Considerations for **System Power Management and Thermal Options** Using i.MX 6 Series Applications Processors

AMF-DES-T1059

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MAR.2015

External Use

Agenda

- Things Get Hot – Setting Expectations
- Cooling Things Down – Some Examples
- Spreading the Heat – Thermal Design
- Beating the Heat – i.MX 6 Series Processors
- Managing the Heat – The SW Approach

Things Get Hot

Setting Expectations

- **Highly integrated SOCs using ARM-based cores are powerful and can generate significant heat**
  - However, typically in the sub 5W range vs. 100W range

- **Heat is a function of what you are doing with the processor + memory**
  - The Thermal Design Power (TDP), also referred to the thermal design point, is of primary interest to the thermal solution designer and it represents the **maximum sustained power dissipated** by the processor, **across a set of realistic applications**.
  - Only running Video (~2W)
  - Only running 3D GPU (~1.7W)
  - Video + 3D + 3 ARM Cortex A9s at high speed (~ 4.6W)
  - Quad ARM Cortex A9s at high speed only (~ 2.3W)

  Note: all based on SOC + DDR3 power consumption

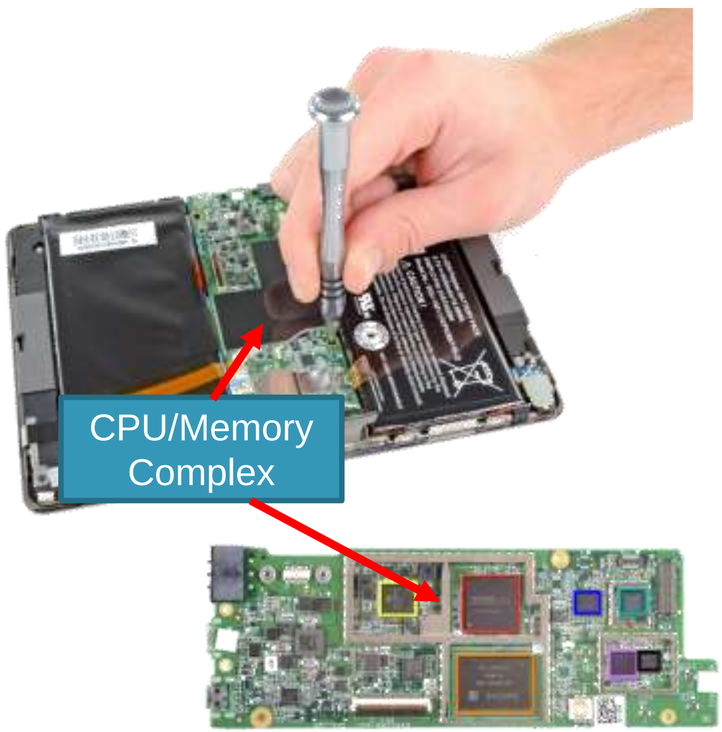
- **Many modern day devices using ARM based processors have some sort of thermal management system in place**
  - Typically: cheap graphite heat spreader
  - Sometimes: metal tabs for conducting heat
  - Rarely: a full active heat sink

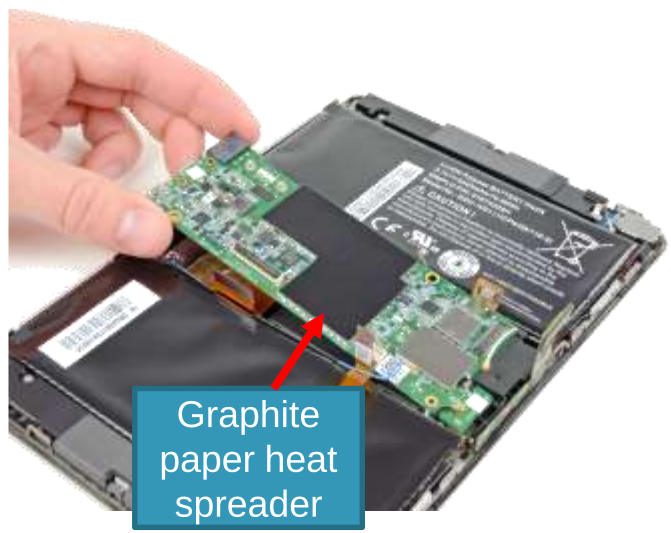
Cooling Things Down – Some Examples

Thermal Heat Spreader Example

Simple Thermal Solution

- Teardown : RIM Playbook
- Processor: TI OMAP4 @ 1.2 GHz
- Source: http://www.ifixit.com/Teardown/BlackBerry-PlayBook-Teardown/5265/1#.T8kAB1KRMgc





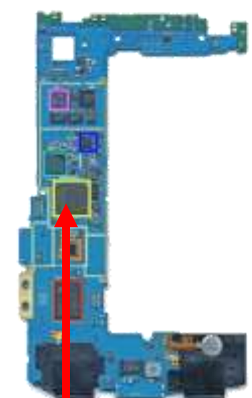
Graphite heat spreaders are cheap. Easily cut into any dimension to spread heat into other components.

Thermal Heat Spreader Example

- Teardown: Samsung Galaxy Tab
- Processor: 1.5 GHz NVIDIA Tegra 3 Quad Core
- Source: http://www.ifixit.com/Teardown/Samsung-Galaxy-Tab-Teardown/4103/1#.T8kG31KRMgc
- Source: http://www.youtube.com/watch?v=urGUKerJOhg

Samsung uses EMI shield + heat spreader metal

Back cover metal heat spreader in direct contact with EMI shield



IC Motherboard

EMI Shield

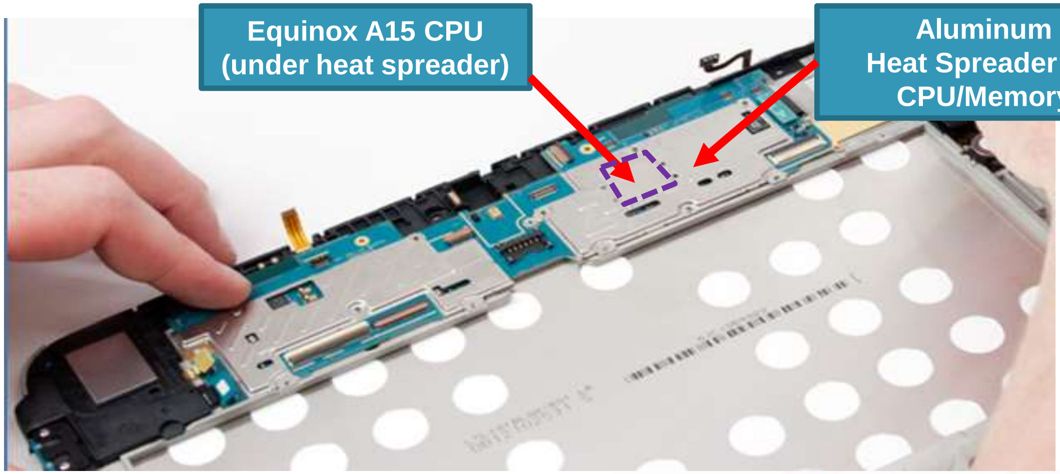
CPU

Thermal Heat Spreader Example

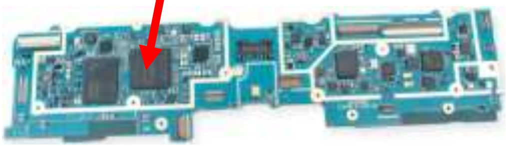
Nexus 10 – Extensive Thermal Management

Equinox A15 CPU (under heat spreader)

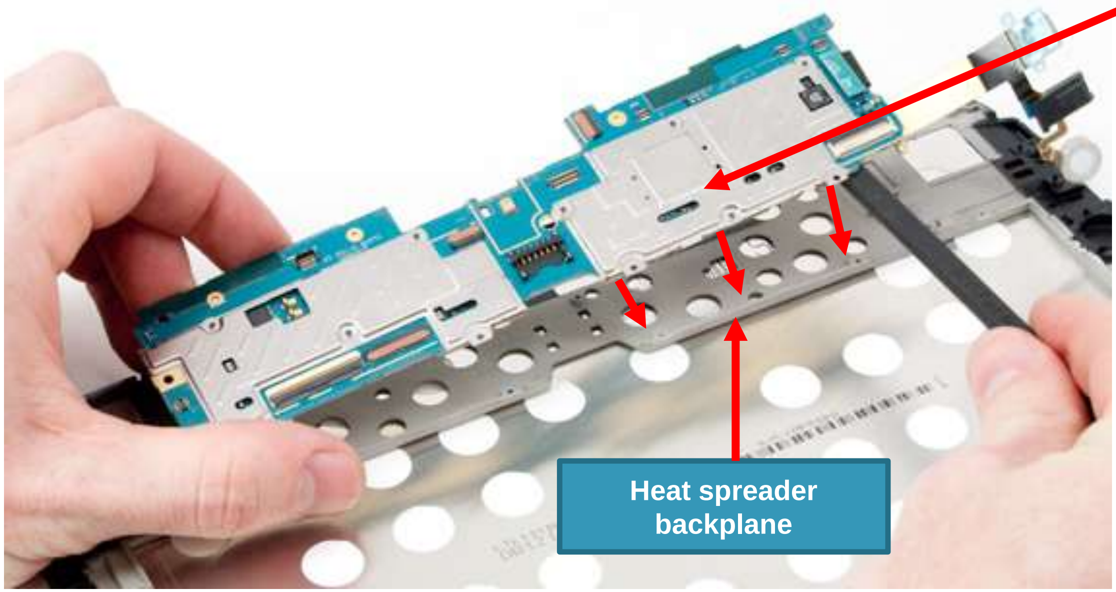
Aluminum Heat Spreader for CPU/Memory



Equinox A15 CPU



CPU Aluminum Heat Spreader attached to massive heat spreader backplane on LCD side and a Graphite strip on the backside case



Heat spreader backplane

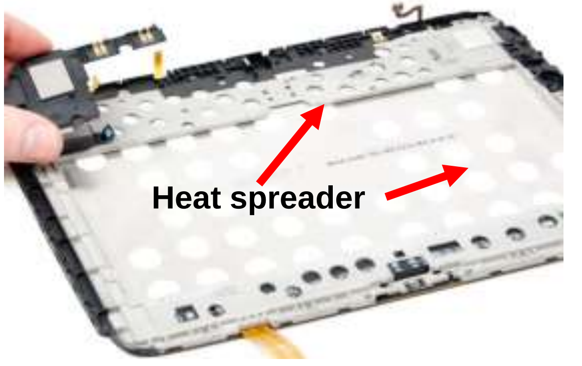
Graphite strip which adheres to top of CPU assembly's aluminum heat spreader

Source: PowerbookMedic

Thermal Heat Spreader Example

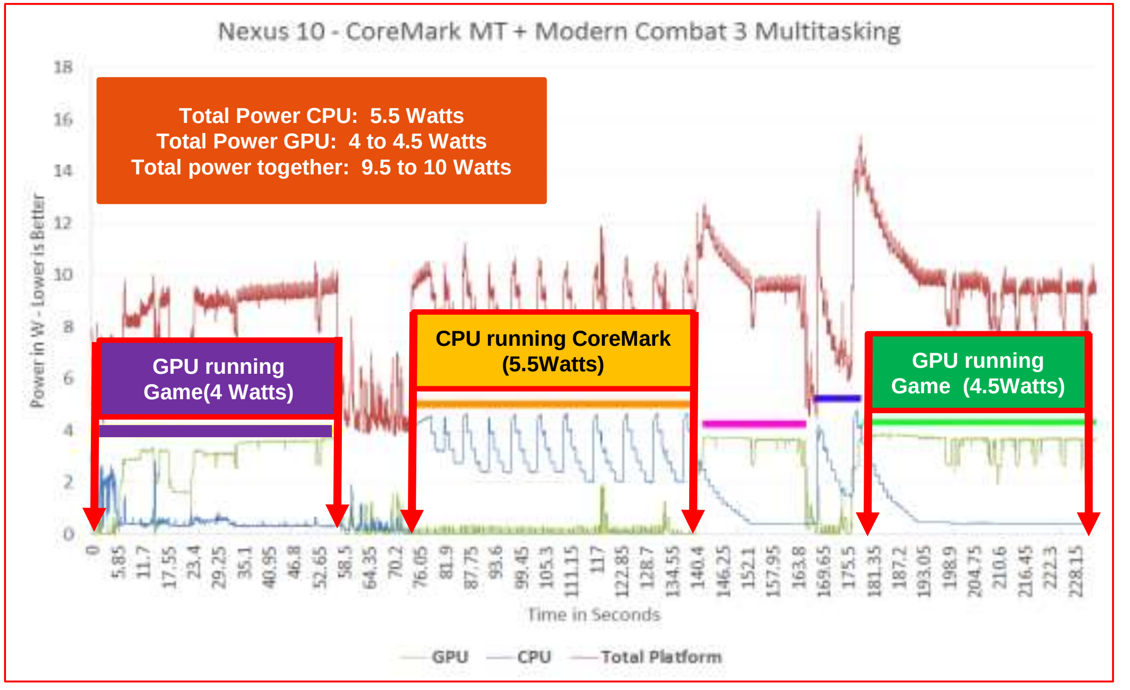
Nexus 10 – Why is such Thermal Management Required

- Tested Nexus 10 running CoreMark MT (CPU test) + Modern Combat 3 (Game)
- Measured GPU, CPU power consumption
- CPU or GPU consume between 4.0 to 5.5 Watts each
- Test below has user switching between game/CPU test
  - with only one app running at a given time, not concurrently
- **If apps running concurrently: 9.5 to 10Watts!**



Graphite or Copper heat spreaders cannot handle more than 5.7W unless covering the entire platform enclosure (high cost)

i.MX 6Quad Package	Heat Spreader Option (Assumes entire PCB covered but not the rest of the enclosure)	Max Power that can be dissipated (To maintain 85Deg C within the enclosure & <=105Deg Tj on die)
Un-lidded	None	2.3 W
Un-lidded	Graphite (eGraph SS500	5.6 W
Un-lidded	Copper (0.2mm)	4.6 W
Un-lidded	Copper (0.6mm)	5.7W



Spreading the Heat – Thermal Design

Overview : Thermal Management

Consume Less Power - Generate Less heat

Heat is a by-product of power and the **best way to generate less heat is to consume less power**.

Once heat is generated, the job then becomes to transfer it effectively by providing an efficient path from the device to the environment via thermal pads, epoxy or any method that makes use of conduction, convection, or facilitates radiation.

The general strategy for thermal management focuses on:

- **Increasing the heat-dissipation** capability of the thermal solutions
- **Expanding the thermal envelopes** of systems
- Minimizing impact of local hot spots **by improving heat spreading**
- Developing **thermal solutions** that meet **cost constraints**
- Solutions that **fit within form factor** considerations of the product chassis

Thermal Management Strategies

There are basically two types of thermal management strategies:

- **Active** thermal management techniques available for embedded systems provide lower thermal resistances and better heat dissipation, however are expensive and have large form factors
- **Passive** thermal management techniques by enhancing conduction and natural convection provide more cost effective solutions, up to certain power levels without introducing any reliability concerns

Overview : Thermal Management

System Design

- **Thermal Design Strategy:** A holistic thermal design strategy needs to consider all aspects of the thermal hierarchy.
- Historically, the processor was the most energy hungry component of a typical embedded computing system.
- i.MX6 family have become more energy efficient and more effective at managing their own power consumption
- **Designing for TDP** is important to ensure reliable long-term performance.

- **Thermal Contributors:** Typical high power devices in a system include but are not limited to the following:
    - Power Management IC's or External LDO's
    - RF components such as PA, transmitters & Modems
    - LCD, LED and OLED displays
    - High Speed memories and Transceivers

Overview : Thermal Constraints

- In handheld computing products, there are multiple temperature limits that must be considered.

1. **External case** or screen temperature : which generally must not exceed 40C.
    - Temperatures higher than this impact the user experience
    - comes into effect in a longer duration, steady-state use case of SoC power dissipation
2. **Junction Temperature**: the maximum temperature at which IC functionality can be guaranteed.
    - Varies based on Market segment with Auto being the highest (125C for i.MX)
    - Also, local hotspots of up to +15-25C can be expected on die
3. **Adjacent Components**: DRAM such as a PoP (Package on Package) devices can enable additional thermal constraints since they are not typically rated as high
    - Lesser concern with BGA or FCBGA devices

Overview : Thermal Dissipation

Activity Profile

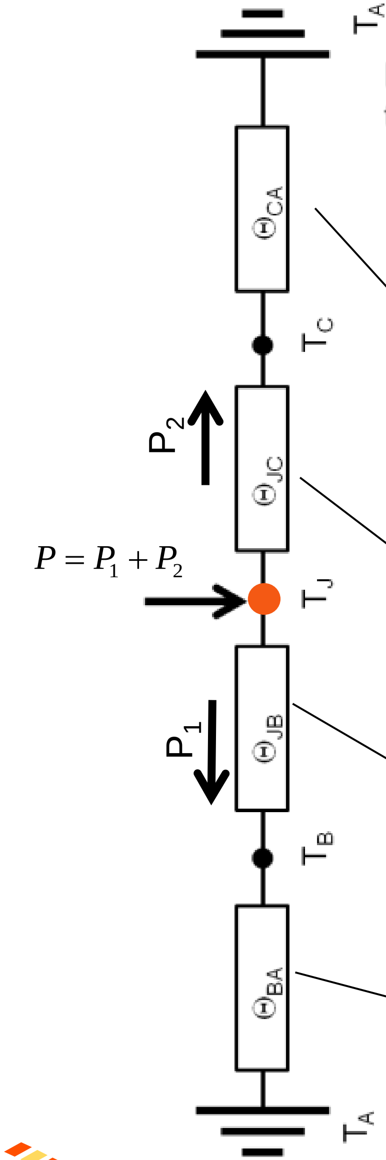
The activity profile of the application can have a significant impact on the thermal management techniques used and on the TDP.

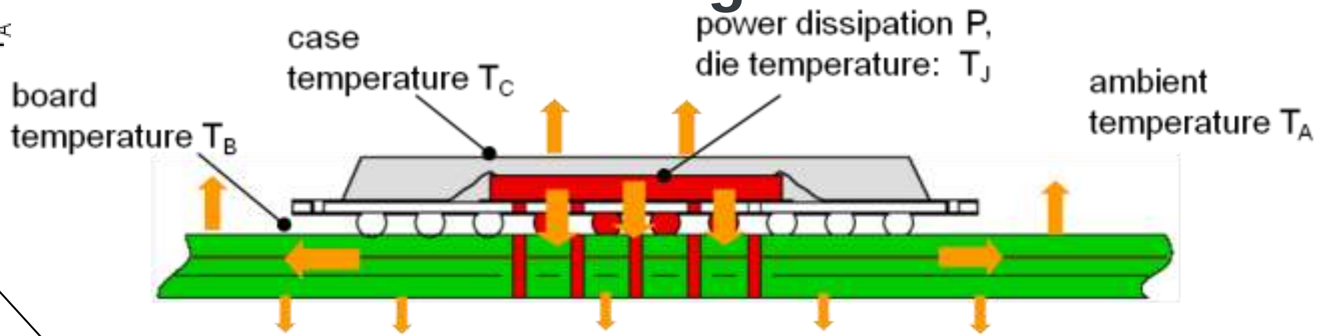
The **time constant** sets the length of time to average the consumption of the chip over for bursty operations and will scale up and down with the board and packaging size/mass.

The main types of activities can be classified as follows:

- **Short Bursts** below thermal time constant
  - Short bursts of intensive processing followed by long intervals of the IC/System being idle can automatically regulate the heat without much external intervention.
- **Long Bursts** above thermal time constant
  - Long bursts of intensive processing followed by long intervals of the IC/System being idle may require some external intervention such as SW Thermal management.
- **Continuous Operation** at an average power
  - Continuous high performance usage without any idling can cause the IC temperature to rise
  - Since leakage has an exponential increase with die temperature, a positive feedback loop (**thermal runaway**) can occur that must be controlled by thermal throttling

Package Thermal Performance Ratings





case to ambient

$$\Theta_{CA} = \frac{T_C - T_A}{P_2}$$

junction to case

$$\Theta_{JC} = \frac{T_J - T_C}{P_2}$$

junction to board

$$\Theta_{JB} = \frac{T_J - T_C}{P_1}$$

board to ambient

$$\Theta_{BA} = \frac{T_B - T_A}{P_1}$$

assembly

junction to ambient

$$\Theta_{JA} = \frac{T_J - T_A}{P}$$

$$\Theta_{JA} = \frac{(\Theta_{JB} + \Theta_{BA})(\Theta_{JC} + \Theta_{CA})}{\Theta_{JB} + \Theta_{BA} + \Theta_{JC} + \Theta_{CA}}$$

junction to top

$$\Psi_{JT} = \frac{T_J - T_C}{P}$$

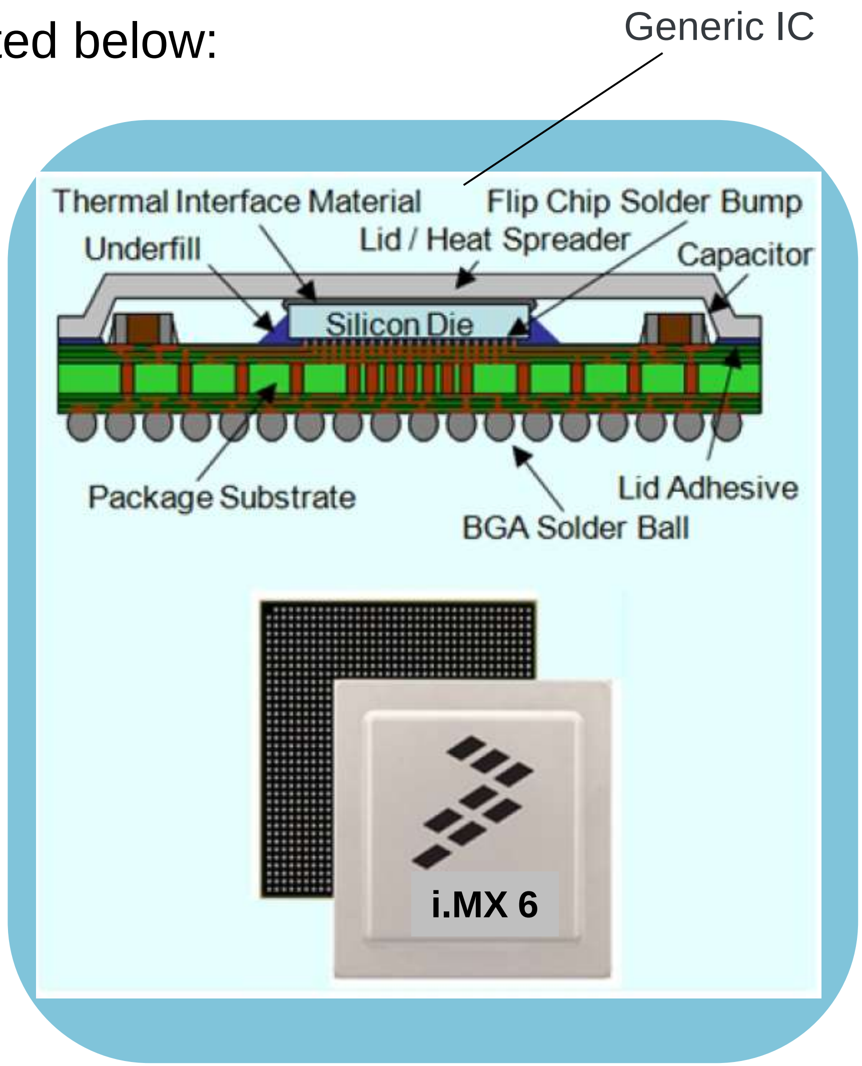
$$\Psi_{JT} = \frac{(\Theta_{JB} + \Theta_{BA})\Theta_{JC}}{\Theta_{JB} + \Theta_{BA} + \Theta_{JC} + \Theta_{CA}}$$

Thermal Management Techniques

Passive Thermal Management

Techniques that are typically used are listed below:

- **Thermal Interface Materials**
  - Thermal Gap Fillers
- **Heat Spreaders**
  - Copper
  - Graphite
  - Aluminum
- **Heat Shields**
  - Aluminum backing plates
- **Board Design**
  - Layout
  - Metallization

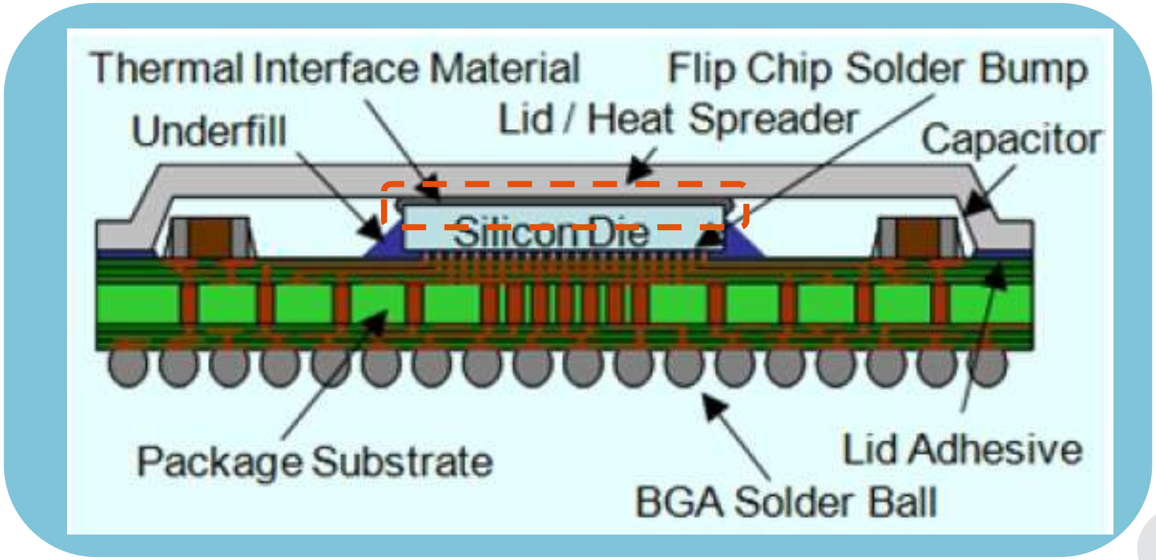


Thermal Management Techniques:
Thermal Interface Material (TIM)

- Consider the thermal interface material (TIM) options **early in your design**, as this choice depends on cost targets, package application, manufacturing dynamics, and the performance requirements of the thermal solution

- By selecting the appropriate TIM, you can help **reduce the size/cost of other thermal solutions.** In the long-term, the appropriate TIM can **mitigate** the potential **cost** of changing **heat sinks** or **redesigning** a **chassis**

- Because lidless flip-chip packages have a **small surface area compared** with that of lidded or molded packages, the combination of an **adhesive TIM and heat sink is not recommended**



Thermal Management Techniques:
Thermal Interface Material (TIM)

- Freescale can not recommend TIM materials external to the part. This will depend on the customer's system thermal constraints and reliability requirements

- The following TIMs are typically used for lidless packages:
  - Phase Change TIM (PCTIM)
  - Cross-linked thermal gels
  - Thermal pads and tapes
  - Thermal grease

- **High-performance TIMs** like greases, compounds and gels, are **expensive** and may be more difficult to handle during installation

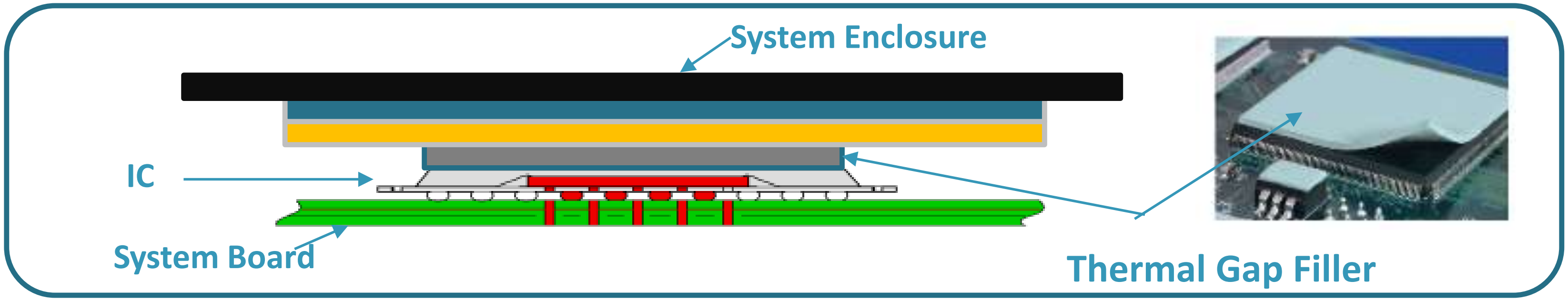
- **Thermal pads** and tape offer an easier heat-sink attachment process, but with **reduced performance**

- **Phase-change** TIMs - Thermal phase change materials are solid pads at room temperature that melt at operating temperatures to produce low thermal resistance – they provide a **compromise** solution, which offers ease-of-assembly with good performance

As a general rule FSL does not provide recommendations of which exact material or vendor to use

Thermal Management Techniques:
Thermal Gap Filler

- A Gap filler is a TIM typically placed between the **top/bottom of the high power component** and **case**, **removing air gap** around the package, which is a **thermal barrier** due to very minimal air circulation as well as for better **shock resistance**.



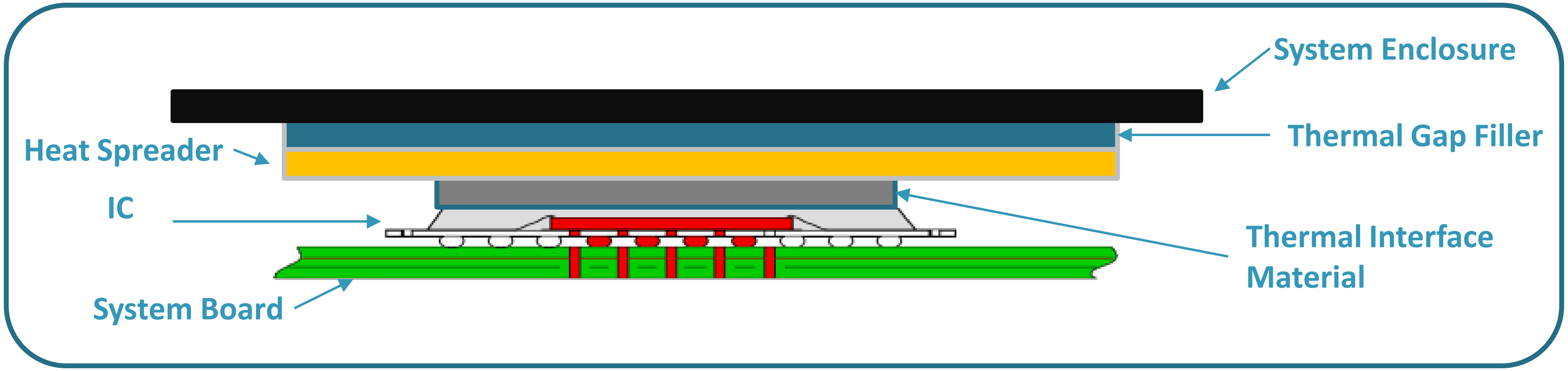
- The use of a Gap filler with a higher thermal conductivity will result in better thermal dissipation capability. It helps in reducing Tj, however, if **used in isolation** the direct heat path from the package to the system enclosure results in the skin temperature rise, **generating hot spots**.

- Complete elimination of the air gap inside the system using a gap filler material has significant thermal benefits however the **thermal benefit from the use of gap filler** is significantly limited by the **heat spreading capability of the system enclosure**

- Proper attachment of the gap filler is important as well the correct thermal contact adhesives**. Improper application** can severely **reduce the thermal conductivity** of the filler.

Thermal Management Techniques:
Heat Spreaders

- A thermally conductive heat spreader can be placed on the high power components and this heat spreader can enable spreading and evening out of the hot spots and could be designed to make direct contact with the system enclosure



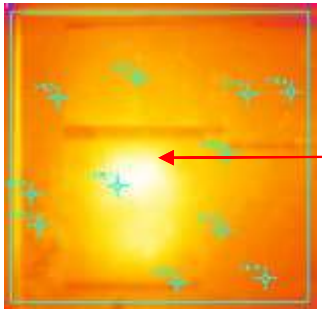
- This design concept significantly increased the power dissipation capability, by reducing overall system thermal resistance.

- The type of heat spreader to be used is dependent on the customers' application available enclosure space and budget considerations

Thermal Management Techniques

Copper Heat Spreaders

- **Copper Advantages**
  - Copper has been used extensively in many thermal applications including heat spreaders
  - The **excellent thermal conductivity** of copper(400W/mK) in **all directions** (x,y & z) makes it an effective heat spreader
  - Simulations with the Copper heat spreader always showed **better heat dissipation** capability when comparing a model without the heat spreader, again due to better heat dissipation capability
- **Copper Limitations**
  - Although copper does have good thermal conductivity the **increasing cost of copper** has made it more inhibitive for mass deployment. Hence the area of the copper could be limited to the area on the enclosure to reduce cost or by using cheaper copper tape. Also can oxidize and tarnish.
  - The thermal conductivity of copper(400W/K) in all directions can be problematic since a **hot spot could just translate vertically** to a different location, possibly closer to the enclosure hence creating a hot spot on the case. Copper hence is **not best suited for touch temperature reduction** applications.



Hot Spot on a high power component can easily appear as a similar hot spot on a copper spreader if not sized correctly

Thermal Management Techniques

Graphite Heat Spreaders

- In applications heat spreader are typically used: to **spread heat** (in contact with the heat source) and to **shield heat** (usually a gap between the heat source and housing/user).
- Graphite matches the thermal performance of copper in two directions(x, y), at a lower weight and cost. The **high in-plane (basal)** thermal conductivity results in spreading and evening out of the hot spots
- Due its **low cost** the **area** that the graphite heat spreader covers, could be potentially **larger** covering all heat generating components
- Some of the key product applications are listed below:
  - **Cooling** of sensitive components
  - **Elimination of fans** & active cooling
  - **Touch temperature** reduction
  - **Thermal shielding** of Li-Ion batteries
  - Cooling of LED and power components
    - Mitigation of AMOLED and LCD display hot spots
    - Improves brightness uniformity
    - Decreases image sticking and burn-in
    - Minimizes warping of back light unit and films
    - Reduces chassis distortion
    - Reduces the severity of stress-induced birefringence

Thermal Management Techniques

Factor Thermals in Early in the Board Design Phase

PCBs should be designed with the thermal requirements available and **factored in up front**. The sooner the better !

Thermal issues with the PCB design are determined in the **component selection and layout phases** (only remedial actions are possible after)

Typically more than **80% of the heat** generated by a high power component is **dissipated** through the **system board**, when no thermal solution is implemented on the top of the package. This indicates that the **primary heat path is from junction to the board**

Under-fill

- It is common industrial practice doing **under-fill for the key components** in to improve the mechanical strength.
- Further thermal improvement can be achieved using the **board level under-fill** by **reducing junction-to board** thermal resistance

As a general rule FSL does not provide recommendations of which exact material or vendor to use

More Thermal Attach Points

- Special care should also be taken in design PCB thermal attach points which allow heat from the high power component or attached heat spreader to be effectively dissipated.
- EMI shields are often used for thermal attach points to the PCB

Under-Fill Techniques

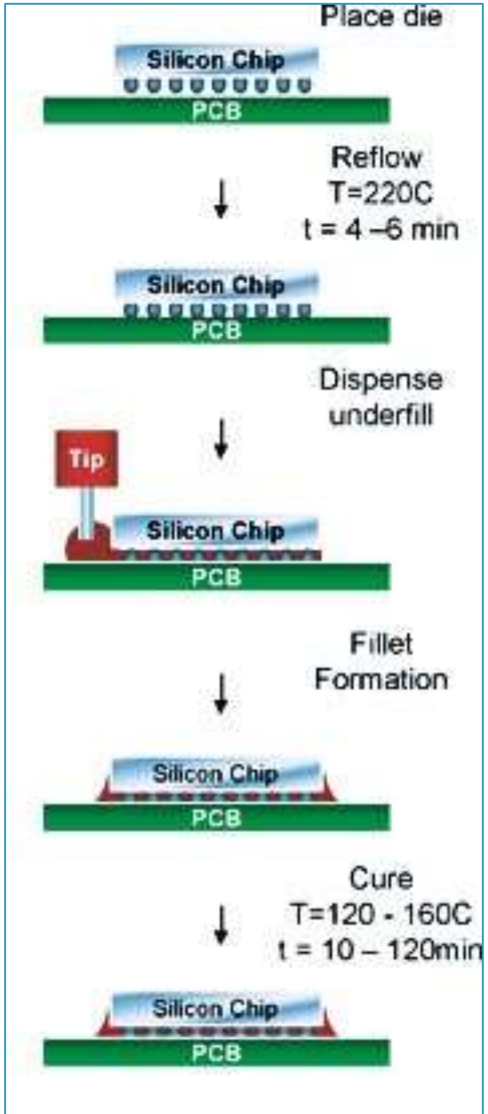


Figure 1: Capillary Underfill

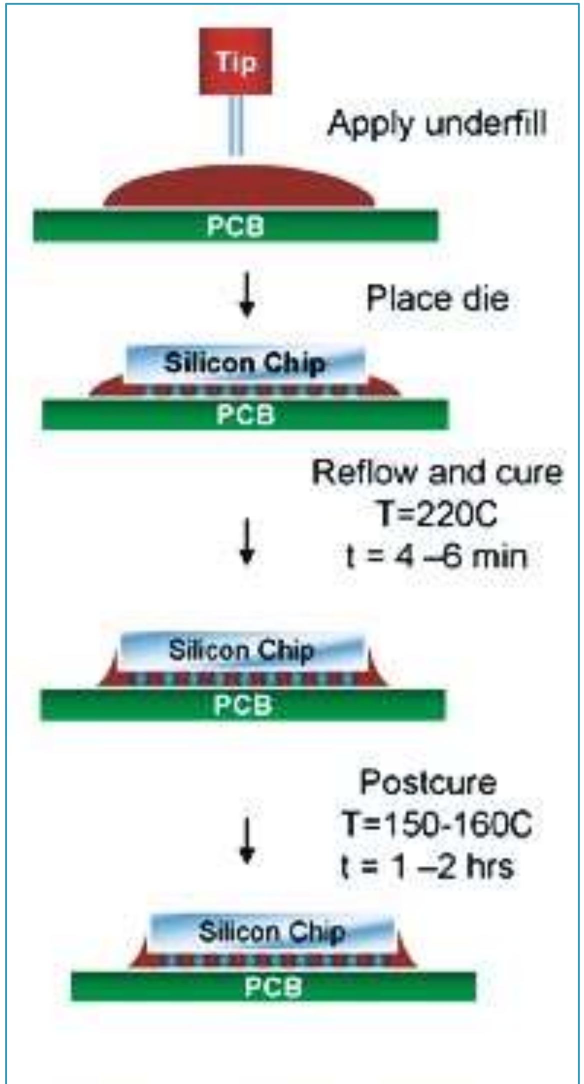


Figure 2: No Flow Underfill

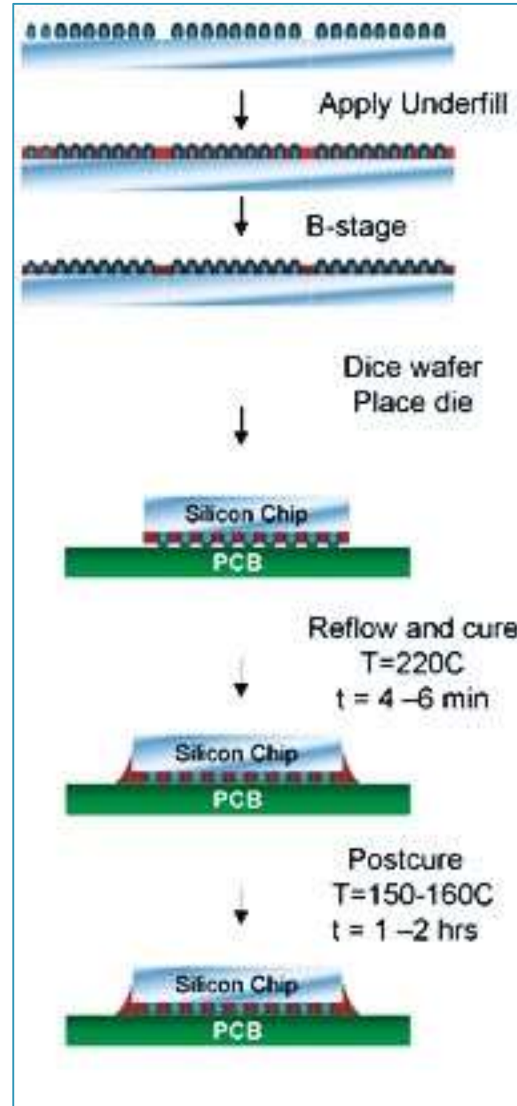


Figure 3: Wafer Level Underfill

Thermal Management Techniques

Board Design

Increased PCB Metallization

- Increase the heat dissipation (reducing thermal resistance) can also be achieved by increasing the metallization in the system board.
- PCBs are made up of copper and dielectric material, with the copper being orders of magnitude more thermally conductive
- It's important to get an estimate of **how many signal, and power or ground layers. JEDEC** data sheets show the effect of **4-layer vs. single layer boards**

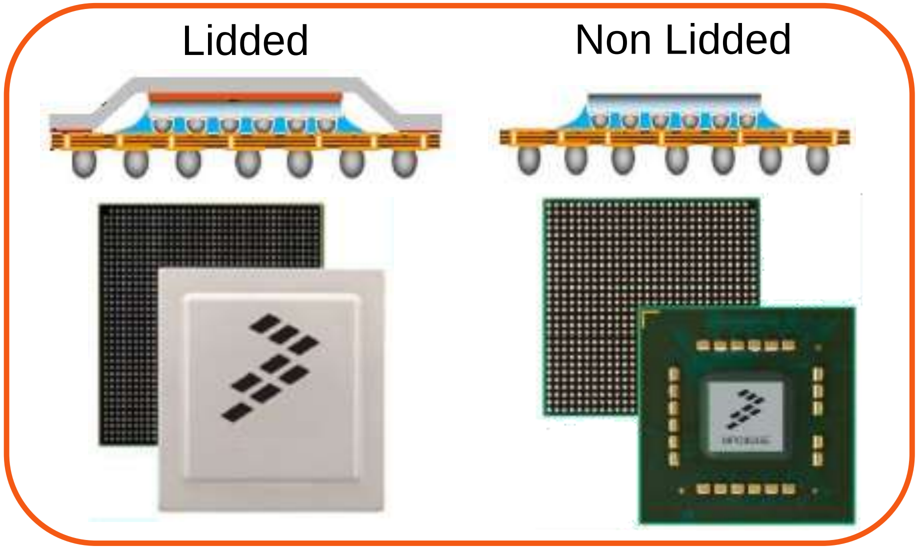
PCB Stack Up				
Layer	Type	Thickness (mil)		
	Top side solder mask		0.50	mils
L1	TOP	copper+plating	1.78	mils
		dielectric thickness	3.50	mils
L2	GND Plane 1	copper	1.30	mils
		dielectric thickness	6.00	mils
L3	Internal 1	copper	1.30	mils
		dielectric thickness	6.50	mils
L4	Power 1	copper	1.30	mils
		dielectric thickness	18.00	mils
L5	Power 4	copper	1.30	mils
		dielectric thickness	6.50	mils
L6	Internal 2	copper	1.30	mils
		dielectric thickness	6.00	mils
L7	GND Plane 2	copper	1.30	mils
		dielectric thickness	3.50	mils
L8	?	copper	1.30	mils
L9	?	copper	1.30	mils
L10	Bottom	copper+plating	1.78	mils

- Traces on the surface of the PCB **locally spread heat away** from the package solder balls, whereas **buried power** and ground planes **increase the in-plane** thermal conductivity
- From a thermal perspective, the contribution of these copper-containing layers on the **performance of the PCB is influenced by their thickness**. The most common thicknesses are 0.5Oz or **1.0Oz copper**.
- Placement of these thicker copper planes to help manage the Chip thermal dissipation is important and often thermal vias **below the pad** are used to conduct heat down to a buried copper ground plane.
- Metal core PCB (MCPCB), provides heat spreading on either the top or back of the PCB or memory module however needs to be designed in from the outset

Beating the Heat – i.MX 6 Series

Packaging – 21x21 FCBGA Package

- **Lidded** – Auto and Industrial
  - Contains a metal lid covering the processor
  - More robust for industrial or automotive environments
- **Non-Lidded** – Consumer
  - Exposes the back side of the die (flipchip)
  - Lower Z-height for space constrained devices
  - Easier to attach custom heat spreaders
  - Three types of Qual for i.MX 6Series
- **Consumer**: Highest Frequency
  - Automotive: Maximum environmental support
  - Industrial: Longest duration (“always on”)
- **Only Non-Lidded packaging will be available in Consumer Temp**



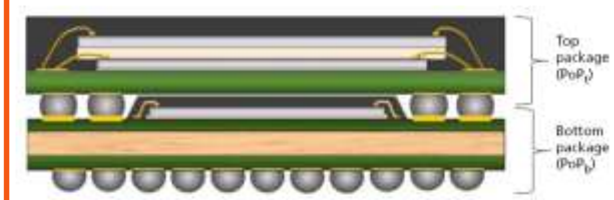
Type	Characteristics
Consumer	• -20 to 105Deg Tj • 5 year life cycle @ 50% duty cycle • Max of 1.2Ghz CPU speed
Automotive	• -40 to 125Deg Tj • 10 year life cycle @ 10% duty cycle • Max of 1Ghz CPU speed
Industrial	• -40 to 105Deg Tj • 10 year life cycle @ 100% duty cycle • Max of 800Mhz CPU speed

AN4871 FC-BGA Manufacturing App note (Lidded & non-Lidded) Available on Freescale.com

Packaging – PoP FCPBGA

- The i.MX 6Dual/6Quad processor is now available in a Package-on-package (PoP) packaging technology.
- PoP semiconductor packaging technology requires unique considerations in the up-front board design.
- Since the PoP system locates the heat-generating applications processor in close proximity to the heat-generating memory. It is important to consider the implications of this configuration.
- In a typical BGA, heat is dissipated through the PCB and the surrounding air. In a PoP system, the two packages are in close proximity to each other, resulting in a small temperature gradient between them.
- In this package the generated heat must sink through the PCB and ambient air (or case, if a thermal interface is placed between the memory and the case)
- The usage model of the particular system ultimately determines the temperature-performance capability required of the memory solution.
- LPDDR2 Speed is limited to 400 MHz and the ARM Processor also limited to 800 MHz due to Memory thermal constraints

LPDDR2 Memory



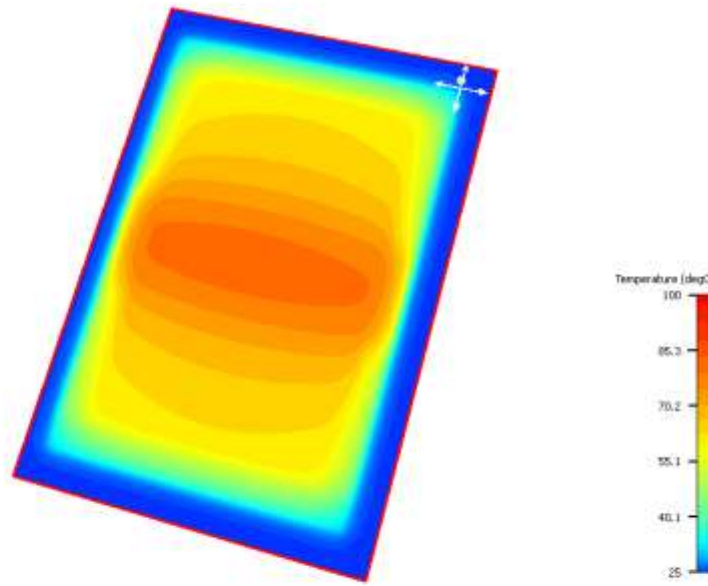
FCPBGA PoP 12 x 12 mm, 0.4 mm pitch

Placement of thicker copper planes to help manage the Chip thermal dissipation is very important for PoP PCB designs.

Thermal Simulations

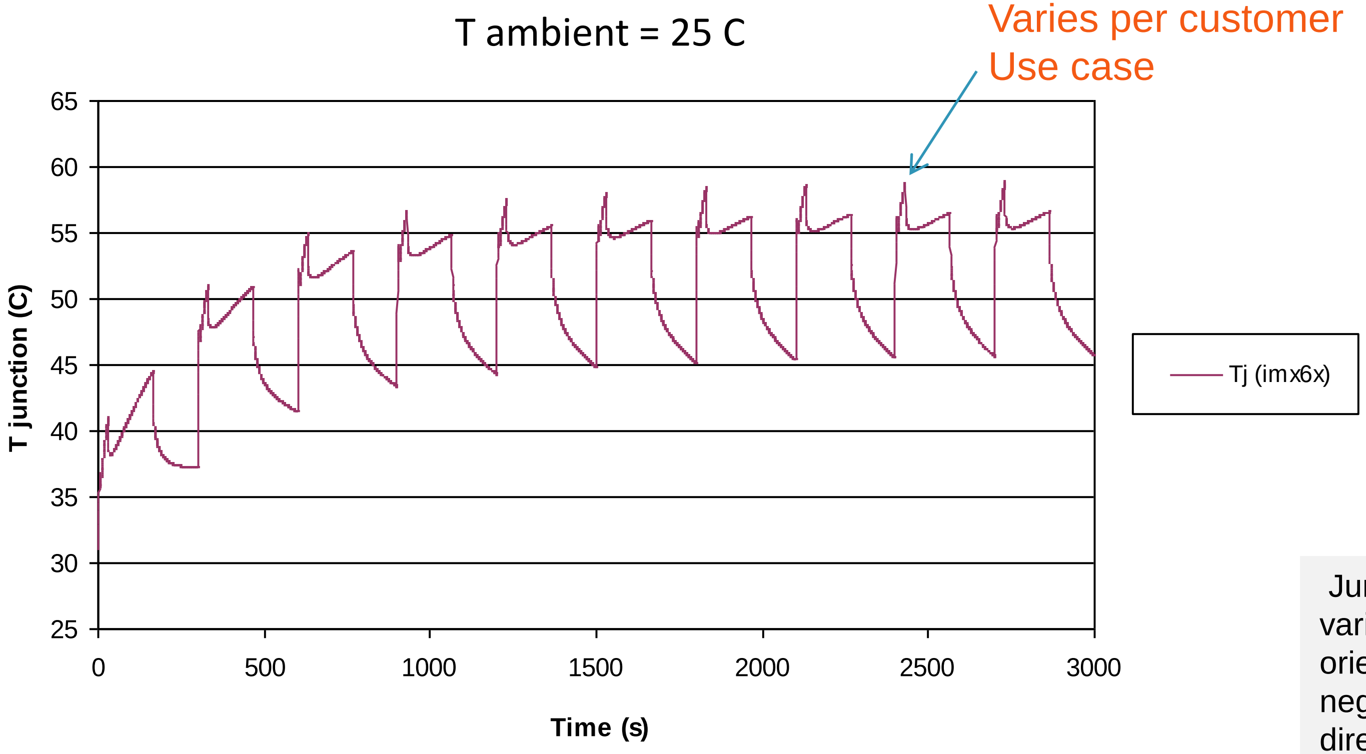
The intent of the simulations are to illustrate some of the benefits of thermal management techniques and which work better (best bang for your buck)
A form-factor specific product case model can simulate temperature at the points of interest versus time as a function of SoC power dissipation.

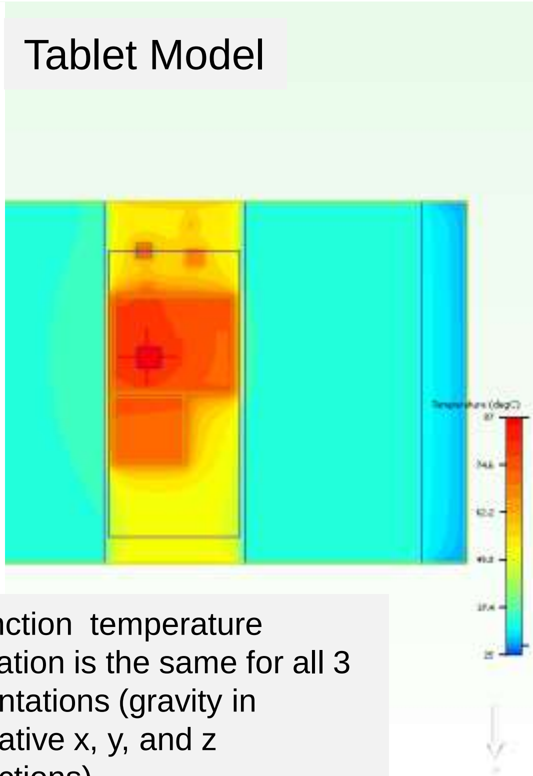
- Obviously this particular tablet simulation does not fit all customer applications, it does demonstrate the benefits of various thermal solutions and guidelines on when such solutions are required
- Freescale recommends that customers should perform system level simulations to gain more accurate thermal results for their specific application
- Freescale can provide Mentor FloTHERM thermal models for customers with an NDA on request



i.MX 6 Series Power Profile

Junction Temperature Variation with Time





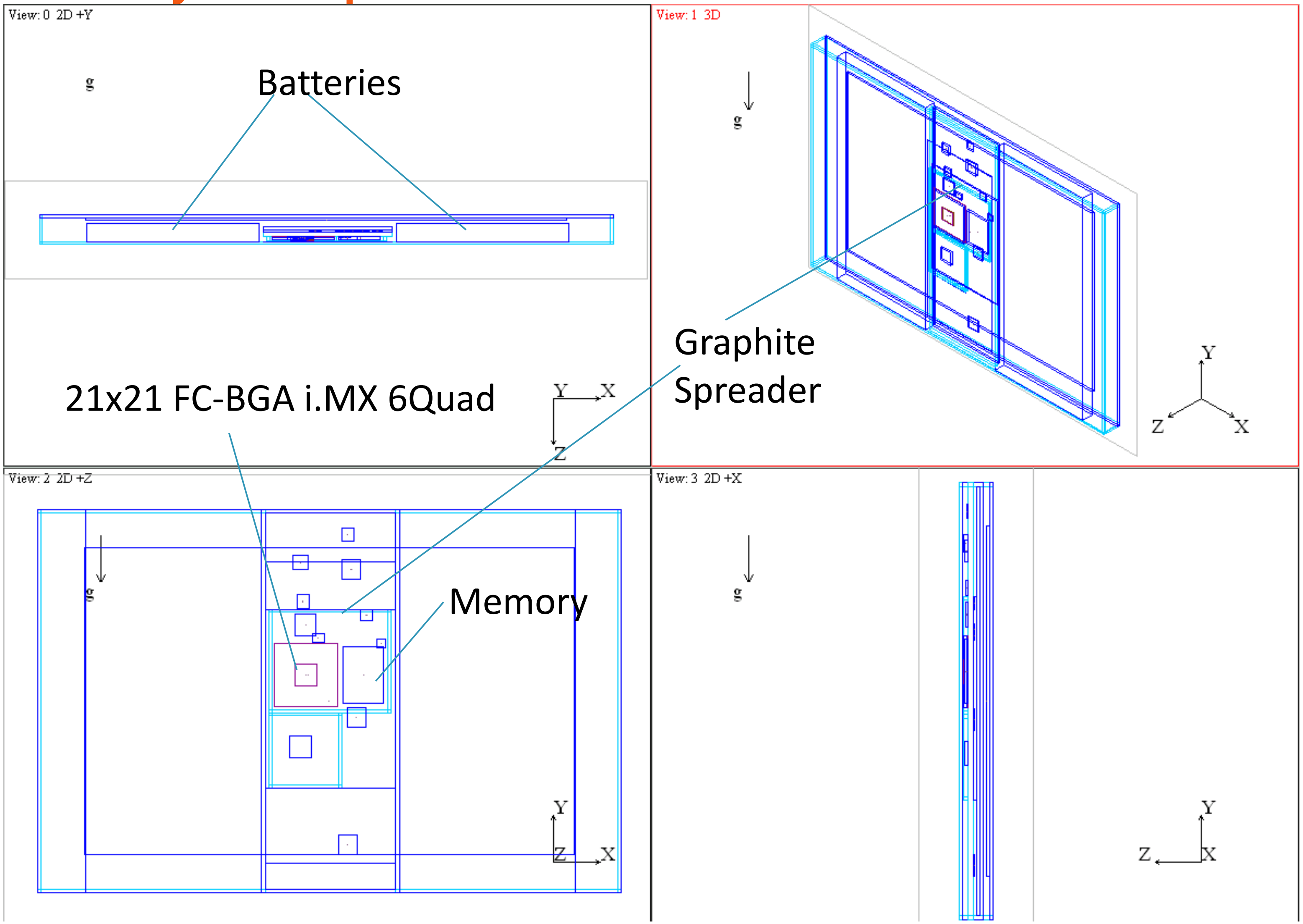
Junction temperature variation is the same for all 3 orientations (gravity in negative x, y, and z directions)

Example Duty cycle considered:

- 5s at max power, 25s at of 80% of max power, 135 s at max power/2 and 135 s at low power
- System eventually reaches a steady state over time

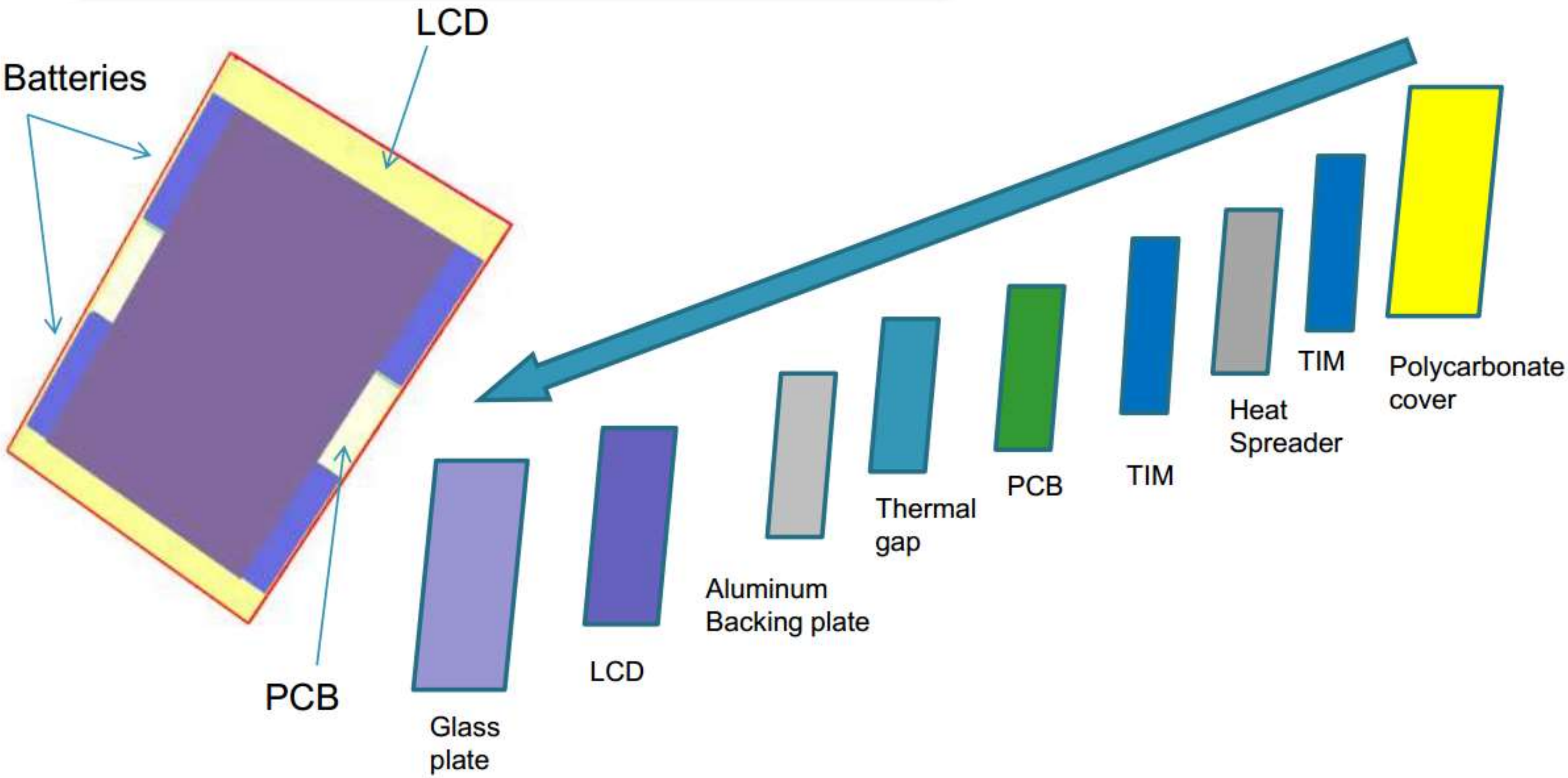
Thermal Simulations

Geometry of Simplified Thermal Model



System Components

Tablet model showing various system components that were included in the thermal analysis

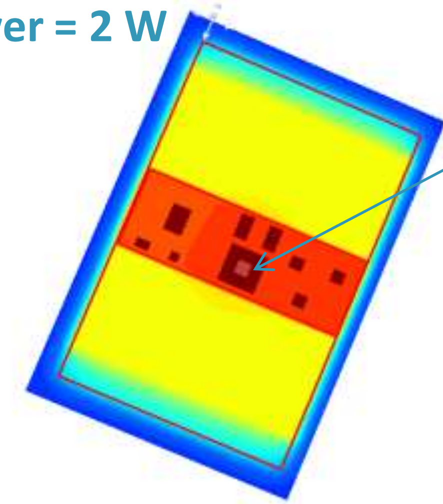


Thermal Simulation Results

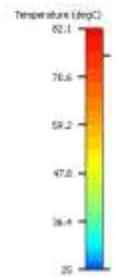
Simulated i.MX 6Dual/6Quad Power

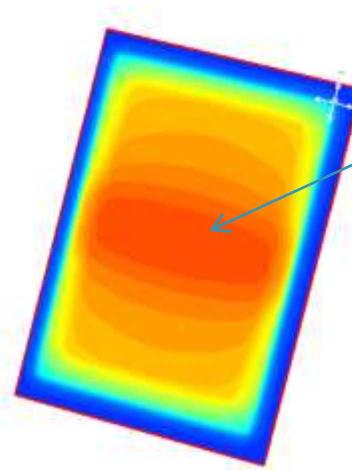
Note : Colors denote the relative temperature and not absolute

Power = 2 W

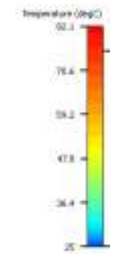


i.MX 6Dual/6Quad reaches a temperature of 80 ˚ C

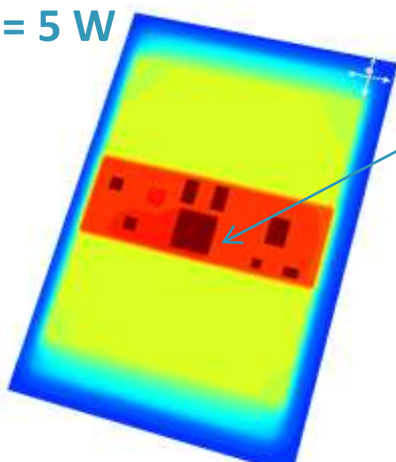




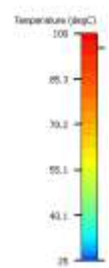
LCD Temp 70 ˚ C



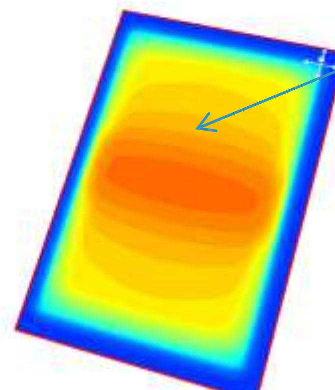
Power = 5 W

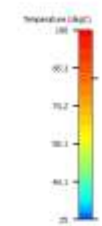


i.MX 6Dual/6Quad reaches a temperature of 100 ˚ C



LCD Temp 80 ˚ C





Simulations can also show Thermal Bottlenecks – culprit locations that cause that temperature rise Due to the difficulty the heat experiences as it flows

Thermal Simulation Results

Heat Spreader Advantages

The goal of these simulations was to determine what is the **maximum processor power** to maintain **85Deg C within the enclosure** and <=105Deg C Tj on the die, with different thermal management techniques applied. Various models were created that varied the package lid options as well as the heat spreader to be used in the tablet.

i.MX 6Dual/6Quad Package Configuration	Heat Spreader Option (Assumes entire PCB dimension coverage)	Max Power (W) (To maintain 85Deg C within the enclosure and <=105Deg Tj on die)
Un-lidded	None	2.3
Lidded	None	3.5
Un-lidded	Graphite (eGraph SS500 0.6mm)	5.6
Un-lidded	Copper (0.2mm)	4.6
Un-lidded	Copper (0.6mm)	5.7

Same Max (W) with lower cost Graphite

The results show that using a heat spreader increases the thermal design power and hence allows running higher power consuming applications within the same thermal envelope

Thermal Simulation Results

Heat Spreader Dimensions

The goal of these simulations was to determine what is the **maximum processor power** with different **heat spreader dimensions** to be used in the tablet. The table below shows results of different heat spreaders with varying dimensions including the **spreader thickness**

Heat Spreader Options	Max Power (W) (To maintain 85Deg C within the enclosure and <=105Deg Tj on die)		
	30% PCB Coverage Spreader dimensions: 43x37mm	**55% PCB Coverage** Spreader dimensions: 43x71mm	**100% PCB Coverage** Spreader dimensions: 43x127mm
Graphite (eGRAF SS600 Thickness: 0.127mm)	2.9	3.2	3.6
Graphite (eGRAF SS500 Thickness : 0.6mm)	3.8	4.4	5.2
Graphite (eGRAF SS400 Thickness : 0.6mm)	3.8	4.4	5.1
Copper (K= 389 Thickness : 0.6mm)	3.9	4.5	5.7
Copper (K= 389 Thickness : 0.2mm)	2.9	3.7	4.6

Almost same Max (W) with lower cost Graphite vs. Copper

The results show that **increasing the heat spreader coverage and thickness increases the thermal design power** and hence allows running higher power consuming applications within the same thermal envelope

Thermal Simulation Results

Thermal Interface Material Selection

The goal of these simulations was to determine what is the maximum processor power with different thermal interface materials to be used in the tablet. The table below shows results of different heat spreaders with varying dimensions including the spreader thickness

Thermal Interface Material (TIM)	Max Power (W) (To maintain 85Deg C within the enclosure and <=105Deg Tj on die)		
	30% PCB Coverage Spreader dimensions: 43x37mm	**55% PCB Coverage** Spreader dimensions: 43x71mm	**100% PCB Coverage** Spreader dimensions: 43x127mm
TIM K = 2 W/m K (eGRAF SS500 Thickness : 0.6mm)	3.8	4.4	5.2
TIM K = 2 W/m K (eGRAF SS400 Thickness : 0.6mm)	3.8	4.4	5.1
TIM K = 17 W/m K (eGRAF SS500 Thickness : 0.6mm)	4.0	4.7	5.6
TIM K = 17 W/m K (eGRAF SS400 Thickness : 0.6mm)	4.0	4.7	5.6

The results show that increasing the thermal conductivity of the TIM does marginally increase the thermal design power which is aided by increased thermal conductivity and dimensions of the heat spreader

Managing the Heat – The SW Approach

Software Thermal Management Techniques

Software Leverages Hardware

- The i.MX 6 series and incorporates several low-power design techniques, to meet requirements of low-power design, while sustaining high performance operation
- Even with these techniques in place managing the heat dissipated needs to be considered depending on application use case.
- **Heat is a function of what you are doing with the processor + memory**
  - Only running Video (~2W)
  - Only running 3D GPU (~1.7W)
  - Video + 3D + 3 ARM Cortex A9s at high speed (4.6W)
  - Quad ARM Cortex A9s at high speed only (2.3W)
- Leveraging features and power saving strategies implemented at the device and micro architectural level can have a significant impact on thermal demand.
- Software can take advantage of various hardware features that allow power optimization thereby managing heat dynamically and reducing the need for heat spreaders, heat sinks and metal enclosures.

Software Thermal Management Techniques

Technique	HW Support	BSP Support	Comments
Dynamic Voltage and Frequency Scaling	Yes	✓	Pre defined set points defined for frequency and Bus Scaling
Temperature Monitor	Yes	✓	Define thresholds based on temp sensor readings
Temperature Aware DVFS	Yes	✓	Throttle CPU based on temp sensor readings
Temperature Aware CPU Pool Management	Yes	No	Thermal framework does NOT have CPU pool management support integrated yet.
Clock & Power Gating	Yes	✓	Gate clocks and power domains when not in use
DDR (MMDC) and I/O Power Optimizations	Yes	✓	Optimized ODT settings, Auto power down modes and support for frequency scaling
GPU Power Management	Yes	✓	Reduce Core clock frequency, reducing shader clocks
LDO Full Bypass	Yes	✓	Bypass LDO and use external PMIC.

SW Thermal Management

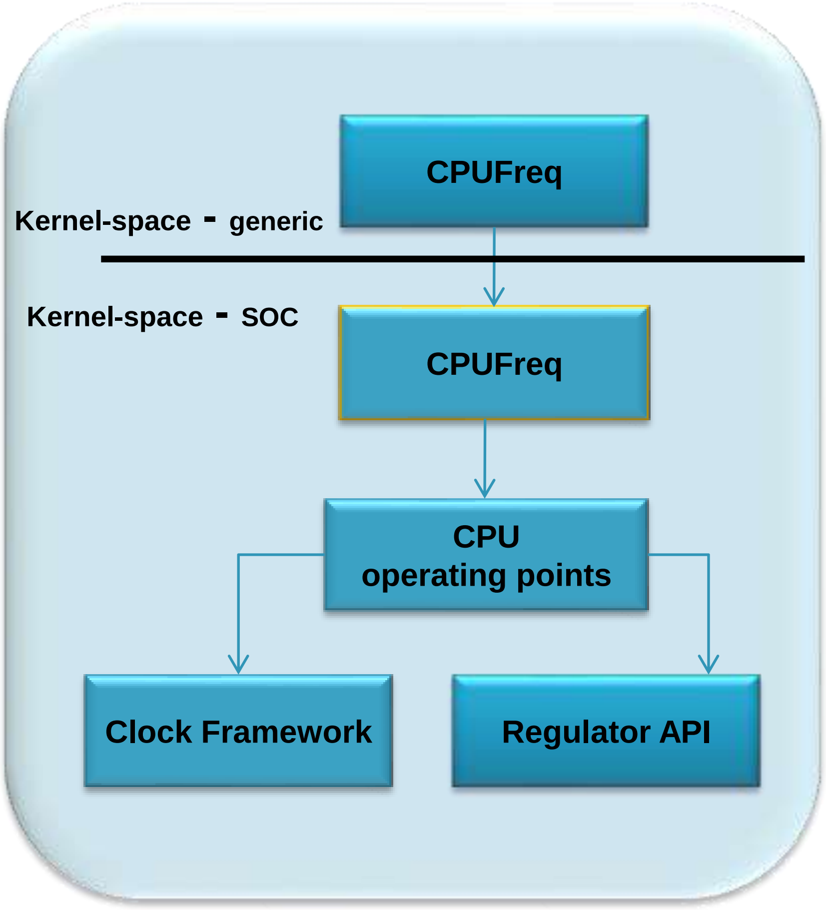
Memory or Processing Bounded

- For high performance multimedia use cases such as 3D playback, thermal and power management of the GPU3D core become essential
- Such use cases not only utilize the GPU but are also very DDR memory intensive hence increasing the total system power (DDR + IO)
- It is important to determine, if the system is “memory” bounded or “processing” bounded in target use cases that utilize multiple high performance IP . This is also required for different stages of execution within the use case.
  - Use “top” to determine CPU utilizations and “MMDC2” unit test to determine DDR bus utilization
- This determination assists in identifying where the power and heat is being generated hence allows users to throttle the correct master
- In theory, **run fast and idle is the best strategy** as **graphics** workloads can be variably sensitive to render latency
- The DVFS strategy for CPU and GPU/VPU/IPU should be **“run fast” if “processing” bounded** case and **frequency downscaling** for processing modules in **“memory” bounded** cases
- DVFS strategies are concepts that are realized by the use of governors which control what frequency the CPU is running – see */rpm/Build/Linux_xx/Documentation/cpu-freq* for more information

CPU Freq Mechanism

(Included in latest BSP GA release)

- To use DVFS, pre defined policies are employed that govern when to switch between set points in the application.
- In the Linux BSP release, there is operating system support for managing DVFS via CPUFreq utilities, and is comprised of a driver and one or more governors.
- Example governors exist for
  - *performance*
  - *power*
  - *userspace*
  - *ondemand*
- The *userspace* governor allows applications to control when, specifically, to move between set points.
- The *ondemand* governor scales up when there is high CPU utilization and down when there is low CPU utilization.



CPU Pool Management

- For multi-core systems such as the i.MX 6Dual/6Quad processors, it is possible to add and remove available cores from the CPU pool
- This CPU pool management was originally designed to allow hot-swapping of CPU boards on multi-core systems **without taking** the entire system offline
- In embedded systems, cores can be removed from the available CPU pool during periods of low CPU loading or when managing the temperature. The cores removed from the CPU pool can remain in a low-power state
- As defined thermal thresholds are reached the thermal driver will remove one of the secondary cores
- If the system temperature keeps increasing, the thermal driver will continue to remove additional cores until **only the primary CPU0 core is left running**
- When the **temperature falls back** to the safe range, all additional cores that were removed will be **bought back online**
- The Linux BSP mapping of this feature is referred to *CPU Hotplug* however is not currently enabled in our BSP GA release.

BUS Frequency Scaling
(Included in latest BSP GA Release)

- DVFS for ARM and scaling the frequencies of the DDR, AXI, AHB, and IPG bus clocks can significantly **reduce the power consumption**
- However, due to the **reduced operation frequency**, the accesses to the DDR take longer, which **increases the power consumption**
- This **tradeoff** needs to be taken into account for each mode, to quantify the overall affect on system power.
- Algorithms used to scale internal bus frequencies ideally should match the bus bandwidth required for the current use case. In the absence of bus monitors, it may be possible to scale bus frequencies based on the activity of bus masters
- It is also important to determine, if the system is "**memory" bounded** or "**processing" bounded** in target use cases and different stages of execution within the use case

DDR freq (MHz)	AXI (MHz)	AHB (MHz)	Power saved
528	264	132	Full Speed
400	200	133	Mid speed
50 (DLL off)	50	25	Audio bus mode
24 (DLL off)	24	24	Low bus mode

Clock Gating & Power Domain Control

(Included in the latest BSP GA Release)

Clock Gating

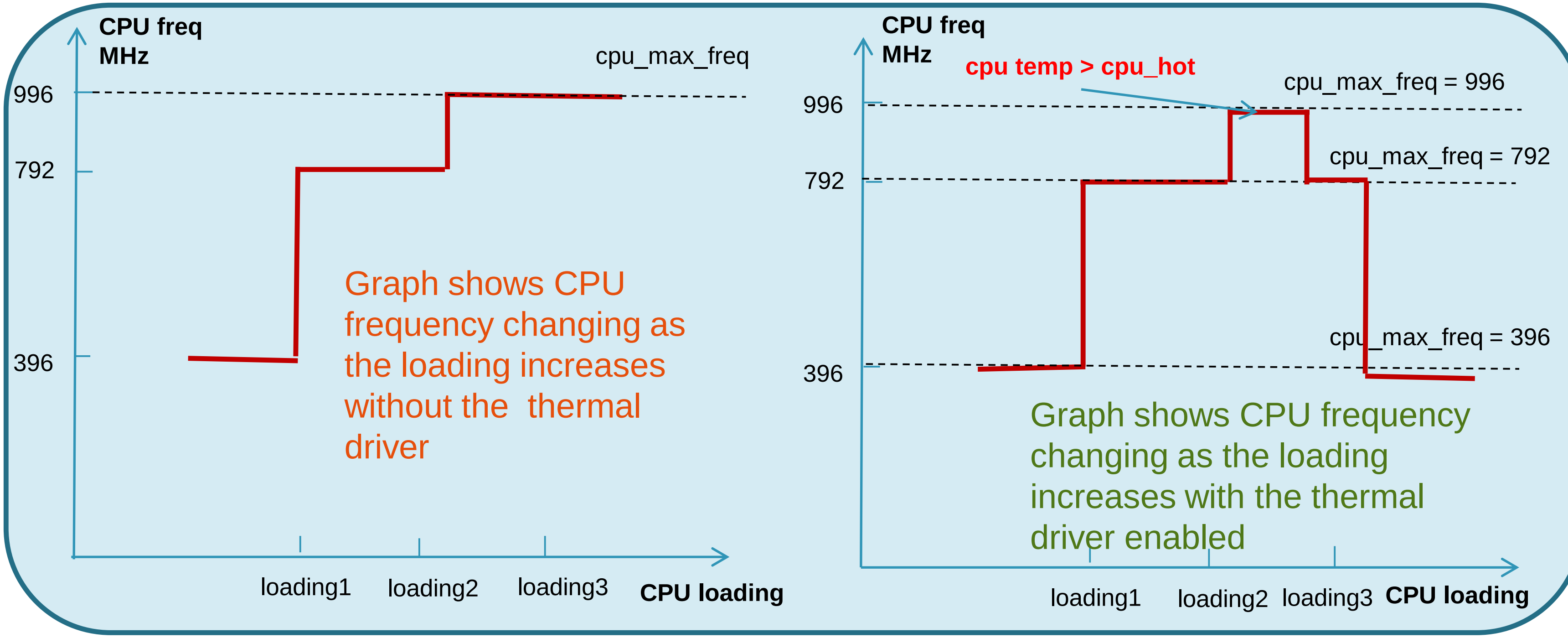
- Maintain clock parent/children dependency in clock tree, all drivers need to disable their clocks when they are not active
- The clock driver framework to auto disable all the clocks whose use count is 0. This ensures all unused clocks are disabled
- If aggressive clock gating is utilized (run-fast-and-stop), then Dynamic Frequency Scaling (DFS) offers little benefit and could actually increase power due to longer bus duty cycles

Power Gating

- Power gate unused domains under certain use cases, such as the PU domain when system is in low power audio mode and system idle mode
- The GPUs and VPU are part of the PU power domain, which can be powered off by power gating their corresponding LDO. The PU domain is managed by GPU/VPU drivers.
- The bus freq driver performs this when migrating into low power audio or system idle modes

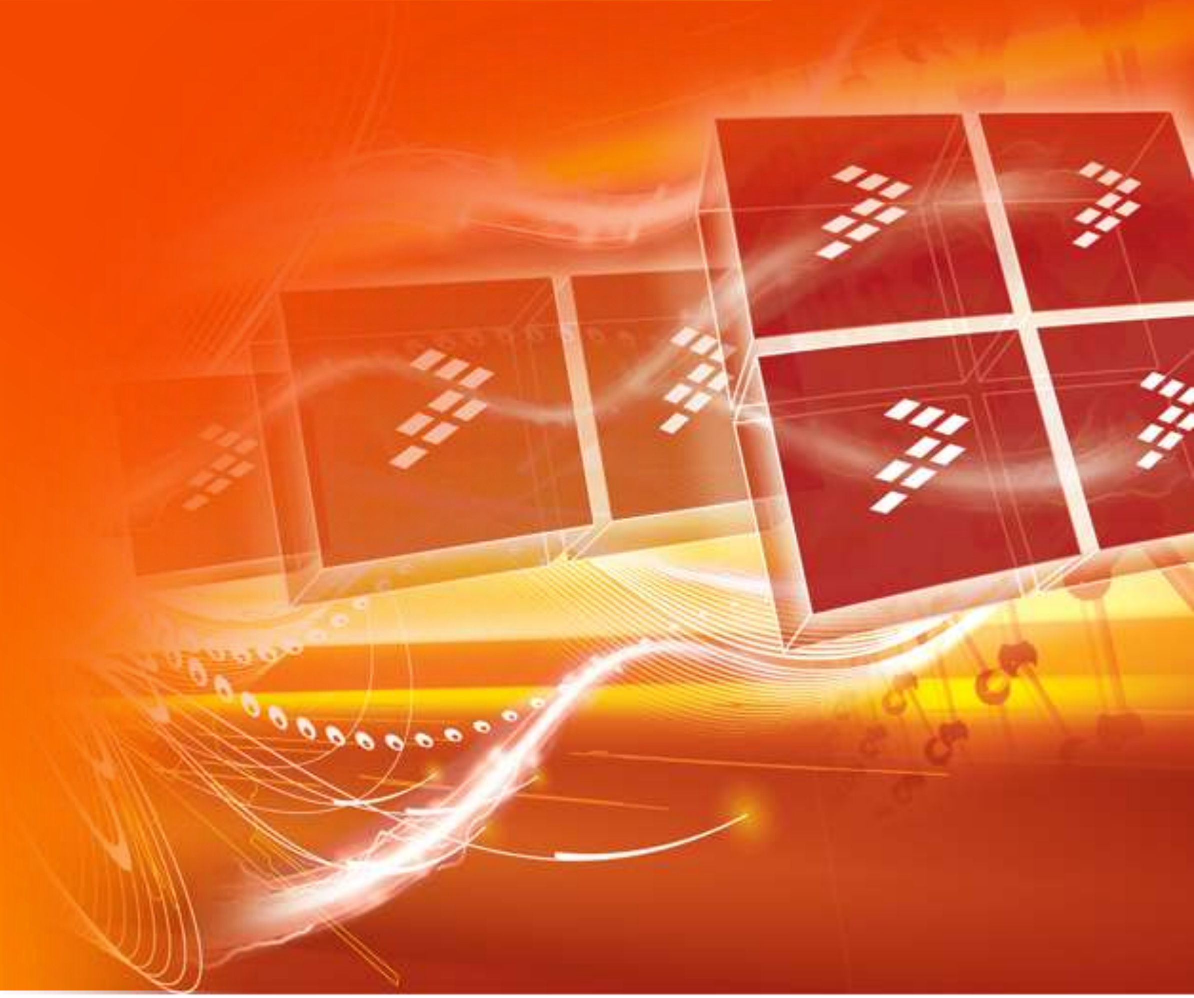
  (For a definition of these low power modes please refer to *AN4509 i.MX 6Dual/6Quad Power Consumption Measurement* available on the Freescale Extranet)
- The PU domain is automatically restored when the system exits from these two modes
- PHY's can consume considerable power if the circuits are left enabled and the recommendation is to place all unused PHY's to the lowest power state such as SATA, HDMI and PCIe

DFS Based on CPU Temperature



- As an example for a given CPU loading the *CPU freq* set point is 996MHz and the temperature exceeds the *cpu_hot* threshold. The CPU thermal driver will adjust the *CPU Freq* governor's cpu_max_freq to the next lower set point (792MHz). As a result, the CPU frequency is automatically lowered below the *cpu_max_freq*
- If the CPU temperature keeps increasing, the thermal driver will again automatically lower the *cpu_max_freq* to the next set point (396MHz)
- **The number of thresholds and respective actions for each, is completely defined in software**

Sum up the Heat – Conclusion



Conclusions

- **All current generation SOCs generate heat**
  - Exacerbated by complex use cases (3D, video, CPU)
- **Traditional methods of cooling include:**
  - Active heat management → cost prohibitive and lower battery life
  - Passive heat management → typically copper. Very cost prohibitive
  - Thermal Spreaders → typically Graphite.
- **Graphite heat spreaders are the recommended solution**
  - Excellent at transferring heat in X,Y plane vs. Z plane with copper
  - Easily cut into any shape needed
  - Easily attached to any part of the system
- **Board Design**
  - Factor thermals in early in your design process
  - Run thermal simulations to get a holistic system thermal design & identify possible thermal bottlenecks
  - Improve PCB thermal dissipation especially for PoP designs
- **Software Thermal Management Techniques**
  - Software should take advantage of i.MX6 hardware features that allow power optimization
  - Techniques employed should be chosen based on customer use case

Refer to the AN4579 i.MX 6 Series Thermal Management Guidelines, Available on www.freescale.com/imx6series

Example

- From the i.MX6DQ datasheet you have:
  - θ_{JA} = 24 and θ_{JC} = 1 for a device with a metal lid.
    - $\theta_{JA} = \theta_{JC} + \theta_{CA}$ $24 = 1 + \theta_{CA}$ therefore $\theta_{CA} = 23$ (°C/W)
  - This shows heat flows easily from the die to the case, but it much harder to move the heat from case to ambient air.
- Given 1W of power used by the i.MX6DQ then
  - $T_J = T_A + (R_{\theta JA} \times P_D)$
    - $T_J = T_A + (24°C/W \times 1W)$ $T_J = T_A + 24°C$
    - Thus the die junction will be 24°C above a **"*perfect*"** ambient temperature above the package.
    - With 50°C forced air on the package, the junction would be ~74°C
  - $T_J = T_C + (R_{\theta JC} \times P_D)$
    - $T_J = T_C + (1°C/W \times 1W)$ $T_J = T_C + 1°C$
    - Thus the die junction will be 1°C above the case temperature for that specific case measurement. With a cold plate attached the package temperature at 50°C then the junction would be ~51°C
- You can see by both examples that if the Ambient or Case temperatures are allowed to rise, then the Junction temperature will rise accordingly.

Resources

Application Notes

- AN4579, i.MX 6 Series Thermal Management Guidelines
- AN4871, FC-BGA Manufacturing (Lidded & non-Lidded)
- AN4724, i.MX 6Dual/6Quad Product Usage Lifetime Estimates
- AN4509, i.MX 6Dual/6Quad Power Consumption Measurement

HW User Guide

- IMX6DQ6SDLHDG, Hardware Development Guide for i.MX 6Quad, 6Dual, 6DualLite, 6Solo Families of Applications Processors

Resources

The Thermal Checklist

- ✓ Determine the TDP – Thermal Design Power
- ✓ Determine the Activity Profile – Customer use case dependent
- ✓ Determine the form factor constraints – Convection, x, y, and z limits
- ✓ Determine the environmental operating conditions – what is T_A
- ✓ Determine the Tj for the device customer plans to use – Auto, Consumer, Package
- ✓ Factor in Board Design considerations – Layers, metallization
- ✓ Run thermal simulations to determine the best thermal management approach
- ✓ Investigate adding heat spreading techniques to alleviate bottlenecks
- ✓ Determine the SW Power Management techniques that can be enabled
- ✓ Ensure power is minimized in customer use case – less power - less heat
- ✓ Investigate Lower power memory, heat sinks or retarget use case – last resort as more expensive options

Resources

Freescale does not have any formal recommendations on the TIM however, some information the common TIM providers:

- **GrafTech International**:
  - http://graftechaet.com/eGRAF/eGRAF-Products/HITHERM-Thermal-Interface-Materials.aspx
- **Fujipoly**
  - http://www.fujipoly.com/usa/assets/files/2010_data_sheets/090930_Sarcon%20XR-m%20technical%20info.pdf
- **Shin-Etsu Thermal Greases**: http://www.silicone.jp/e/products/type/grease/index.shtml
- **Dow Corning**: http://www.dowcorning.com/content/publishedlit/11-1712-01.pdf
- **Chomerics**: http://www.chomerics.com/products/thermal/
- **Bergquist**: http://www.bergquistcompany.com/thermal_materials/index.htm
- **Laird**: http://www.lairdtech.com/Products/Thermal-Management-Solutions/Thermal-Interface Materials/#.VBnrgmBOVxI

Resources

Further information on PoP can be found in the following Micron Technical notes:

- “CSN34: Customer Service Note- Package-on-Package (PoP) User Guide”
- “ TN-10-08: LPDDR – Thermal Implications for Die Stacks”
- “TN-00-18: Up rating Semiconductors for High- Temperature Applications”

www.Freescale.com