DIGITAL WE DAYS 2024

ENGINEERING COOL: TROUBLESHOOTING IN THERMAL DESIGN OF ELECTRONICS

Antonio Agapito

WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

UNDERSTANDING THERMAL DESIGN CHALLENGES

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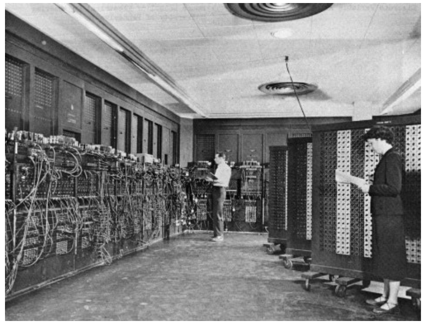
The Need for Thermal Management

- Electronic design tendencies: computer as an example



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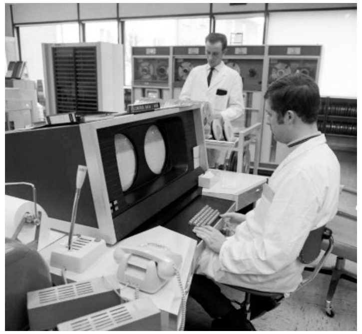
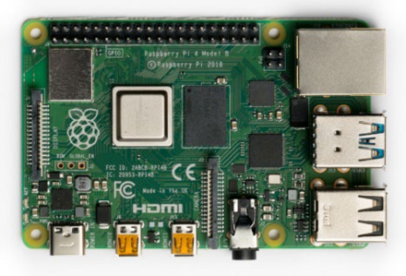


CDC 6400

Commodore 64

Powerbook



Raspberry Pi 4

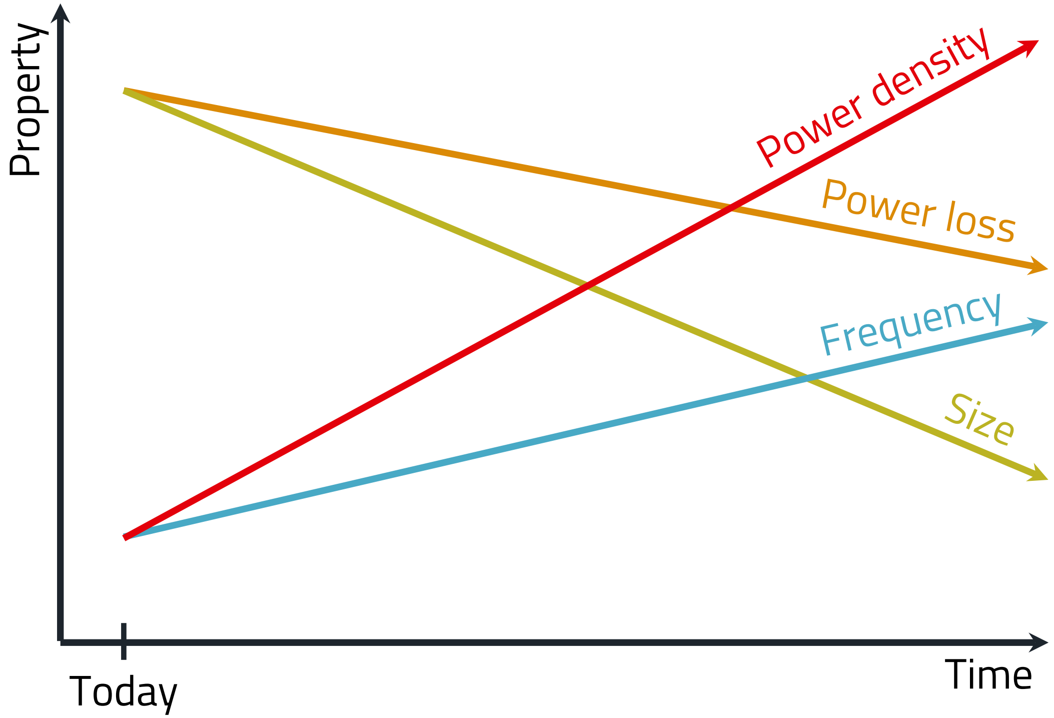
1946 **1964** **1982** **1991** **2019**

Eniac0 : U.S. Army / Public domain ▪ CDC6400_0 : Jens Gathmann ▪ C64c_system : Bill Bertram ▪ Powerbook_ 150 : Dana Sibera ▪ rpi4top : Michael Henzler

UNDERSTANDING THERMAL DESIGN CHALLENGES

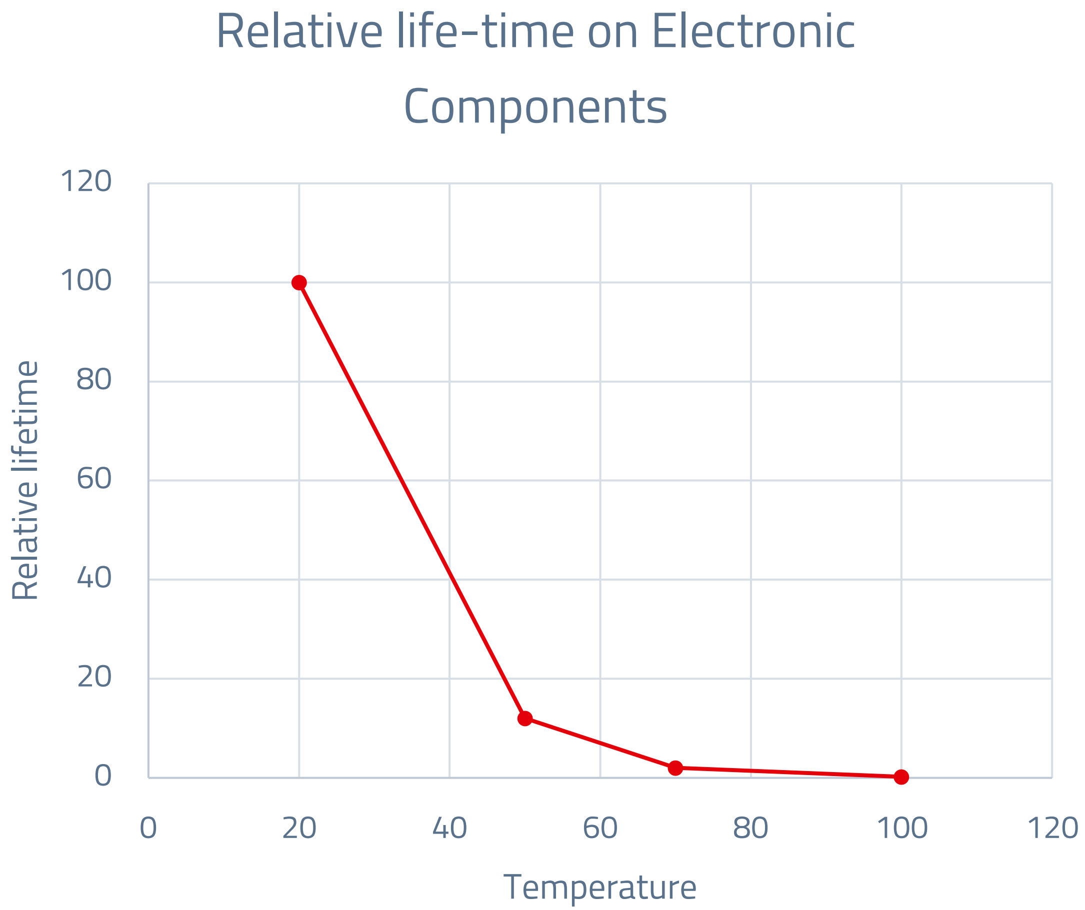
The Need for Thermal Management

- Electronic design tendencies:

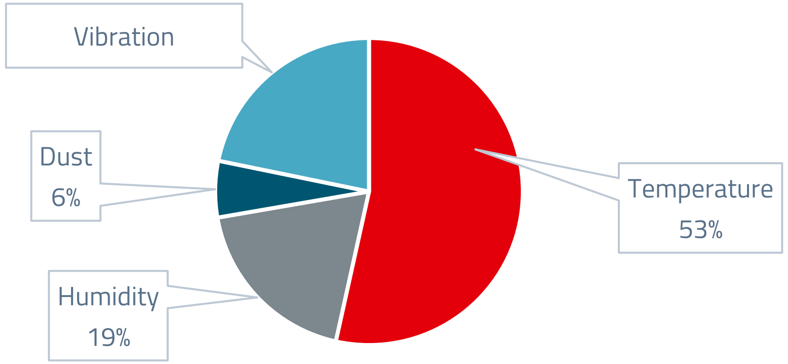


UNDERSTANDING THERMAL DESIGN CHALLENGES

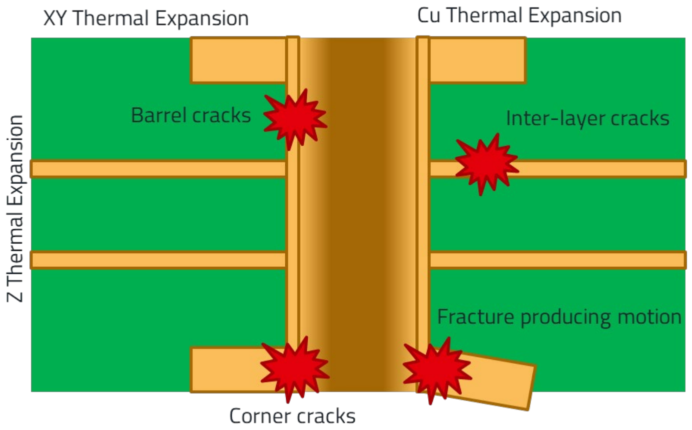
Temperature & Lifetime



Device Failure



Mechanical Stress Failure



CASE STUDY: THERMAL MANAGEMENT ON RECTIFIERS

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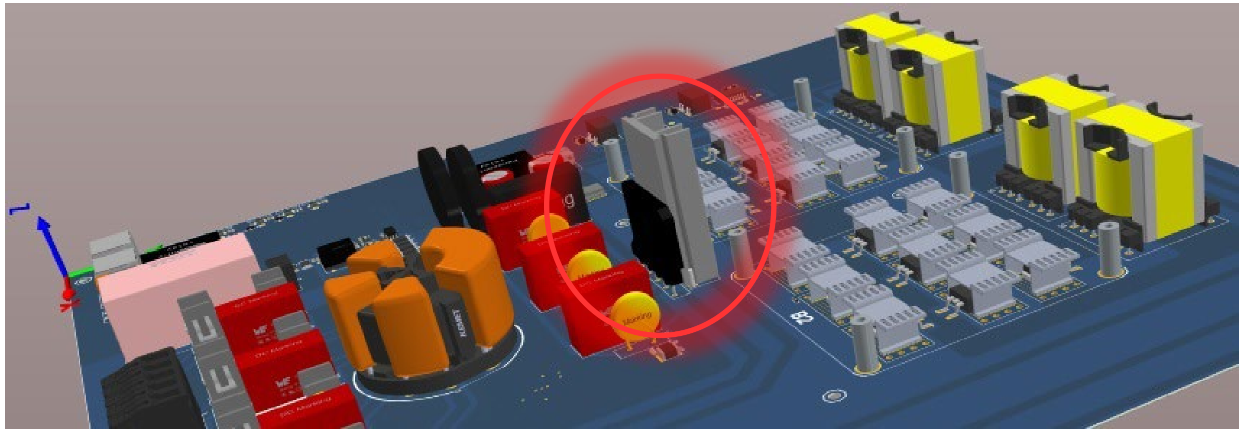
The **four** stages of thermal management:

1. Definition of the case scenario
2. Definition of the system
3. Find related values for the thermal resistance
4. Final Assessment

CASE STUDY: THERMAL MANAGEMENT ON RECTIFIERS

1. Define Case Scenario

- First, we define our thermal budget and case scenarios
  - Airflows
  - Ambient temperatures
  - TIMs
  - Heat sinks
  - …



CASE STUDY: THERMAL MANAGEMENT ON RECTIFIERS

1. Define Case Scenario

1. TIM Selection: since it’s a heatsink screwed to our component an Electrically insulating thermal is a good choice
   1. 1.6 W/m*K
   2. 3.5 W/m*K
2. Selection of the airflow:
   1. 200 LFM
   2. 400 LFM
3. Estimation of different ambient temperatures:
   1. 20 °C
   2. 40 °C
   3. 60 °C
4. Forward current from the component

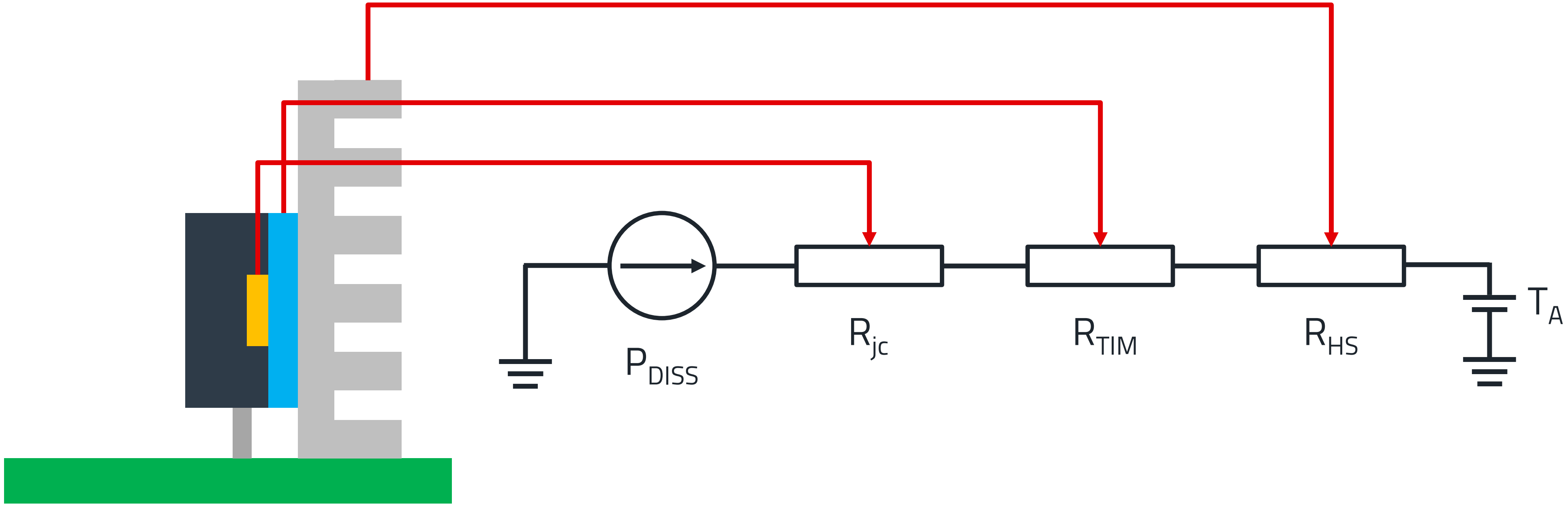
Case Study	Description	Ambient Temperature [°C]	Forward current [A]	Air Speed [LFM]
S1	Electrically insulating thermal pad 1.6 W/m*K	20	10	200
S2		40	10	200
S3		60	10	200
S4	Electrically insulating thermal 1.6 W/m*K	20	10	400
S5		40	10	400
S6		60	10	400
S7	Electrically insulating thermal 3.5 W/m*K	20	10	200
S8		40	10	200
S9		60	10	200
S10	Electrically insulating thermal 3.5 W/m*K	20	10	400
S11		40	10	400
S12		60	10	400

There can be more variables but these four are a good start for any thermal design!

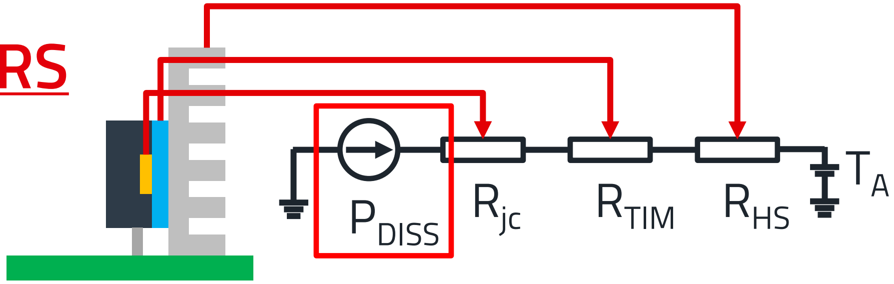
CASE STUDY: THERMAL MANAGEMENT ON RECTIFIERS

2. System Draft

- We can do a static analysis using the electrical-thermal analogy



CASE STUDY: THERMAL MANAGEMENT ON RECTIFIERS



3. Find P_{DISS}

- For power dissipation, 10A is being forwarded, we assume a duty cycle of 1

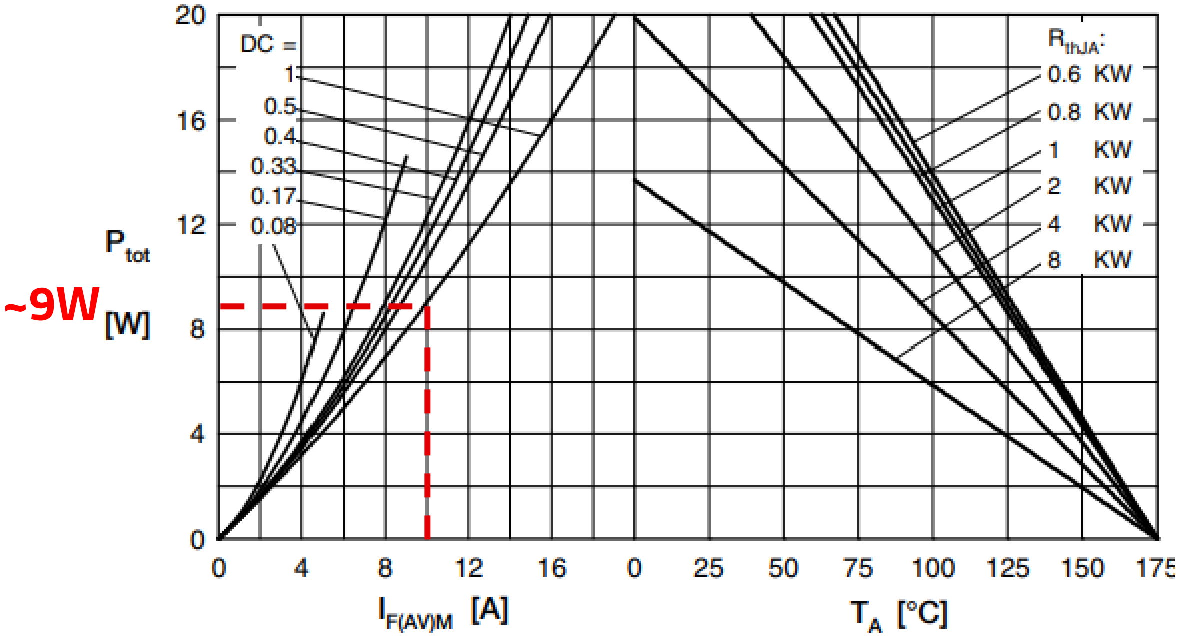
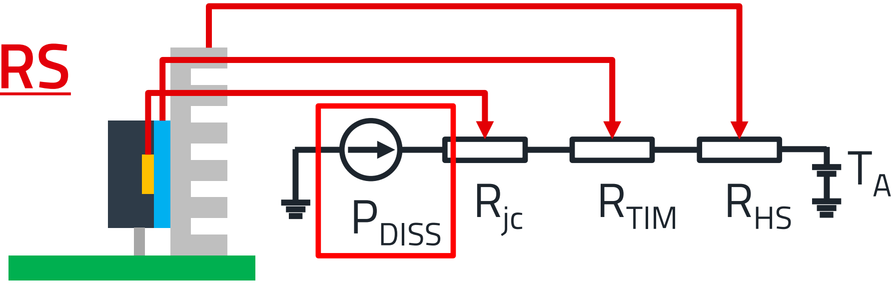


Fig. 4 Power dissipation vs. forward current and ambient temperature per diode

Rectifier is: GUO40-12NO1

CASE STUDY: THERMAL MANAGEMENT ON RECTIFIERS



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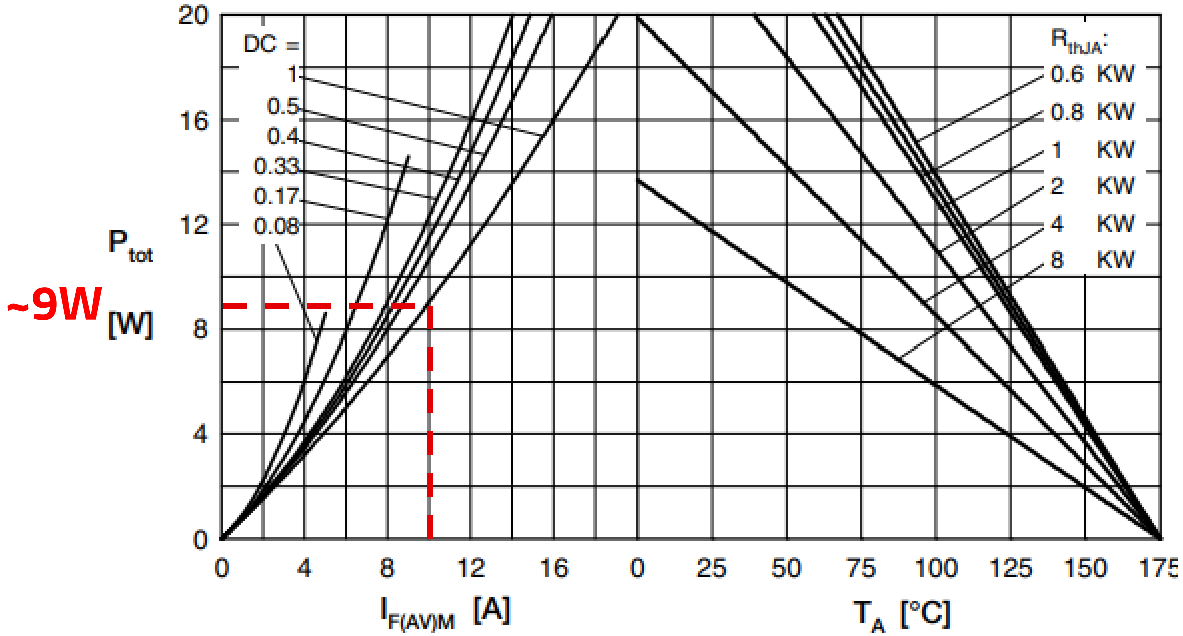

Fig. 4 Power dissipation vs. forward current and ambient temperature per diode

Case Study	Description	Ambient Temperature [°C]	Forward current [A]	Air Speed [LFM]
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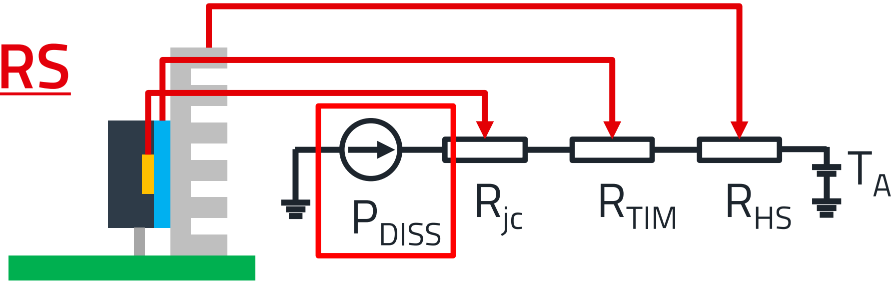

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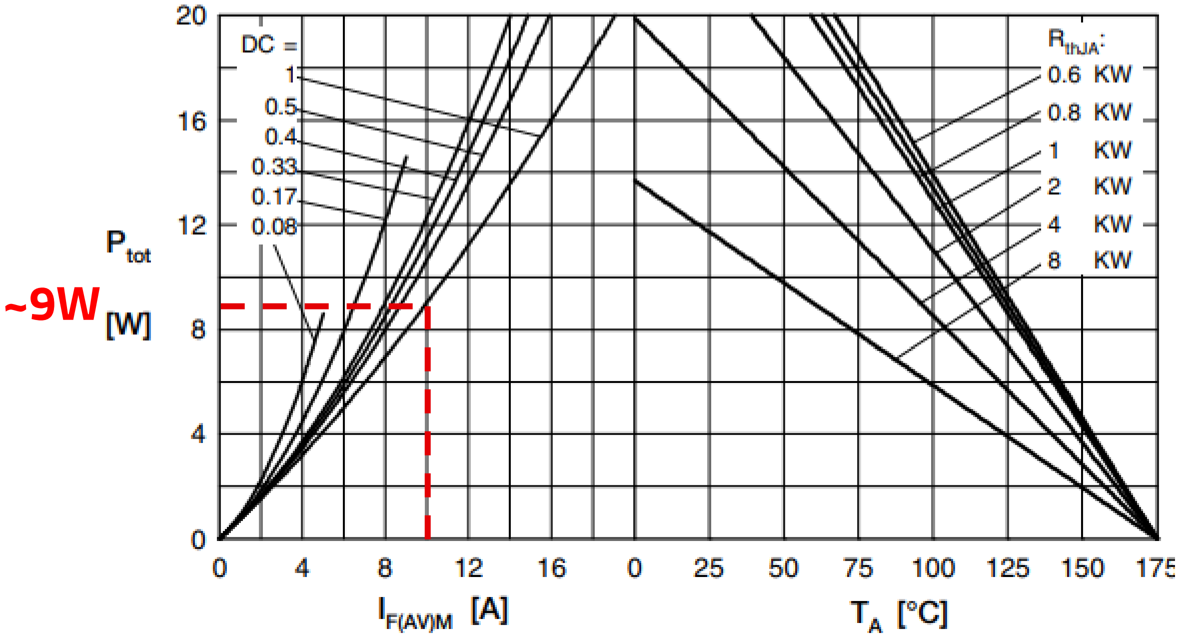

Fig. 4 Power dissipation vs. forward current and ambient temperature per diode

Case Study	Description	Ambient Temperature [°C]	Dissipated current [W]	Air Speed [LFM]
S1	Electrically insulating thermal pad 1.6 W/mK	20	9	200
S2		40	9	200
S3		60	9	200
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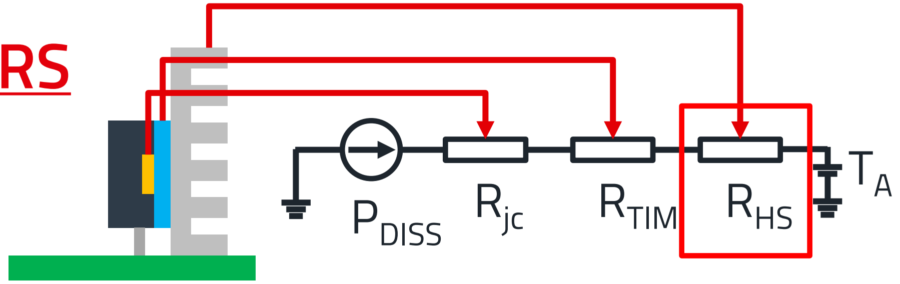
CASE STUDY: THERMAL MANAGEMENT ON RECTIFIERS

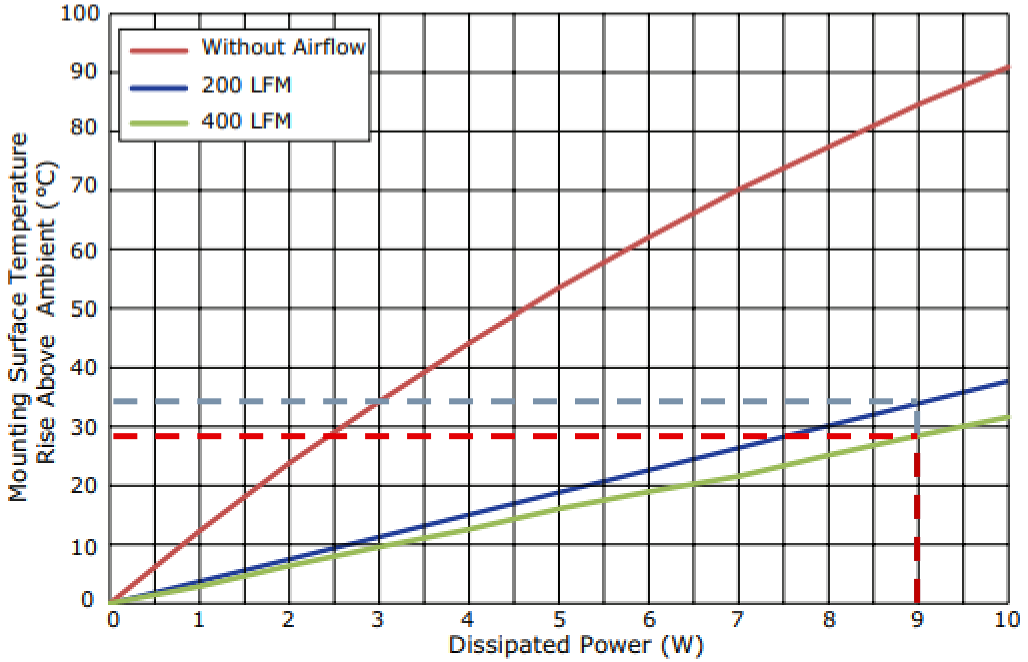


3. Find R_{HS}

- Now knowing we must dissipate around 9W we can calculate estimate R_{HS} with the heat sink's datasheet

For 200 LFM 34°C

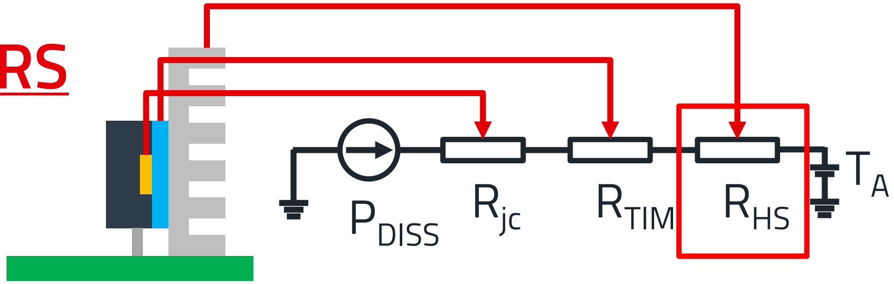
For 400 LFM 29°C



Heatsink is: HSE-B20250-045H

CASE STUDY: THERMAL MANAGEMENT ON RECTIFIERS

3. Find R_{HS}



- Heat sink manufacturers measure performance by forcing air through the fins, so it is a good habit to add 20-30% safety margin.

$$R_{HS} = \frac{Rise\ Above\ Ambient\ T}{Dissipated\ Power}\left(\frac{ºC}{W}\right) \cdot 1.25$$

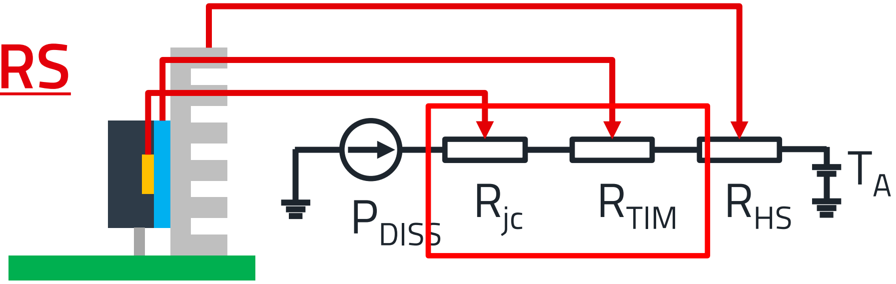
200 LFM

$$R_{HS} = \frac{34\ ºC}{9\ W} \cdot 1.25 \approx 4.7\ \frac{K}{W}$$

400 LFM

$$R_{HS} = \frac{29\ ºC}{9\ W} \cdot 1.25 \approx 4\ \frac{K}{W}$$

CASE STUDY: THERMAL MANAGEMENT ON RECTIFIERS

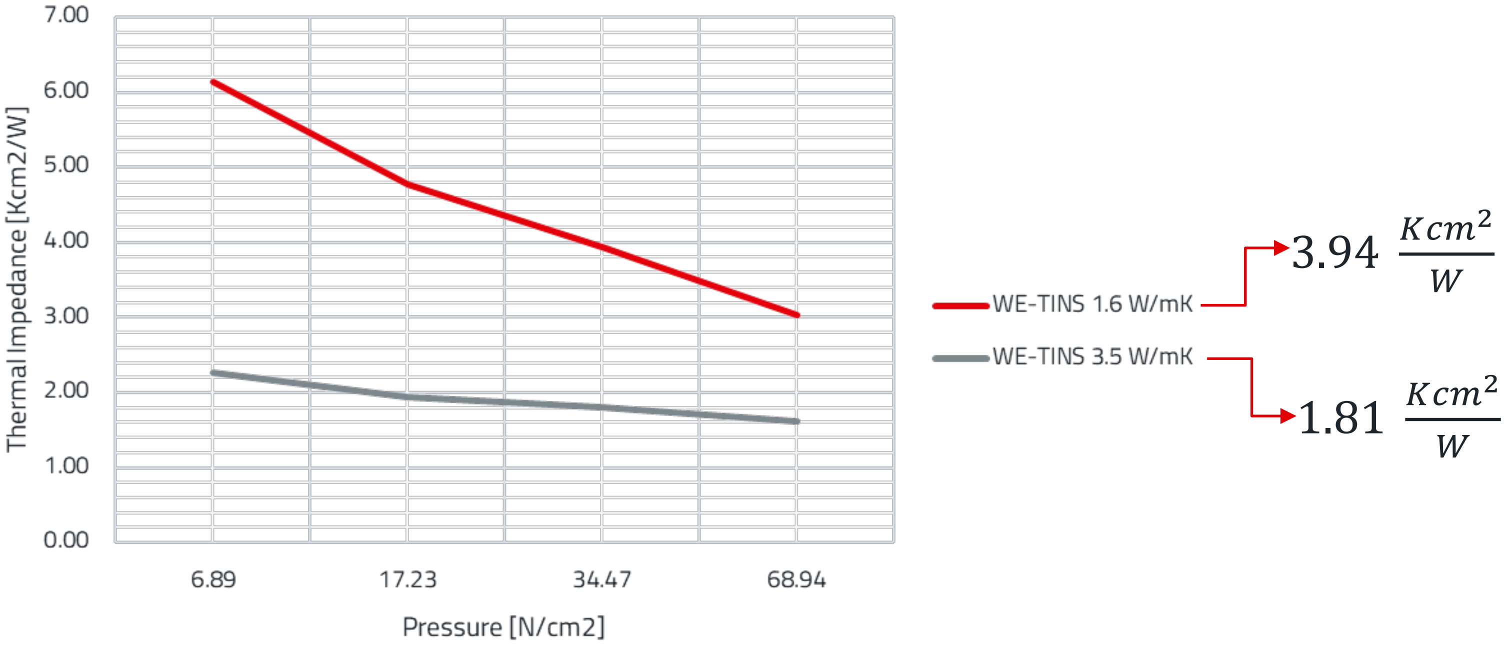


3. Find R_{jc} & R_{TIM}

- R_{jc} is very straight forward, we can get it from the rectifier’s datasheet:

R_{thJC}	thermal resistance junction to case			4.3	K/W
R_{thCH}	thermal resistance case to heatsink		0.50		K/W

- In our case scenario, we considered 2 different TIMs assuming a clamping force of 34 N/cm²:

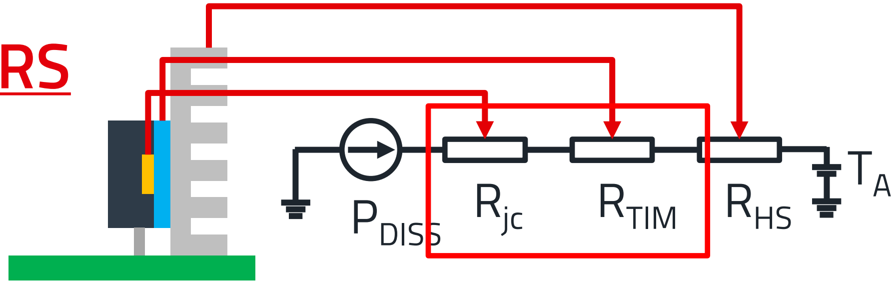


$3.94\ \frac{Kcm^2}{W}$

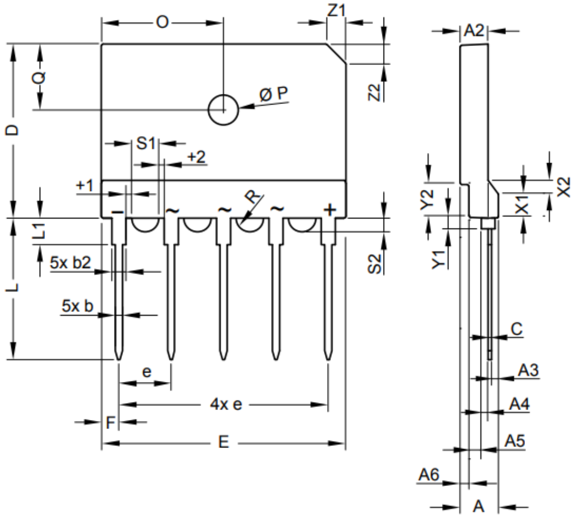
$1.81\ \frac{Kcm^2}{W}$

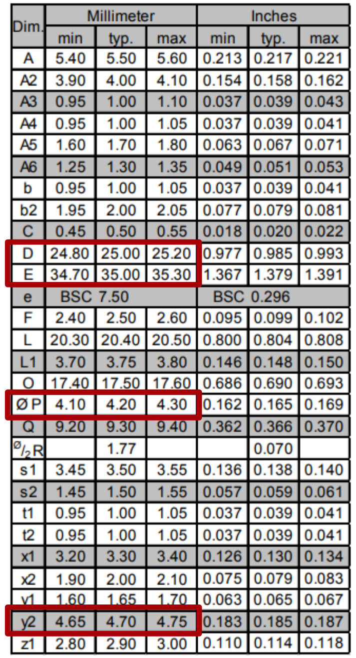
CASE STUDY: THERMAL MANAGEMENT ON RECTIFIERS

3. Find R_{jc} & R_{TIM}



- The data we got from the graph is Thermal Impedance (Z), to get the equivalent thermal resistance (R) we simply dive it by the material’s surface area





Dim.	Millimeter			Inches		
	min	typ.	max	min	typ.	max
A	5.40	5.50	5.60	0.213	0.217	0.221
A2	3.90	4.00	4.10	0.154	0.158	0.162
A3	0.95	1.00	1.10	0.037	0.039	0.043
A4	0.95	1.00	1.05	0.037	0.039	0.041
A5	1.60	1.70	1.80	0.063	0.067	0.071
A6	1.25	1.30	1.35	0.049	0.051	0.053
b	0.95	1.00	1.05	0.037	0.039	0.041
b2	1.95	2.00	2.05	0.077	0.079	0.081
C	0.45	0.50	0.55	0.018	0.020	0.022
D	24.80	25.00	25.20	0.977	0.985	0.993
E	34.70	35.00	35.30	1.367	1.379	1.391
e	BSC 7.50			BSC 0.296		
F	2.40	2.50	2.60	0.095	0.099	0.102
L	20.30	20.40	20.50	0.800	0.804	0.808
L1	3.70	3.75	3.80	0.146	0.148	0.150
O	17.40	17.50	17.60	0.686	0.690	0.693
Ø P	4.10	4.20	4.30	0.162	0.165	0.169
Q	9.20	9.30	9.40	0.362	0.366	0.370
Ø/2 R		1.77			0.070	
s1	3.45	3.50	3.55	0.136	0.138	0.140
s2	1.45	1.50	1.55	0.057	0.059	0.061
t1	0.95	1.00	1.05	0.037	0.039	0.041
t2	0.95	1.00	1.05	0.037	0.039	0.041
x1	3.20	3.30	3.40	0.126	0.130	0.134
x2	1.90	2.00	2.10	0.075	0.079	0.083
y1	1.60	1.65	1.70	0.063	0.065	0.067
y2	4.65	4.70	4.75	0.183	0.185	0.187
z1	2.80	2.90	3.00	0.110	0.114	0.118

TIM 1.6 W/mK

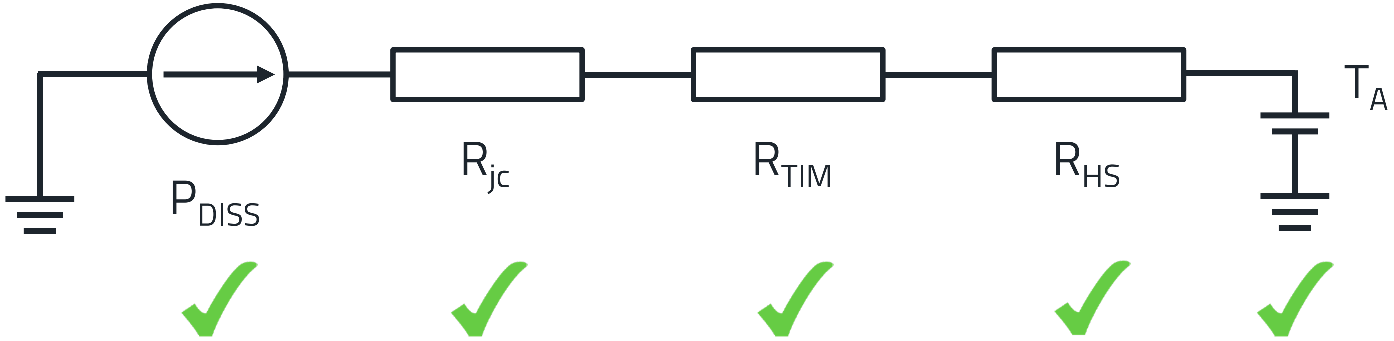
$$3.94\ \frac{Kcm^2}{W} \div 6.97\ cm^2 = 0.57\ \frac{K}{W}$$

TIM 3.5 W/mK

$$1.81\ \frac{Kcm^2}{W} \div 6.97\ cm^2 = 0.25\ \frac{K}{W}$$

CASE STUDY: THERMAL MANAGEMENT ON RECTIFIERS

3. System Draft



$$T_j = 20ºC + 5.7\frac{K}{W} \cdot 9\mathrm{W} \approx 71.3ºC$$

$$T_j = T_A + \mathrm{R} \cdot \mathrm{P}$$

CASE STUDY: THERMAL MANAGEMENT ON RECTIFIERS

4. Final Assessment

Case Study	Description	Ambient Temperature [°C]	Dissipated current [W]	Air Speed [LFM]
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S9		60	9	200
S10	Electrically insulating thermal 3.5 W/mK	20	9	400
S11		40	9	400
S12		60	9	400

- Now that we have all the data, we can layout our case scenarios and asses:

Value	Unit	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
T_A	°C	20	40	60	20	40	60	20	40	60	20	40	60
Air Speed	LFM	200	200	200	400	400	400	200	200	200	400	400	400
P_{DISS}	W	9	9	9	9	9	9	9	9	9	9	9	9
R_{HS}	K/W	4.7	4.7	4.7	4	4	4	4.7	4.7	4.7	4	4	4
R_{TIM}	K/W	0.57	0.57	0.57	0.57	0.57	0.57	0.25	0.25	0.25	0.25	0.25	0.25
R_{cj}	K/W	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
T_{HS}	°C	62.3	82.3	102.3	56	76	96	62.3	82.3	102.3	56	76	96
T_{TIM}	°C	67.43	87.43	107.43	61.13	81.13	101.13	64.55	84.55	104.55	58.25	78.25	98.25
Tj	°C	71.93	91.93	111.93	65.63	85.63	105.63	69.05	89.05	109.05	62.75	82.75	102.75

- In no scenario we reach the maximum junction temperature, although we do get close to it
- With a WE-TINS 3.5 W/mK and an airflow of 400 LFM, as expected, we get the lowest T_j

CASE STUDY: THERMAL MANAGEMENT ON RECTIFIERS

Estimation tool?

- The thermal-resistance model is a unidimensional analysis
  - It assumes all heat goes flows in one direction and that there are no other sources / emissions

- It is a static analysis, the values that we get are when the system reaches a thermal balance

- **Using a higher performing TIM has a limit**, at some point it will have a larger impact a more efficient heatsink

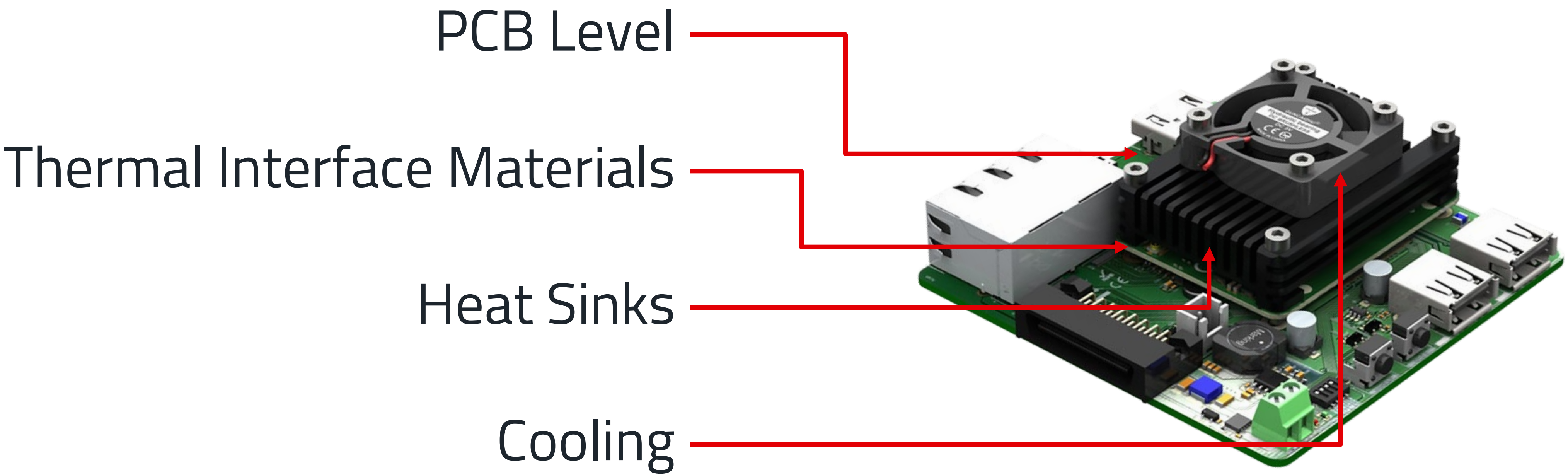
- Take these conclusions as a reference, not as a fact

- Next Steps:
  - Simulation -> Evaluate PCB layout, thermal coupling
  - Prototype validation

BEST PRACTICES IN THERMAL DESIGN TROUBLESHOOTING

BEST PRACTICES

Thermal Management “Stakeholders”



BEST PRACTICES

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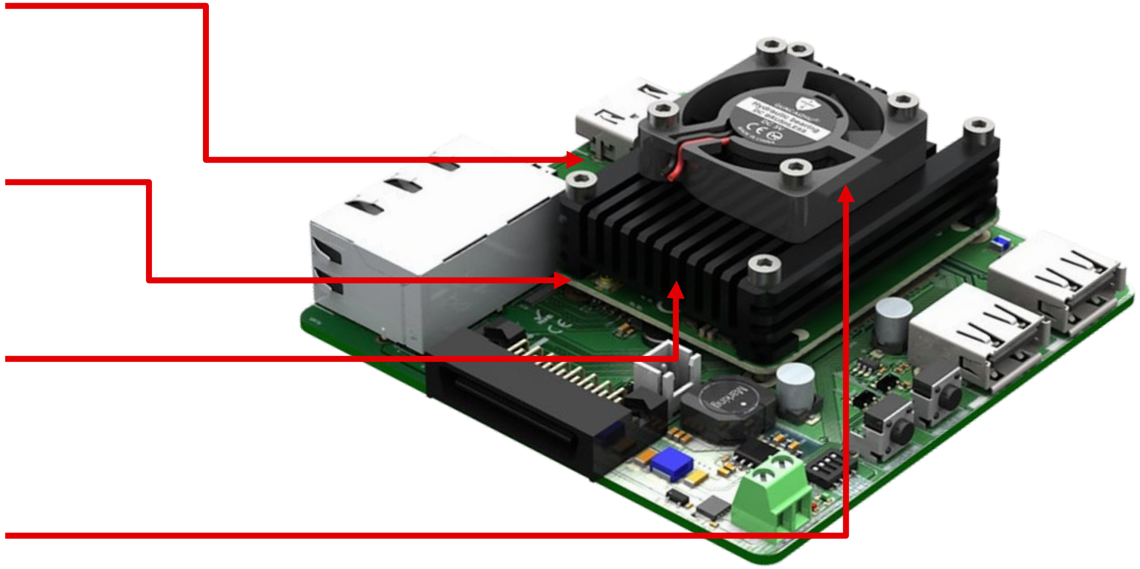


PCB Level

Thermal Interface Materials

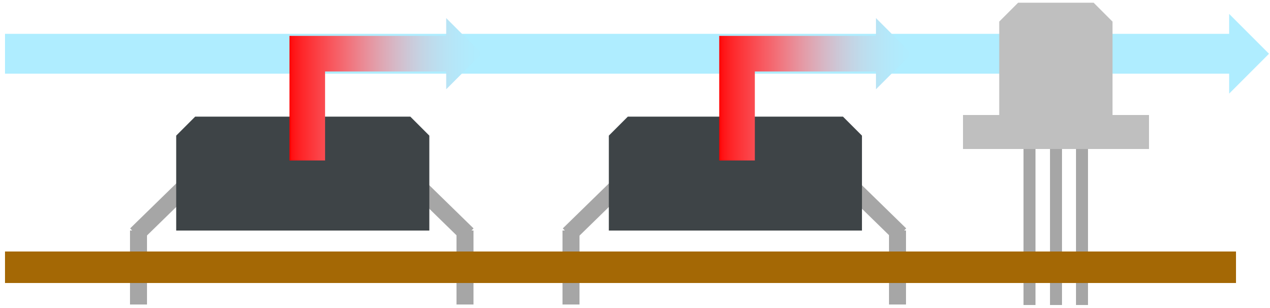
Heat Sinks

Cooling

BEST PRACTICES

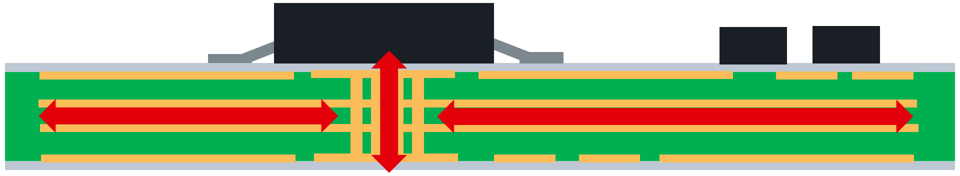
Thermal Management “Stakeholders”: PCB Level

- The THT to SMD transition
  - Circuit boards started as a physical support that allowed the mounting & interconnection of components



$$T_j = T_a + P \cdot R_{ja}$$

  - Due to miniaturization now 80-90% of heat flows to the ambient through the PCB

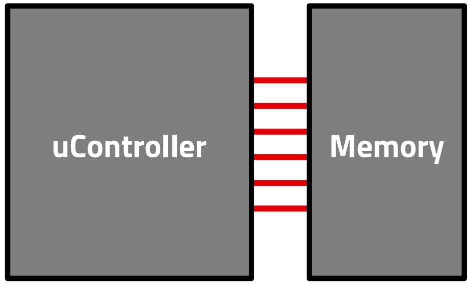


Material	k (W/mK)
Air	0.027
Glass	1
Steel	45
Aluminum	237
Gold	318
Copper	386
Plastic	0.1-0.4
FR4	0.25-0.3

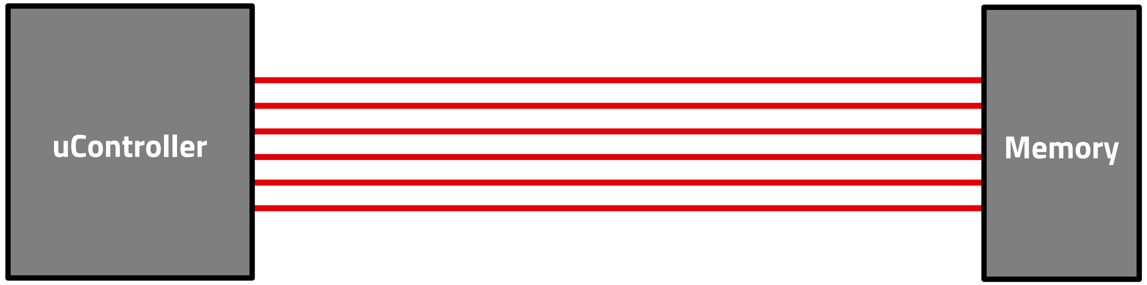
BEST PRACTICES

Thermal Management “Stakeholders”: PCB Level; Placement & PCB layout

- Single & most important thermal design decision

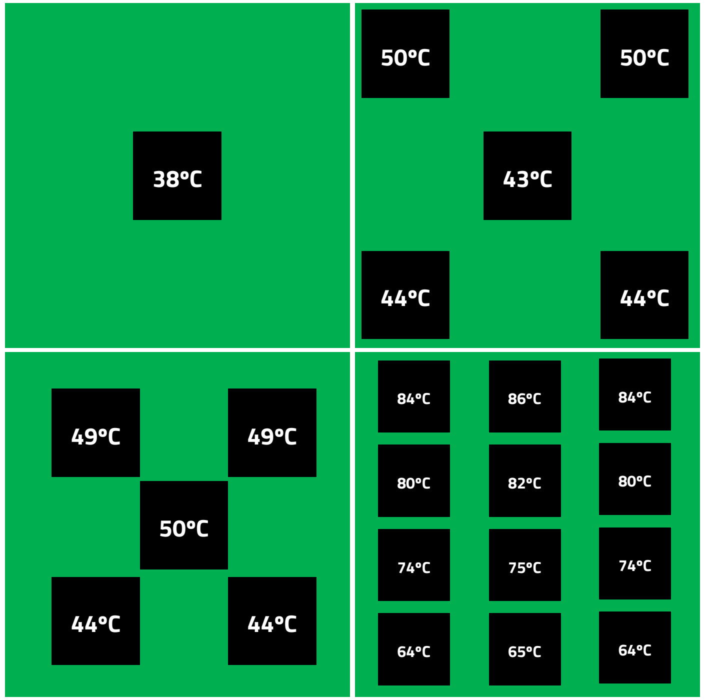


Best placement by Electronic Criteria



Best placement by Thermal Criteria

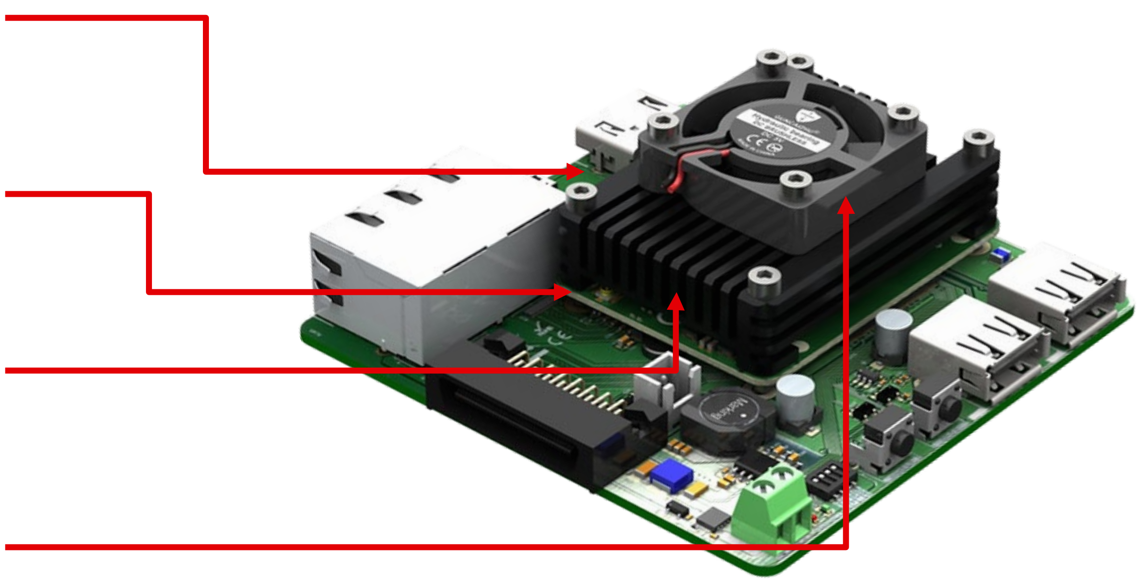
- Same IC, same operating criteria, same ambient can have different temperatures depending on PCB placement



1W IC, Vertical Placement,
Ambient Temperature: 20°C

BEST PRACTICES

Thermal Management “Stakeholders”



PCB Level

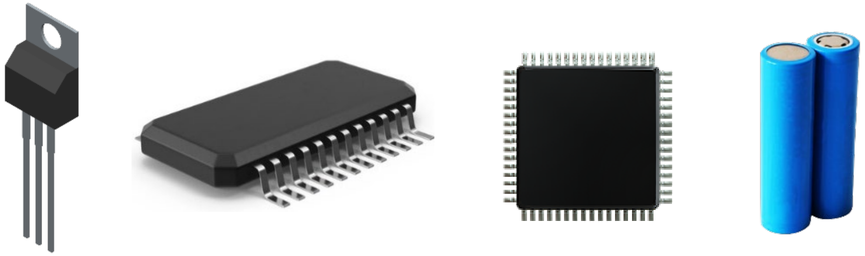
Thermal Interface Materials

Heat Sinks

Cooling

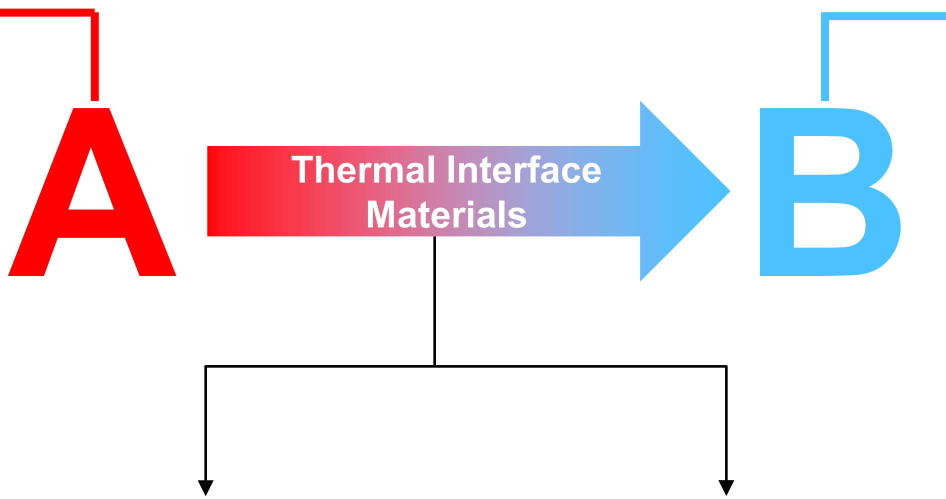
BEST PRACTICES

Thermal Management “Stakeholders”: Thermal Interface Materials



Heat Source

Cooling Assembly



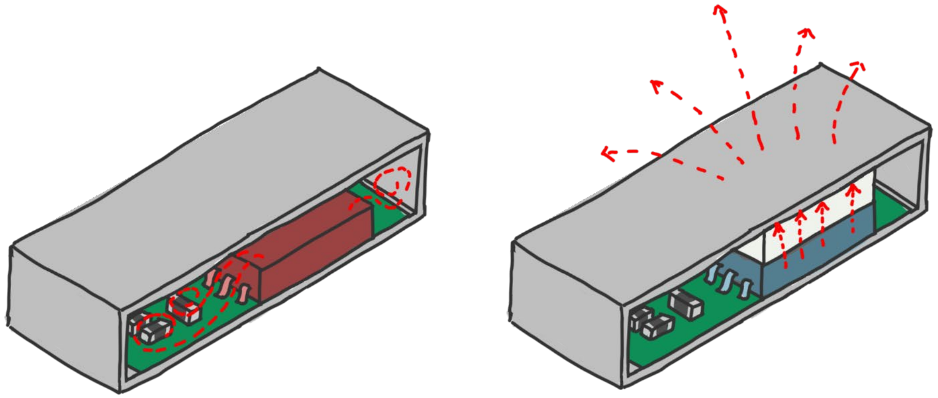
Gap Fillers

Heat Spreaders

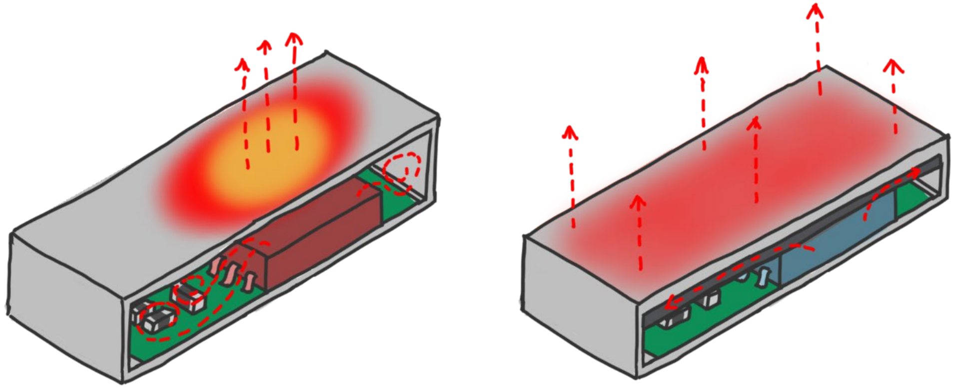
BEST PRACTICES

Thermal Management “Stakeholders”: Thermal Interface Materials

- Vertical heat transportation, realized by **thermal interface materials** (TIM) or **gap fillers**



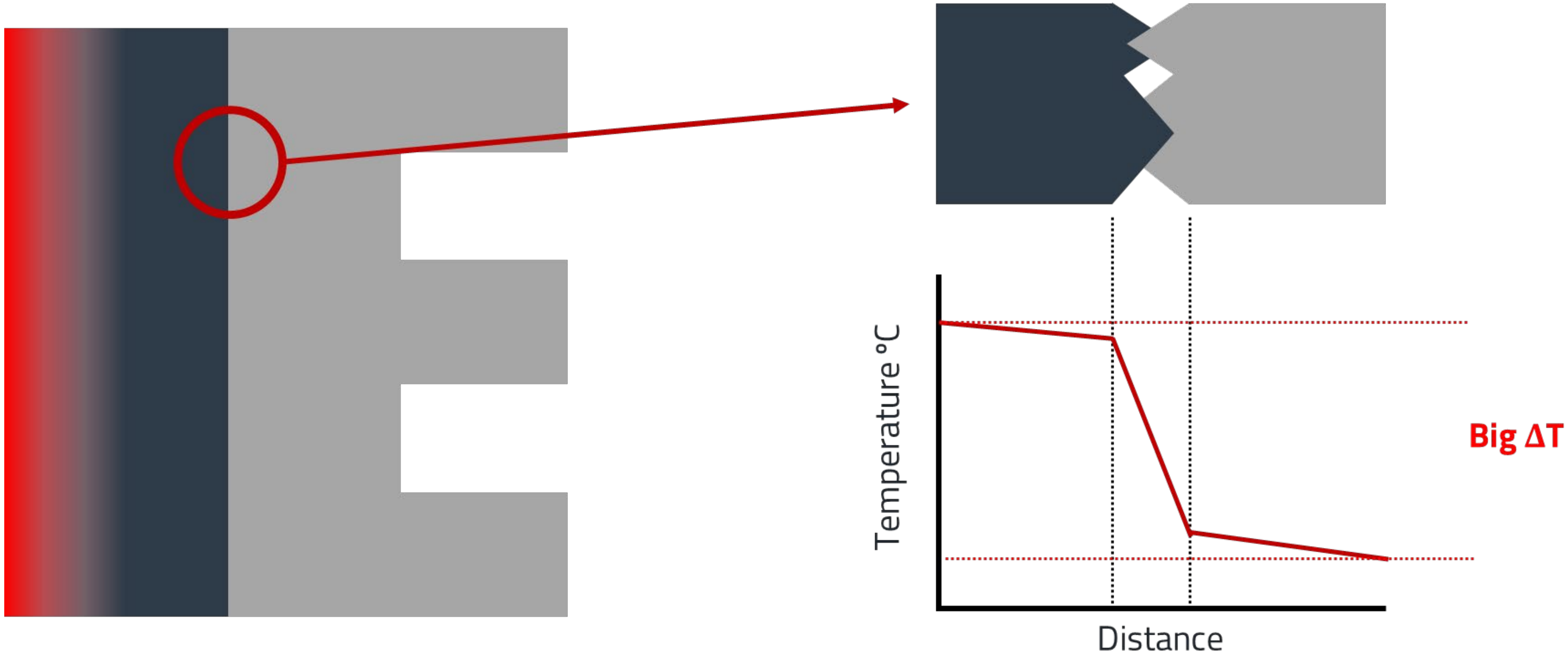
- Horizontal heat transportation, realized by **heat spreaders**



BEST PRACTICES

Thermal Management “Stakeholders”: Thermal Interface Materials

- Gap Fillers



BEST PRACTICES

Thermal Management “Stakeholders”: Thermal Interface Materials

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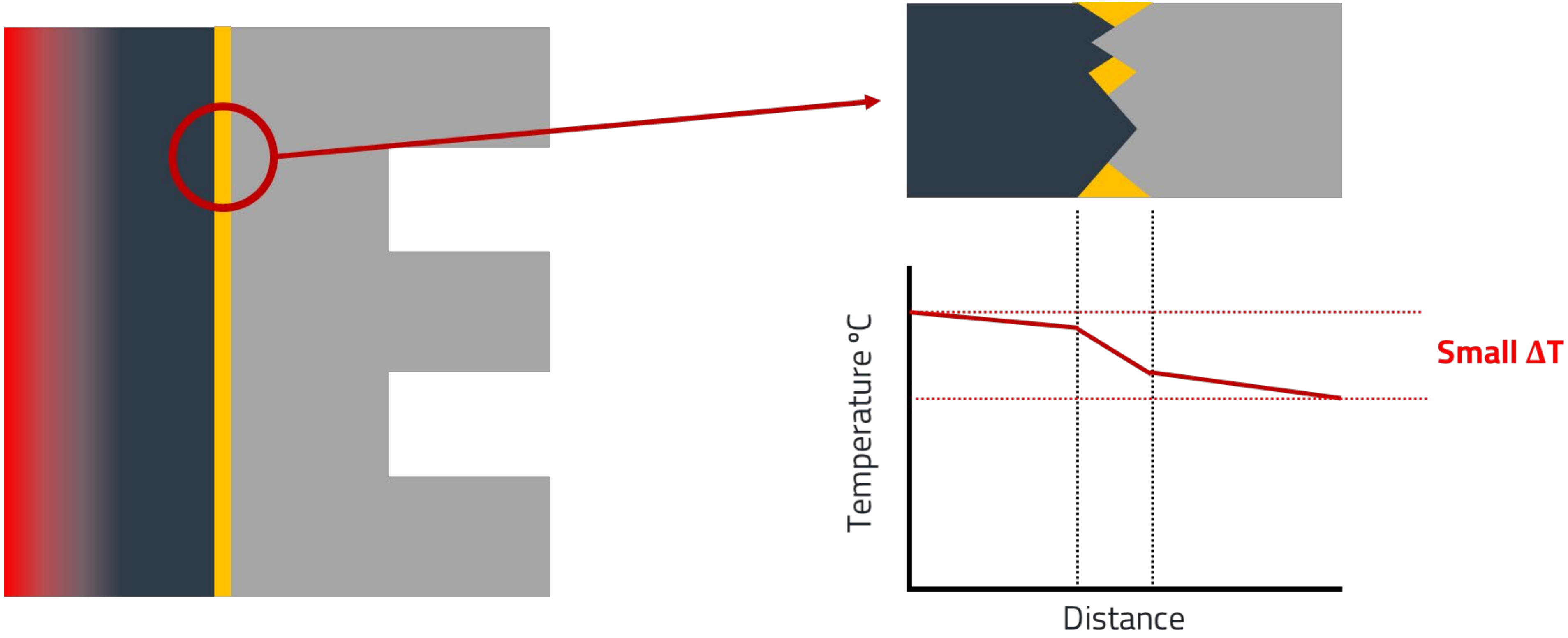
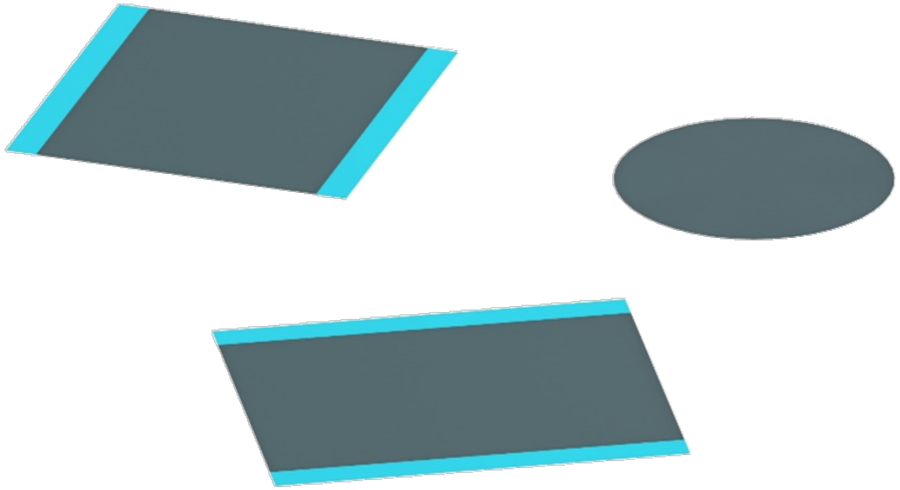
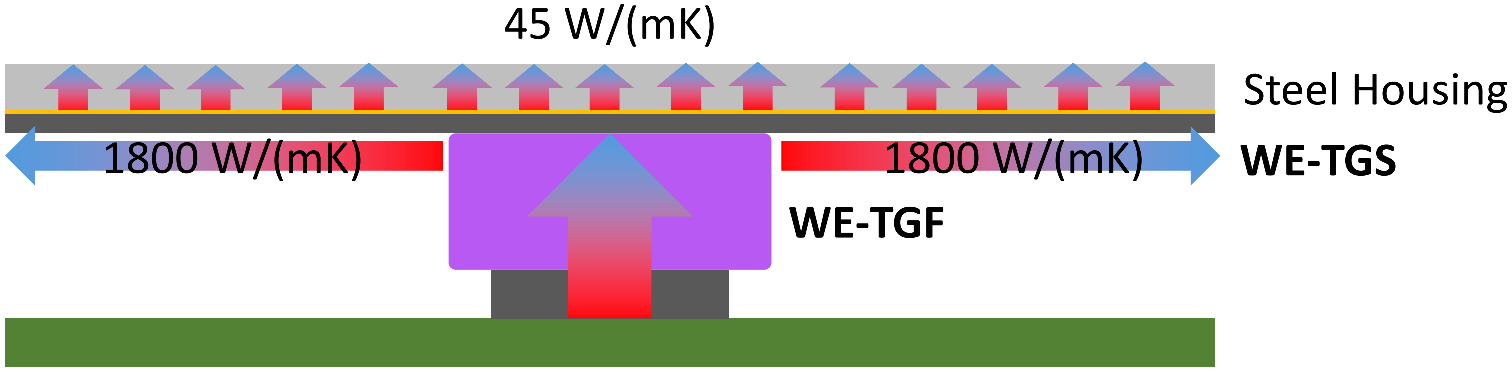


BEST PRACTICES

Thermal Management “Stakeholders”: Thermal Interface Materials

- Heat Spreaders:
  - Synthetic Graphite
  - Horizontal thermal conductivity: 1800 W/m·K
  - Thickness: 37um
  - 1kV AC electrical insulation
  - One side adhesive

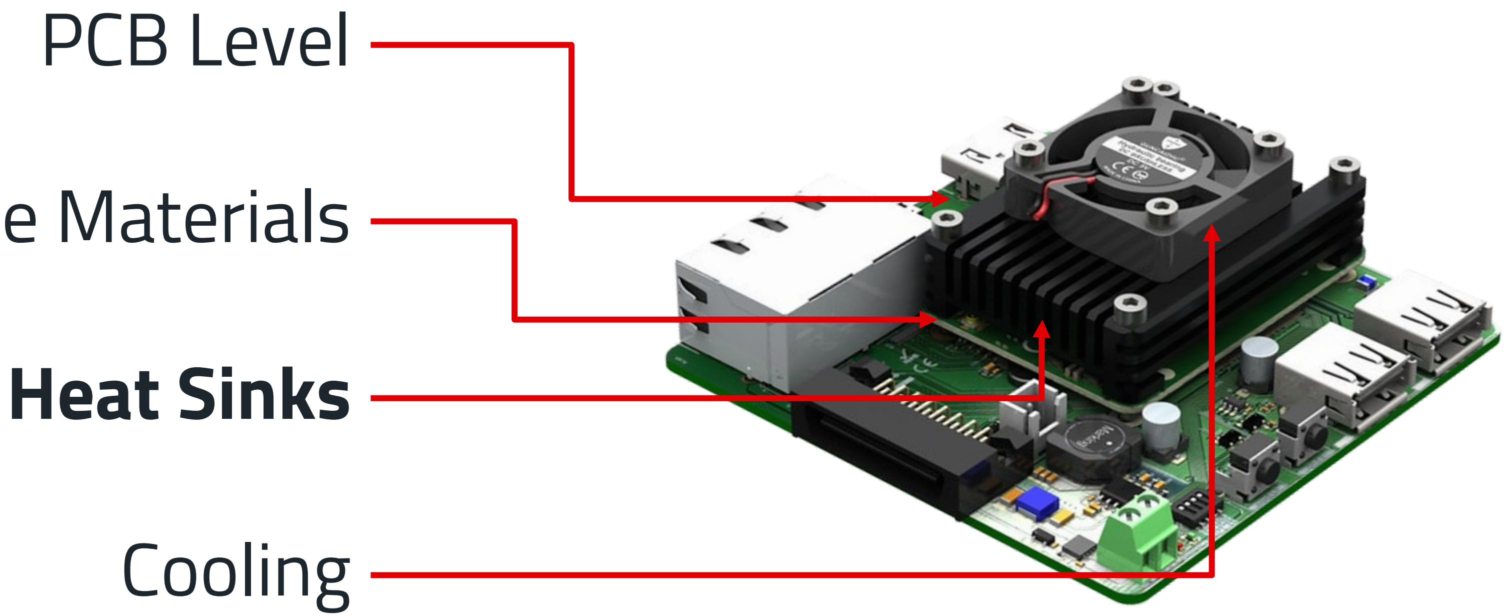




Material	k (W/mK)
Air	0.027
Glass	1
Steel	45
Aluminum	237
Gold	318
Copper	386

BEST PRACTICES

Thermal Management “Stakeholders”



PCB Level

Thermal Interface Materials

Heat Sinks

Cooling

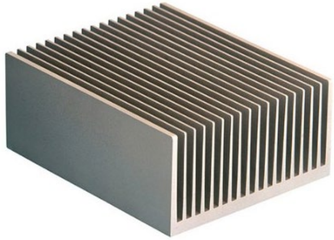
BEST PRACTICES

Thermal Management “Stakeholders”: Heat Sinks

- There are several types and manufacturing methods, the most general are:

Extruded

Pin-Fin



BEST PRACTICES

Thermal Management “Stakeholders”: Heat Sinks

- There are several types and manufacturing methods, the most general are:

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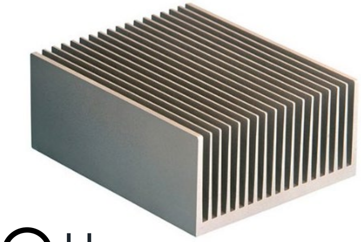
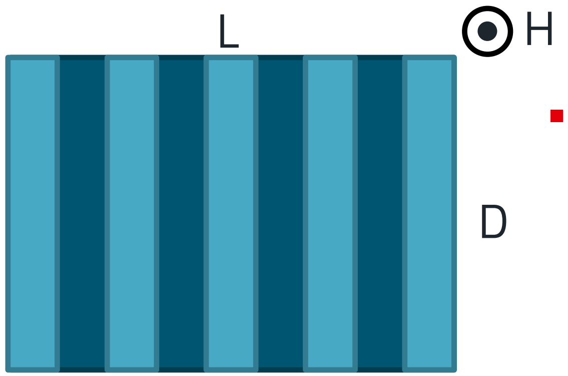


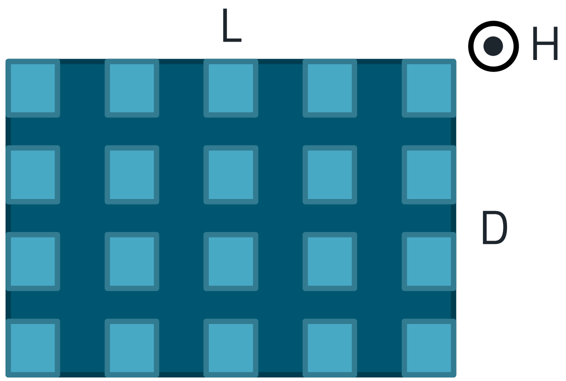


$$A = 10 \cdot D \cdot H$$

- Use case scenario:
  - A device that is in a fixed position
  - Perpendicular to airflow (natural, forced)

Pin-Fin

- Use case scenario:
  - Airflow direction unknown or changing



$$A_Y = 10 \cdot D \cdot H \cdot 4/7$$

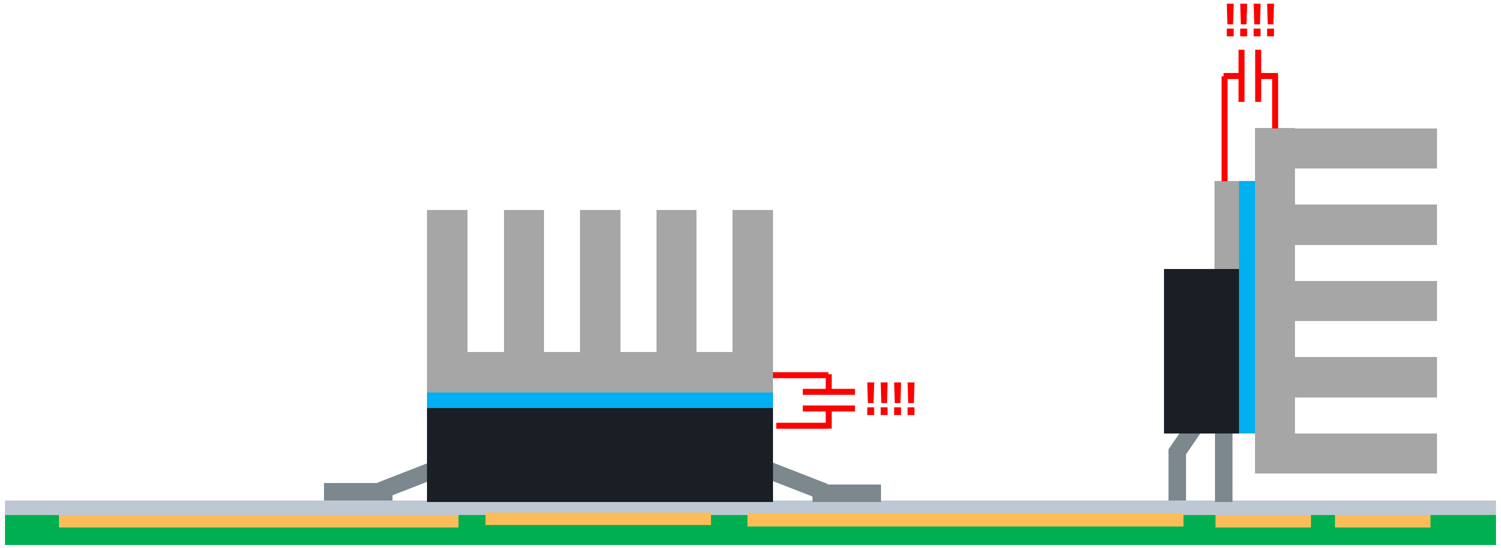
$$A_X = 8 \cdot D \cdot H \cdot 5/7$$

$$A_{XY} = 5.7 \cdot D \cdot H$$

BEST PRACTICES

Thermal Management “Stakeholders”: Heat Sinks

- EMC Considerations:
  - IC or transistor interfaced with a heatsink can lead to EMI issues
  - TIMs can be very thin → Capacitance
  - When currents fluctuate, capacitances inject stray currents into heatsinks
  - Stray currents should be controlled and returned to sources

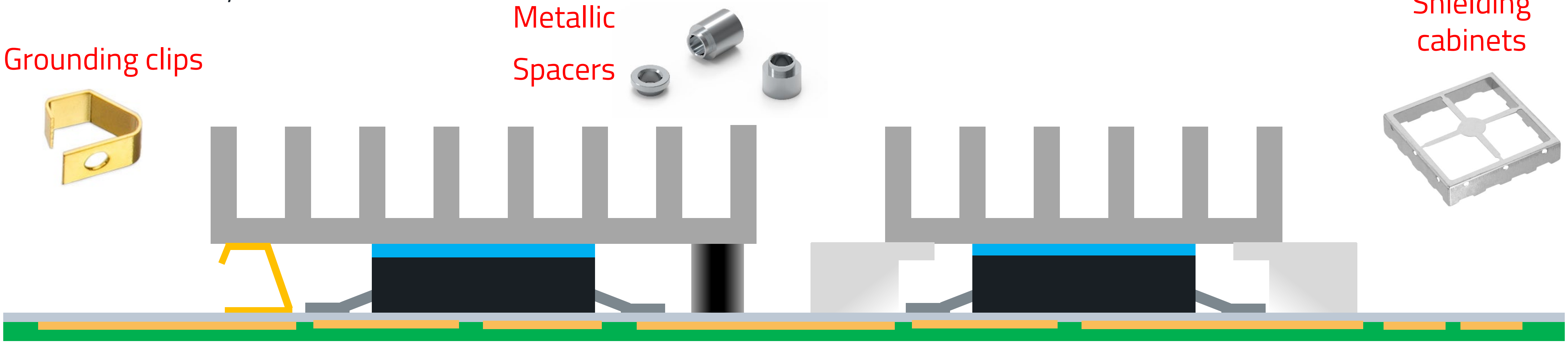


BEST PRACTICES

Thermal Management “Stakeholders”: Heat Sinks

- EMC Considerations:
  - IC or transistor interfaced with a heatsink can lead to EMI issues
  - TIMs can be pretty thin → Capacitance
  - When voltages fluctuate, capacitances inject stray currents into heatsinks
  - Stray currents should be controlled and returned to sources

- Return stray currents to source:



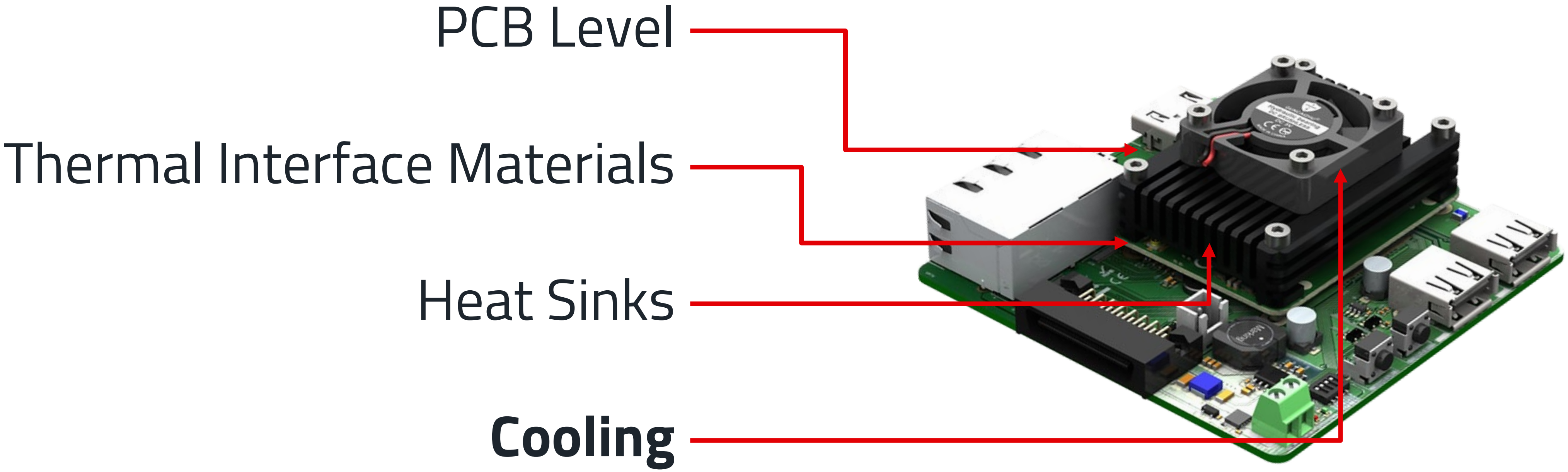
Grounding clips

Metallic Spacers

Shielding cabinets

BEST PRACTICES

Thermal Management “Stakeholders”



PCB Level

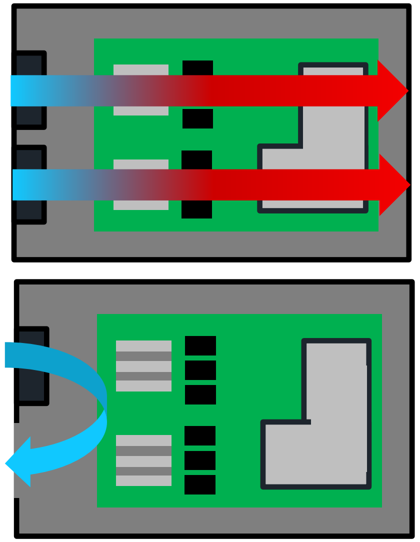
Thermal Interface Materials

Heat Sinks

Cooling

BEST PRACTICES

Thermal Management “Stakeholders”: Cooling

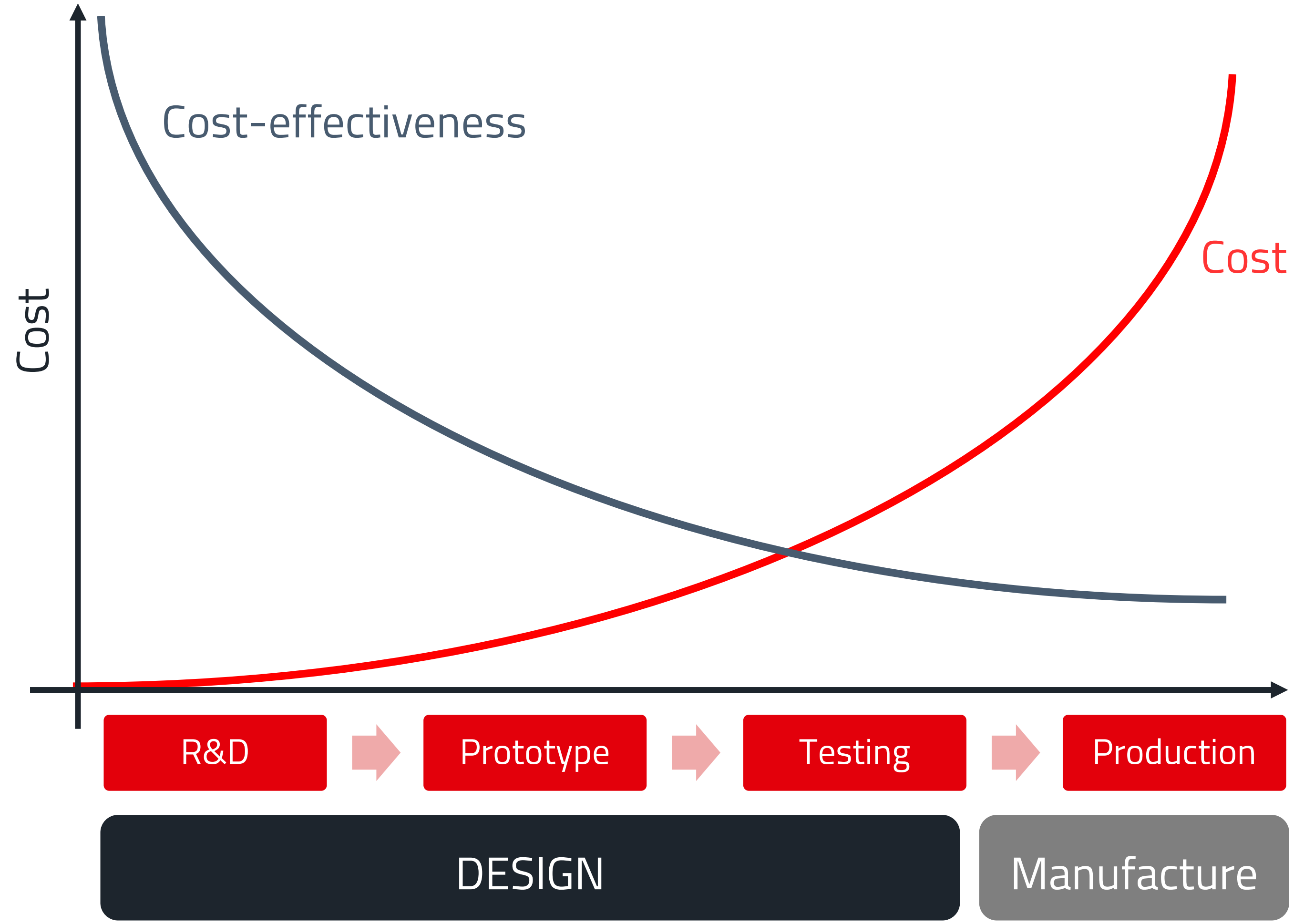


- Airflow Direction
- Fan Placement
- Fan Size
- Noise Levels
- Airflow Obstructions
- Fan Speed Control
- Redundancy

CONCLUSION

KEY STRATEGIES FOR ADDRESSING THERMAL ISSUES

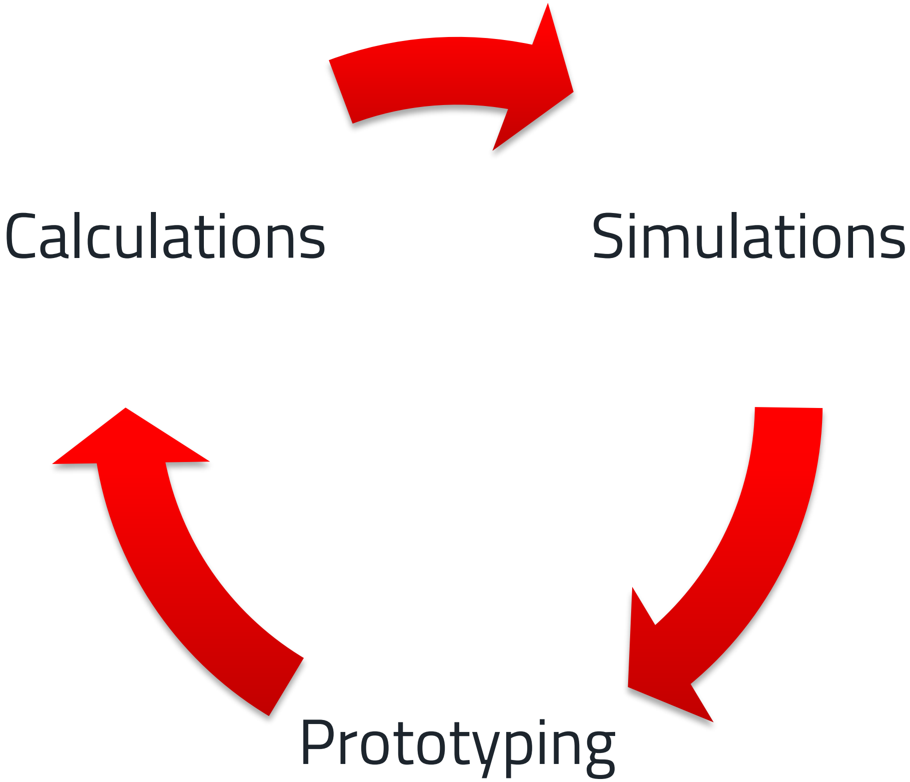
Importance of early consideration of thermal management in the design process



KEY STRATEGIES FOR ADDRESSING THERMAL ISSUES

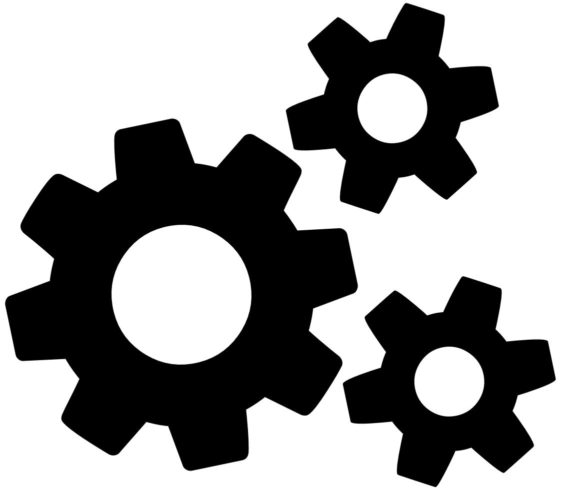
Importance of early consideration of thermal management in the design process

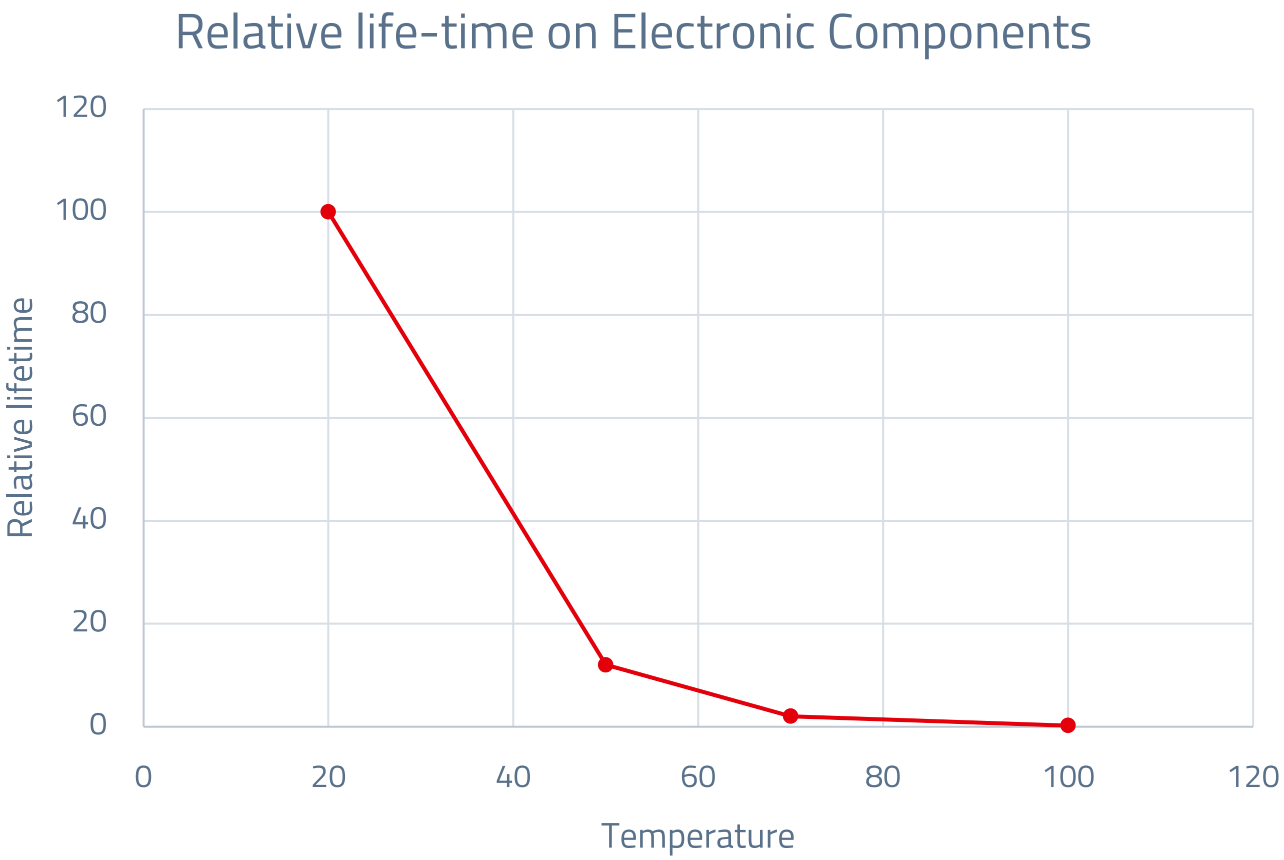
- Error asociated by the nature of the iterations:
  - Calculations: Normally the estimated error is around 10°C, but can go as high as 20°C since doesn't take into account many other factors that are happening in the surroundings, like pressure drops, too high power density on the PCB and more heat ways.
  - Simulation: Normally the estimated error is around 2°C.
  - Prototyping: No error.



IMPORTANCE OF PROACTIVE THERMAL MANAGEMENT

- Improved reliability.
- Reduced risk of failure.
- Enhanced performance.





Questions

& Answers

We are here for you now!
Ask us directly via our chat or via E-Mail.

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Toni.Agapito@we-online.de