Estimation of the junction temperature on Kentsfield
by Stephen Mounioloux, 7-16-07

Note: This study is only suitable for rev. B3 chips.

- # Introduction

CPU temperatures monitoring by end users:
For an end user, the only available values to monitor the temperature of a CPU are the cores temperatures from the DTS (Digital Temperature Sensors) built-in the very silicon. The accuracy of these is limited to +/- 1C. In general, each core has its own DTS. For example, an Intel QX6700 is composed of four DTS, one per core. Each DTS is readable at any time from a register. We will call these temperatures: junction temperatures. In this document, we will mostly refer to THE Junction Temperature which is defined as the average of all temperatures read by the different DTS.

Cooling Devices:
A cooling device (particularly for CPU) is characterized by its thermal resistance. A thermal resistance is defined physically by the following equation:
$Rth = DT / Q$
Where Rth is a thermal resistance, DT is a Delta of temperature and Q the heat dissipated going through into the cooling device.

Ultimately the heat from the CPU is dissipated into the ambient. For that particular reason the Delta of temperature will be built as follow:
$DT = Tcpu - Tair$
Where Tcpu is one particular temperature of the CPU and Tair is the ambient temperature.

Design and Validation:
Cooling devices design requires obviously accuracy. Yet, from this accuracy standpoint using the built-in probes to design and to validate cooling systems is just not possible. Fortunately, CPU manufacturers have developed tools able to simulate CPU behaviors and to monitor with more accuracy one characteristic temperature. Called Thermal Test Vehicles, these are reliable/repeatable/convenient tools for both CPU and cooling systems manufacturers.

The chosen temperature to characterize the CPU temperature is named Tcase. Located at the very geometrical center of the IHS, Tcase is measured with a thermocouple. For this geometrical reason, Tcase is obviously and always colder than a die temperature. From our standpoint, the unknown remains the Delta of temperature between the Junction and the Case.

Quote:

Important notice: In this study, we are postulating that the Delta of temperature

between the Junction and the Case is:
- not dependant on the cooling device
- not dependant on the Thermal Interface between the IHS and the cooling device
- ONLY dependant on the heat dissipated into the cooling device

This affirmation will be confirmed in a short study to be published in the next weeks.

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Objectives:

The objective of this study is to build a method to estimate the actual cores temperatures in function of these five parameters:
- the CPU architecture
- the actual CPU voltage
- the CPU clock
- the software (level of CPU stress)
- the ambient temperature

From a deep testing standpoint, this study will (within the DTS probes accuracy) show how this method can "predict" the cores temperatures. Reciprocally, a good prediction will tend to validate the use of the TTV in our industry.

Eventually, these results can be used to:
- Give our customers a better idea about what temperatures they can expect with our cooling solutions.
- Check if a system is properly installed.

Note on TTV:

There are many different TTV. Almost CPU architecture/package has its own. There are also differences between server TTV and desktop TTV. For the past years, Swiftech has published data using one single type of TTV. Lately, we introduced a second type of TTV suitable for Kentsfield being also technologically more advanced on a thermal and mechanical standpoint. For that particular reason, we have chosen to dedicate this document to Kentsfield being more

likely the CPU for enthusiasts/gamers and/or overclockers/benchmark addicts.

• From the die to the ambient: How to evaluate the Cores Temperatures?

The actual heat source in a CPU is the silicon itself composed of millions of transistors. Most(*) of the heat generated (H) by the CPU goes into the heat spreader via the thermal interface (1) and then through the cooling device via the thermal interface (2). All those "stacked" components represent a resistance for the heat, resulting in a core temperature higher than the ambient. Let's imagine a null resistance between the ambient air and the cores: automatically the cores will be affected by the same temperature as the ambient. Looking at this chain of components along the heat path, the overall thermal resistance can defined as the Junction to Air Thermal Resistance.

(*) *Some of the heat dissipated by the CPU goes through the socket and the motherboard. This percentage has been measured in different conditions. It represents up to 5% of the heat measured through the cooling device.*
This can be translated by the heat dissipated: Q ~ H.(1-0.05).

Junction to Air Thermal Resistance:
C/W(J to Air) = (Tj – Tair) / Q
C/W(J to Air) = (Tj – Tcase) / Q + (Tcase – Tair) / Q
C/W(J to Air) = C/W(J to Case) + C/W(Case to Air) [1]

<=> Tj = Tair + Q.C/W(J to Air)
<=> Tj = Tair + Q. [C/W(J to Case) + C/W(Case to Air)]

Where, Case to Air Thermal Resistance: C/W(case to air) = (Tcase – Tair) / Q
And, Junction to Case Thermal Resistance: C/W(J to Case) = (Tj – Tcase) / Q

• Tair is the actual ambient temperature. Tair is commonly measured at the inlet

of the Air heat exchanger.

• C/W(Case to Air) is determined with a TTV.

• Q is initially unknown but Q will be determined by measurements with the same technique used with radiators testing. Q is not TDP! Q is the actual heat going through the cooling device.

• C/W(J to Case) is THE unknown.

<u>Note</u>: The Case to Air Thermal Resistance includes the thermal interface (2) thermal resistance. For that particular reason, the matter of thermal interface is not entering this study.

• Determination of the actual heat dissipated in the cooling device

The heat dissipated by the CPU through the cooling device is a function of several parameters. It is common sense that the CPU will get hotter if the user stresses the CPU than if it keeps idling. It is also always well known by overclockers that CPU will get hotter with a higher supplied voltage and/or higher clock.

Different CPU packages or even different CPU architectures will affect the heat dissipated. Anyone who has used both a Intel Core2Duo AND a Intel quad-core Q/QX series knows that with about the same clock and voltage the quad-core dissipates more Watts into the cooling device because of the two physical dies on the package.

Methodology:
With all this in mind, we just implemented our radiator testing methodology to a "live" CPU. Practically, we installed a whole computer in an environmental chamber. The CPU is liquid cooled with a "thermally defined" (Case to Water Thermal Resistance known at various flow rates) waterblock: the Apogee GT with a flat base. Inlet and outlet lines temperatures are measured with RTD. Flow rate is controlled and measured (flow rate is maintained at 0.5 gpm). The coolant inlet temperature is kept constant to 25C.

It's basically all we need to actually measure the heat dissipated by the CPU. In order to optimize measurement accuracy, we have a chosen a low flow rate of 0.5 GPM which will force a higher Delta of temperature between the inlet and the outlet in order to minimize measure errors.
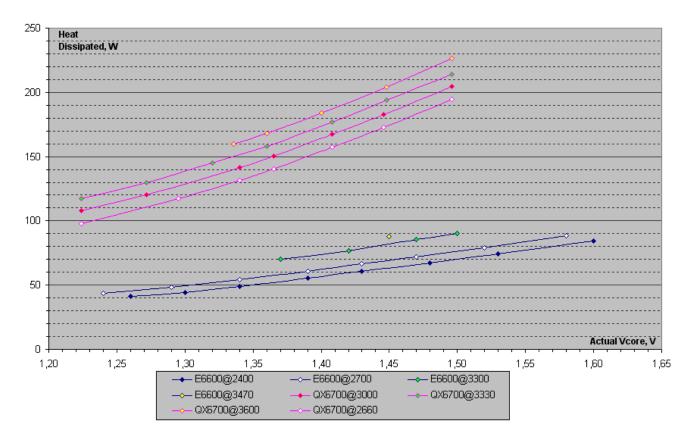
With so many different types of applications available, we chose 4 or 5 applications and we gathered data by changing parameters such as CPU clock, supplied voltage and applications. It will take too much time to detail all the results, but let's just say that we have learned very interesting things related to application's stress and heat load.

For this study, we have found very interesting to compare two processors of the same architecture but with a very different package: an E6600 and a QX6700. The more stressful (in terms of heat dissipation) software that was available for both processors is BurnK6. For the record, TAT will make our E6600 generate more heat than BurnK6 by ~ 6%. Unfortunately, TAT won't work with quad-core processors.

The BIOS voltage is recorded as well as the actual supplied voltage. For obvious reasons, we will only use actual supplied voltage (i.e. after voltage droop) in our analysis.

Real CPU Heat Dissipated Vs. Supplied Voltage
BurnK6 on ALL cores - Actual Vcore (i.e. after droop)

At same clock and voltage, Kentsfield dissipates more than twice heat than Conroe does. That's an interesting observation since Kentsfield being basically a package composed of "two Conroe dies".

A brief graphical or numerical analysis shows the true second order behaviour for the heat dissipated in function of the supplied voltage. The total amount of heat generated by the CPU is H and is a function of several parameters: $H = k.f.V2$. Where f is the CPU clock; V is the supplied voltage and k a corrective coefficient. Q (the heat dissipated into the cooling device) being a percentage (~95%) of this heat generated, then Q is also a function of these parameters: $Q = K.f.V2$. Where K is another corrective coefficient.

It is also very important to realize that Kentsfield will not necessarily tend to get hotter

than Conroe simply because of their different Junction to Case Thermal Resistances.

Limitations of the heat dissipated measurement:
Overall, the only limitations to these measurements were: -the physical and/or overclocking capacities of the hardware we used; -the cores temperatures (we limited our tests to a maximum core temperature of 85C; a colder inlet temperature, we would have probably get us data on a wider clock range). We also got a voltage limitation to ~ 1.50 V when using Kentsfield on our motherboard.

At this point, knowing the differences in terms of overclocking from a CPU to another, it would be very important to repeat a couple of points in each parabola with other E6600 and QX6700: some very interesting questions might be answered such as: Will two identical CPU dissipate the same amount of heat in the cooling device? Is the overclocking potential somehow related to the heat dissipated?

• Junction to Case Thermal Resistance evaluation

There are at least two ways to evaluate the Junction to Case Thermal Resistance:
• The first is the direct method which consists in measuring the case temperature on a "live" CPU. This method actually requires machining of a groove on the top on the IHS. A thin thermocouple is then installed to measure the temperature at the geometrical center of the IHS. The Junction to Case Thermal Resistance is then given by the equation: C/W(J to Case) = (Tj – Tcase) / Q
• The indirect method will calculate this thermal resistance by the following equation:
C/W(J to Case) = C/W(J to Water) + C/W(Water to Case)
C/W(J to Case) = C/W(J to Water) – C/W(Case to Water)

Where C/W(J to Water) can be measured in a lab environment with the known limitations of the Cores DTS and where C/W(Case to Water) is a known function of the flow rate.

With this indirect method we are about to evaluate the Junction to Case Thermal Resistance by the knowledge of both the Junction to Water Thermal Resistance AND the Case to Water Thermal Resistance.

a) Junction to Water Thermal Resistance:

We used the same setup as for the heat dissipated determination: we recorded the maximum core temperature for each core: 2 records for the E6600 and 4 records for the QX6700.

Every single test made before for the heat dissipated measurement is now utilized to calculate the Junction to Water Thermal Resistance: $C/W(J\ to\ Water) = (T_j - T_{water}) / Q$
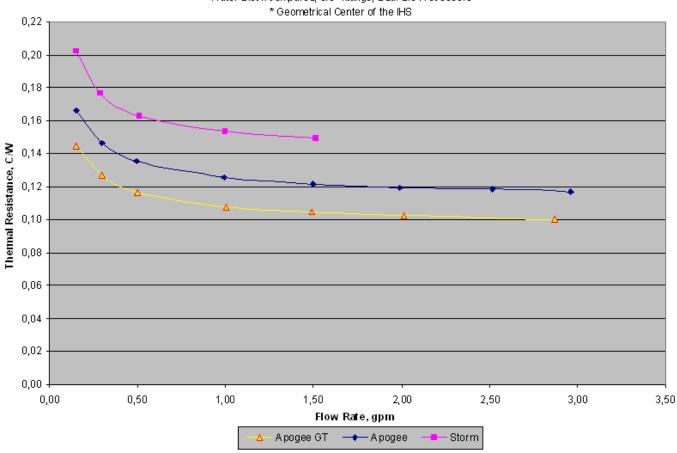
Where T_j is the average core temperature, T_{water} is the water temperature measured at the inlet of the waterblock and Q the heat dissipated in the water.

Based on ~ 30 measurements, for the QX6700 the average Junction to Water Thermal Resistance is 0.230 C/W. Standard deviation is less than 0.004 C/W.

C/W(J to Water) = 0.230 C/W

b) Case to Water Thermal Resistance:

The Case to Water Thermal Resistance is already properly defined for the waterblock we are using in this setup. We need to refer to our published data to get the correct thermal resistance for this particular test.

Thermal Resistance (Case* to Coolant) Vs. Flow Rate
Water Block compared; 3/8" fittings; Dual-Die Processors
* Geometrical Center of the IHS

At 0.5 GPM, the Apogee GT in its flat based configuration has a thermal resistance of 0.117 C/W.

C/W(Case to Water) = 0.117 C/W

c) Junction to Case Thermal Resistance:

We can now calculate the Junction to Case Thermal Resistance:

C/W(J to Case) = C/W(J to Water) − C/W(Case to Water)
C/W(J to Case) = 0.230 − 0.117
C/W(J to Case) = 0.113 C/W

Kentsfield shows a Junction to Case Thermal Resistance of 0.113 C/W. For example, if we considered heat dissipated of 100 W through the cooling system, the difference between the Case and the Junction would be around 11 C - the Case would be actually 11 C colder than the Junction.

This thermal resistance is quite low. The biggest reason for that is without any doubt the large die surface. This surface is just twice larger than Conroe's. It can be seen as a larger or a less resistive path for the heat. With such a big heat dissipation, keeping a low Junction to Case Thermal Resistance has been more than a need for Intel.

d) Limitations:

Using the direct method to actually measure the Junction to Case Thermal Resistance would be an excellent way to validate this number. Our Kentsfield will not be machined but our E6600 is currently going through this process.

Update: The same study with our E6600 in fewer details will feature verification with the direct method.

• Junction Temperature estimation

We have already established the equation to determine the junction temperature:

Tj = Tair + Q. [C/W(J to Case) + C/W(Case to Air)]

The Case to Air Thermal Resistance characterizes the thermal performance for a given cooling device. Swiftech has always provided this specification for all cooling devices such as heatsinks and liquid cooling kits. It represents the rise of temperature for the Case - above the ambient - per W dissipated.

We built a liquid cooling loop around an H2O-120 Compact kit (Apogee Drive, MCR120-Res, around a foot of 3/8" tubing). The whole setup is installed on the dual-die TTV in

the environmental chamber. We measure the Case temperature, the air temperature at the fan intake (with RTD) and the heat generated by the dual-die TTV. The Case to Air Thermal Resistance for this setup is 0.188 C/W.

Using the equation [1], we can calculate the estimated Junction to Air Thermal Resistance for Kentsfield in this particular liquid cooling loop:

C/W(J to Air) = C/W(J to Case) + C/W(Case to Air)
C/W(J to Air) = 0.113 + 0.188
C/W(J to Air) = 0.301 C/W

We now want to actually verify this estimation. The liquid cooling loop is now installed on a system based on Kentsfield.

a) Test setup:

- Evga 680i
- Intel QX6700
- 2x 1GB Corsair (675 MHz / 4 4 4 12)
- 1x WD Raptor 36GB

In order to compare our estimated Junction temperature to the actual measured temperature on our rig, we need to know the heat dissipated into the cooling device. To do so, we are using the same BIOS settings as the Heat Dissipated tests.
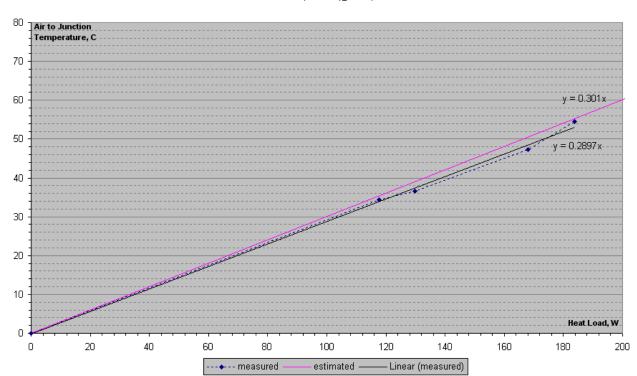
b) Settings:

Test #	CPU Clock	BIOS Voltage	Actual Voltage	Heat Dissipated
1	3330 MHz	1.30 V	1.224 V	118 W
2	3330 MHz	1.35 V	1.272 V	130 W
3	3600 MHz	1.45 V	1.360 V	168 W
4	3600 MHz	1.50 V	1.400 V	184 W

For each test, we record all cores temperatures and the air temperature at the fan intake. Cores temperatures are averaged. The following table confronts data from

"measure" against numbers from our estimation.

c) Results:

Test #	Air Temperature (Fan Intake)	Measured Core Temperature (Avg. on 4 cores)	Estimated Core Temperature	Measure to Estimation (error)
1	21.1	55.5	56.5 C	1.8 %
2	21.4	58.0	60.5 C	4.3 %
3	20.8	68.0	71.3 C	4.9 %
4	20.5	75.5	75.8 C	1.1 %

The following graph shows the actual trend line for our four measure points. Its inclination is smaller than the estimation's.

Junction Temperature estimation on Kentsfield
Junction to Air Thermal Resistance; BurnK6 on all 4 cores
H2O-120 Compact kit (@ 12 V)

- # **Conclusions**

This study is definitely the first chapter of at least four aiming at a better knowledge of CPU thermal behaviours.

Based around theory, laboratory testing and end users style validations, we have been able to estimate a very reasonable value of the Junction to Case Thermal Resistance for Kentsfield. We will be using soon this value as an asset at several levels such as specifications and/or technical support. This result can obviously be extended to any CPU based on Kentsfield such as Q6600, QX6700 or QX6800.

The next step will repeat this procedure (in much fewer details) to Conroe. The main objectives will be: - to give another verification of this method by measuring the Junction to Case Thermal Resistance with the direct method; - to use this tool to show this thermal resistance is only dependant on the heat dissipated into the cooling device.

At the time we are publishing this document, there is no real interest to repeat this technique to another CPU architecture. Obviously, as the technology moves on we will need to repeat this procedure.

Swiftech's online Thermal Calulator is based on the results of this study (and the one for Conroe). You can use this tool to estimate your CPU head load.