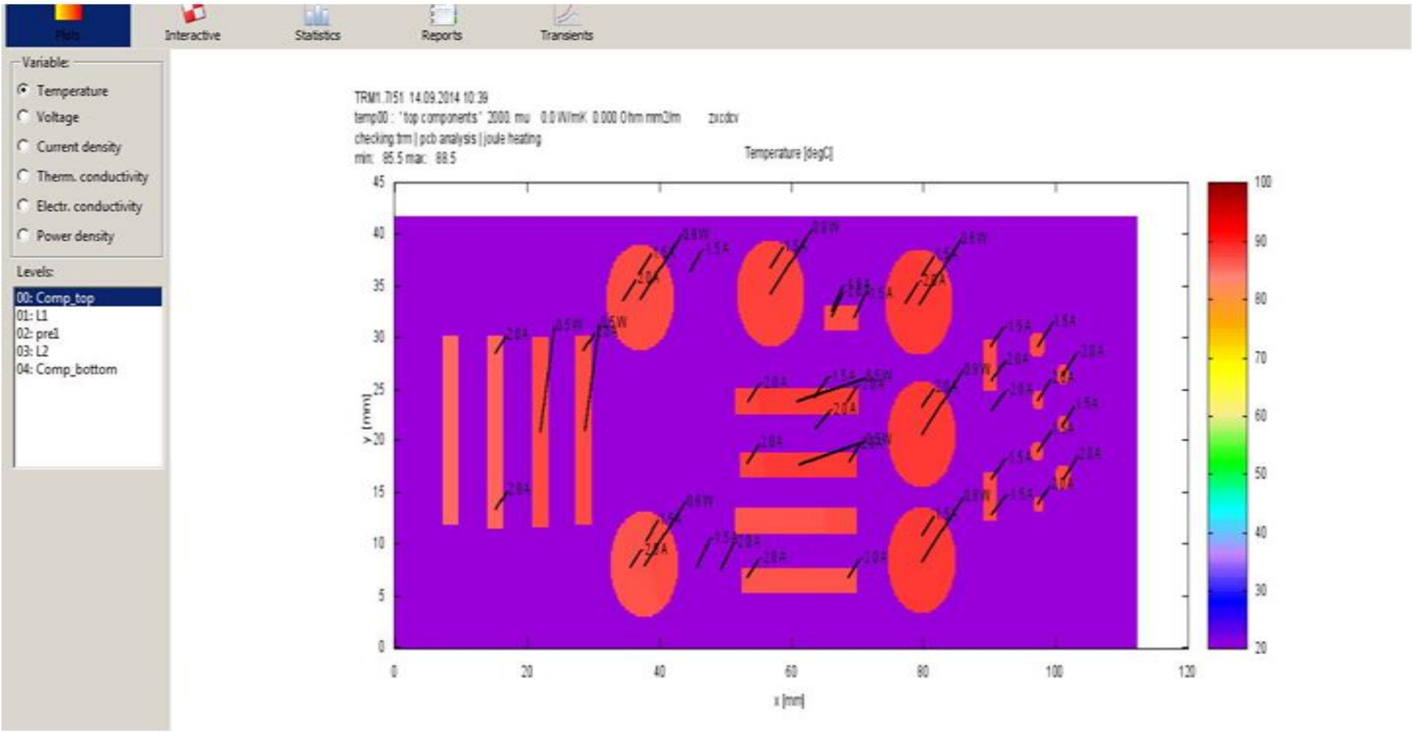
Where, Q is the total heat energy generated.

the steady state temperature of a PCB has to be done in the problem. Affects due to various thermal parameters assigned to the components and board are studied and analyzed.

Problem: A printed circuit board is taken with 4.8inx4.4in in dimension and 0.066 in thick. An academic problem with total 24 components with a total power dissipation of 8.3 W is assigned and solved. The component and board details are given below. The problem is solved for joule heating in TRM. The problem is solved for both 2-Layer board and 6-Layer board. The ambient temperature taken as 20 degrees.

Temperature Results for 2-Layer Board with Thermal Vias:

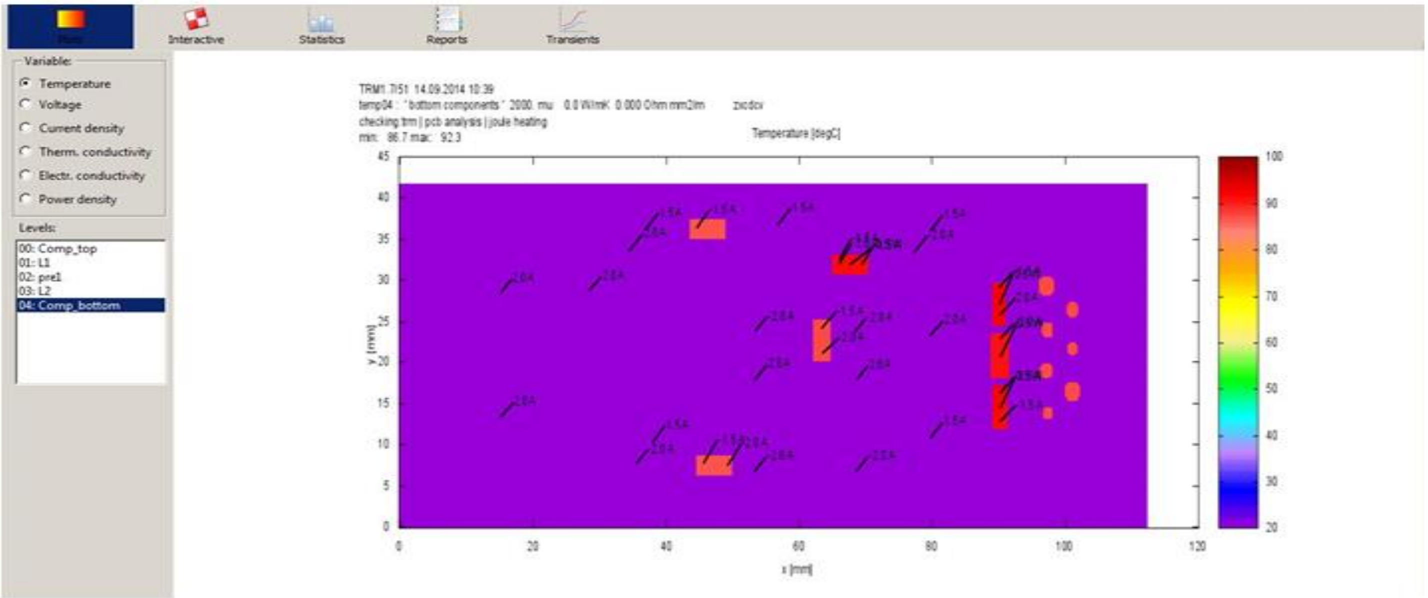
Top component:



TRM1.7i51 14.09.2014 10:39
temp00 : 'top components' 2000. mu 0.0 W/mK 0.000 Ohm mm2/m zxcdxv
checking trm | pcb analysis | joule heating
min: 85.5 max: 88.5

Max Temperature: 88.5 Deg C
Min Temperature: 85.5 Deg C

Bottom component:



Variable:
● Temperature
○ Voltage
○ Current density
○ Therm. conductivity
○ Electr. conductivity
○ Power density

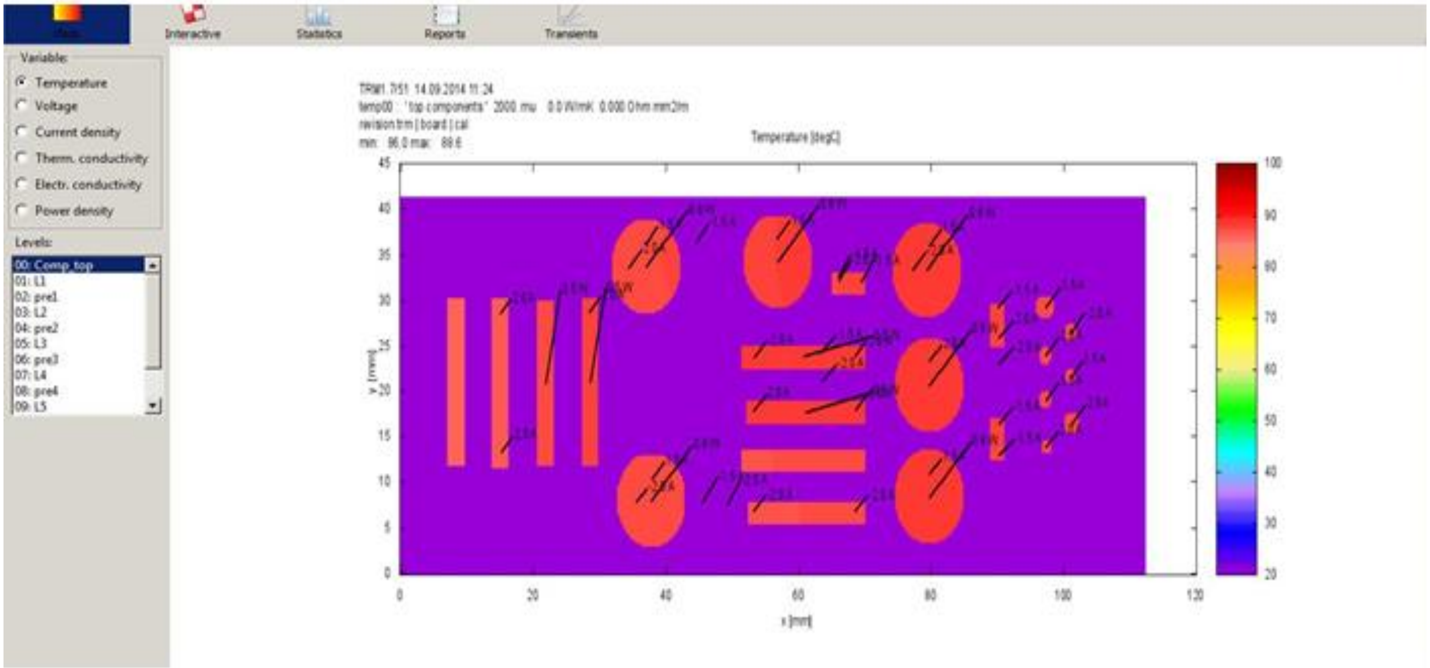
Levels:
00: Comp_top
01: L1
02: pre1
03: L2
04: Comp_bottom

```
TRM1 7/51  14.09.2014 10:39
temp04 : ' bottom components ' 2000. mu   0.0 W/mK  0.000 Ohm mm2/m        zxcdcx
checking.trm | pcb analysis | joule heating
min:   86.7 max:   92.3
```

Max Temperature: 92.3 Deg C
Min Temperature:86.7 Deg C

Temperature Results For 6-Layer Board With Thermal Vias:

Top component:



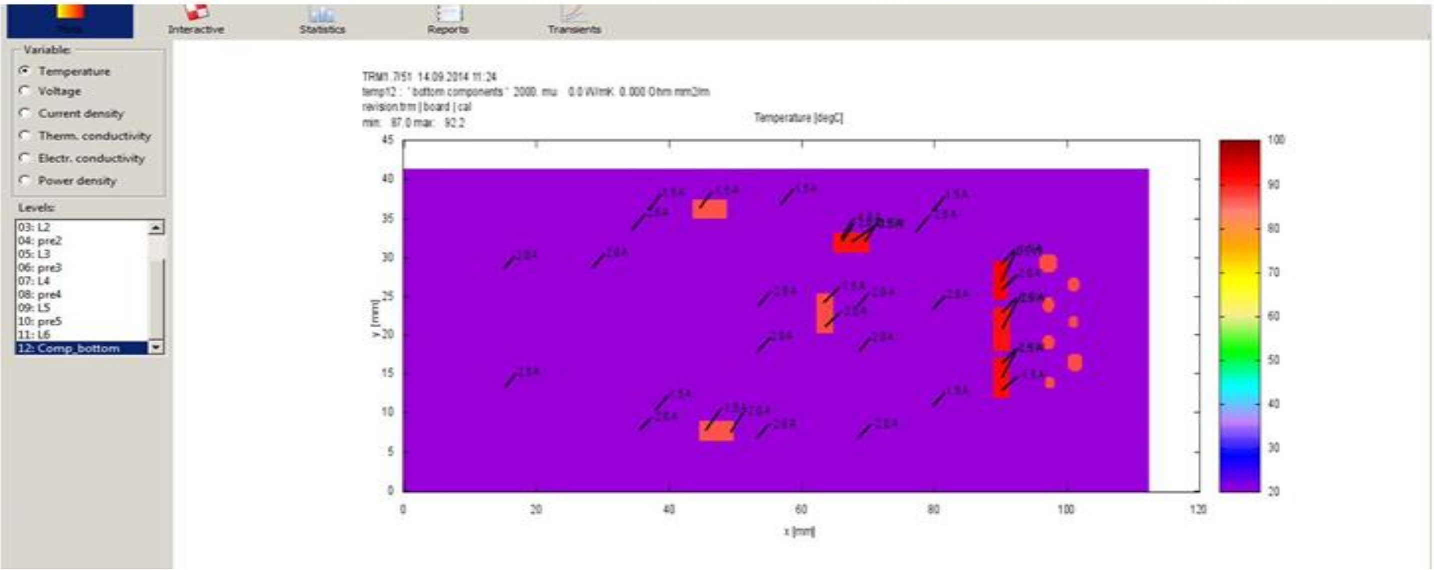
Variable:
● Temperature
○ Voltage
○ Current density
○ Therm. conductivity
○ Electr. conductivity
○ Power density

Levels:
00: Comp_top
01: L1
02: pre1
03: L2
04: pre2
05: L3
06: pre3
07: L4
08: pre4
09: L5

```
TRM1 7/51  14.09.2014 11:24
temp00 : 'top components ' 2000. mu   0.0 W/mK  0.000 Ohm mm2/m
revision.trm | board | cal
min:   86.0 max:   88.6
```

Max Temperature: 88.6 Deg C
Min Temperature: 86.0 Deg C

Bottom component:



TRM1.7/51 14.09.2014 11:24
temp12 : ' bottom components ' 2000. mu 0.0 W/mK 0.000 Ohm mm2/m
revision.trm | board | cal
min: 87.0 max: 92.2

Max Temperature: 92.2 Deg C
Min Temperature: 87.0 Deg C

VI. RESULTS AND COMPARISONS

A. Comparison of Temperature Results:

- No-Joule Heating Case:

Problem: Results from PC Analyze and TRM Without thermal Vias
2-layer Board:

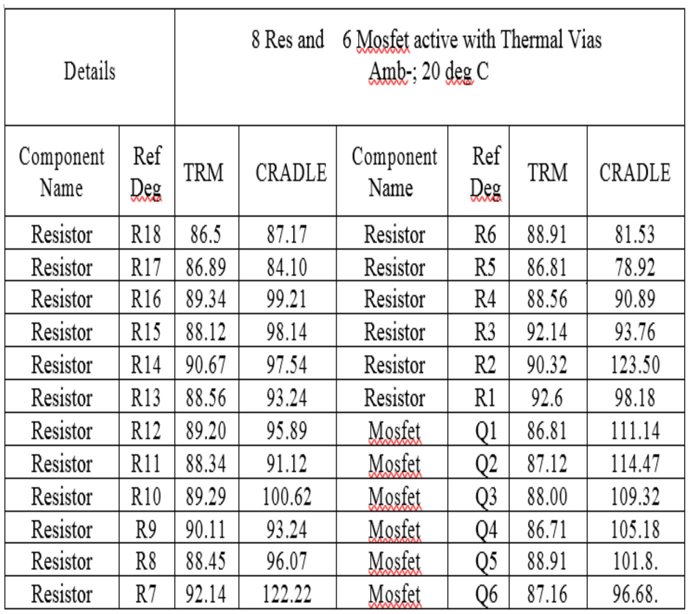
Details		8 Res and 6 Mosfet active with Thermal Vias Amb-; 20 deg C					
Component Name	Ref Deg	TRM	CRADLE	Component Name	Ref Deg	TRM	CRADLE
Resistor	R18	89.81	87.17	Resistor	R6	88.90	76.6
Resistor	R17	86.39	84.10	Resistor	R5	86.5	73.62
Resistor	R16	89.90	89.21	Resistor	R4	86.90	84.17
Resistor	R15	87.77	88.14	Resistor	R3	87.12	87.55
Resistor	R14	86.54	87.54	Resistor	R2	97.8	119.35
Resistor	R13	87.24	83.24	Resistor	R1	88.32	94.43
Resistor	R12	86.56.	85.89	Mosfet	Q1	96.64	106.22
Resistor	R11	87.33	91.12	Mosfet	Q2	97.8	109.84
Resistor	R10	90.17	100.62	Mosfet	Q3	96.23	105.11
Resistor	R9	86.87	93.24	Mosfet	Q4	95.9	100.55
Resistor	R8	88.45	91.63	Mosfet	Q5	92.1	97.56
Resistor	R7	97.19	118.06	Mosfet	Q6	87.11	91.83

Details		8 Res and 6 Mosfet active without Thermal Vias Amb-; 20 deg C					
Component Name	Ref Deg	PC Analyze	TRM	Component Name	Ref Deg	PC Analyze	TRM
Resistor	R18	143.78	138.24	Resistor	R6	157.89	182.82
Resistor	R17	142.13	112.67	Resistor	R5	153.12	173.21
Resistor	R16	140.12	132.13	Resistor	R4	155.89	189.89
Resistor	R15	143.76	128.41	Resistor	R3	149.45	165.87
Resistor	R14	144.12	131.28	Resistor	R2	157.68	210.45
Resistor	R13	147.90	122.21	Resistor	R1	159.32	240.23
Resistor	R12	143.78	143.24	Mosfet	Q1	127.56	139.90
Resistor	R11	141.21	117.23	Mosfet	Q2	141.78	107.8
Resistor	R10	139.89	112.43	Mosfet	Q3	139.89	112.65
Resistor	R9	140.23	123.89	Mosfet	Q4	140.64	127.31
Resistor	R8	157.12	191.29	Mosfet	Q5	142.87	125.76
Resistor	R7	156.33	189.32	Mosfet	Q6	139.78	101.89

- Joule Heating Case:

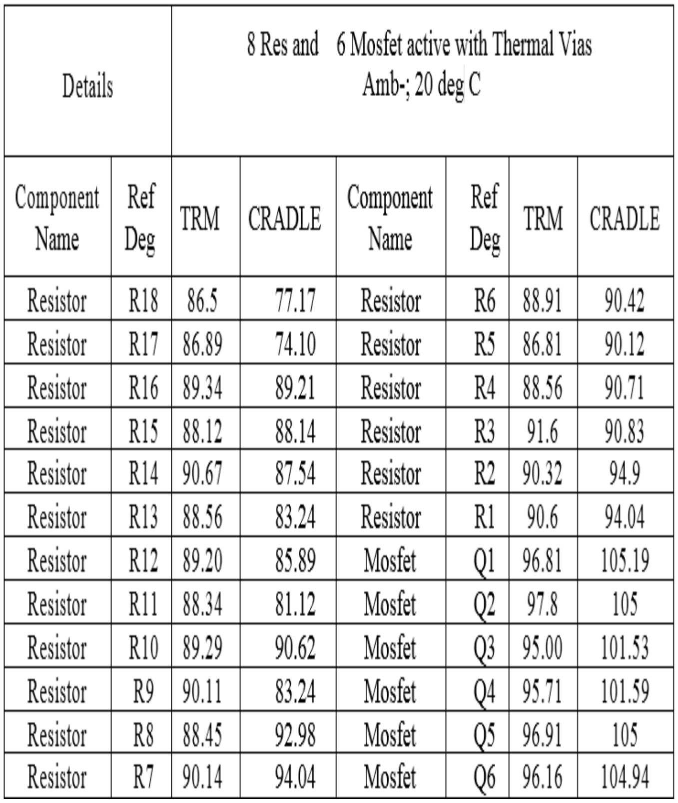
Problem: Results from TRM compared with Cradle, which includes current

2-layer Board:



Details		8 Res and 6 Mosfet active with Thermal Vias Amb-; 20 deg C					
Component Name	Ref Deg	TRM	CRADLE	Component Name	Ref Deg	TRM	CRADLE
Resistor	R18	86.5	87.17	Resistor	R6	88.91	81.53
Resistor	R17	86.89	84.10	Resistor	R5	86.81	78.92
Resistor	R16	89.34	99.21	Resistor	R4	88.56	90.89
Resistor	R15	88.12	98.14	Resistor	R3	92.14	93.76
Resistor	R14	90.67	97.54	Resistor	R2	90.32	123.50
Resistor	R13	88.56	93.24	Resistor	R1	92.6	98.18
Resistor	R12	89.20	95.89	Mosfet	Q1	86.81	111.14
Resistor	R11	88.34	91.12	Mosfet	Q2	87.12	114.47
Resistor	R10	89.29	100.62	Mosfet	Q3	88.00	109.32
Resistor	R9	90.11	93.24	Mosfet	Q4	86.71	105.18
Resistor	R8	88.45	96.07	Mosfet	Q5	88.91	101.8.
Resistor	R7	92.14	122.22	Mosfet	Q6	87.16	96.68.

6-layer Board:



Details		8 Res and 6 Mosfet active with Thermal Vias Amb-; 20 deg C					
Component Name	Ref Deg	TRM	CRADLE	Component Name	Ref Deg	TRM	CRADLE
Resistor	R18	86.5	77.17	Resistor	R6	88.91	90.42
Resistor	R17	86.89	74.10	Resistor	R5	86.81	90.12
Resistor	R16	89.34	89.21	Resistor	R4	88.56	90.71
Resistor	R15	88.12	88.14	Resistor	R3	91.6	90.83
Resistor	R14	90.67	87.54	Resistor	R2	90.32	94.9
Resistor	R13	88.56	83.24	Resistor	R1	90.6	94.04
Resistor	R12	89.20	85.89	Mosfet	Q1	96.81	105.19
Resistor	R11	88.34	81.12	Mosfet	Q2	97.8	105
Resistor	R10	89.29	90.62	Mosfet	Q3	95.00	101.53
Resistor	R9	90.11	83.24	Mosfet	Q4	95.71	101.59
Resistor	R8	88.45	92.98	Mosfet	Q5	96.91	105
Resistor	R7	90.14	94.04	Mosfet	Q6	96.16	104.94

VII. DISCUSSIONS

A steady state thermal analysis for a PCB board has been carried out. The PCB card was assigned with appropriate material, boundary conditions, and properties. The assignment of thermal properties of materials was made by taking the standard values. The problems are solved for both NO-JOULE heating case and JOULE heating case. The problems are solved and compared with different software's. As discussed before joule heating in cards affect the final temperatures, so the changes, which had been taken place due to joule heating, are shown in the above comparisons. And by addition of thermal vias in the board shows a drastic change in the total temperatures. The boundary conditions which are used like radiation, power dissipation and contact conductance affects the temperatures. Both Orthotropic thermal conductivity and isotropic Conductivity values are taken for board conductivities and solved. There will be a difference of 3-5 degrees temperature with joule heating case and no-joule heating case. The problems are solved with and without thermal vias to show the variation in change of temperatures. The final results are compared with different software's and results are approximately matching the available data.

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