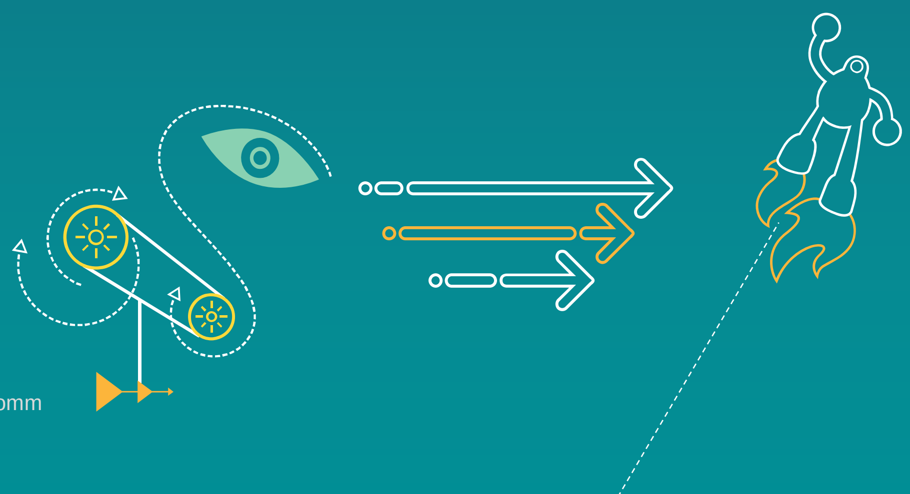
Figure of Merit for Mobile Thermal Management

Coefficient of Thermal Spreading (CTS)

Qualcomm Technologies, Inc.



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Revision History

Revision	Date	Description
A	December 2013	Initial release
B	June 2014	Added Appendix A (*CTS Measurement Procedure by the IR Camera*) and Appendix C (*CTS Extraction from Icepak*).

Contents

What Is the CTS?

The coefficient of thermal spreading (CTS) is a general thermal figure of merit for mobile thermal management. It is defined as:

$$CTS = \frac{T_{ave,skin} - T_{ambient}}{T_{max,skin} - T_{ambient}}$$

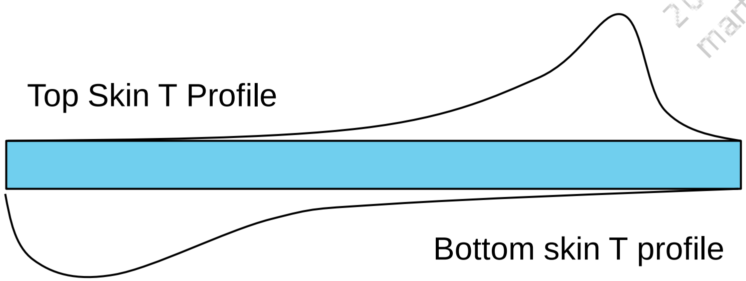
$T_{ave,skin}$ is the average temperature on the mobile device surface.

$T_{max,skin}$ is the maximum temperature on the mobile device surface.

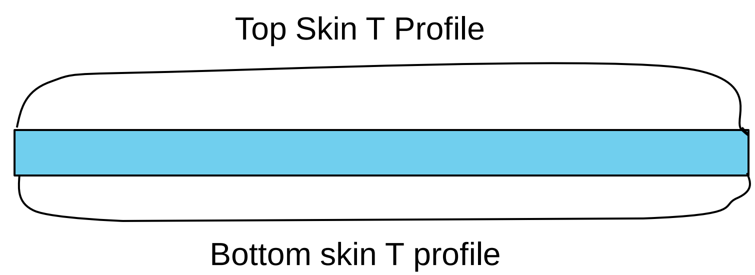
$T_{ambient}$ is the ambient environmental temperature.

For inefficient thermal spreading (on a poorly designed device), the CTS tends toward 0.

For efficient thermal spreading (on a well-designed device), the CTS tends toward 1.



Poorly designed device: CTS → 0



Well-designed device: CTS → 1

Why Do We Need the CTS?

- The CTS quantifies a good thermal design that mitigates case hot spots and results in a more uniform case temperature.
- The CTS tells whether a given device has good thermal design.
- General thermal figure of merit — a dimensionless coefficient that represents the efficiency of heat/energy spreading over the external surface of a mobile device.

Why Is the CTS Important?

- Simple metric to measure the quality of the thermal design.
- Easily extracted both numerically and experimentally.
- Enables quick comparison of mechanical design tradeoffs during the simulation phase (~two to three months before first PCB build).
- Higher CTS allows more heat to be dissipated in the same form factor.
- Higher CTS correlates to lower IC junction temperature and lower maximum skin temperatures.
- Higher CTS will lead to higher CPU and GPU benchmark scores because the need for software thermal mitigation will be delayed; hence, the device performance and user experience is improved as well.

What Improves the CTS? (Thermal Design BKMs)

Spreading the heat

- Utilizing heat spreaders
  - Spreads heat from key IC's ICs (MSM™, PMIC, PA, WLAN, camera) to the shield, device skin, and battery case
  - Uses a large surface area with high thermal conductivity
- Utilizing thermal interface material (TIM)
  - Makes good thermal contact between the top of key ICs and the heat spreaders; using TIM under compression and thermal grease for best thermal connection
- Maximizing surface area
  - Uses a large metal frame/bracket to help spread the heat
  - Uses surface roughness on plastic skin for higher touch temperatures
- Utilizing air gaps
  - Balances the heat flow between the front and back side of the overall device
  - Reduces hot spots on the phone skin due to hot internal areas
- Optimizing the PCB ground plane
  - Uses larger copper content for a solid ground plane layer
  - Connects all ground pins of key ICs directly to this layer
- Separating hottest ICs
  - Does not allow high-power ICs to overlap on opposite sides of the PCB
  - Places connectors on opposite sides of key ICs where possible. (e.g., SIM and SD card)

Absorbing the heat

- Utilizing battery and internal frame mass
  - Requires good thermal flow through battery and other internal structural components
- Utilizing phase change material or vapor chamber and heat pipes to effectively help spread the heat

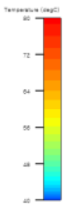
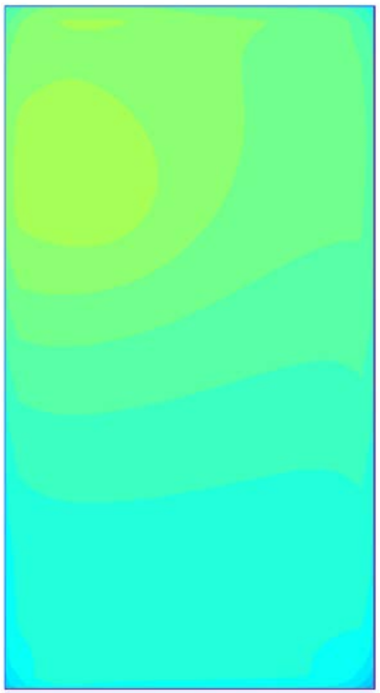
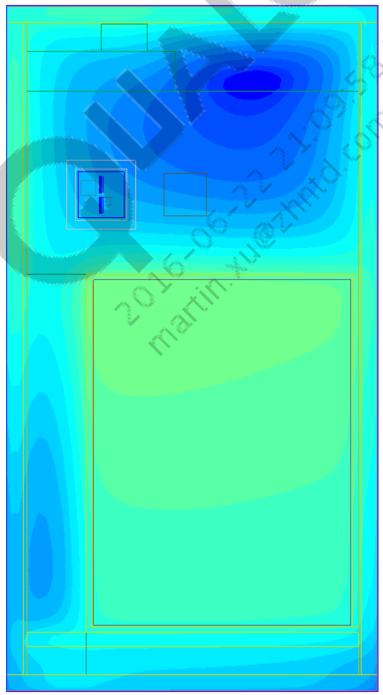
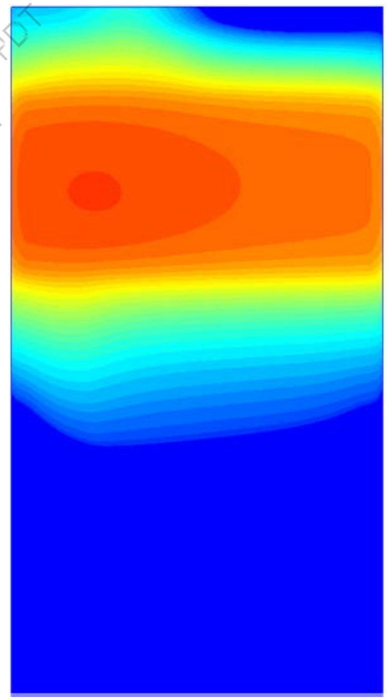
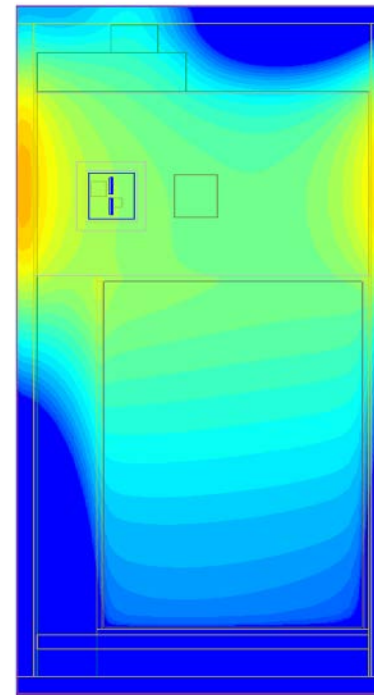
What Has No Affect on the CTS? (Thermal Design BKMs)

Reducing heat

- Meeting the PCB PDN specification (enables minimum but adequate operating voltages on each rail)
- Enabling AVS (enables minimum, but adequate operating voltage)
- Disabling all unused clocks
- Enabling software thermal mitigation (caution: reduces performance)

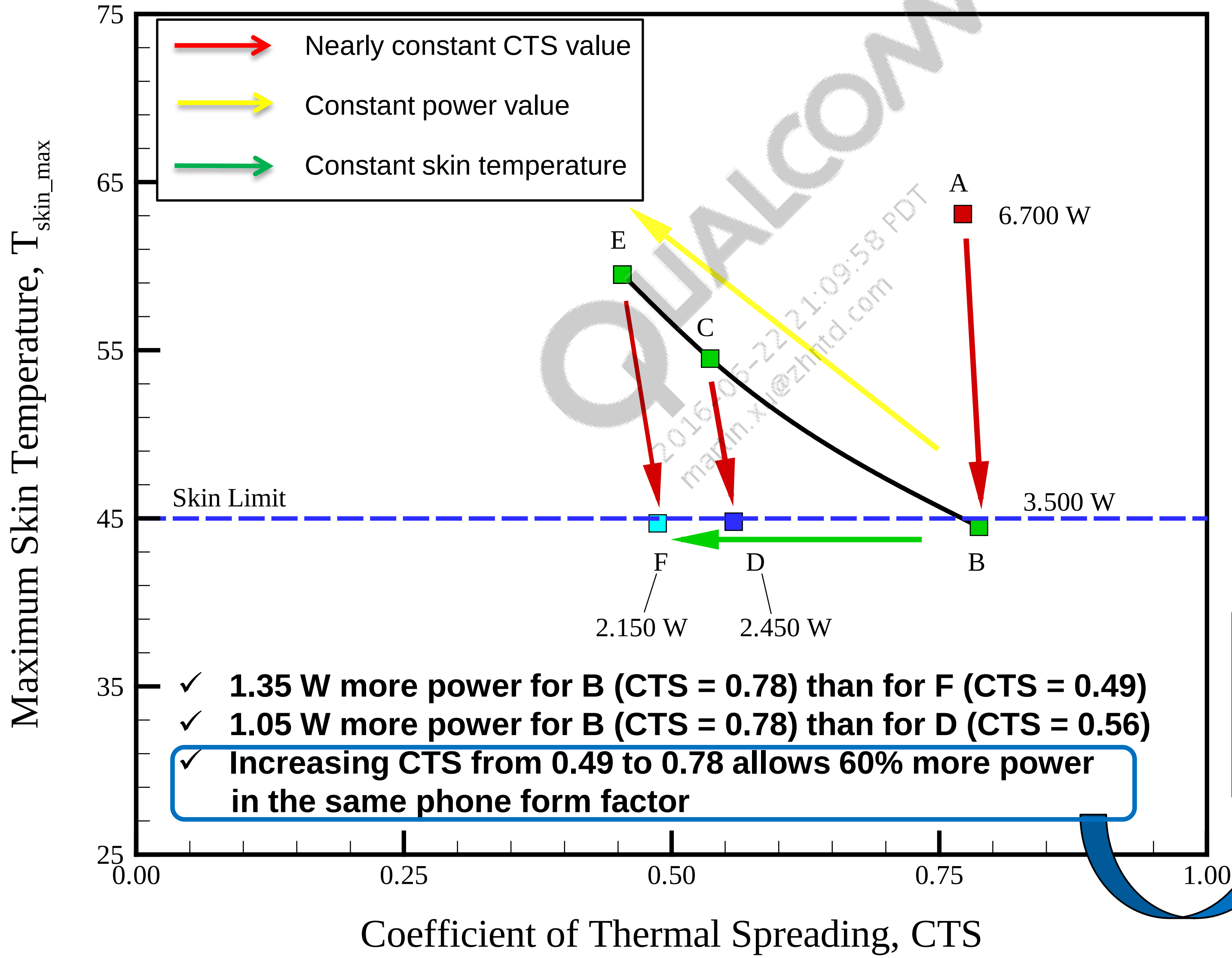
CTS Example – Same Power Dissipation

Target: CTS greater than 0.8

	CTS = 0.84 (good)		CTS = 0.42 (poor)	
	LCD skin	Back skin	LCD skin	Back skin
				

HIGH CTS device LOW CTS device

CTS Example - CTS versus Maximum Skin T



- ✓ 1.35 W more power for B (CTS = 0.78) than for F (CTS = 0.49)
- ✓ 1.05 W more power for B (CTS = 0.78) than for D (CTS = 0.56)
- ✓ **Increasing CTS from 0.49 to 0.78 allows 60% more power in the same phone form factor**

A – Baseline phone (full size heat spreader) – full power [6.7 W]

B – Case A with reduced power [3.5 W] to meet 45°C skin limit

C – Case B with reduced heat spreader to unbalance phone [3.50 W]

D – Case C with reduced power [2.45 W] to meet 45°C skin limit

E – Case C with shifted heat spreader to further unbalance phone [3.50 W] – battery now decoupled

F – Case E with reduced power [2.15 W] to meet 45°C skin limit

- **1°C difference in skin T translates to 0.16 W change in total power**
- **1°C difference in skin T achieved by reducing CTS by 0.03 (small delta)**

Note: This is applicable to the specific example phone.

CTS Summary

- The CTS quantifies the thermal spreading in a mobile device, providing a specific metric to improve the thermal design and device performance.
- The CTS indicates how much phone performance can be improved for the given shape and size/form factor.
- Well-designed phones have a CTS value over 0.8 while poorly designed phones have CTS values below 0.5.
- The CTS is used to help improve the thermal energy spreading over a phone surface and reduce $T_{max,skin}$.
- Use of the CTS in the simulation and design process will lead to higher performance devices.

Appendix A
CTS Measurement Procedure by the IR Camera

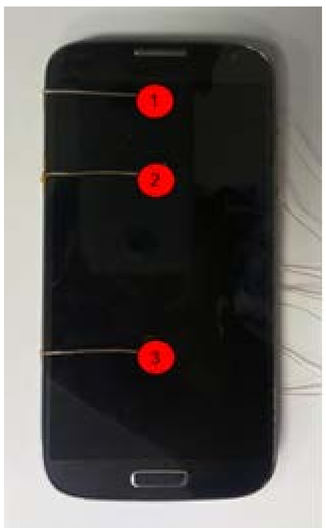
Thermal Testing Setup

- CPU intensive use case: Quad-core Dhrystone
- Wi-Fi: Off
- Airplane mode: On
- Brightness: Maximum (optional)
- Device orientation: Vertical
- Test equipment:
  - Use the K-type thermocouple to measure ambient temperature
  - Use the Agilent data logger (mode: 34901A) to record thermocouple temperature
  - Use the FLIR IR camera (mode: SC 8243) to measure peak temperature and average temperature over the LCD and the back cover
  - Wait 30 to 40 minutes until the steady-state surface temperatures are reached and then start CTS measurement

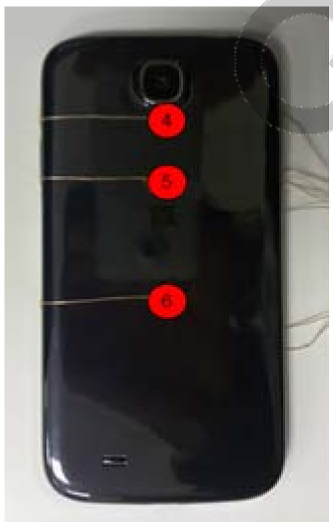
Infrared Thermal Imaging – Calibration

1. Since the surface emissivity of LCD and back cover is unknown, three K-type thermocouples are mounted at low-, medium-, and high-temperature zones at the LCD and back cover. The recorded thermocouple readings are used as the reference temperature to calibrate the emissivity of the LCD surface and back cover surface.
2. Adjust the surface emissivity setting of the IR camera until the temperature difference between thermocouple reading and IR camera reading is less than 1°C. The determined surface emissivity will be the emissivity of the LCD surface and back cover surface.

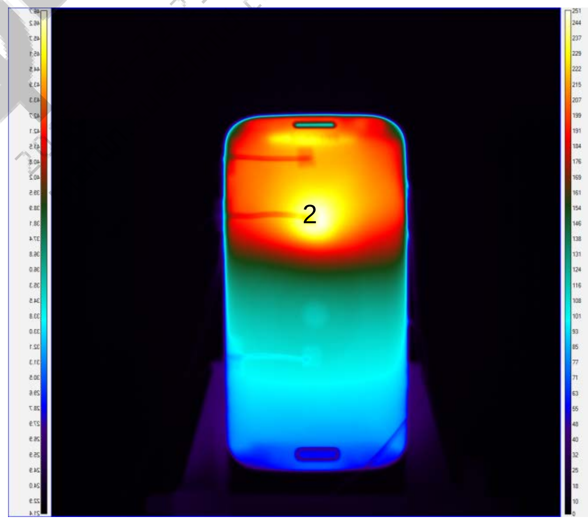
LCD
(Thermocouple location)



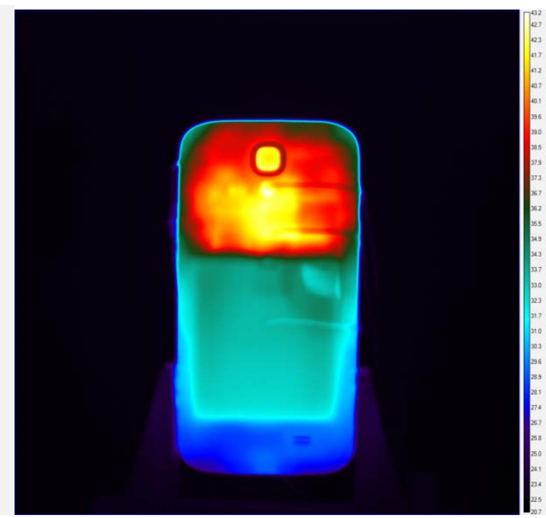
Back cover
(Thermocouple location)



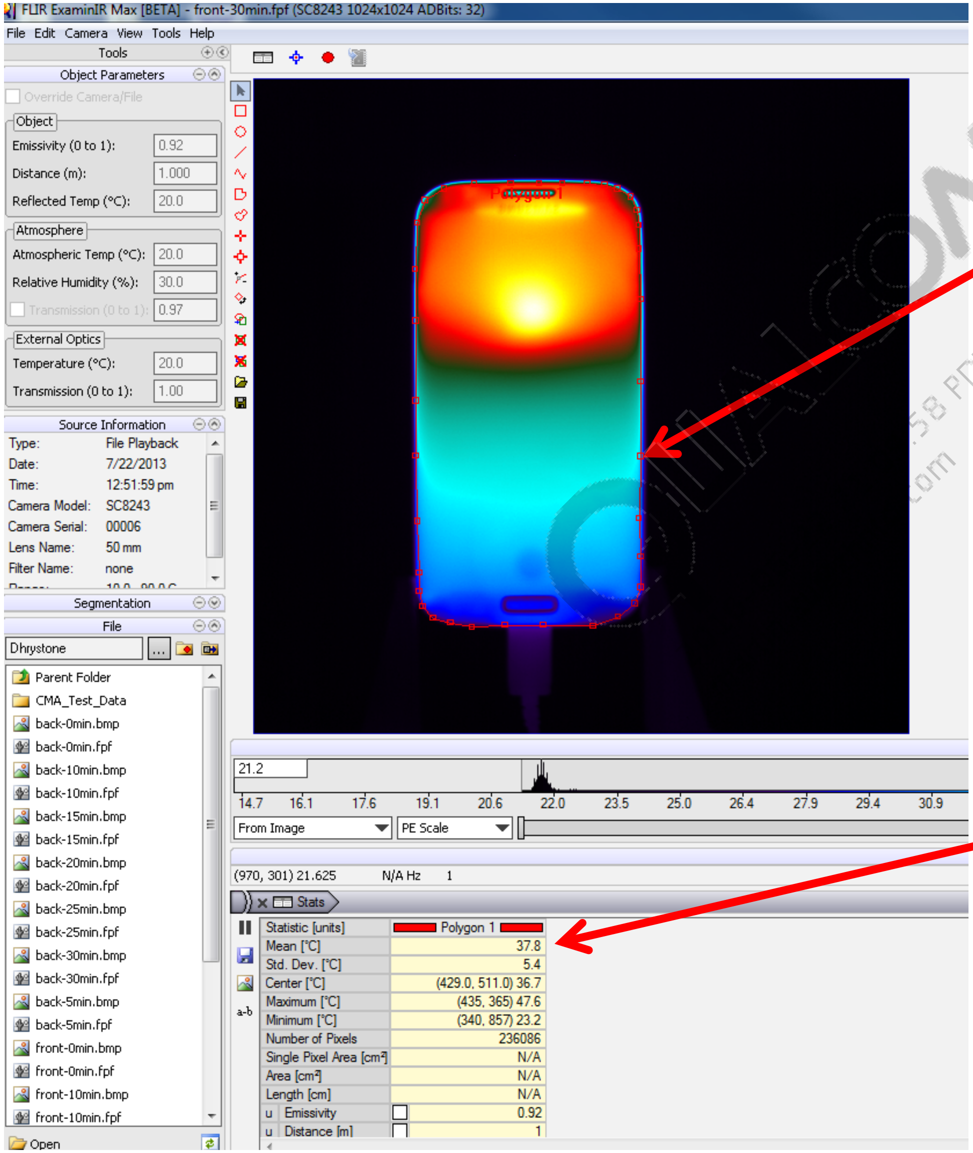
LCD
(Thermal imaging)



Back cover
(Thermal imaging)



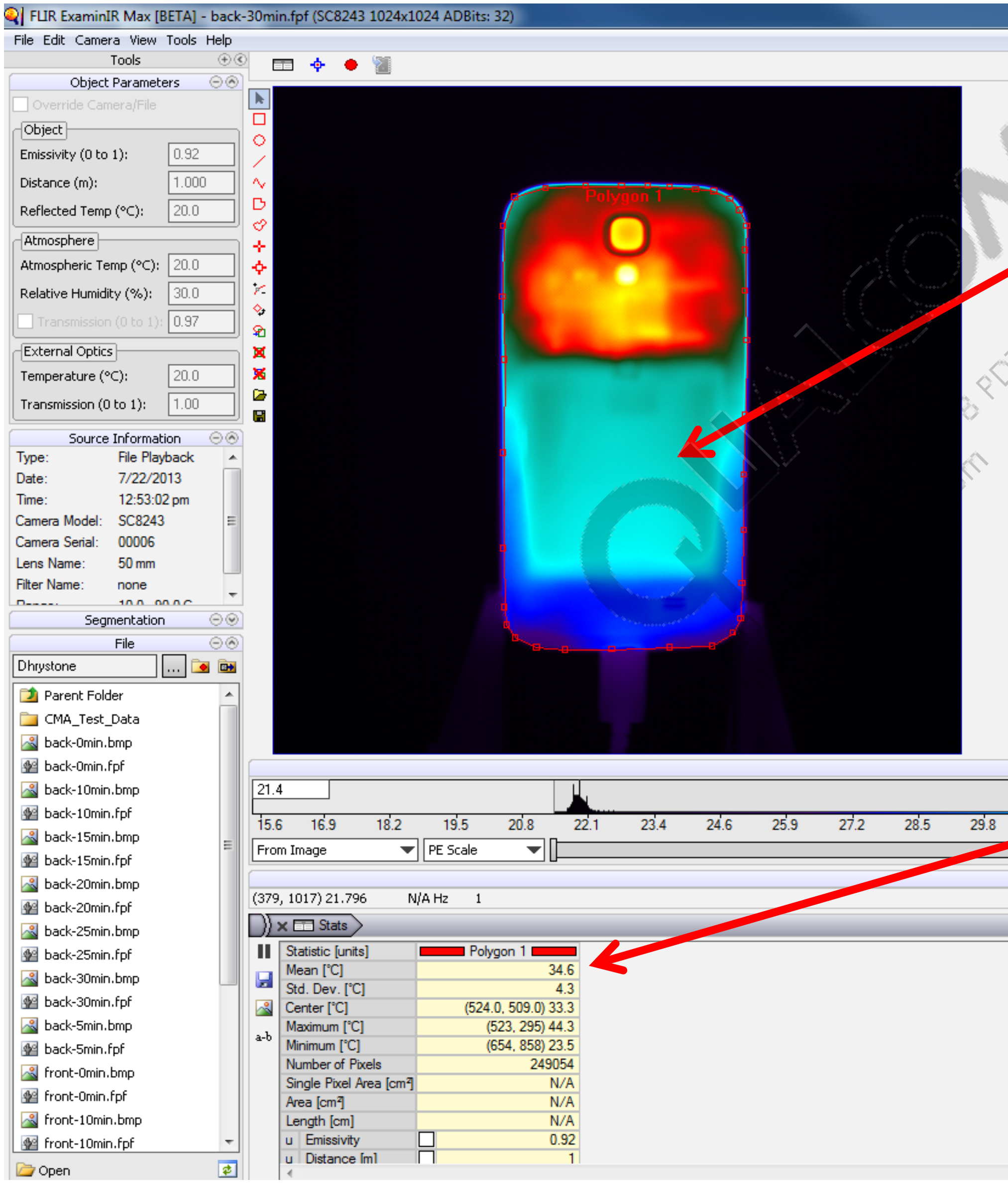
Infrared Thermal Imaging – Data Analysis (1 of 2)



1. Manually draw a polygon ROI to capture the thermal image of the LCD surface.

2. Use ExaminIR software for data analysis to extract the peak temperature (T_{max}) and the averaged surface temperature (T_{ave}) of the LCD surface.

Infrared Thermal Imaging – Data Analysis (2 of 2)



1. Manually draw a polygon ROI to capture the thermal image of back cover surface.

2. Use ExaminIR software for data analysis to extract the peak temperature (T_{max}) and the averaged surface temperature (T_{ave}) of the back cover surface.

Coefficient of Thermal Spreading Calculation

To characterize the overall thermal spreading effect of the phone:

$$CTS = \frac{T_{Global,ave} - T_{amb}}{T_{Global,max} - T_{amb}}$$

$T_{Global,ave}$ is the average temperature over the phone surfaces (including the LCD and back cover).

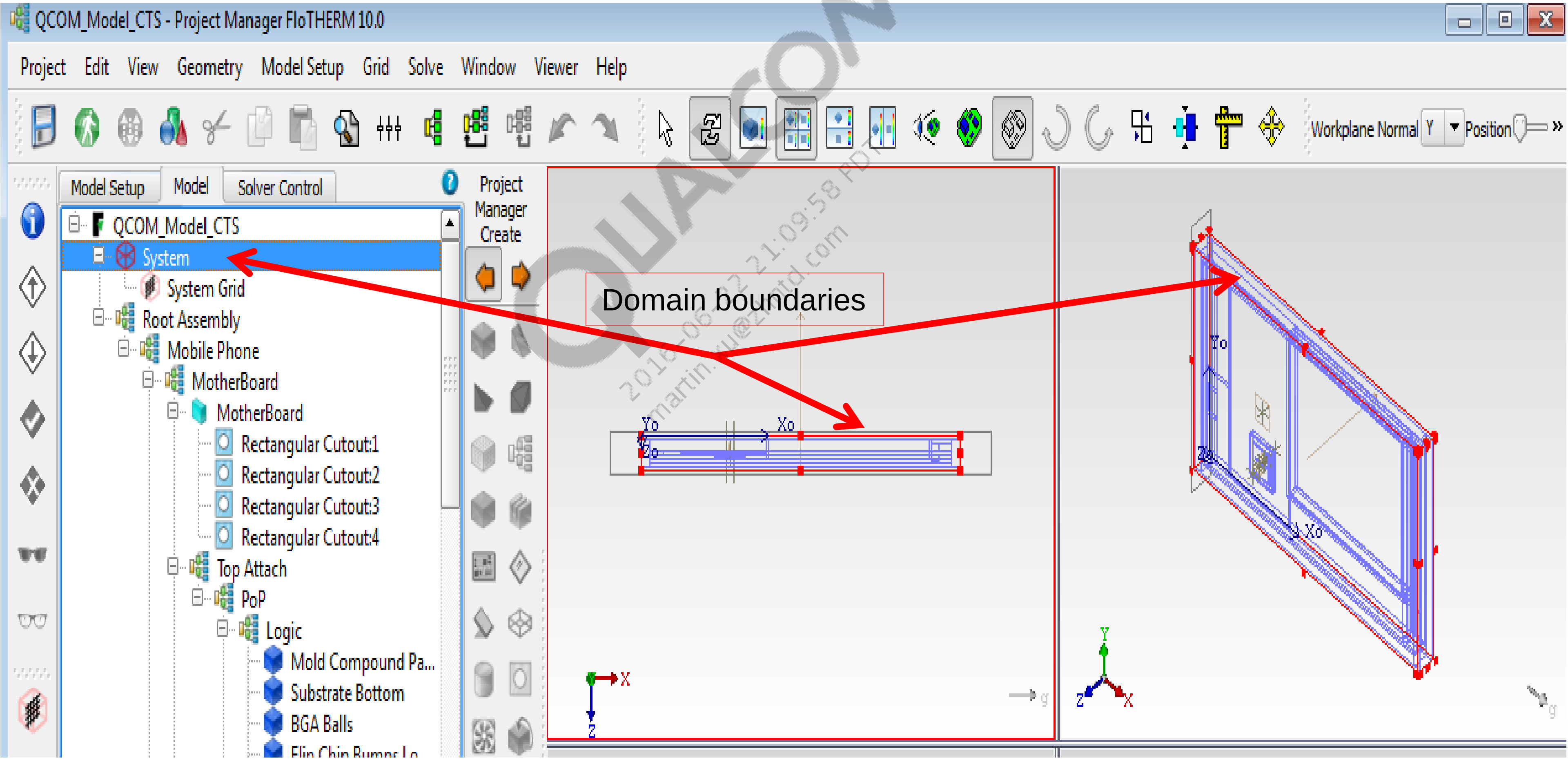
$T_{Global,max}$ is the peak temperature over the phone surfaces (including the LCD and back cover).

T_{amb} is the ambient temperature in the test environment.

Appendix B
CTS Extraction from FloTHERM

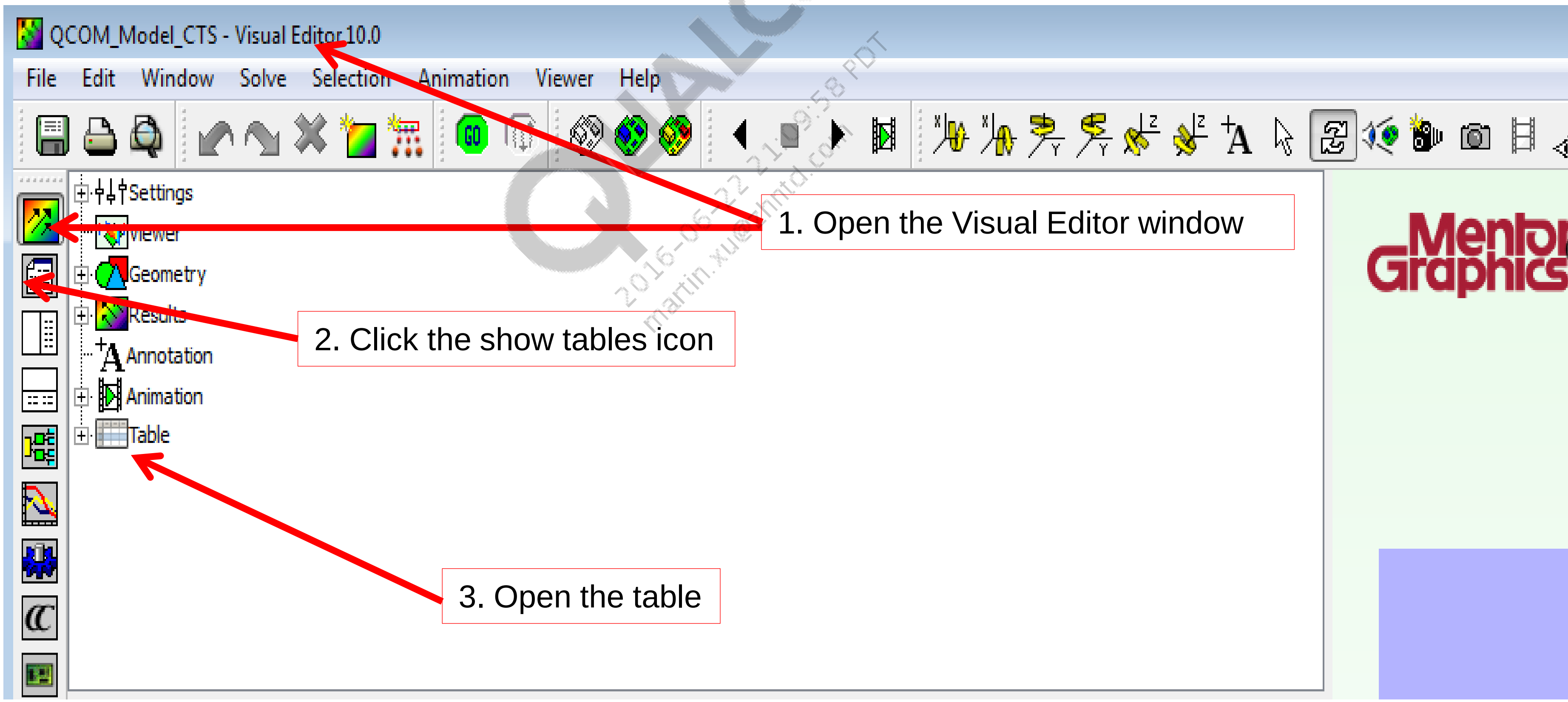
CTS Extraction from FloTHERM – Step 1

The CTS can be extracted from the CFD tool during the thermal simulation phase. The following slides show the steps in sequence for FloTHERM. Before running a specific FloTHERM simulation of a device (e.g., smartphone, tablet, etc), the overall system domain should coincide with the device boundaries.



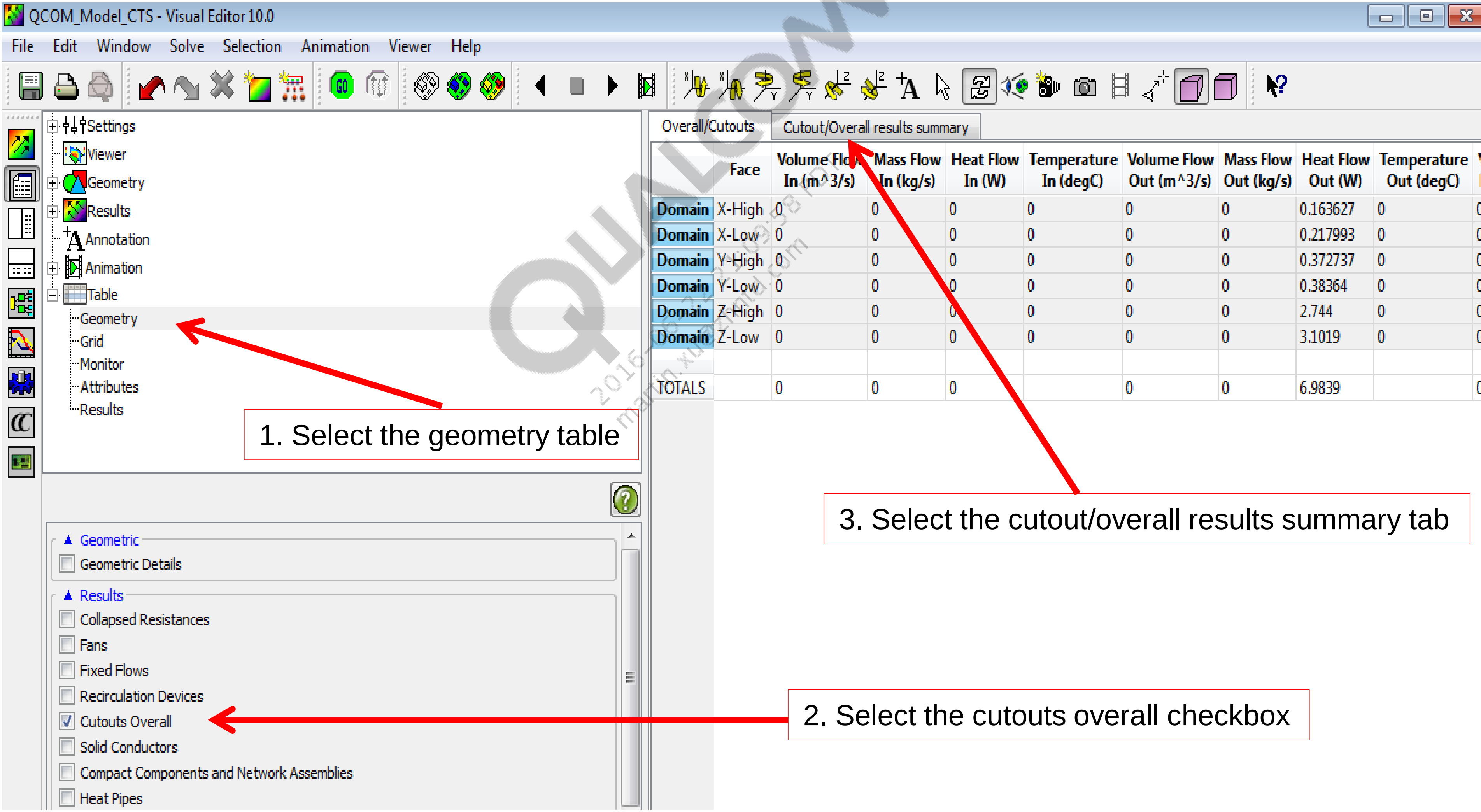
CTS Extraction from FloTHERM – Step 2

1. After running the FloTHERM simulation of the specific device, open the Visual Editor window.
2. Click the show tables icon.
3. Open the table.



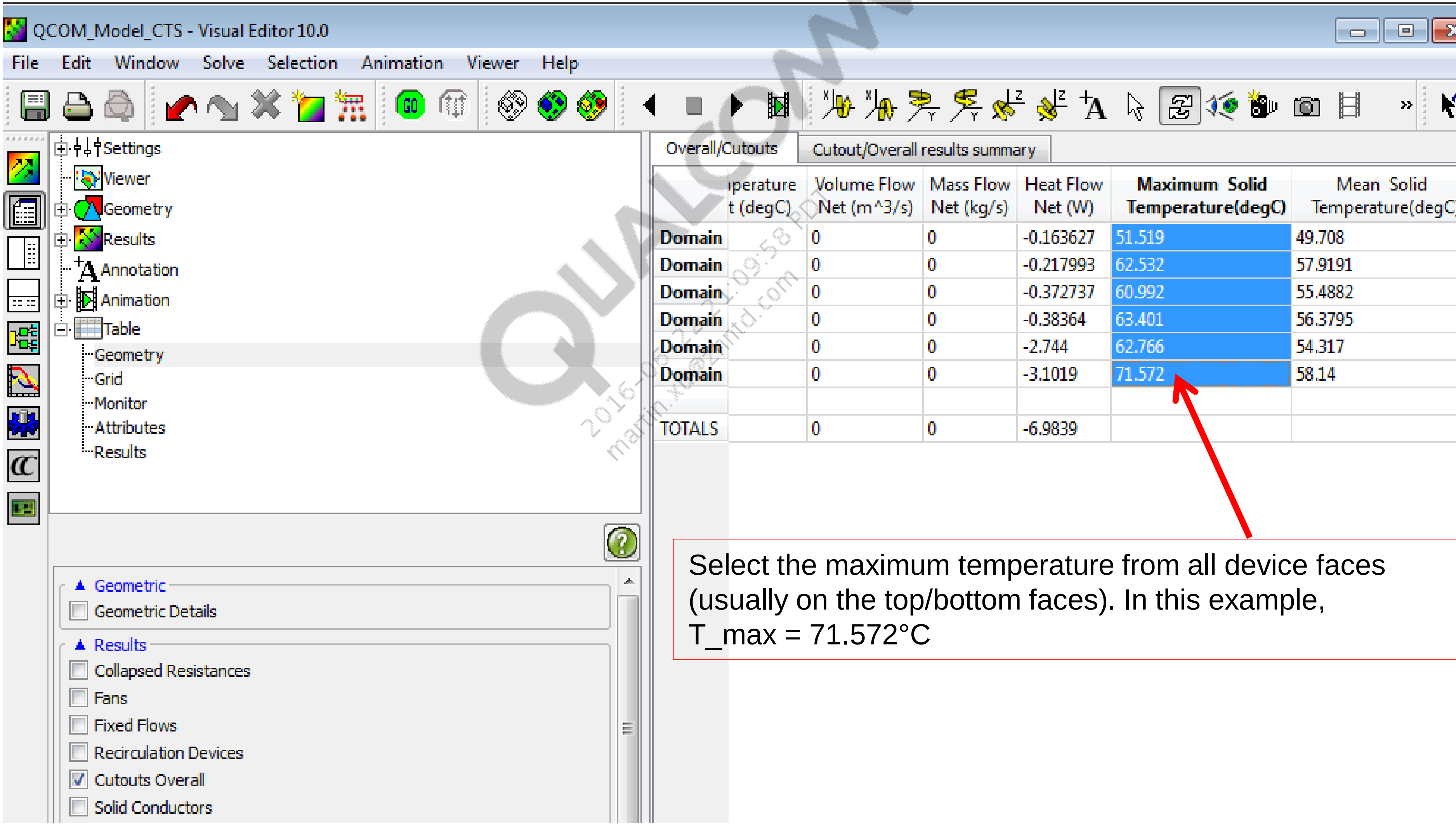
CTS Extraction from FloTHERM – Step 3

1. After the table is open, select the geometry table.
2. Select the cutouts overall checkbox.
3. Select the cutout/overall results summary tab



CTS Extraction from FloTHERM – Step 4

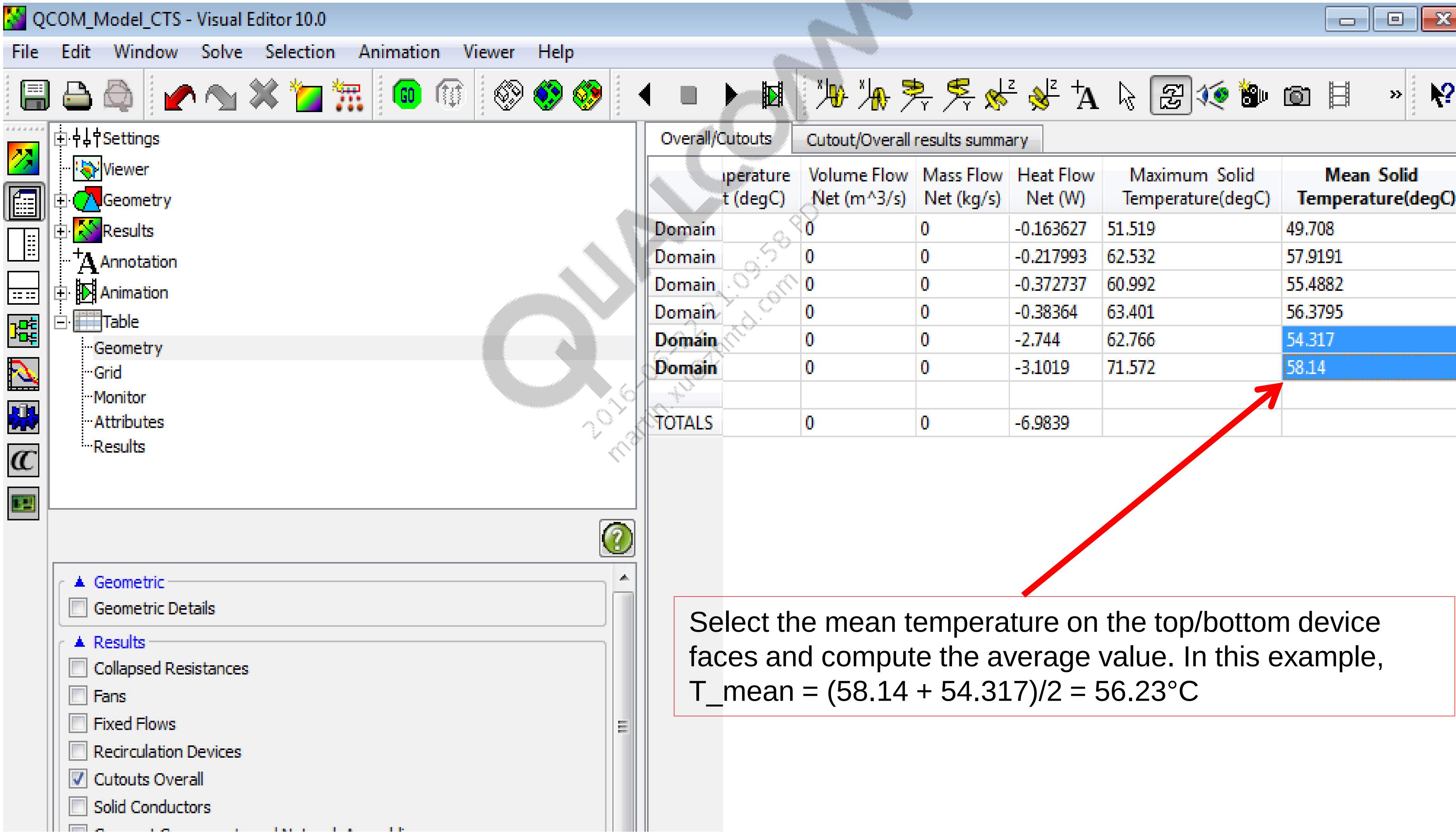
In the cutout/overall results table, scroll to the right to the maximum solid temperature column. Select the maximum temperature from all device faces.



Select the maximum temperature from all device faces (usually on the top/bottom faces). In this example, T_max = 71.572°C

CTS Extraction from FloTHERM – Step 5

In the cutout/overall results table, scroll to the right to the mean solid temperature column and select the average mean temperatures on the top/bottom device faces.



Select the mean temperature on the top/bottom device faces and compute the average value. In this example, T_mean = (58.14 + 54.317)/2 = 56.23°C

CTS Extraction from FloTHERM – Step 6

Using the T_max Value (from step 4) and T_mean Value (from step 5) calculate the CTS value:

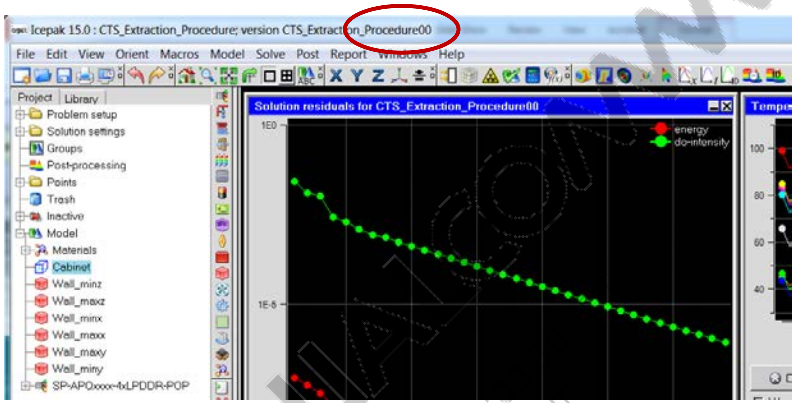
$$CTS = (T_{mean} - T_{ambient})/(T_{max} - T_{ambient})$$

Example: CTS = (56.23 – 25)/(71.57 – 25) = 0.67

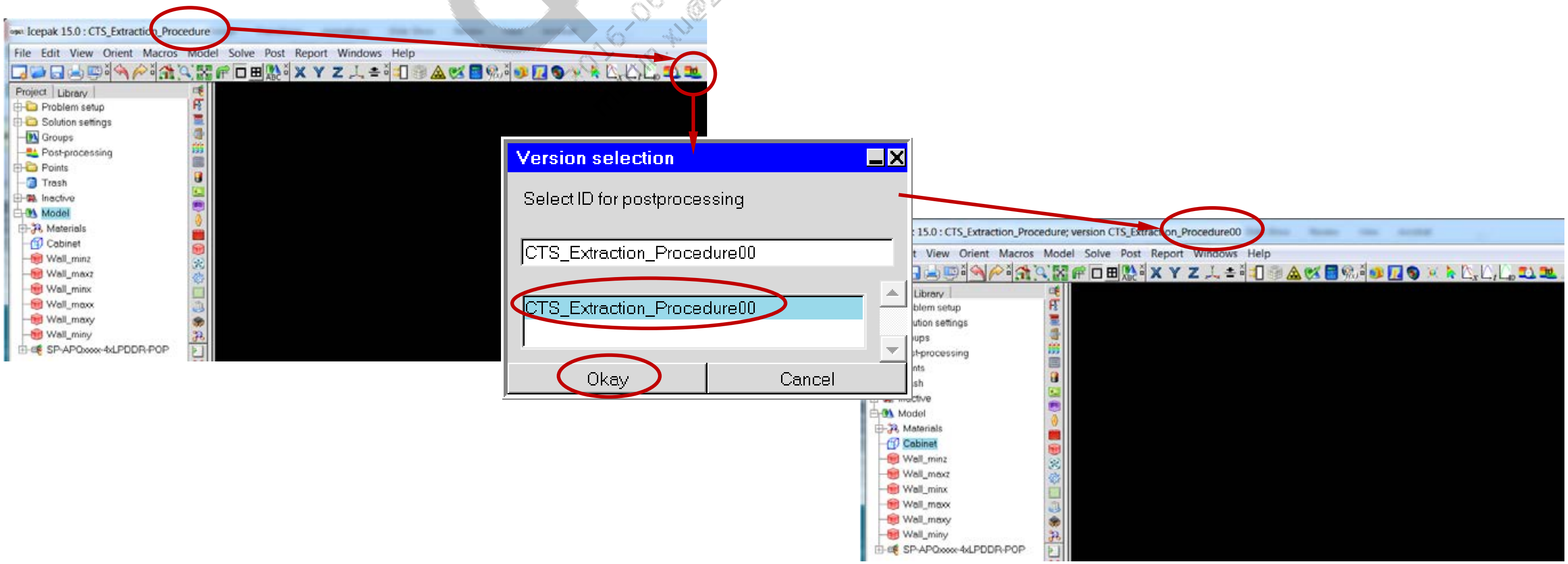
Appendix C
CTS Extraction from Icepak

Step 1: Make a Set of Simulation Results Available

When a simulation case is just done, its results are directly available, which can be told by its solution ID on the Icepak window.



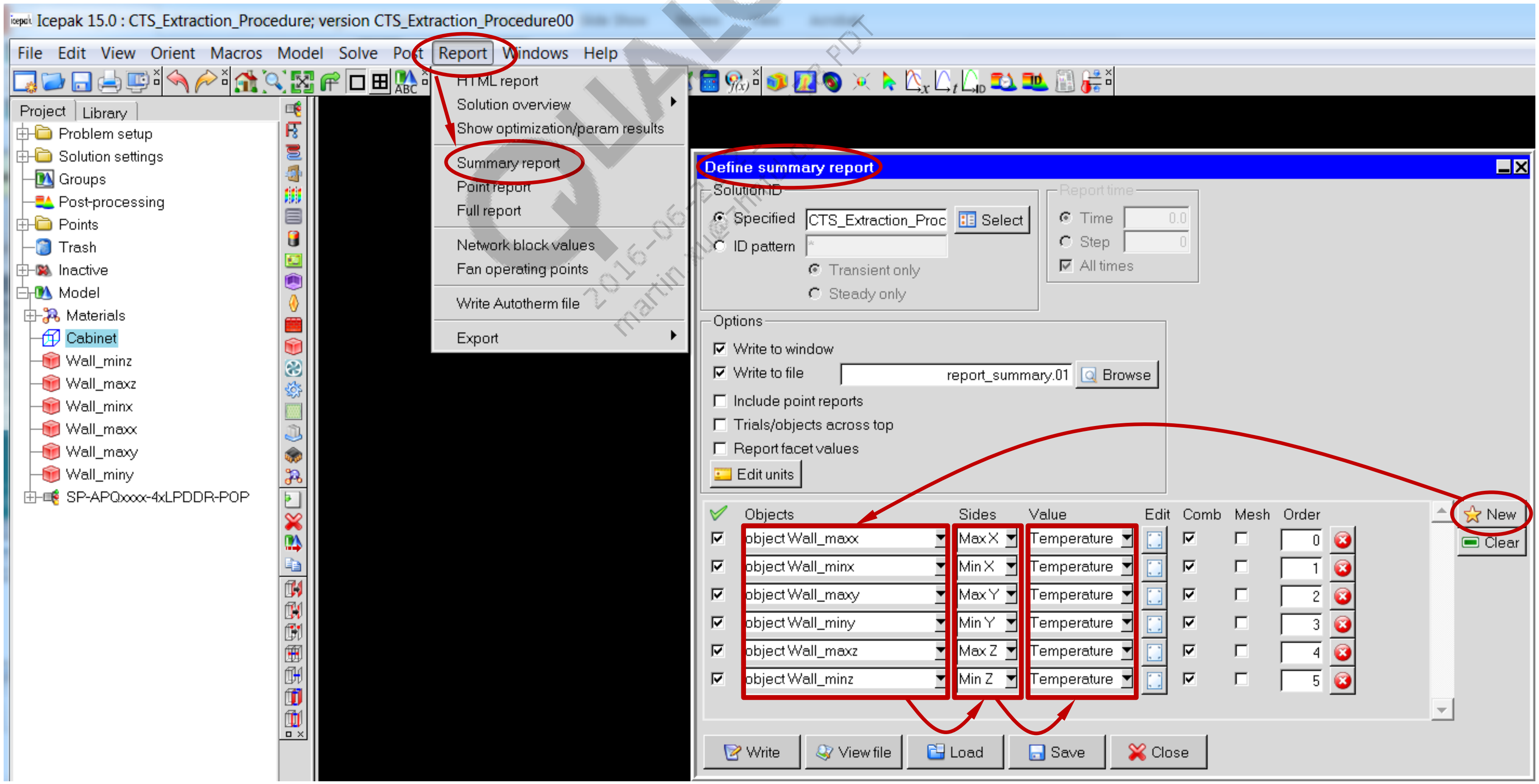
When a simulation case was done previously, load the case first.



Step 2: Define the Device Surfaces

1. Go to **Report > Summary report**.
   The Define summary report window opens.
2. Click **New** to add a device surface one by one. There are six surfaces in total, although only front and back surfaces are usually considered.
3. For each surface, specify its outer side and temperature for value.

   Note: An object/surface may be removed by using the red cross button next to the order column.



Step 3: Find the Maximum and Mean Temperatures on Device Surfaces

1. Click **Write** (located at mid bottom of the figure on previous slide).
   The Report summary data window opens.
2. The maximum and mean temperatures on each surface are summarized in the window.
3. The maximum and mean temperatures on the front and back surfaces are among the summary (boxed in green below).

Report summary data

Object	Section	Sides	Value	Min	Max	Mean	Stdev	Area/volume	Mesh
Wall_maxx	All	Max X	Temperature (C)	27.1398	37.5429	32.7046	2.35403	0.000813645 m2	Full
Wall_minx	All	Min X	Temperature (C)	26.6985	51.8988	40.0959	7.14328	0.000813645 m2	Full
Wall_maxy	All	Max Y	Temperature (C)	26.7819	29.7476	28.713	0.622761	0.00040572 m2	Full
Wall_miny	All	Min Y	Temperature (C)	27.9278	32.8642	30.4432	1.39123	0.00040572 m2	Full
Wall_maxz	All	Max Z	Temperature (C)	27.8928	54.0317	39.9348	6.40965	0.00633204 m2	Full
Wall_minz	All	Min Z	Temperature (C)	26.5133	56.9652	35.951	6.83751	0.00633204 m2	Full

Done | Export

Step 4: Calculate the CTS of the Device

The mean temperature on the device skin T_{mean} = (39.93 + 25.95)/2 = 37.93°C.
The maximum temperature on the device skin T_{max} = max(54.03, 56.97) = 56.97°C.
The ambient temperature in this case is T_{amb} = 25.0°C.
CTS is calculated as:

$$CTS = (T_{mean} - T_{amb}) / (T_{max} - T_{amb}) = (37.93 - 25.0) / (56.97 - 25.0) = 0.40$$

Note: The 0.40 CTS indicates that the thermal design in this example is very poor.

Thank You!

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