Thermal Design Considerations

Application Note

80-VU794-5 Rev. D

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Revision History

Revision	Date	Description
A	November 2009	Initial release
B	March 2010	Page 5 – Added additional information on chipset power contribution Page 6 – Updated the carrier requirements description Page 8 – Updated the QCT MDM8200™ prototype dongle information Page 9 – Updated Plastic or mechanical selection information Deleted former page 10 – Simple Heat Dissipation Modeling Page 11 – Added additional information on the assumptions made by the Simple Heat Dissipation model Page 14 – Updated temperature value to 140 in third Conclusions bullet Added PA temperature in last Other bullet Updated text in fourth Other bullet Page 15 – Updated steady state PA temperature Page 16 – Updated values in Results bullet, step 1 and step 2
C	June 2010	Updated title to *Thermal Design Consideration Application Note* Page 5 – Added smart phone form factor as area of focus Page 9 – Updated bullet text under number 4 Pages 10 and 11 – New slides with additional thermal design considerations
D	November 2010	Pages 9, 10, 11 – Added additional thermal design approaches Pages 12, 13 – Added routing examples Pages 27, 28,29 – Added information on thermal tests and their results Pages 5, 30 – Updated references

Agenda

- Introduction
- Thermal design approach, simulation, and testing:
  - Thermal design guidelines, approach, and trade-offs
    - Applying thermal fundamentals during the conceptual stage of a product design
    - Used to drive trade-offs for cooling method, size, part location, etc.
  - Thermal simulation
  - Simple heat dissipation modeling
    - 3D computational fluid dynamics software used to predict flow and temperature
  - Thermal testing
    - Measured temperature used to validate design intent and may drive redesign
- Appendix – Heat transfer fundamentals:
  - Thermal resistance equation
  - Heat transfer modes
    - Conduction
    - Convection
    - Radiation
  - The Qualcomm MDM8200-based prototype USB dongle resistances example

Introduction

Introduction

- Purpose:
  - The purpose of this application note is to assist OEMs with the proper thermal design of:
    - USB dongle form factors
    - Smart phone form factors heat dissipation
- Background:
  - Due to the small form factor of USB dongles, there is less surface area to dissipate heat.
    - Even though smart phones have a bigger form factor, heat dissipation is still a problem.
  - Heat generated by the device can greatly impact the end-user experience and introduce health and safety concerns.
  - High MDM8k/9k power consumption (> 1 W) is due to the new architecture for increased data throughput.
  - PA power (> 1 W), along with the MDM™/MSM™, are the highest power contributors.
- References:
  - *Thermal Protection Algorithm Overview* (80-VT344-1)
  - *Thermal Protection Algorithm Application Note* (80-VJ372-14)
  - *MDM9200/MDM9600 Thermal Issues and Protection Software* (80-VP146-28)

Note: The thermal protection algorithm is a software thermal mitigation algorithm that can help improve thermal performance of existing hardware designs.

International Standards and Carrier Requirements

- Several governing standards:
  - US: Underwriters Lab 60950 specification from Part 2 of Table 4A (Section 4.5.1, Temperature rises). The applicable part in that table as understood should be "Handles, knobs, grips, etc., continuously held in normal use." The maximum temperature in the UL specification is 75°C (167°F) for plastic.
  - EU: 1991 copy of the IEC specification: 610.1 (more medical) Clause 42, has a "continuously held" molded plastic device at a maximum temperature of 75°C.
  - Asia: TBD
- Carrier requirements:
  - Carriers are starting to define strict thermal specifications.
    - i.e., AT&T stated devices and associated accessories being submitted for technical acceptance shall not exceed the touch temperature limits defined by the most current version of UL 60950-1.

Thermal Design – Approach, Simulation, and Testing

Thermal Design Approach

- Thermal design guidelines:
  - Apply thermal fundamentals during the conceptual stage of a product design.
  - Drive trade-offs for cooling method, size, part location, etc.

1. Increase the surface area of the printed wiring board (PWB) and housing with consideration of industrial design goals.
2. Gather power dissipation and size of each heat generating item or component. Prioritize cooling based on the power density, watts per inch squared <w/in2>.
   - The QCT MDM8200™ prototype dongle example: Cell PA is 76 W/in2 (1.07 W/1/8” sq.), and MDM is 3.5 W/in2 (1.2 W/15 mm sq.).
3. Gather the maximum junction or surface temperature rating of parts and prioritize by temperature; ambient ratings of parts should not be used.

Thermal Design Approach (cont.)

4. Material selection, color, and finish: Aluminum is 1000 times more conductive than plastic. White and painted surfaces have higher emissivity (high e – low R – low delta T) than black or rough surfaces.
   - Metals conduct heat better than plastic. Metals have a lower touch temperature rating because they can conduct heat to fingers faster than plastics. When metals are used instead of plastic for electronics packaging, they can reduce peak heat source temperatures, but the packaging can reach a higher temperature.
5. Avoid co-locating high-power density parts side-by-side or front-to-back on the single PWB or face-to-face on two parallel PWBs.
   - Keep the PA away from other heat sources.
   - Keep very hot components away from a battery.
   - Keep the PMIC away from the MDM device.
   - Keep VCTCXO or any XO away from heat sources/gradients.
6. Plastic or mechanical selection:
   - Use proper heat vents that allow heat escape.
   - Thermal resistance is proportional to wall thickness.
   - Use ribbing for extra surface area for a given form factor.

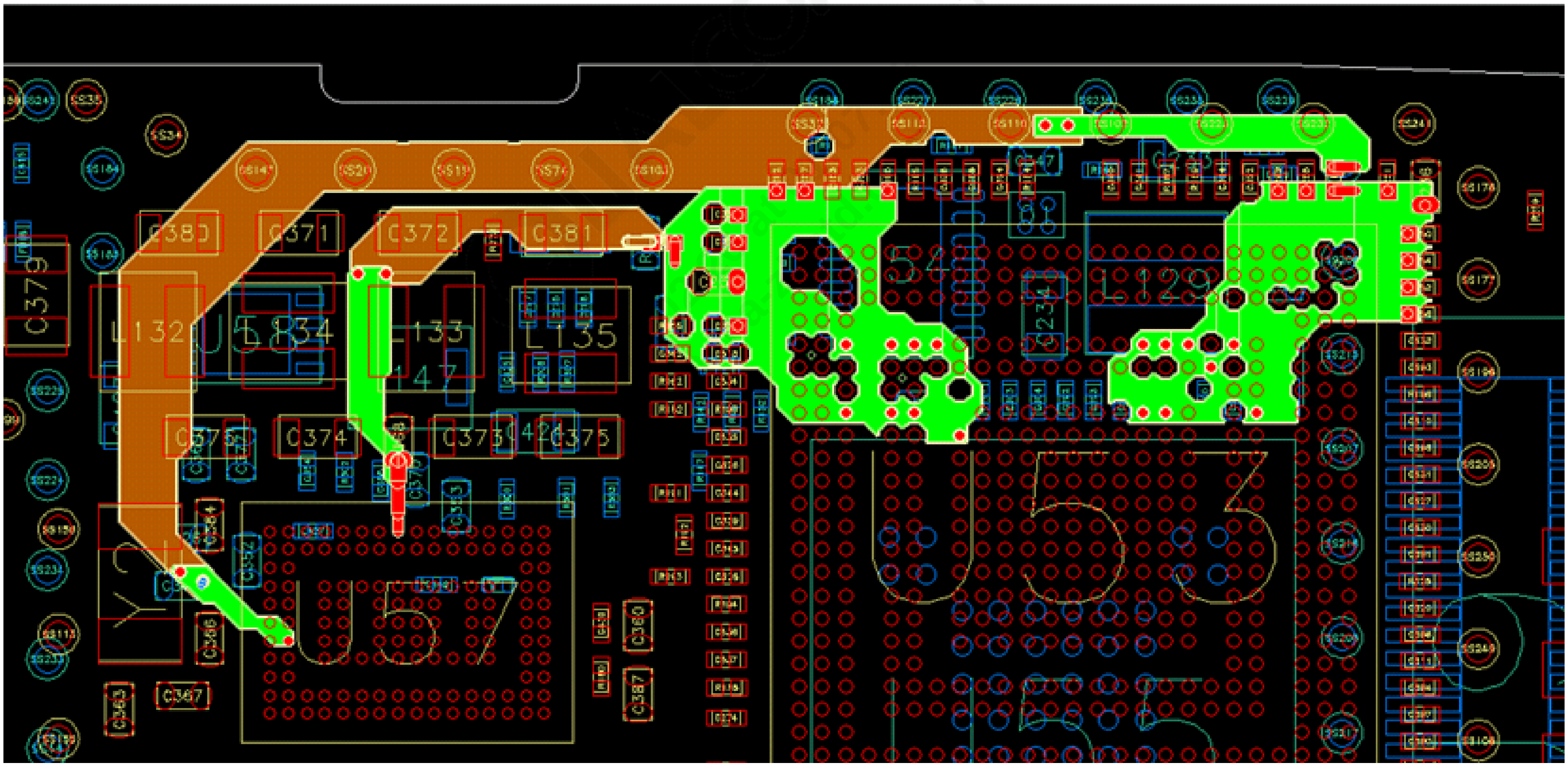
Thermal Design Approach (cont.)

7. Provide a low-resistance cooling path for small and other critical components.
   - Mount components on the top side of the PWB for better natural convection.
   - Increase the conductivity of the PWB with added layers and copper on each layer.
   - A higher copper density provides better thermal relief/heat transport.
     - The power amplifier is too small to rely on air dissipation only. A large amount of copper in the PWB is necessary to help heat sink the thermal load.
     - Fill empty board layers with copper wherever possible.
     - Layer 1 copper is very important.
     - Increase the copper using thick traces as much as possible. Especially recommended for voltage rails that consume high current.
   - Add ample PWB vias under or near hot spots.
     - Vias should go to a large radiating plane for better heat dissipation.
     - Via material is very important. Solid copper is better than paste.
     - Stacked vias are better than staggered.
     - Vias in the PA ground pad are very important. Use as many as you can. Stacked vias to the ground pad is best.
   - Use power planes instead of routing.

Thermal Design Approach (cont.)

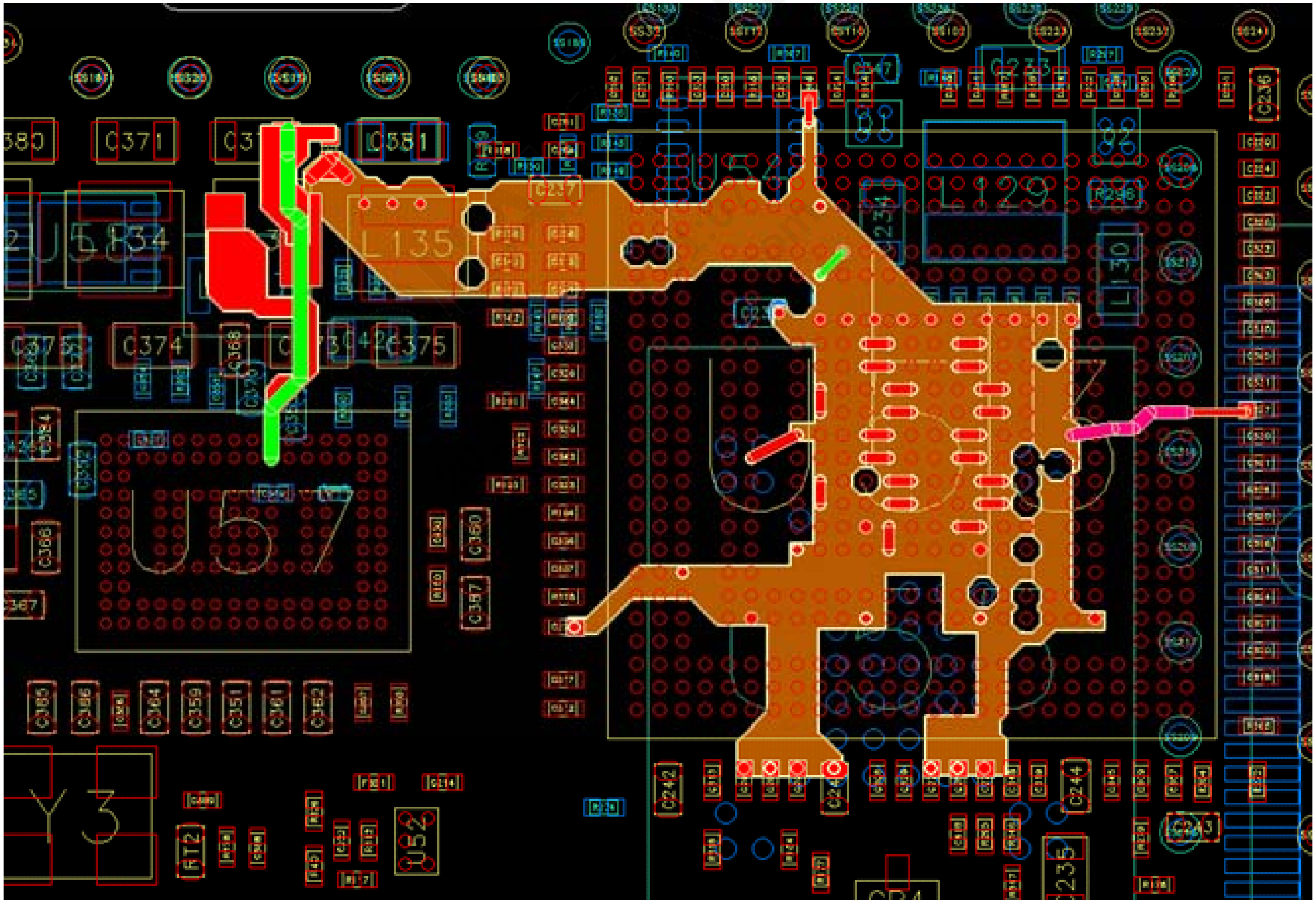
8. Additional considerations:
   - Use wide traces vs. standard width, where possible.
   - Use plated mounting holes where possible.
   - Use thermal interface material.
     - Helps reduce component case temperature
     - Can also potentially increase the product case touch temperature
     - Be mindful of this trade-off
   - There may be ways to adjust the size and location of thermal hot spots by adding material of various thermal conductivities. This will help to evenly spread thermal dissipation across the entire surface.
   - For USB dongle designs, consider reducing the thermal resistance from the PWB through the USB connector to the laptop.
   - VCTCXO should be placed in a good spot thermally.
     - Check GSM performance/noise/signal integrity
     - TXCO track LO adjust is also a very sensitive line that needs to be routed carefully

Q6_FW and Q6_SW power



Qualcomm FFA Example (cont.)

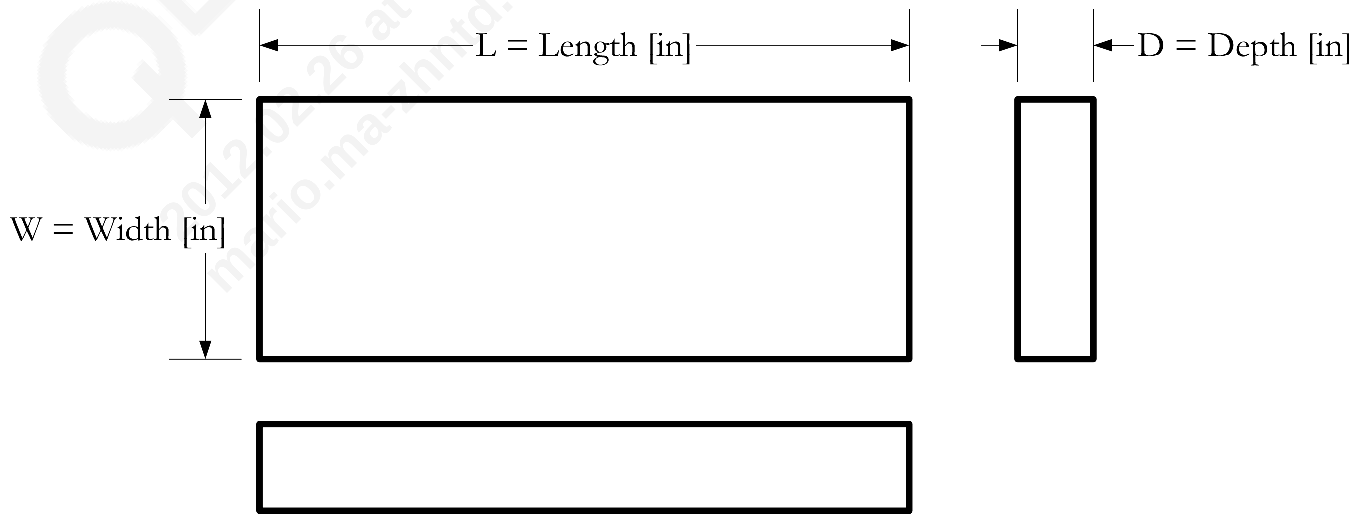
Routing VREG_MSMC_1: red layer 1, brown layer 5.
Keep it as a plane (red straps are thick traces to the MSM pins).



Simple Heat Dissipation (Temperature Rise) Modeling

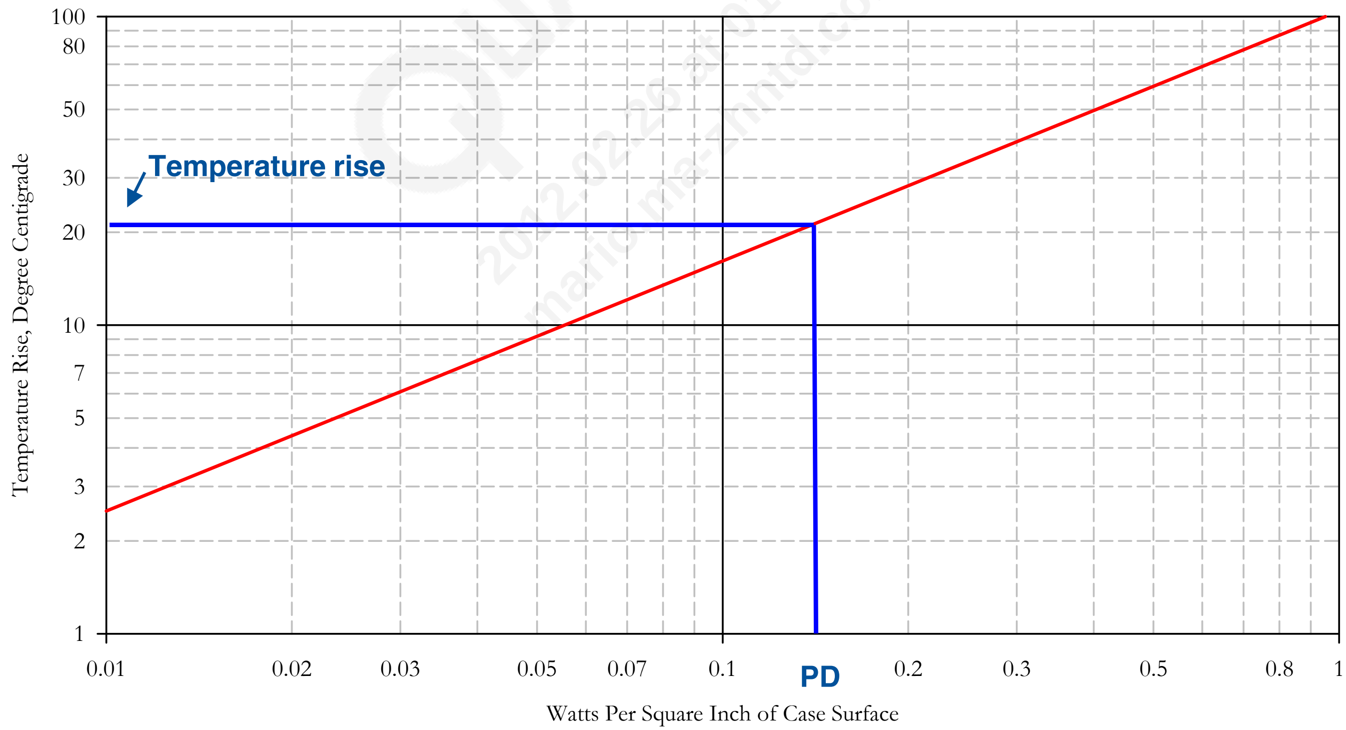
- Modeling for temperature rising on the UE surface:
  - Key parameters:
    - Total power dissipation
    - Surface area

1. Calculate the surface area.
   - $A_{surface} = 2(L \times W) + 2(L \times D) + 2(W \times D)$



Simple Heat Dissipation (Temperature Rise) Modeling (cont.)

2. Calculate the surface power density.
   - $PD_{surface} = P_{average} / A_{surface}$
3. Determine the surface temperature from the T_rise model.
   - The average case temperature rise as a function of power density



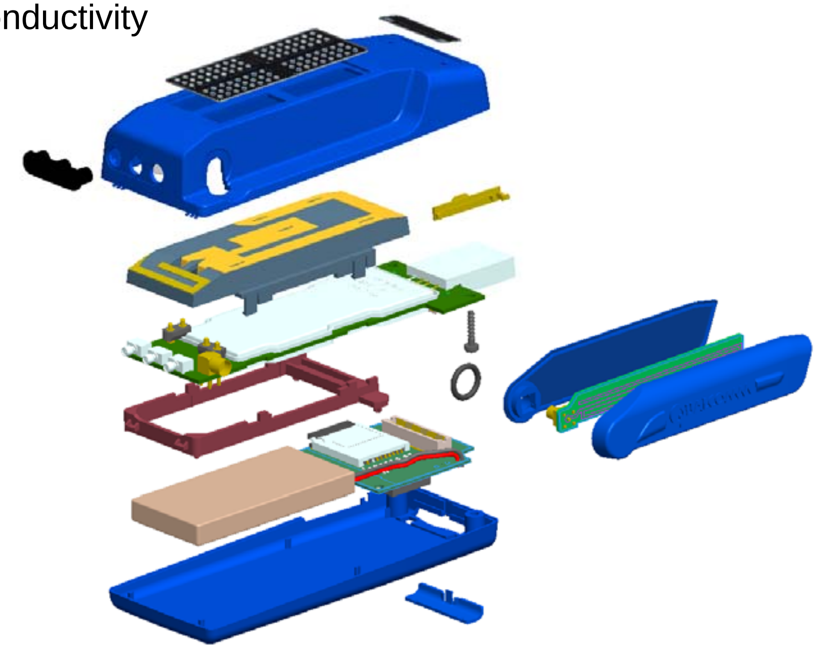
Assumption
- Black body thermal model
- Mono-block form factor
- Heat distributed evenly
- At room temperature (25°C)
- Total power dissipation range (1.5 W to 4.5 W)

Thermal Simulation (FloTherm – Fluid Dynamics Software)

- FloTherm:
  - 3D computational fluid dynamics software provided by Flometrics
  - Predicts airflow and heat transfer in and around electronic equipment
  - Includes the coupled effects of conduction, convection, and radiation

Note: Multiple solution iterations can be run to address design changes and optimization.

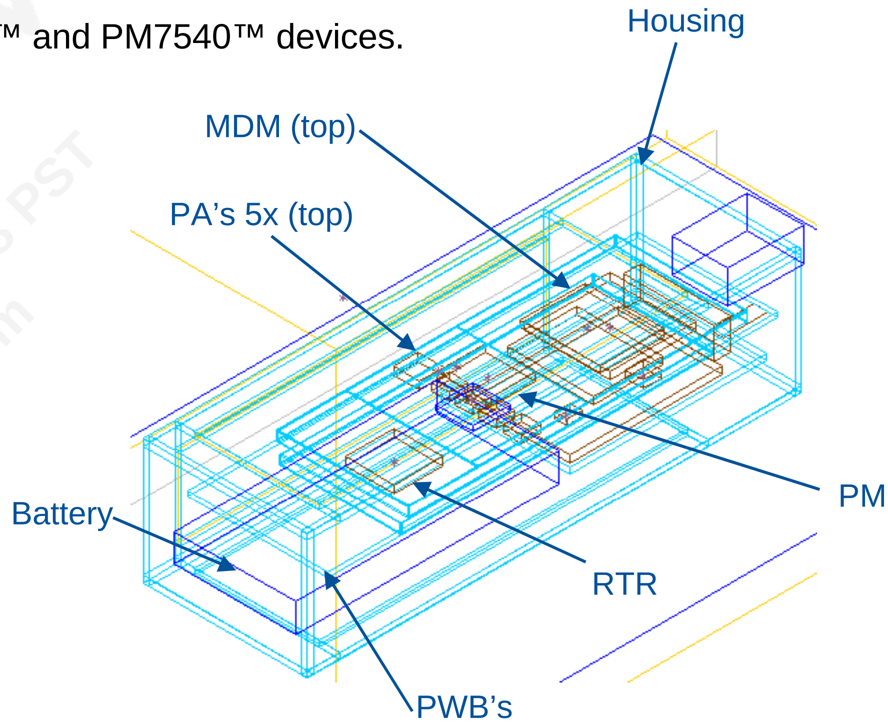
- Input:
  - Geometry: Size and shape housing parts, PWB with layer count and copper content (in %)
  - Materials: Density, specific heat, surface type, and thermal conductivity
  - Power: Apply power <watts> to specific parts
  - Radiation: Surface exchange accuracy parameter
  - Ambient conditions
  - Gravity vector
  - Grid: Subdivide (finite) volume
  - Set for steady state or transient solution



- Output (at each grid point):
  - Pressure
  - Velocity in vector form
  - Temperature in scalar plots

Thermal Simulation (Steady State) Analysis

- FloTherm steady state analysis for MDM8200-based prototype USB dongle:
  - The prototype is based on the MDM8200 IC with the RTR6285™ and PM7540™ devices.
- Model physical:
  - Housing: 81 × 27 × 20 mm, 1.0 mm, polycarbonate
  - Top vent: 38 × 14 mm, 20% open
  - Shields: 20 × 55 × 1.6 mm and 20 × 57 × 1.4 mm, .17 thick polycarbonate
  - Battery size: 43 × 21 × 4.7 mm
  - PWB: 73 × 23 × .80, PWB material FR4, 8 layer, 1 and 8 1.4 mil thick cu
  - 80% covered, 2 through 7 .7 mil thick cu 50%, 13% by volume, no vias in model
  - PWB with sim and SD card, no antenna



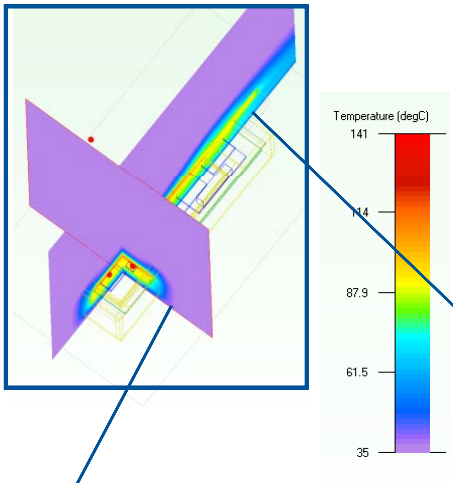
Flotherm wire frame model of Qualcomm prototype

- Boundary conditions:
  - 35°C ambient
  - Unit horizontal with air buoyancy path restriction; no conduction to laptop
  - Component power = 2.75 total W (PA 1.07, LTC 0.18, MDM 0.65, PM 0.55, RTR 0.25, battery 0.05, NAND, and VCTCXO zero)

Thermal Simulation (Steady State) Results

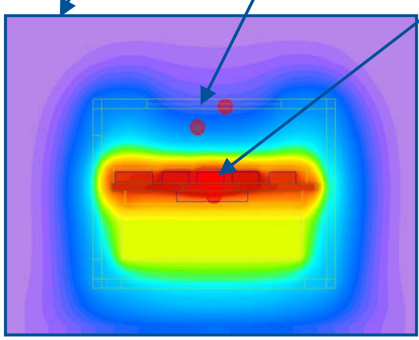
FloTherm results for MDM8200-based prototype USB dongle:

- Conclusion:
  - Component junction and maximum junction temperature (shown)
  - PA power up to 1.07 W, temperature at 140°C, recommended 85°C, maximum 125°C
  - 16 vias around PA (PWB 54 w/mk in-plane conductivity, 0.34 Z axis) increased z axis condition to 0.60, temperature reduced from 150°C to 140°C
  - Estimated that PA would need to dissipate 0.91 W to reduce the temperature from 140 to 125°C, and 0.71 W would drop the temperature to 100°C



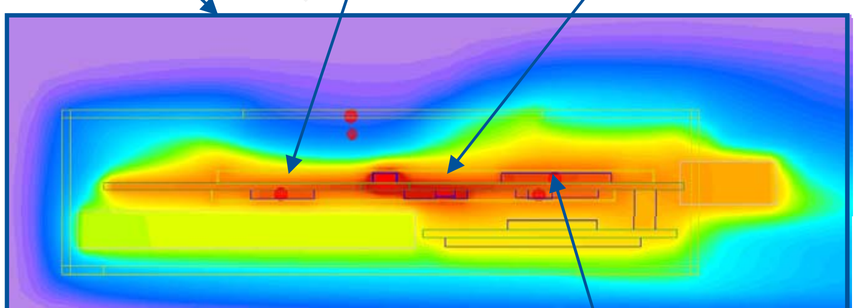
Int. Amb → 53°C

PA → 140°C (125°C)



RTR → 117°C (150°C)

PM → 127C (150°C)



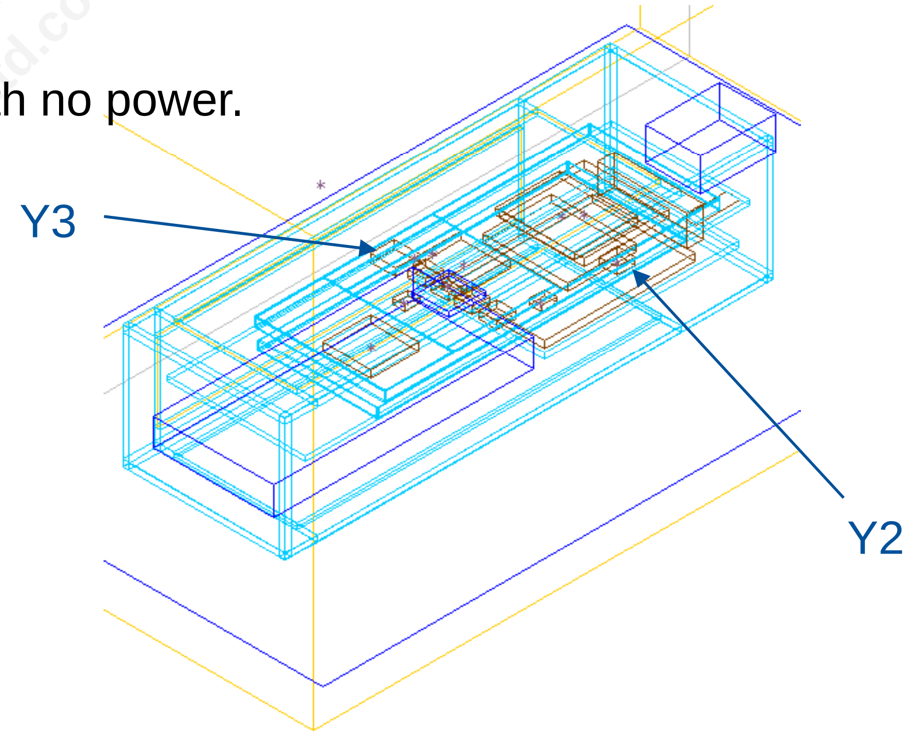
MDM →119C (125C)

- Other:
  - Top vents drop ambient temperature by 20°C and components by 5°C.
  - Side or bottom vents created no change in temperature.
  - Metal shields drop PA temperature by 4°C.
  - PA thermally conducted to metal shield has no noticeable effect.
  - PA temperature will vary based on package size and type.

Thermal Simulation (Transient) Analysis

- FloTherm transient simulation for the MDM8200-based prototype USB dongle:
  - Determines thermal time constant and temperature rate of change information for components and housing
- Background:
  - The steady state (ss) component temperatures for PA is 140°C, and VCTCXO is 122°C.
  - This analysis added two components with no power.
    - Y2 – SLEEP_CLK
    - Y3 – VCTCXO

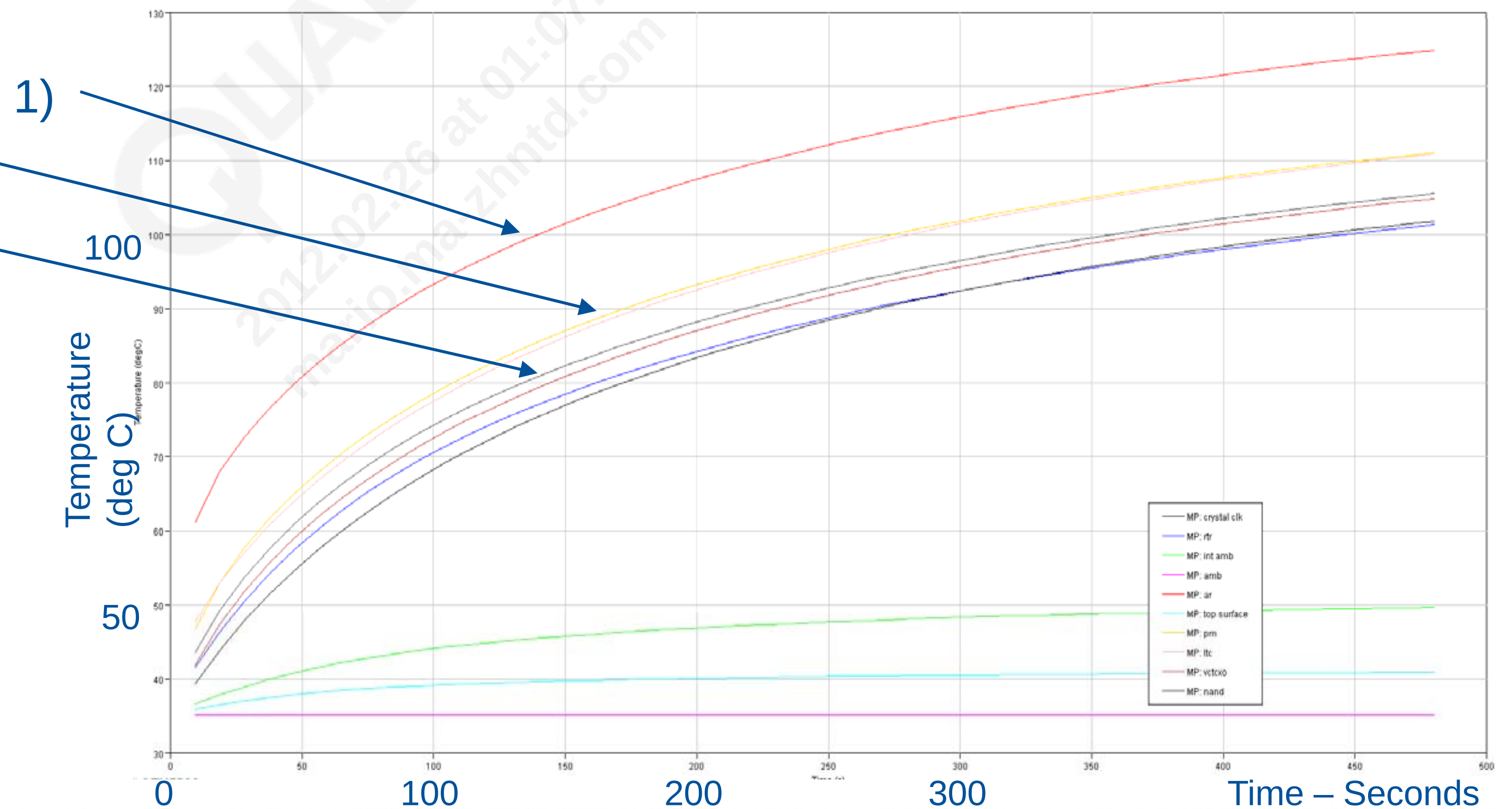
  Note: Both are located at bottom of the PCB.



Thermal Simulation (Transient) Results

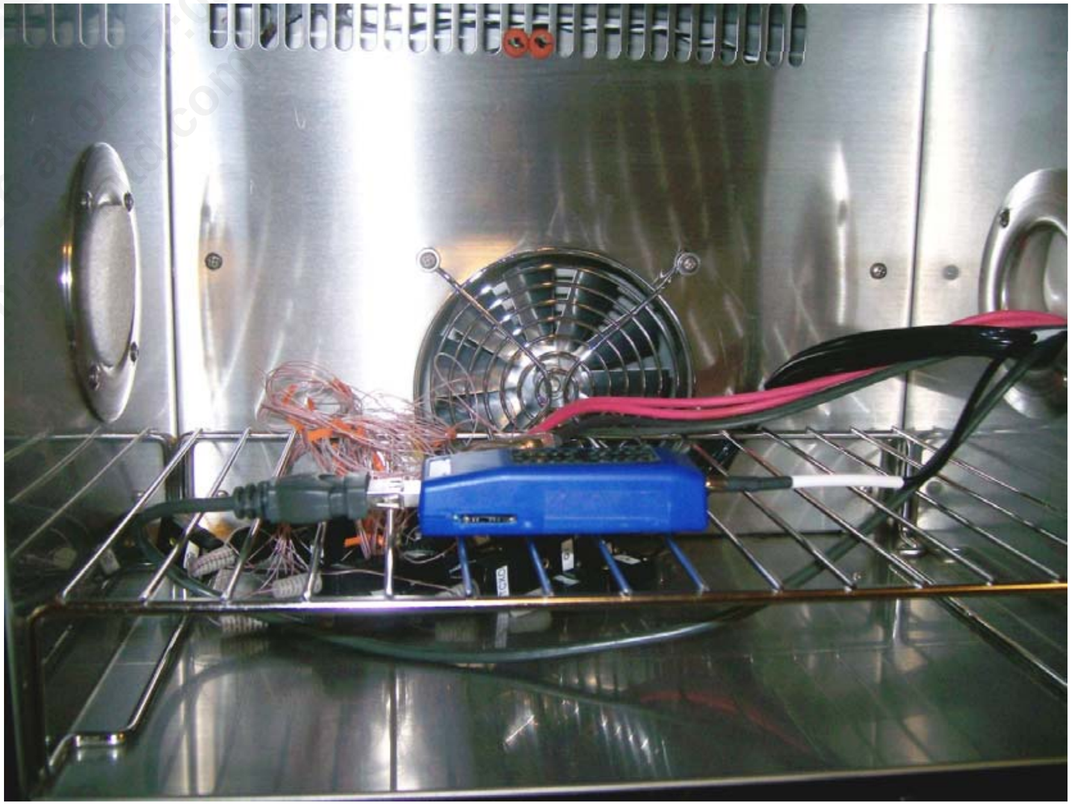
- FloTherm transient analysis for the MDM8200-based prototype USB dongle:
- Results: Flotherm result plot is shown below, one time constant (tc) defined as 63% of steady state, approximately 5 tc’s to ss.
  1. PA: 35 + .63 * (140 - 35) = 101°C, <u>tc = 137 seconds</u>; rate of change is 66°C/137 seconds = 28.9°C/minute.
  2. VCTCXO: 35 + .63 * (122 - 35) = 89.8°C, <u>tc = 225 seconds</u>; rate of change is 54.8C/225 seconds = 14.7°C/minute.
  3. Crystal: 35 + .63 * (110 - 35) = 82.3°C, <u>tc = 175 seconds</u>; rate of change is 47.3C/175 seconds = 16.2°C/minute.

- Conclusion:
  - The analysis has a maximum rate of change of the VCTCXO component to be about 14.7°C/minute.
  - The VCTCXO goal is to keep change below 1 to 2°C/second, or 60 to 120°C/minute.

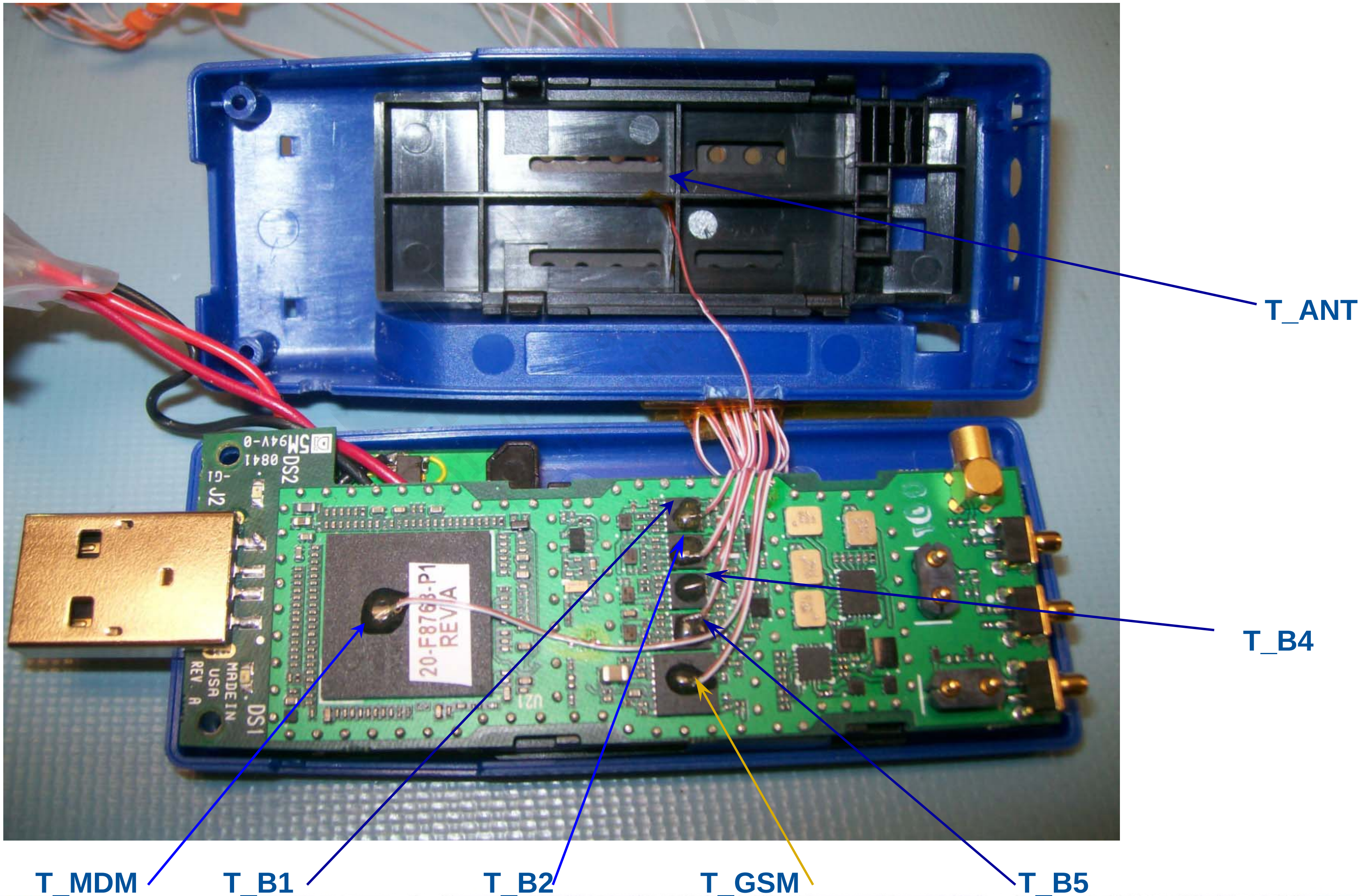


Thermal Testing

- Purpose and results:
  - Validate design approach
  - Confirm simulations
- Testing details:
  - A thermal camera or thermocouples can be used to measure temperatures.
  - The unit under test (UUT) is placed in the oven chamber and protected from the fan air swirl.
  - The design is tested over temperature.
  - The thermocouple wire has two dissimilar conductors joined together at their ends; the thermoelectric voltage developed between the two junctions is proportional to the temperature difference between the junctions.

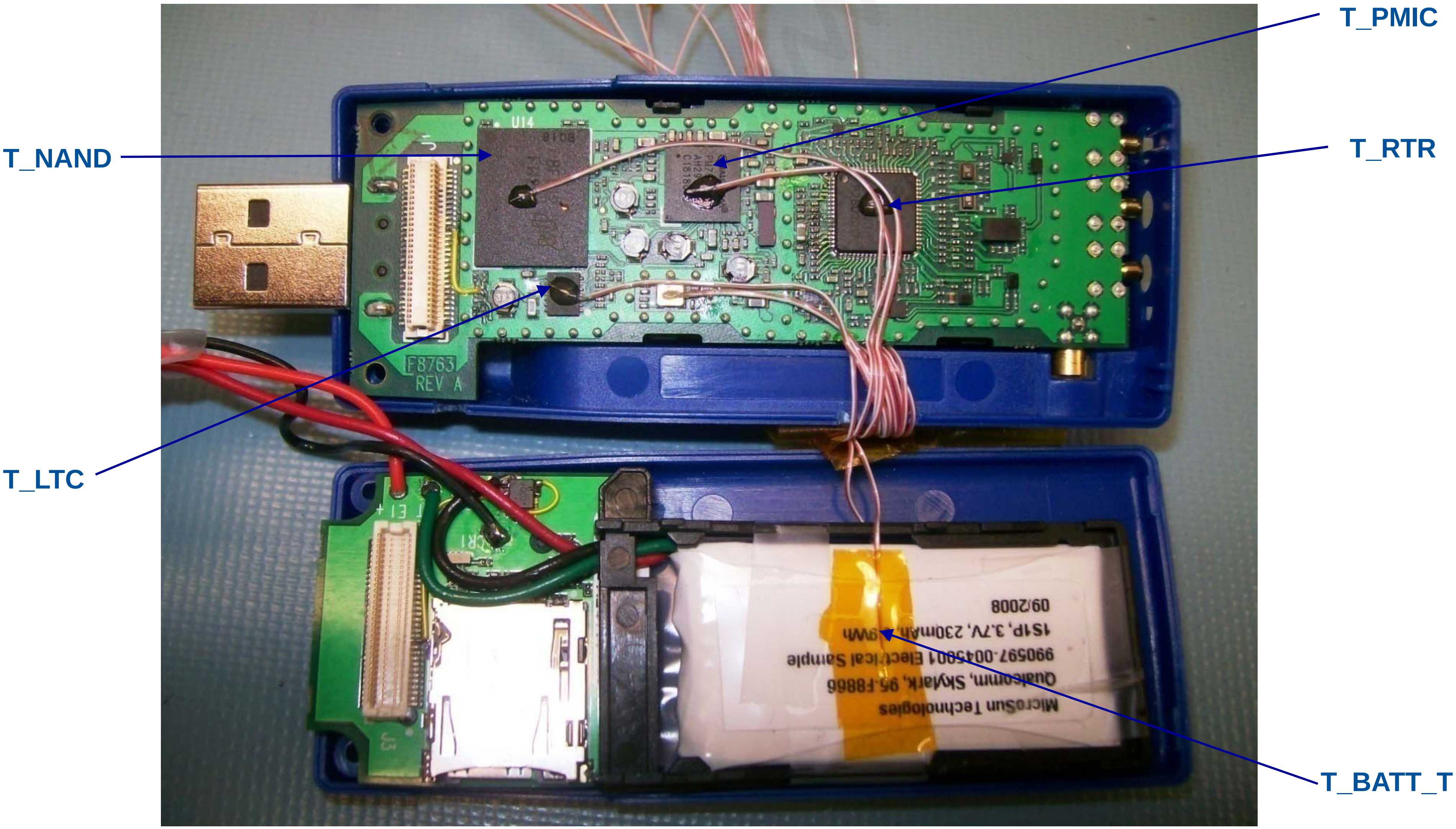


- Thermocouple connections to components:



Thermal Testing (cont.)

- Thermocouple connections to components:

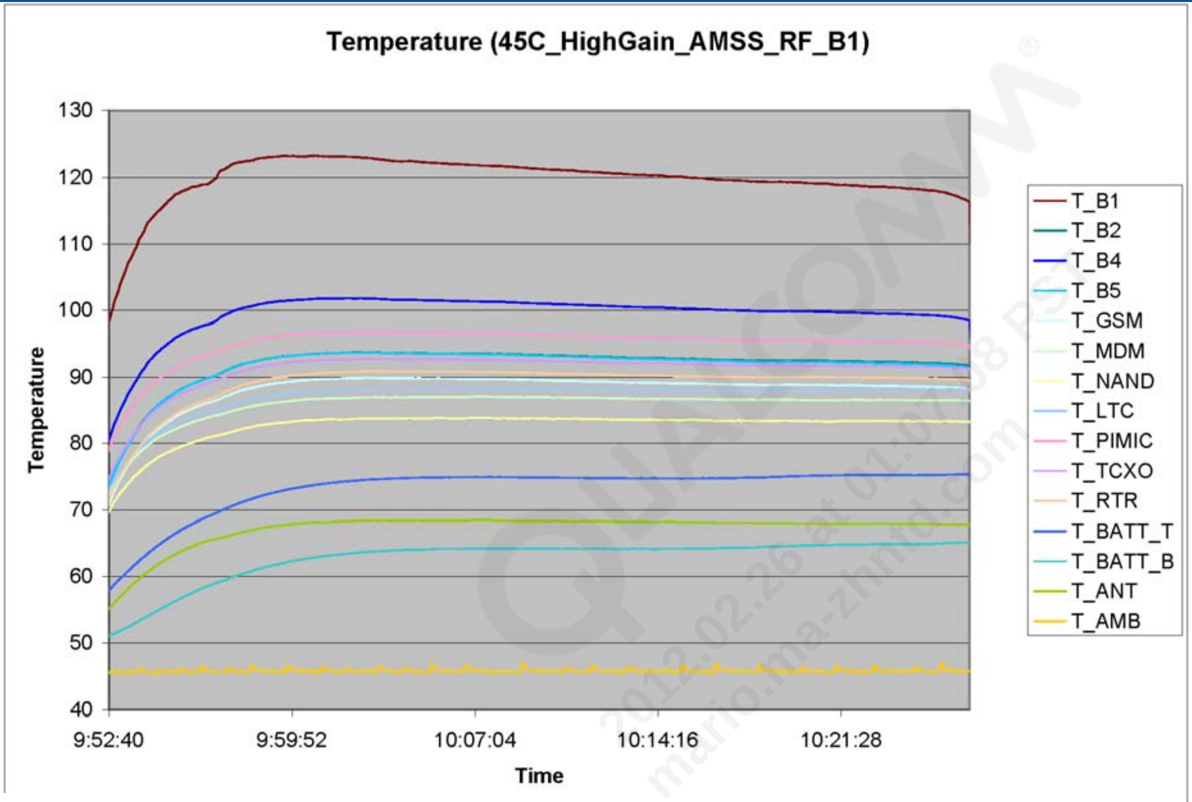


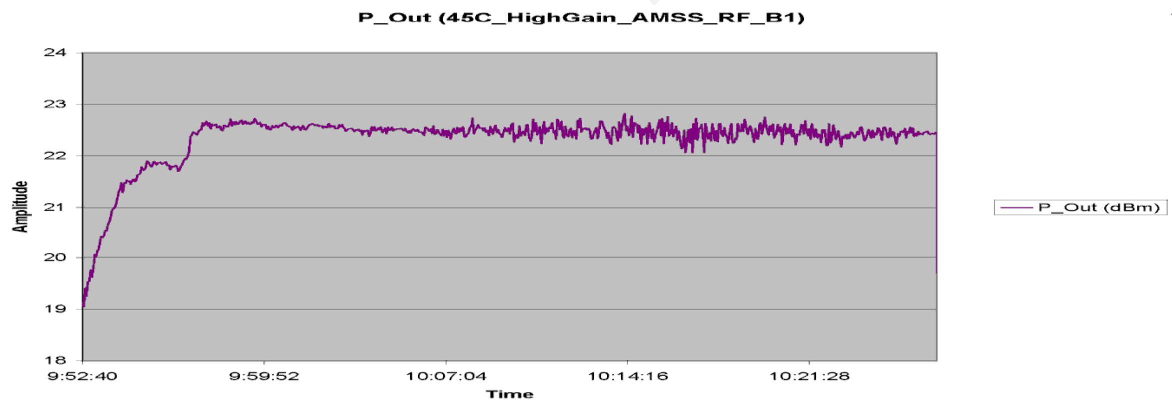
Thermal Testing

- Component part maximum temperature ratings:

Component	Recommended operating temperature (°C)	Absolute maximum temperature (°C)
WCDMA IMT PA (T_B1)	85 (GND pad)	110 (GND pad) 125 (storage)
WCDMA PCS PA (T_B2)	85 (GND pad)	110 (GND pad) 125 (storage)
WCDMA AWS PA (T_B4)	90 (case)	150 (storage)
WCDMA CELL PA (T_B5)	85 (GND pad)	110 (GND pad) 125 (storage)
GSM PA (T_GSM)	85 (case)	150 (storage)
MDM8200 (T_MDM)	100 (case maximum)	150 (storage) 125 (junction)
NAND Flash (T_NAND)	85	150 (storage)
LTC4088 USB/battery power manager (T_LTC)	85	125 (storage) 125 (junction)
PM7540 (T_PMIC)	85 (case maximum)	125 (storage) 150 (junction)
VCTCXO (T_TCXO)	85	85 (storage)
RTR6285 (T_RTR)	85 (case maximum)	150 (storage)
T_BATT_T	45 (charging) 60 (discharging)	

Thermal Testing Results

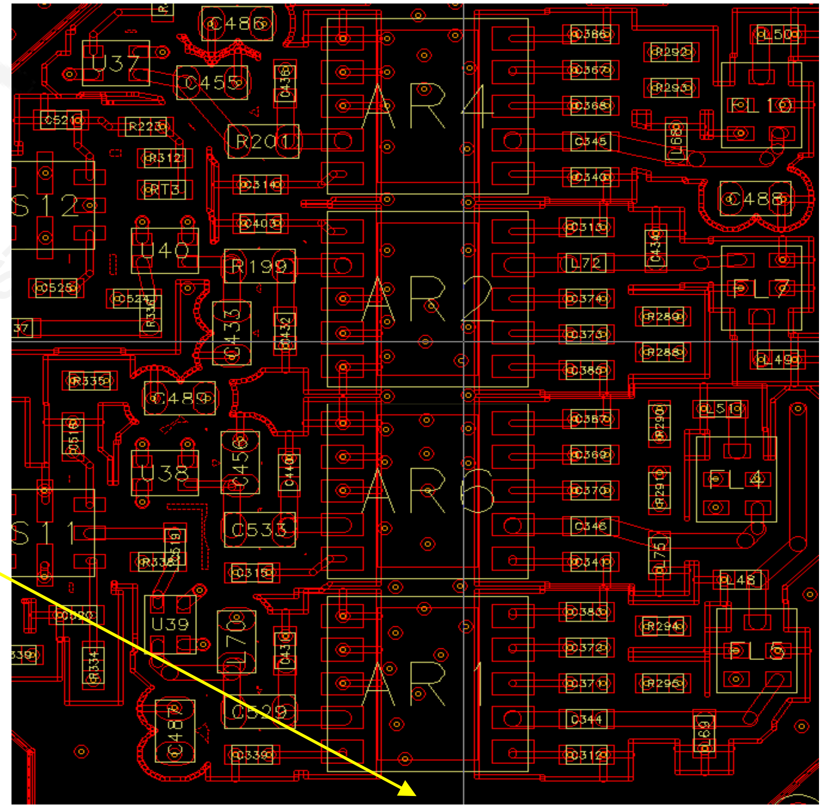


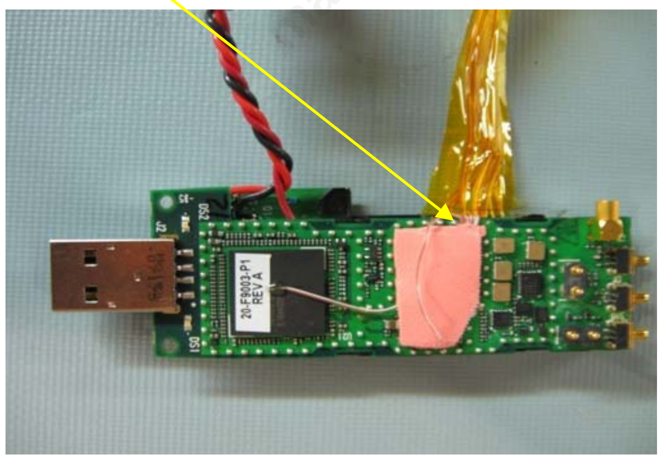


Maximum temperature (°C)	
T_B1	123.306
T_B2	93.73
T_B4	101.805
T_B5	93.711
T_GSM	89.9
T_MDM	87.067
T_NAND	83.917
T_LTC	88.37
T_PMIC	96.798
T_TCXO	92.765
T_RTR	90.883
T_BATT_T	75.339
T_BATT_B	65.16
T_ANT	68.545
T_AMB	47.106

Thermal Testing Conclusion

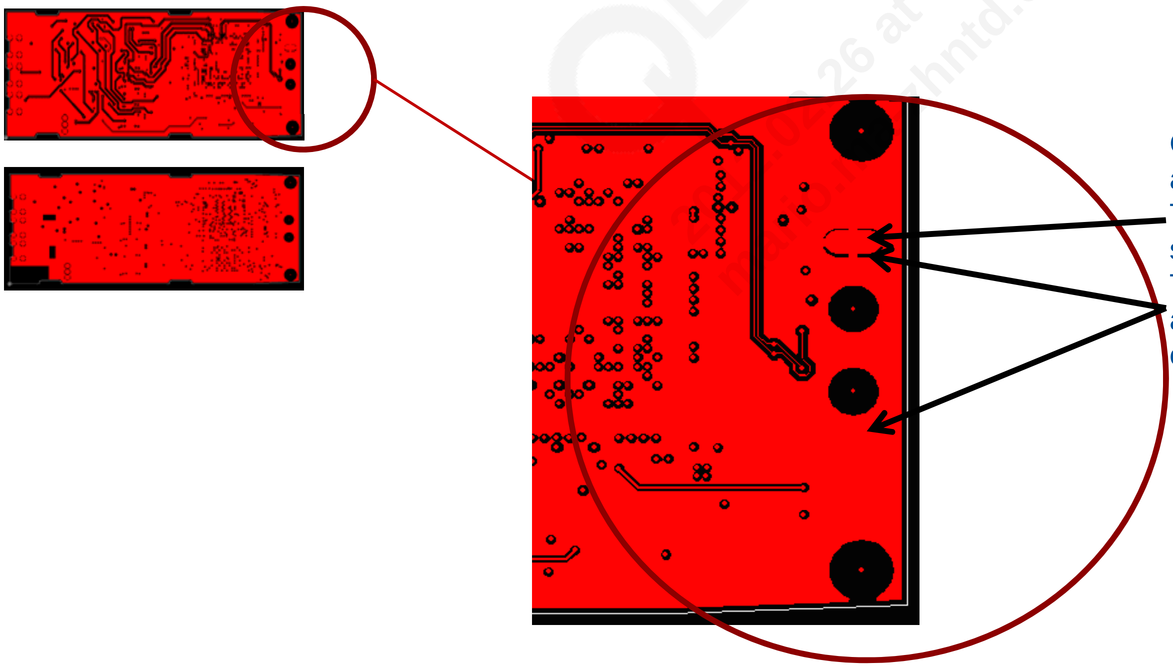
- Prototype dongle goal and opportunity to lower PA temperature:
  - PWB
    - Added more vias to PWB in area of PAs
    - Reduce temperature as much as 10°C
  - Added gap pad material to the assembly
    - From PAs to shield and on top of shield to spread heat





Copper Layer Thermal Analysis

- Experimental data concluded that copper flooding, instead of thermal relief, on a single layer of a multi-layer board helps to lower component temperatures on average up to 1°C, without affecting the hand solder, joint solder, time, or quality.



Gerber file data shows the copper before any holes are drilled and plated.
This oval pattern is thermally relieved to ease hand soldering.
There are two oval-plated through-holes here that aren’t shown because this is and example of the copper prior to hole drilling and plating.

Experiment: Solid Copper vs. Paste Vias

- Board construction affects component temperatures; it may affect the external touch temperature.
  - Experiments were conducted on Qualcomm boards with a different construction.
  - Boards with solid copper-plated stacked microvias had cooler components than Panasonic's ALIVH G (which uses paste vias) by approximately 10°C.
  - ALIVH C (which uses plated vias on the outer layers) components were cooler than ALIVH G by 0 to 3°C.
  - The experiments were conducted on phone boards of identical layout, but with a different construction.
  - The effect of board construction on peak external touch temperature was not measured in these experiment. It's possible that board construction could increase or decrease external touch temperature, depending on the design details of the housing.

Miscellaneous Thermal Experiments on Qualcomm FFA

- Dongle form factor mitigations to component temperatures:
  - Reducing power consumption on a dongle-type product reduces temperatures by 11 to 14°C per watt.
  - Testing a dongle product when connected to a laptop reduces temperatures 3-4°C vs. suspended in air with no laptop.
  - Testing a dongle product without baffles to slow chamber air cooling effects reduces measured temperatures by 5-10°C.
  - Adding small vents and openings to dongle form factor products with internal shielding reduces temperatures by <1°C.
  - Adding thermal interface material + graphite to dongle product reduced temperatures by 9°C.

Thermal Protection Algorithm

- As mentioned in the introduction, Qualcomm has developed a thermal protection algorithm that will regulate various RF and USB controls.
- The use of the thermal protection algorithm, with proper design of the USB dongle form factor, should minimize thermal impact.
- See the following documents for more information about the thermal protection algorithm.
  - *Thermal Protection Algorithm Overview* (80-VT344-1)
  - *Thermal Protection Algorithm Application Note* (80-VJ372-14)
  - *MDM9200/MDM9600 Thermal Issues and Protection Software* (80-VP146-28)

Appendix: Heat Transfer Fundamentals

Heat Transfer Fundamentals

- Steady state thermal resistance equation:
  - Heat flowing away equals heat generated, heat dissipation is a constant.

$\Delta T = Q R$,

T is temperature, <degrees Celsius>
Q is heat, <watts>, current flows and heat is generated
R is resistance, <C/W>

- Resistance and three modes of heat transfer:

1. **Conduction** – through solids
   R = L/K * A, L = length, K = thermal conductivity, A = area

2. **Convection**
   a. **Forced** – air driven cooling, i.e., fan on components
      R = 1/h * A

Heat Transfer Fundamentals (cont.)

b. **Natural** – free air buoyancy velocity driven by density change

$R = 1/h * A$, h = heat transfer coefficient, A = area

i. Heat transfer coefficient from a vertical surface

$h = 0.29 * (\Delta T/L_c)^{.25}$, L_c characteristic length, $= 2 * L * W/(L + W)$

ii. Heat transfer coefficient from a horizontal surface facing upwards

$h = 0.27 * (\Delta T/L_c)^{.25}$

iii. Heat transfer coefficient from a horizontal surface facing downwards

$h = .13 * (\Delta T/L_c)^{.25}$

Note: A horizontal surface facing downwards, compared to upwards, has approximately double the heat transfer resistance and will produce double the temperature rise to ambient.

Heat Transfer Fundamentals (cont.)

3. **Radiation** – heat transfer by electromagnetic waves, from surface to surface

   $R = 1/(o * f * e * A)^{.25}$

   o = stefan-boltzmann constant
   f = view factor – fraction of radiation leaving one surface and intercepted by another
   A = area
   e = emissivity – radiated from surface relative to 'black body'

b. Natural – free air buoyancy velocity driven by density change

$R = 1/h * A$, h = heat transfer coefficient, A = area

i. Heat transfer coefficient from a vertical surface

$h = 0.29 * (\Delta T/L_c)^{.25}$, L_c characteristic length, $= 2 * L * W/(L + W)$

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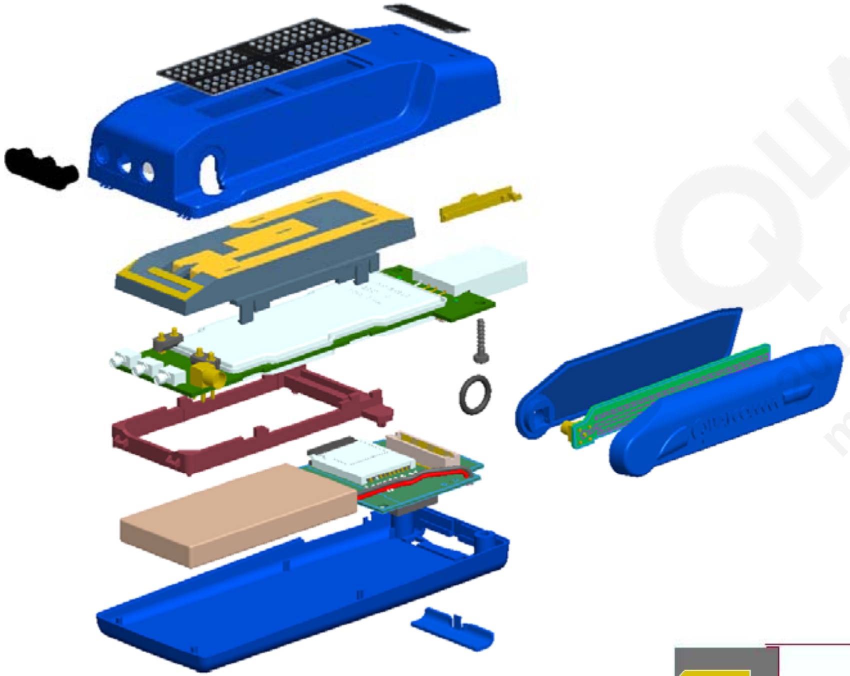
$h = 0.13 * (\Delta T/L_c)^{.25}$

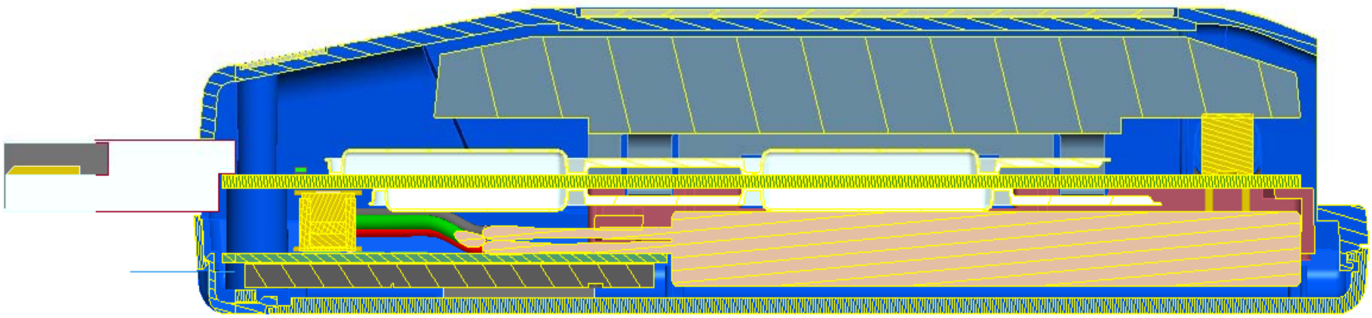
Note: A horizontal surface facing downwards, compared to upwards, has approximately double the heat transfer resistance and will produce double the temperature rise to ambient.

Heat Transfer Fundamentals – USB Dongle Example

- Qualcomm prototype USB dongle thermal resistances example:
  - Prototype based on the MDM8200 IC with the RTR6285 and PM7540 devices
  - Develop thermal resistance network for a generic USB dongle housing assembly
  - Based on heat sources, materials, geometry, and heat transfer modes



$\Delta T = Q\ R,\ R = \text{resistance}$



Heat Transfer Fundamentals – USB Dongle Example (cont.)

Nodes 1–2: Conduction – component to board

Nodes 2–3: Natural convection and Radiation- component to housing wall

Nodes 3–4: Conduction – through housing wall

Node 4: Ambient: natural convection and radiation – bottom housing to ambient air

Nodes 1–5: Conduction – component to board

Nodes 5–6: Natural convection and radiation - component to housing wall

Nodes 6–7: Conduction – through housing wall

Node 7: Ambient: natural convection and radiation – top housing to ambient air

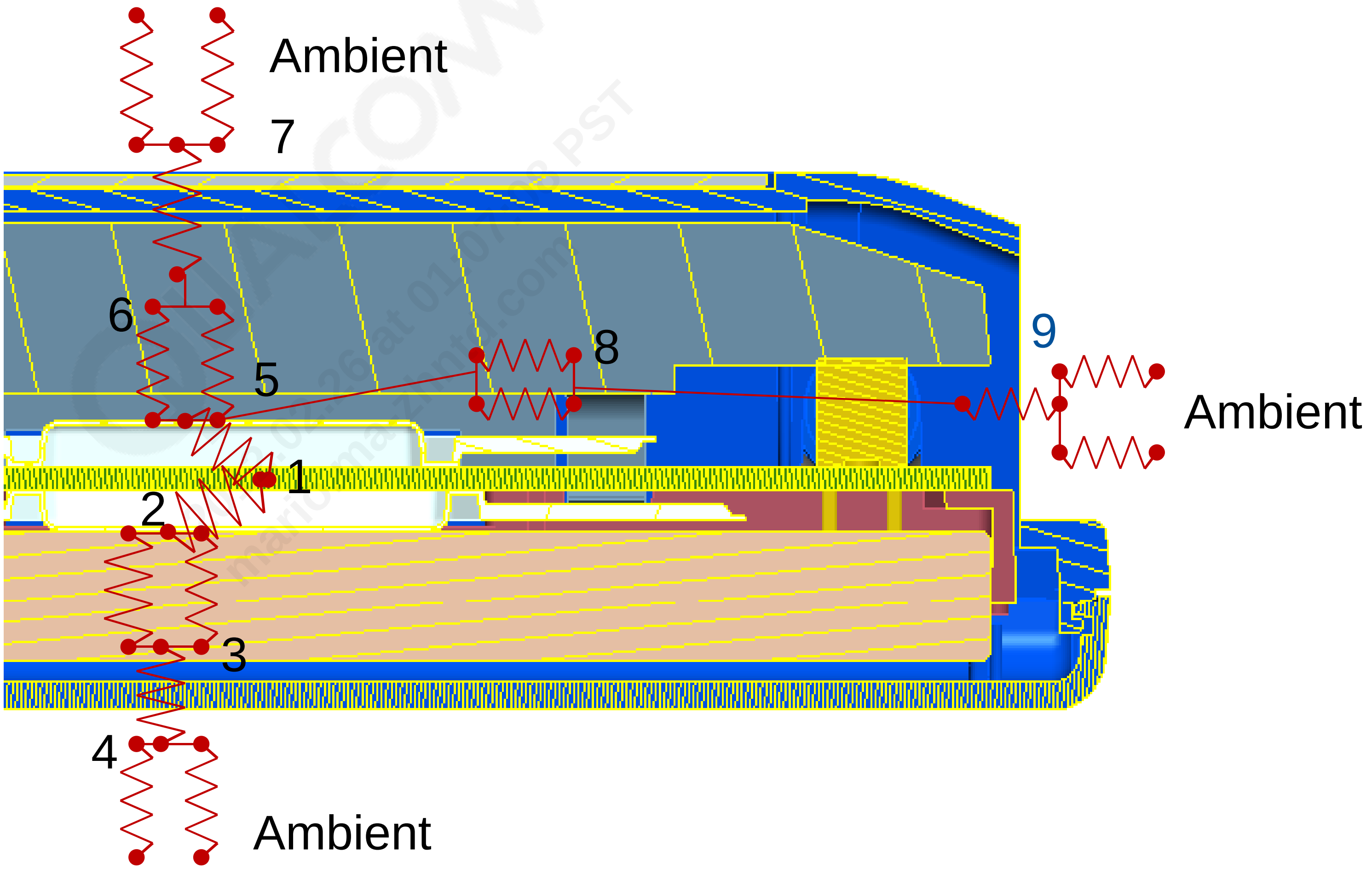
Nodes 5–8: Natural convection and radiation - component to housing wall

Nodes 8–9: Conduction – through housing wall

Node 9: Ambient: natural convection and radiation – side housing to ambient air

Thermal resistance example

Nodes 2 and 5 are heat sources.



Note: Convection and conduction heat transfer dominates the cooling of the USB dongle.

Questions?

https://support.cdmatech.com