Heat in Electronic Circuits and Material Selection Criteria for Cooling Solutions

Er. Pal Riya Bipradas Sanchita

Dept. ETRX Research Student (Master Of Engineering) of Pillai Institute Of Information Technology,Engineering, Media Studies and Research affiliated to Mumbai University, India

Abstract — **Electronic cooling has made its way** practically **to every aspect of modern life from small components to scientific computers. Continuous miniaturization of electronic systems has resulted in a dramatic increase in the level of heat generated. This paper deals with levels of heat dissipated by various electronic products**, where and **which type of cooling technique is to be applied and rules to be followed while selecting materials for circuit cooling purpose**.

Index Terms— **British thermal unit (BTU), critical heat flux (CHF), drop test (DT), printed circuit board (PCB).**

I.   INTRODUCTION

Field of electronics deals with construction and utilization of devices involving current flow through them accompanied by heat by heat generated in the amount of I^2R where I is current flowing through the device and R is the resistance offered by device towards current flow. The heat generating components in electronic packages are microprocessors, transistors, resistors, batteries, solder joints, and semiconductors. The reliability of the electronics of a system is a major factor in the overall reliability of the system. When thousands and millions of components are packed in a small volume, heat level increases exponentially. The cooler the electronic device operates, more reliable it is.

II.   HEAT MANAGEMENT LEVELS

There are three fundamental thermal management degrees in electronics analysis: **Component level**, **Board level and** and **System level**. Each has different objectives and analysis strategies.

A.   Component level

Component level thermal management deals with:
1) Total number of components on PCB.
2) Spacing between each components on PCB.

Fig.1: Number of Components and spacing between them.

3) Nature of die or grease attached (die/grease attach is a critical factor at component level thermal management as they can degrade the performance due to mismatch in thermal expansion of materials on either side of the bond line).
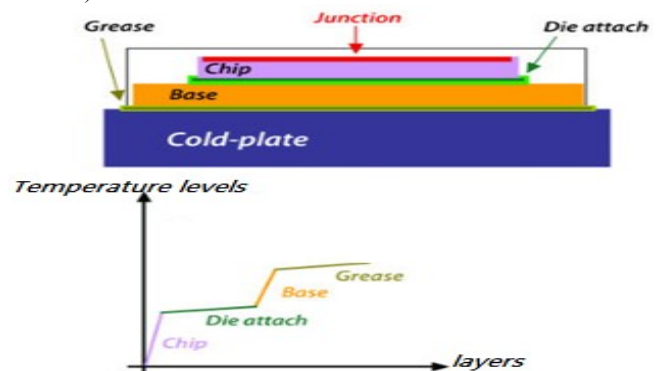

Fig.2: Thermal expansion levels of each layer.

B.   Board level or PCB level

Thermal management at this level deals with:
1) Thickness of component board (i.e. PCB).
2) PCB cooling depends strongly on the local air flow distribution, which is disrupted as air passes over the components on the board.
3) Decisions are made whether which cooling technique (fans or heat sinks or heat pipes or hybrid technique) to be used for PCB.
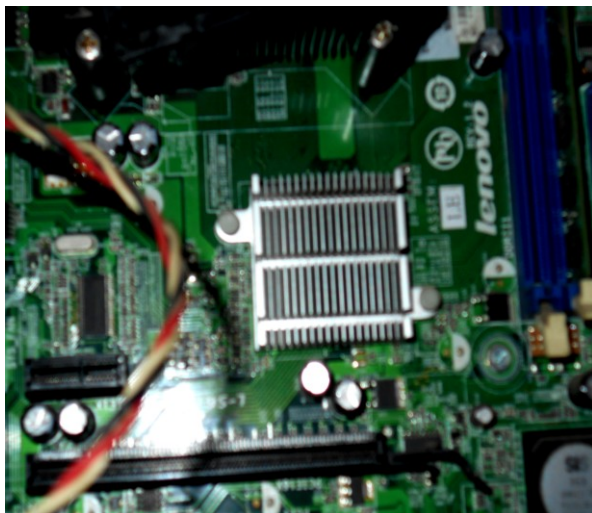
Fig.3: Heat Sink used to cool CPU PCB

C. System level or enclosure level

Electronics cooling is a challenging .Air flow through the system cools the electronics, but is disrupted by electronics and other internal geometry. Improper enclosure/package design also alters the air flow direction and acts as obstacle in air flow path. System level deals with:

1) Enclosure /package material selection.
2) (Length*breadth*height) parameter selection.
3) Vent (ventilation) size design.
4) Type of cooling technique to be used (like: fans, number of fans, positioning of fans, heat sink size etc).

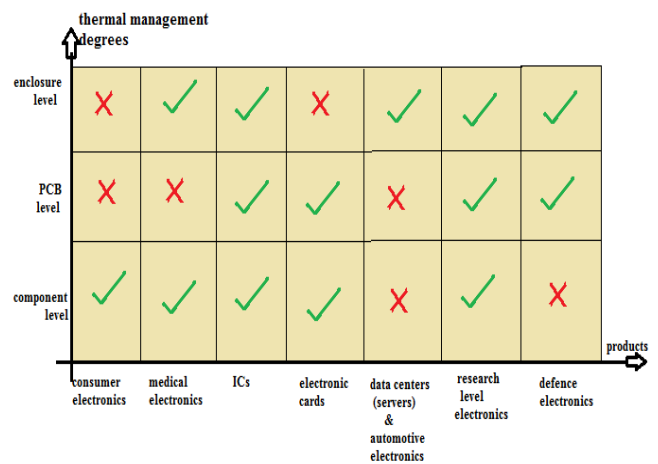Fig.4: Fans used to cool internal air of the enclosed CPU

Fig.5: Level of heat management needed by various electronic systems

III.   PROBLEMS FACED DURING HEAT MANAGEMENT OF PCBS

There are lots of problems needed to be faced or handled during designing and establishing heat management solutions. Those challenges are:

1) Miniaturization of PCBs area.
2) Increasing demand in circuit performance speed.
3) Final product cost.
4) Fulfilling certain protocols.
5) Effect of surrounding temperature.
6) System's internal temperature (i.e. heat released by individual components).
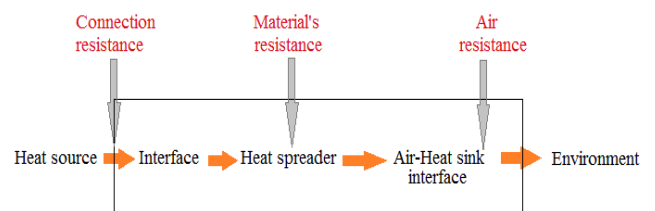7) Junction resistance, heat spreader resistance and air resistance are 3 important hurdles.

Fig.6: diagram illustrating 3 main resistances

8) Negative role of system's vibration on its own components.
9) Negative role of external vibrations.
10) Dust (more the dust level, more it will result in internal heating as proper heat transfer from individual component's surface to exterior air will not take place).
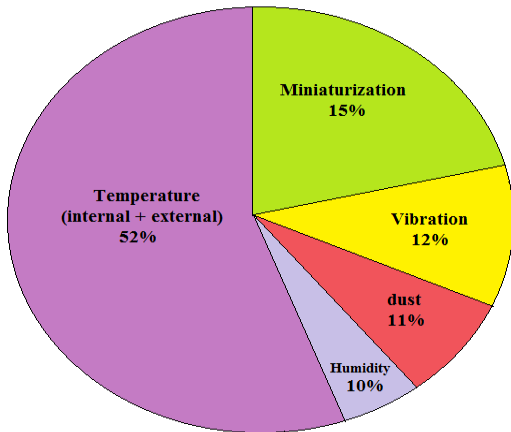
Fig.7: Causes of overheating of PCBs

IV. INFLUENCE OF TIME ON HEAT DISSIPATION

A. Time, Power and Temperature relation

Heat is no longer a number but a distribution. There exist a positive feedback loop between time, power and temperature. This is best explained using below fig.7.
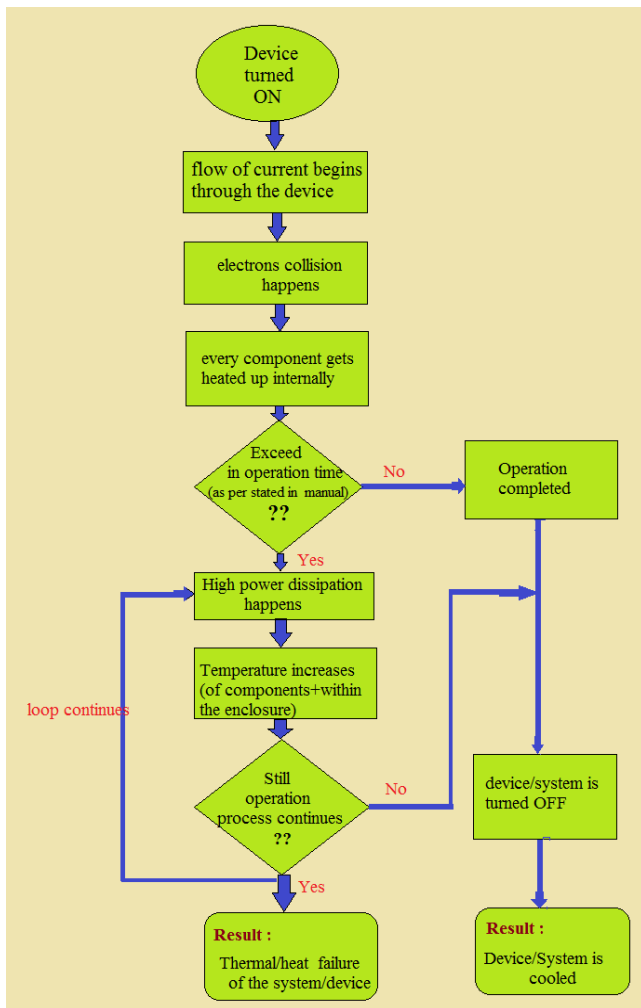

Fig.8: Flow diagram relating time, power and temperature.

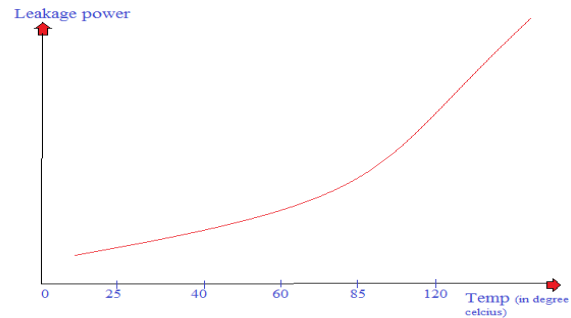Leakage power increases exponentially with temperature at small technology node.

Fig.9: Temperature Vs Leakage power

B. Numerical illustration of Time, Power and Temperature relation

It is nice to have at least 1 approximate mathematical approach to estimate how hot the system will become before building the actual device/system and its modeling. We know that electrical heat dissipation is measured in **watts**. The energy in **joule** and heat is measured in **calories**.

Consider we have 300g of water. If the water is heated for 10sec at 10Watts.What will be the amount of temperature rise then???? Answer is:

Watt = Joules / time   (1)
Energy = watt* time   (2)
Energy = 10watts *10sec   (unit: joule)
Energy = 100 Joule
1Joule is 4.185 calories them 100Joules would be 418.5 Calories. So
Temperature rise (^{0}C) = calories / gram   (3)
^{0}C = 418.5/300
^{0}C = 1.395

Hence approximately we can say 10seconds of operation would cause a temperature rise by 1^0C if 10W of supply is used.

C. Heat / Power Dissipation Model

TABLE.1: THERMAL TO ELECTRICAL DOMAIN

Electrical Domain		Thermal domain	
Variables	Units	Variables	Units
Current (I)	Amperes (A)	Power /heat flux (P_D)	Watts (W)
Voltage (V)	Volts	Temperature (T)	Centigrade (^{0}C)
Electrical resistance (R)	Ohms (Ω)	Thermal resistance (R_θ)	^{0}C/W
Electrical Capacitance (C)	Farads	Thermal capacitance (C_θ)	Joules/^{0}C

Heat /power dissipated by individual components can be calculated by:-

τ (tou) = C_θ x R_θ (4)
C_θ = specific heat x density x volume   (5)
C_θ = [(J/kg K) x   (Kg/m^3) x (m^3)]   units
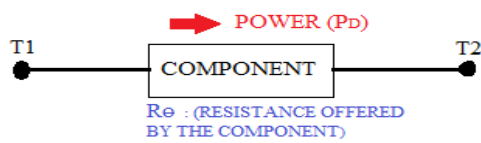P_D = Tc / [R_θ x (1-e$^{-t/\tau}$)]   (6)

Fig.10: Power dissipated by individual component.

TABLE.2: HEAT DISSIPATION LEVELS BY CERTAIN DEVICES

Devices	Level of heat dissipated (at 28^{0}C)
8086 processor	2.5W
BJT Transistor	0.5W
Low voltage audio amplifier	1.25W
General purpose diode (IN 4007)	500mW
MOSFET Transistor	0.3W (at 28^{0}C) to 481W (at 175^{0}C)
PCBs(printed circuit board)	5W to 100W (depends on number of components and PCB size)
Semiconductor lasers	2000W
Microwave devices	1000W
Radar system	2000W

TABLE.3: CRITICAL TEMPERATURE LIMITS

Temperature in (^{0}C)	Devices
-44	Minimum **automotive** operating temperature
-55	Semiconductor **storage** lowest temperature
60	Metal surfaces are painfully hot
85	Max temperature of **electrolytic capacitors**
125	Max operating temperature of **digital circuits**
150	Max allowable **junction** temperature
160	**Power transistor** junction temperature
1400	**Melting** point of all **semiconductor products**

V. HEAT REMOVAL OPTIONS AVAILABLE

A. Options available

   Vast options are available to remove heat from circuits/PCBs. Before going for any particular technique, one should always find the total amount of power dissipated by the board. This can be done by going through the user manual provided for every components or one can directly measure heat released by individual components by using heat sensors. Example: If your PCB board generates maximum heat / heat

flux at around 50W/cm^2, then alone use of heat sinks will work good. Below Table.4 properly explains which cooling option/technique to be used for electronic circuits generating heat flux (in: W/cm^2) at various levels. Heat flux is defined as the amount of heat transferred per unit area per unit time from one surface to another. Critical Heat Flux (CHF) is the peak heat flux .Any further increase in flux level above CHF would cause the circuit/component to get damaged.

TABLE.4: HEAT REMOVAL OPTIONS

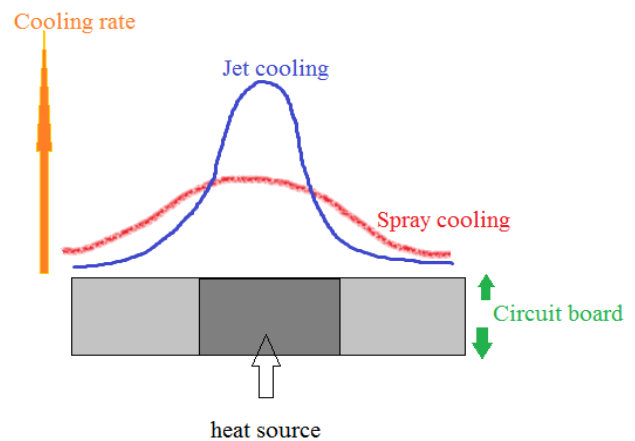| Techniques	Heat flux level (W/cm^2)
Heat sink	50
Heat pipe	10 to 300
EDIFICE (embedded droplet impingement for integrated cooling of electronics)	100
Simple copper heat pipe using water as coolant	110
Spray cooling	150 to 200
Jet cooling	160
Water (2 phase method)	200
Standard fans	350
Copper plates	790

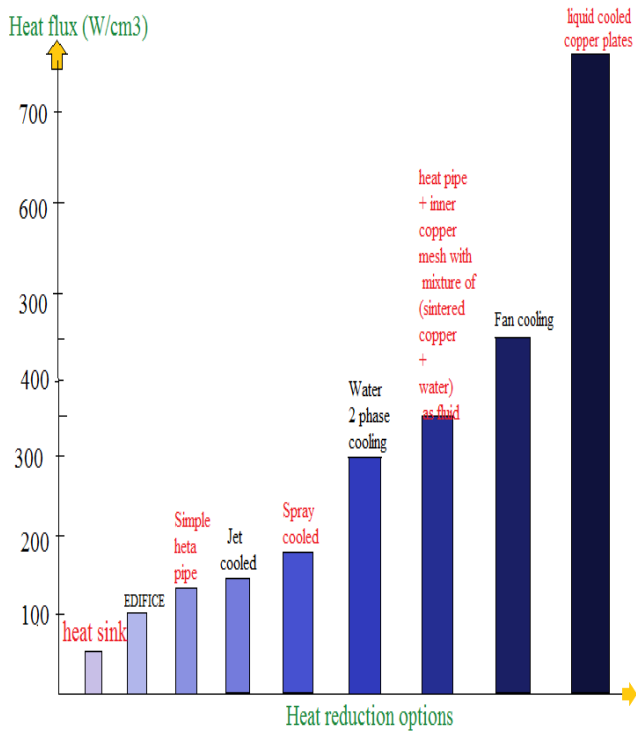Fig.11: Jet cooling rate Vs Spray cooling rate

Fig.12: Graph illustrating Heat cooling options Vs amount of flux that can be removed

VI. HEAT MANAGEMENT RULES

A. Rule 1: Life span and Temperature relation

Rule 1 state that for every 10^0C rise in circuit or component's temperature, the reliability or the lifespan reduces by 50%.

B. Rule 2: Little finger test (for circuits operated in free air (not enclosed))

Use your little finger to touch capacitors, resistors etc when they are being operated. If you can maintain your touch for very long duration (if hottest component is bearable by your little finger) then your circuit is less likely to develop temperature related failure and thus will not need any heat sink attachment.

C. Rule 3: for circuits operated within enclosed structure

When circuit is in enclosed form, you probably cannot use 'little finger test'. For such cases, go for product's exterior/environmental operating point stated in user manual provided along with the circuit. Basically, maximum temperature limit suggested is 60^0C.

VII. CONCEPT OF DOUBLE PAYING AND DROP TEST

A. Concept of Double Paying

We all always suffer 'double paying'. At the front end we pay in the form of dollars or INR for the amount of power utilized to run circuits/equipments/devices as well as we pay at the back for reduction in the lifespan of circuits because of heat generated. In mobile devices, drop test are carried out to test for mechanical crack on screen, enclosure as well as internal components along with attached heat sinks (heat absorbing source/material) are also tested.

B. Drop test

Consider a thin heat pipe made up of good thermal conductive material which is to be embedded in PCB. Before attaching it to PCB, drop test is carried out where the heat pipe is dropped from variable heights for approximately say 10 times. If at all it survives all 10 drops without any mechanical (surface crack) failure, it would be embedded in the PCB. But drop test does not guarantees 100%.Drop test is very common in mobile phones to test strength of the mobile screen, its enclosure as well as of the heat sink attached to it.
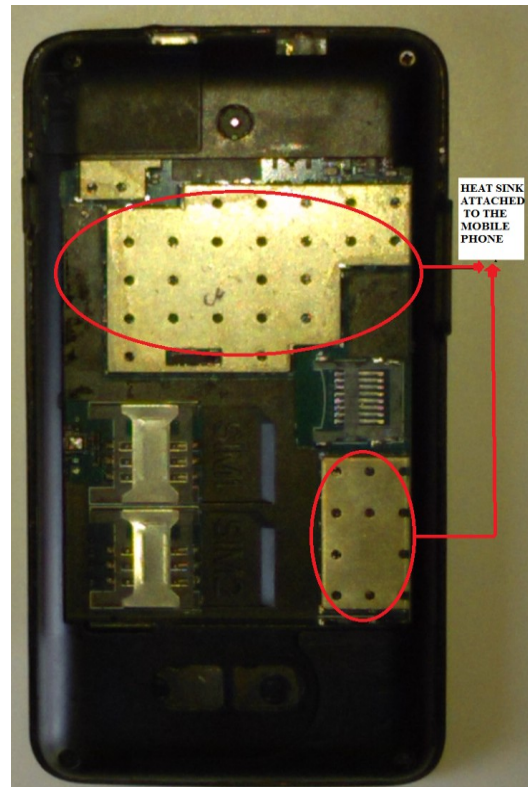

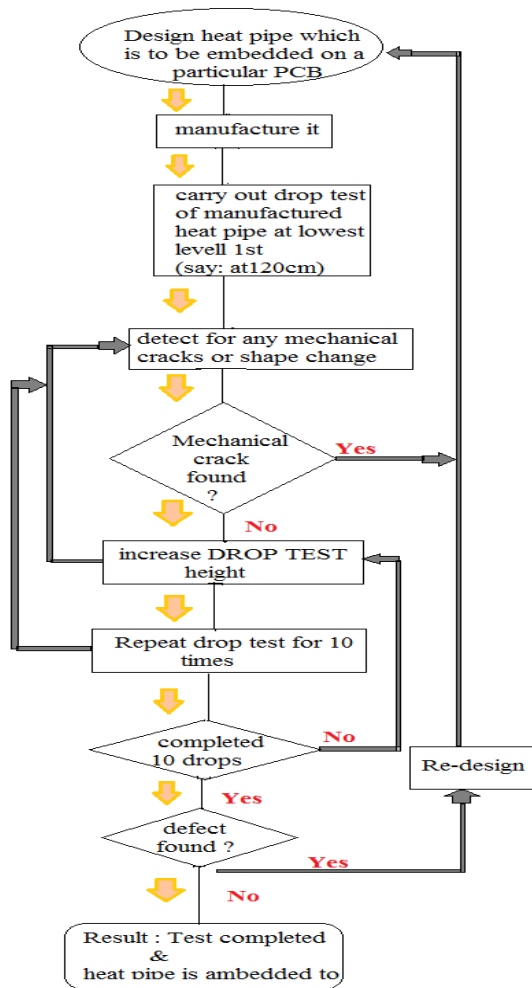Fig.13: Drop test done on mobile phone to test mechanical strength of attached heat sink

Fig.14: Drop test of heat pipe which is to be embedded in PCB

VIII.   HEAT UNITS

Heat is inevitable. Heat can be measured in BTU (British thermal unit) or watts or tons of air. But to avoid confusion of units, there is a simple relation i.e: power consumption is stated in **watts**. Heat rise is stated in **BTU**. Cooling systems such as air conditioners are stated in '**tons of air**'.

1 watt-hour = 3.14BTU   (7)
1BTU = 1055Joules   (8)
1BUT = 252 Calories   (9)
1 Ton of air = 1200 BTU   (10)

IX.   RELIABILITIES ASSOCIATED WHEN DEALING WITH HEAT MANAGEMENT

Reliability means operation of the complete unit/system or component at maximum speed at maximum hours without facing any problems in electrical, thermal, mechanical or electrochemical failure.

A. Electrical reliability

Dealing with electrical reliability, heat absorbing or control materials like heat sinks when used in circuits, should be soldered or screwed in such a way that it does not results in any short circuit path with the PCB tract.

B. Mechanical reliability

Consider an example where we need to screw a small heat sink with the PCB. Heavily tightening the heat sink can severely put stress on PCB and that will result in cracking of PCB as well as electrical path. Thus reducing mechanical reliability.
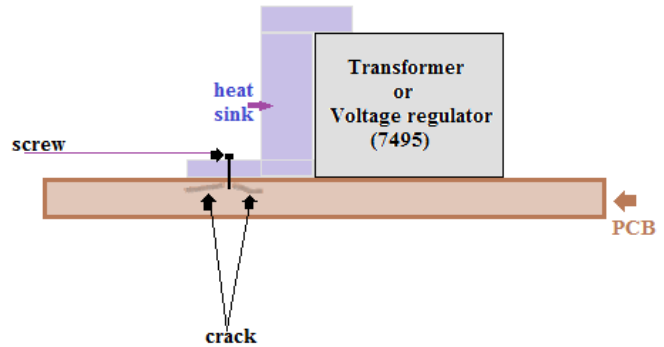

Fig.15: diagram showing the cause of crack in PBC

C. Thermal Reliability

If the rate at which heat produced by component (such as IC (integrated circuit)) is higher than the rate at which heat is releases to the environment then because of tremendous increase in IC's temperature, IC will burn out.

D. Chemical Reliability

If I am using 2 general purpose batteries (attached on the PCB) as DC source and if at all thermal reliability limit fails then high internal heat within the battery will cause its chemical to leak.

X.   MATERIAL SELECTION CRITERIA TO FORM A GOOD HEAT EXCHANGER

Any material you select (whether metals, gases or liquids) to form a good heat exchanger, it must have the following properties:
1) Strong bonding. It implies that atoms separate to a lesser degree when they come in contact with high heat fluxes.
2) Simple structure.
3) High value of fracture strength.
4) Low value of thermal expansion coefficient.
5) High thermal conductivity.
6) Low cost.
7) High value of phase transformation in case of liquids.
8) Low value of elastic module as high vibration leads to thermal and mechanical reliability failure.
9) Low density.
10) High thermal shock resistance.
11) Lowest level of impurity. Thermal conductivity will reduce if impurity level is high.

Aluminum (Al) and copper (Cu) satisfies above properties. Below table illustrated the reason why Al and Cu are best preferred materials to form good heat exchanger/ absorber .Al is used in those applications where weight

reduction is of high concern and if not so high concern is required then copper is used.

TABLE.5: PROPERTIES OF HIGHLY USED HEAT ABSORBER MATERIALS

MATERIALS	MELTING POINT degree centigrade	BOILING POINT degree centigrade	THERMAL CONDUCTIVITY (W/m_K)	DENSITY Kg/m^3	COST INR per TON
ALUMINIUM	860	2467	205	2712	114000
COPPER	1084	2575	385	8940	325000
SILVER	961	2212	406	10490	36301.65
STAINLESS STEEL	1510	2860	50	8000	20692
TITANIUM	1670	3290	22	4500	–
BRONZE	1025	1000	110	8700	288000
BRASS	1000(RED) 930 (YELLOW)	2000	109	8520	288350
IRON	1593	2870	2861	7850	296000
WATER	0	100	0.6	1000	–

XI. THERMLA SHOCK OF COOLING MATERIALS

Materials when selected to form electronic circuit cooling solution must have high **thermal shock resistance (TSR)**.

$$TSR = (\sigma * K)/(E * \alpha) \tag{11}$$

Where:

σ = strength of selected material

K = thermal conductivity of selected material (metals have K in the range (20-40), polymers (0.3) and ceramic (2- 50). This gives a reason why Al and Cu are mainly used to form heat cooling solution)

E = elastic module of selected material

α = thermal expansion coefficient of selected material

$$\alpha = (Lf-Li)/L0 * (Tf-To) \tag{12}$$

Where:

To and Tf are initial and final temperatures in Kelvin, Li and Lf are initial and final dimensions of the selected material.

XII. CONCLUSION

The market driven demand for higher power density designs inevitably leads to higher temperatures at the circuit level. The interconnection of power semiconductor devices and heat sink often forms a limiting bottleneck. Carefully choosing and properly applying heat cooling material is mandatory to get the best possible performance.

Through this paper, I have tried to clearly explain overheating causes, contribution of **time** and what type of cooling solution to be used for various heat levels is also detailed over here. One must not forget about **drop test** which is one of the important criteria in designing and manufacturing cooling solutions especially when dealing with heat pipes and heat sinks.

REFERENCES

[1] Jebin Jacob, "Thermal Management Studies Using Phase Change Materials For Electronic Packages", Vol.V, April-June,2014.

[2] Dan Pound, Richard W. Bonner , "High Heat Flux Heat Pipe Embedded in MCPCB for LED Thermal Management" , ITHERM Conference 2014.

[3] Mahendra Wankhede, Vivek Khaire, Dr. Avijit Goswami, "Evaluation of Cooling Solutions for Outdoor Electronics", September 2007

AUTHOR
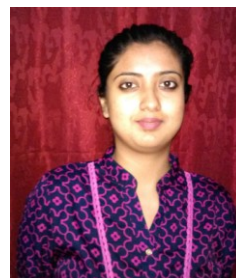
Er. PAL RIYA BIPRADAS SANCHITA received Bachelor Of Engineering in Electronics from PIIT (Pillai Institute Of Information Technology, Engineering, Media Studies & Research) under Mumbai University. Currently pursuing Master of Engineering. Her research areas are Power Electronics and Optical Communication. She is the author of (1) '**Free Space Light Communication**' (2) '**Negative Role of Atmosphere On Free Space Light Communication**'. She has designed Electronics PCB project for **HPST POWER COMPANY** in KBR .