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AM335x Thermal Considerations

AM335x Thermal Considerations

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Purpose[edit]

For most use cases, the AM335x is capable of dissipating its generated heat without the use of costly cooling systems, such as heat sinks or fans. However, during high performance use cases or in extreme environments, there is some concern of overheating. Depending on the system, this can be avoided by employing thermal management techniques in the system design.

Thermal management ensures that every silicon device on the board works within its allowable operating junction temperature. Failure to maintain a junction temperature within the range specified reduces operating lifetime, reliability, and performance—and may cause irreversible damage to the system. Therefore, the product design cycle should include thermal analysis to verify the operating junction temperature of the device is within functional limits. If the temperature is too high, component- or system-level thermal enhancements are required to dissipate the heat from the system.

The information contained within this document is intended to provide a basic understanding of the thermal requirements and thermal management necessary to ensure proper operation of the AM335x. Ultimately, it is the integrator, intermediate application developer, or the end user that must evaluate the system as it pertains to proper thermal management of Texas Instruments Sitara ARM Processors. Each end application is different regardless of whether or not the application is designed for the same market space. By following this document, users will be able to evaluate their systems to determine the need and level of thermal management required. This document analyzes the processor's thermal behavior, provides guidelines for an end system to aid in overcoming some of the existing challenges of producing a good thermal design and provides real power/temperature data measured with TI AM335x Evaluation Modules (EVMs).

Thermal Definitions[edit]

- Junction Temperature—the hottest temperature of the silicon chip inside the package. Refers to a P-N junction on the silicon.
- Case Temperature— the hottest temperature on the top of the device.
- Ambient Temperature—the temperature of the surrounding environment (outside the system enclosure).
- Board Temperature—the temperature of the PCB 1mm away from the processor package.
- Recommended Operating Temperature—the junction temperature at which the device operates continuously at the designated performance over the designed lifetime. The reliability of the device may be degraded if the device operates above this temperature. Some devices will not function electrically above this temperature.
- Absolute Maximum Operating Temperature—the maximum junction temperature at which the device functions electrically. The lifetime of the device is reduced if the device operates continually at this temperature.

- Absolute Maximum Junction Temperature—the temperature beyond which damage occurs to the device. The device may not function or meet expected performance at this temperature.

Thermal Metrics[edit]

Many thermal metrics exist for semiconductor and integrated circuit packages ranging from Theta-ja (θ_{ja}) to Psi-jt (ψ_{jt}). For the purposes of this document, only the metrics required for estimating junction temperature in the thermal chamber experiment are defined. $\Psi_{jt}$and Ψ_{jb} are the latest in thermal metrics used to more accurately estimate in-use junction temperatures from a measured case or board temperature (when a heat sink is not used). Their values are provided in the following table as a function of air flow and package type.
For more detailed information, please refer to Semiconductor and IC Package Thermal Metrics.

Thermal Resistance Characteristics (PBGA Package) [ZCE and ZCZ]

Name	**Description**	**Air Flow (m/s)**	**ZCE (°C/W)**	**ZCZ (°C/W)**
Ψ_{jt}	Junction-to-package top (2S2P)	0.0	0.4	0.3
		1.0	0.6	0.6
		2.0	0.7	0.7
		3.0	0.9	0.8
Ψ_{jb}	Junction-to-board (2S2P)	0.0	11.9	12.7
		1.0	11.7	12.3
		2.0	11.7	12.3
		3.0	11.6	12.2

Psi-jt[edit]

Psi-jt (Ψ_{jt}) is defined as the difference in junction temperature to case temperature at the top center of the package divided by the operating power. Ψ_{jt} is measured when the package is mounted only on the test PCB which allows power to partition itself into any path that it wants to take. The primary use of Ψ_{jt} is to calculate the junction temperature from a measured case temperature when a heat sink is not used. The following equation may be used for this calculation:

$T_{junction} = T_{case} + (Power * \Psi_{jt})$

In an attempt to provide the user community with a thermal metric to estimate in-use junction temperatures from measured case temperatures, Ψ_{jt}, has been adopted by the industry (EIA/JESD 51-2). The measurement procedure for Ψ_{jt} is summarized from EIA/JESD 51-2 below:

1. Mount a test package, usually containing a thermal test die, on a test board.
2. Glue a fine gauge thermocouple wire (36 gauge or smaller) to top center of package.
3. Dress the thermocouple wire along package to minimize heat sinking nature of thermocouple.
4. Dissipate power in test die.
5. Measure the test die junction temperature and thermocouple temperature.
6. Divide the thermal gradient between the junction temperature and surface temperature by the dissipated power.

Psi-jb[edit]

Psi-jb (Ψ_{jb}) is very similar to Ψ_{jt} in concept. It refers to the measurement of the difference between the junction temperature and the center package pin temperature, divided by the power dissipation of the device. Ψ_{jb} is the thermal characterization parameter used to more accurately estimate in-use junction temperatures from a measured board temperature.

$T_{junction} = T_{PCB} + (Power * \Psi_{jb})$

Measurement of Ψ_{jb} is defined by EIA/JESD 51-6. Care should be taken with the selection of the thermocouple type, gauge, and dressing of the thermocouple across the PCB in a similar fashion to the thermocouple intended to measure case temperature for Ψ_{jt} measurements. As with Ψ_{jt} measurements, an IR camera or fiber optic probe can be used to measure the board temperature. However, an IR thermal gun is not appropriate due to the small spot size to be imaged.

Thermal Considerations[edit]

Why should you care?[edit]

Short answer:
Too much heat can cause runtime failures, reduce component lifetimes, and permanently damage the system. In order to prevent this from happening, the heat energy generated by the system must be maintained with thermal management techniques.

Longer answer:
Heat is generated by all semiconductors while operating. Every time a transistor is switched on, current flows through its collector junction, consuming power and dissipating heat into the surrounding environment. This amount of heat is a function of power consumed and the thermal resistance of the

device package. The increase in junction temperature can have an adverse effect on the long term performance and operating life of the transistor—eventually leading to its demise.
In modern processors, junction temperature has become a first-order design constraint. And as technology advances towards smaller process nodes, the thermal issues become even more challenging. Temperature is a dominant factor in processor performance, reliability, leakage power, timing integrity, cooling costs—the list goes on. Today's trends in IC packages are making it increasingly difficult to produce an end product which meets the thermal limitations of its components. Some of these trends are listed below:

- Decreased package size
- Decreased die size
- Increased pin count
- Increased system complexity/integration
- Faster clocks
- Processes with increased leakage
- Need for lower cost
- Higher reliability/lower junction temperatures

For every end product, system design engineers are required to address component- and system-level thermal challenges. Products with small form factors have a high density of components with very little room for a thermal solution. Therefore, it is imperative to meticulously assess each product's thermal management design so that it can safely perform under the intended operating conditions and environments.

What is thermal management?[edit]

Simply put, it is a thermodynamics problem -- a testament to Fourier's Law and the conservation of energy. For any two bodies in contact with each other, the higher temperature object will transfer heat energy to the lower temperature object to achieve a thermal equilibrium. This fundamental law can be observed for any two points in a system; it governs heat transfer between die and package, and also between package and the outside world. A temperature gradient occurs when the rate of energy leaving the system is less than the rate of energy brought into the system. The rate of energy out increases as the temperature difference increases. In order to reduce heat levels, it is necessary to reduce the rate of energy input and also increase the rate of energy out transfer.

There are three mechanisms by which heat may be transferred: radiation, conduction, and convection. Radiation is the simplest and typically the least effective. An IC resting in place will naturally radiate heat into the environment (assuming the environment is a lower temperature than the IC) until thermal equilibrium is obtained. Conduction, unlike radiation, utilizes an interconnecting object (heat sink, thermal posts, thermally conductive material, etc.) to conduct heat away from an IC. Conduction is the primary mechanism for heat transfer between solids. Convection, on the other hand, is the primary process for heat transfer from a solid to a liquid or gas in contact with it. This typically produces the best results for cooling an IC, as heat is eventually dissipated into the ambient air. The best thermal solution (in an ideal configuration) is a combination of all three methods.

To some degree, conduction and radiation are always present in a design. As a processor consumes power, its generated heat is conducted away from the package into the PCB. The heat within the PCB and processor is also naturally radiated into the surrounding environment. The hotter the package surface gets, the more efficient convection and radiation are to heat transfer into the ambient environment. The rate of heat transfer out of the processor is a property of the system, affected by characteristics like material, air flow, and enclosure size. These characteristics define the system's ability to manage thermal issues by ensuring the heat transfer rate out of the system is greater than the rate in. This implies that even at a very low power consumption, a processor may experience thermal issues if the system cannot transfer heat efficiently.

Why is thermal management necessary for the AM335x?[edit]

Maintaining a junction temperature below the absolute maximum is the only thermal requirement TI specifies for the AM335x. The AM335x is considered to be a "medium power" component dissipating enough power that its maximum operating temperatures could be exceeded, if care is not taken with good system and PCB design. It is essential that thermal management considerations are evaluated during system design, and an allowable safe junction temperature is confirmed with measurements during the prototyping phase. At the time of writing this document, the AM335x maximum operating junction temperature was 90°C for commercial/industrial units and 105°C for extended temperature units.

AM335x Operating Junction Temperature Range

	Min (°C)	Max(°C)
Commercial Temperature	0	90
Industrial Temperature	-40	90
Extended Temperature	-40	105

Texas Instrument devices marked Industrial Temperature Range function at ambient temperatures between -40°C and 85°C when proper care is taken to ensure that the absolute maximum operating temperatures are not exceeded. Note that system level thermal design is required to specify that the maximum operating device temperatures are not exceeded even when the input ambient air temperature is between -40°C and 85°C. The minimum operating temperature is -40°C when the industrial temperature range is specified. There is no industry standard defining the meaning of

Industrial temperature capable, so variations will likely exist from company to company. Texas Instrument devices marked Commercial Temperature Range function at ambient temperatures between 0°C and 70°C when proper care is taken to ensure the absolute maximum operating temperatures are not exceeded. The minimum operating temperature is 0°C when the commercial temperature range is specified.

What causes thermal issues in embedded systems?[edit]

Dynamic power is a nonlinear function of capacitance, frequency, and volts squared ($P_{dynamic} = CfV^2$). The nonlinear nature of this relationship illustrates that as the switching frequency gets higher, the amount of power and heat grows exponentially. Operating at the highest frequency to achieve the highest performance implies paying a penalty in terms of power consumption (battery life), and dissipated power in the form of heat. Once heat is generated, the system must provide an efficient heat transfer path from the device to the environment using radiation, conduction, or convection methods. The efficiency of this heat transfer is constrained by system characteristics such as PCB layout and chassis configuration, but also by environmental factors. Because the processor is not the only contributor to the thermal performance of the system, the totality of all components and variables must be considered to meet the maximum temperature specification.

Board- and system-level thermal constraints are the primary factors influencing the processor's ability to transfer heat into the environment. Technology trends continue to push these constraints toward increased performance levels (higher operating speeds), I/O density (smaller packages), and silicon density (more transistors). Power density increases and thermal cooling solution space and airflow become more constrained as operating frequencies increase and packaging sizes decrease. The component die temperature depends on the following:

- Component power dissipation
- Package Size
- Packaging materials (effective thermal conductivity)
- Type of interconnection to the substrate and motherboard
- Presence of a thermal cooling solution
- Thermal conductivity
- Power density of the substrate/package, nearby components, and circuit board to which it is attached

As the system transfers heat into the environment, conditions such as ambient temperature, air flow, and humidity can dramatically impact the thermal behavior of the system. Restrictions should be placed on these environmental variables to minimize the variability of thermal performance. For example, it is common to place limitations on the operating ambient temperature of an end product. Oftentimes, this is in reasonable range of the product's intended environment. Care should be taken to design the system for the intended worst-case environmental conditions and use cases. The environmental thermal constraints include the following:

- Local ambient temperature near the component.
- Airflow over the component and surrounding board
- Temperature cycling (changes in the density, viscosity, and heat capacity of the ambient air)
- Temperature humidity
- Altitude/elevation (changes the cooling efficiency capability and static air pressure)
- Mechanical shock, vibration
- Physical constraints at, above, and surrounding the component that may limit the size of a thermal enhancement

What can be done to address these issues?[edit]

There are a variety of thermal management techniques which utilize combinations of radiation, conduction, and convection methods to remove heat from a system. Your exact thermal management solution will depend greatly on the thermal properties of your system. Before finalizing an AM335x system design, the potential maximum power consumption as well as the system constraints discussed previously must be considered. The final thermal solution will incorporate tradeoffs among cost, size, and user constraints. The following list includes items that can improve a system's ability to dissipate heat. This is not an exhaustive list and each item should be evaluated to see if it is a good fit for your use case.

- Thermal vias connecting BGA balls to spreading planes in PCB
- Ensure the power and ground planes which connect to the AM335x are relatively continuous for a 25-50mm radius around the package
- Apply thicker copper plating on all power and ground planes (e.g., from 1 oz to 2 oz) to allow heat to dissipate from the device balls to the PCB
- Apply copper fills in void areas on planes to dissipate heat to the edge of PCB. Any copper on the PCB, even if it is not electrically connected, helps spread the heat from the package to the air or chassis
- Sparsely populate PCBs with large areas for convection and radiation
- Maximize board size to increase head spreading capability
- Choose mounting hole locations effectively to ease the stress on PCBs with thermal foam

- Heat spreaders and lid materials (Al, Cu, Graphite or Ceramic)
- Heat sinks to increase the rate of power dissipation through the top of the exposed die and also decrease the resistance by increasing the surface area
- Fans, forced air cooling systems
- Interface materials (DowCorning 1-4174), gap fillers
- Thermally-conductive enclosure, with thermally-aware design/dimensions
- Reduce adverse effects of boundary and environmental conditions (low ambient temp, high air flow, etc.)
- Software implemented features to manage power and provide thermal regulation

System Thermal Improvements[edit]

Reducing Power Consumption[edit]

The best way to minimize heat is to consume as little power as possible. Software can take advantage of various AM335x hardware features to optimize power consumption, thereby managing heat dynamically and reducing the need for costly cooling systems. When possible, the following methods should be used to optimize power consumption at the device level:

- Clock gate or power down unused peripherals either statically or dynamically
- Ensure operating frequencies are high enough for the use case. Avoid using higher frequencies for a given module than needed
- Ensure operating voltage is correct for operating frequency
- Power down or sleep external devices when not used
- Operate devices in power optimal modes (DDR ODT only when necessary)
- Use efficient power supply designs (switchers as much as possible)
- Dynamic power switching (DPS)
- Dynamic Voltage and Frequency Scaling (DVFS) across operating performance points (OPP)
- SmartReflex™ adaptive voltage scaling (AVS) based on process variations and temperature
- Low-power modes (DeepSleep0, Deepsleep1, Standby, RTC-Only)

For more information on AM335x Linux power management techniques, please refer to the AM335x Linux Power Management User Guide and the AM335x Power Consumption Summary.

PCB Design[edit]

PCB design is essential for thermal management of medium and high power components. For surface mount devices, most of the heat is conducted through the board and dissipated into the environment when no thermal solution is implemented on the top of the package. The AM335x ZCZ and ZCE packages are designed to allow heat to dissipate from the bottom of the device. Essentially, the PCB acts as a heat sink on the processor's BGA solder balls. The efficiency of this "heat sink" is determined by the pad size, topology, and the overall PCB design.

Because the majority of the heat flows through the balls on the package, any way to spread the heat from the PCB area under/around the processor to the rest of the PCB will improve thermal performance. Using thermal vias and copper planes are simple ways to improve the heat spreading capability of the PCB. The proximity of other components to the AM335x must also be considered during the PCB design phase, as the components will generate heat and contribute to higher junction temperatures.

Thermal Vias[edit]

Thermal vias are the primary method of heat transfer from the PCB thermal land to the internal copper planes or to other heat removal sources. The number of vias used, the size of the vias, and the construction of the vias are all important factors in the package-to-PCB thermal performance. The number of thermal vias varies with each component being assembled to the PCB, depending on the amount of heat that must be moved away from the package, and the efficiency of the system heat removal method. Characterization of the heat removal efficiency versus the thermal via copper surface area should be performed to arrive at an optimum value for a given board construction.

The incorporation of thermal vias in the PCB is intended for efficient heat removal from the device package. The effectiveness of the thermal vias depends on soldering the exposed pad of the package to the PCB. Failure to solder the package to the PCB results in insufficient heat removal and therefore negatively impacts device performance and reliability. More information on thermal vias and soldering can be found here.

Spreading Planes[edit]

The best way to reduce the temperature of a component is to spread the heat out as quickly as possible. Because the AM335x dissipates most of its heat into the PCB, the copper planes should be used to distribute this heat through thermally-conductive materials to anything that will take it away (usually air). The larger the spreading plane, the cooler the devices will run, so it should be as large as possible beyond the minimum area. The plane must be reasonably continuous (minimal breaks in the direction of heat flow) in the area that is considered for spreading.

There must be at least one Cu spreading plane in the PCB. Electrically, the plane is normally held at ground for exposed pad packages. This plane serves to conduct the heat from the small area of the component to a larger area in the PCB, where the heat is then dissipated through convection and radiation into the surrounding environment. As such, the plane must have sufficient thickness and area to provide adequate heat sinking for the component. The minimum thickness of a spreading plane in a typical PCB is 0.5 oz. However, PCBs are often enhanced by using planes that are 1 oz. The spreading plane may be located on the top layer and directly connected to the landing pad. The spreading plane(s) may also be located on a buried layer(s) and connected to the thermal vias.

Trace Layout[edit]

When considering trace layout for signal integrity, it is also important to take into account power rating and thermal/power dissipation. Wider traces are preferred when connecting to the solder balls of the AM335x to improve thermal performance. Where possible, it is recommended that added copper be laid for traces and especially power pads for relative power supplies as recommended in the datasheet. Long traces should be used where not constrained by other routing requirements.

Proper copper thickness is important to the overall impedance, thermal management, and current carrying capabilities of the design. As a general rule of thumb, the inner layers or planes of most PCBs are typically 1 oz. copper while the outer layers are 0.5 oz. copper. Outer layers receive solder masking which in the finished product is usually similar to the 1 oz. inner copper weight.

Component Placement[edit]

Board population density influences the thermal performance of the package, as the sum of components which are in close proximity with one another contribute to the temperature rise of the PCB and overall system. Every system and every component has different heat generating capacities, thermal conductivities, and proximities—so it is nearly impossible to analyze the full list of components on a PCB. Simplifications must be made. The first simplification which is commonly taken is to ignore components such as passives which have very low dissipation, and to focus only on components which have more than 50mW of dissipation (depending on the system and accuracy needed). The next level of simplification which is effective for focusing on a specific component is to use symmetry (or adiabatic) lines which do not allow heat flow across them, so that the interaction between components is effectively negated. Medium power components often have a spreading plane which is effectively dedicated for them, so it is reasonable to draw symmetry lines around the spreading plane. For components which share a spreading plane, it is reasonable to divide the total spreading plane area by the number of components (or a ratio of their power dissipation), to derive an effective copper spreading plane area to use for calculations. Typical high power devices in a system include but are not limited to the following:

- PMICs
- External LDOs
- RF components
- Displays

- High speed memory
- Transceivers
- PHYs (SATA, PCIe, Ethernet)

Some heat-generating devices are required to be in close proximity to each other for signal integrity and layout concerns such as DDR memories. There is no easy solution around this. The component placement process should also be evaluated with respect to the final form factor enclosure.

Other Considerations[edit]

- The landing pad on the top of the PCB should be the same size or larger than the exposed pad of the component. The component should be soldered to the pad with reasonable coverage to ensure good heat conduction from the component to the PCB.
- When connecting ground (thermal) vias to the ground planes, do not use thermal-relief patterns. Thermal-relief patterns are designed to limit heat transfer between the vias and the copper planes, thus constricting the heat flow path from the component to the ground planes in the PCB.
- Special care should 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
- PCB material has a large impact on the overall system design. Materials range from low cost FR4 to high end ceramic material with other variations in between. Unfortunately, what works well for a high performance application where signal integrity and propagation delays are important does not work as well as a thermal transfer medium. Materials that satisfy both conditions tend to be the most costly and not used in mass production.
- If airflow exists, locate the components in the mainstream of the airflow path for maximum thermal performance. Avoid placing the components downstream, behind larger devices or devices with heat sinks that obstruct the air flow or supply excessively heated air.

Note: The above guidelines are not all-inclusive and are defined to give you known, good design practices to maximize the thermal performance of the components. More information on BGA PCB design can be found at General hardware design/BGA PCB design. Please refer to this analog app note for more detailed information on thermal design for PCBs.

Enclosures[edit]

The enclosure in which the PCB sits is an important contributor to the effectiveness of the convection of heat from the PCB to the surrounding air. Enclosure designers must comprehend how much energy needs to be transferred out of the system, and ensure that the enclosure is fully capable of dissipating this heat in its intended operating environment.

Medium power components like the AM335x often do not have forced airflow, and are cooled by natural convection. The effectiveness of natural convection cooling is often dictated by the freedom of air to circulate within the enclosure. One important factor is the orientation with respect to the gravitational direction, as a vertically-oriented PCB can create a strong "chimney effect" which aids in the effectiveness of the convection. Unfortunately, it is rarely possible to ensure that a system stays oriented vertically during its use, so a horizontal orientation is the conservative simplification to use. Another important contributor is the open space above or below the PCB where the air circulates. The general rule is that if the space above and below the board is less than 6mm and there is no fan circulating the air, there is no convection.

Metal Enclosure[edit]

The use of a thermally-conductive metal enclosure results in increased thermal performance. Different metal materials can have vastly different thermal properties. For example, magnesium alloy (AZ91D) is often used in enclosures, but has a low thermal conductivity when compared to other materials such as aluminum alloy or copper. However, these materials with higher thermal conductivities are oftentimes more expensive.

In metal enclosures, screws can be added from the PCB to the enclosure chassis, effectively turning it into a great heat sink. Heat shields and aluminum/copper backing plates can also be used to act as a heat sink to aid in thermal dissipation of the system enclosure. Using a thermal gap filler material between the area underneath the device and the chassis can also help spread the heat from the PCB. The gap between the PCB and chassis should be as small as possible for this cooling scheme to be effective. Applying a thermal pad from the top of the package to the chassis can also help.

Plastic Enclosure[edit]

From a thermal management standpoint, metal enclosures are preferred over plastic ones because of their high thermal conductivity. Although plastic is a poor thermal conductor, the enclosure design can help to overcome the thermal limitations. Getting heat through the plastic into the air is essential. This can be done by spreading the heat out with a metal plate underneath the plastic, or by having holes in the plastic to enable airflow to the PCB. Vent holes enable air to get into the enclosure to remove heat directly. This method is very effective, and reduces heating of the enclosure itself. If the device needs to be somewhat liquid resistant, holes on the top of the case should be avoided. Remember the air has to get in and out, so the most effective systems are the ones that bring in cool air from the bottom and let it naturally rise up and escape due to convection heating. The hot air going out should enable more cool air to be sucked in.

If vent holes are unacceptable, the heat must be spread out under the plastic, but as close to the outside of the enclosure as possible. Spreading heat with an aluminum plate behind the plastic is a common design practice that is effective. The larger surface area of the aluminum makes it easier for the heat to travel through the plastic and escape into the air. Many laptop computer and similar plastic power supplies use this method to dissipate heat.

High Cost Solutions[edit]

Cooling solutions such as heat sinks and fans are considered in this document to be “high cost solutions” because they are only required for extreme use cases. Using heat sinks and fans will increase system cost, size, and noise. High power components often require specific thermal management solutions such as heat sinks, chassis conduction paths, and forced airflow; but the AM335x is not typically considered to be a “high power component”. The following thermal management solutions are only recommended as a last resort.

- Heat sinks are one of the most commonly considered thermal improvement methods. When applied to the top of a package, heat sinks increase the effective surface area of the package, which increases convection and radiation off of the top surface of the package. Typically, without a heat sink, 80%-90% of the heat generated by the device will be dissipated through the PCB. Attaching a heat sink improves the heat flow through the top of the device. Increasing the surface area of the heat sink reduces the thermal resistance from the heat sink to the air, increasing heat transfer.

- Good system airflow is critical to dissipate the highest possible thermal power. Proper design of the PCB such that forced air is allowed to freely move over the processor generally produces the most optimum results. The size and number of fans, vents, and/or ducts, and, their placement in relation to components and airflow channels within the system determine the airflow. If a fan is required for other system components, be sure some of that airflow can be used for the AM335x.

- A gap filler is 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. The thermo-elastic gap filler material is often found in the handheld device for thermal management purpose as well as for better shock resistance.

- For extended operation or for high power consuming use cases, enhancing the heat spreading capability of the device enclosure becomes critical. Heat spreaders are used to spread the heat while transporting it from the die to the PCB, product chassis or a heat sink (if the product design form factor permits), which in turn dissipates heat to the local environment. [copper, graphite] This design concept significantly increased the power dissipation capability, by reducing overall system thermal resistance.

- Fluid immersion (liquid cooling)

- If all else fails, a final way to limit heat is to constrict your operating environment. Specifying an ambient operating temperature range for the device is one way to constrain the environment to your advantage. However, most often the environment defines itself; hence this dimension of thermal performance management can only be used if you have complete control of the operating environment.

Evaluating Your System[edit]

It is impossible to reduce the requirements for proper thermal management to a single formula given all the possible variables and design permutations. The complex interactions between constraints and variables require application level software programs and 3-D models to be constructed in order to get to a first order approximation. However, depending on your use case and operating environment, you may be able to utilize thermal data from Thermal Analysis of Chamber Experiments to to determine if your system is at risk of thermal failure. Your system must be able to sufficiently dissipate the heat generated while running the maximum intended workload in the worst-case intended operating environment. This maximum amount of system power consumption must be quantified to determine the highest case temperature measurement and junction temperature estimation. Before evaluating your system, you should be familiar with the thermal management techniques described in this document.

Interpolating your system's thermal performance using results from Thermal Analysis of Chamber Experiments:

1. Identify your system’s worst-case thermal use case (maximum system power consumption).
2. Identify your AM335x maximum operating junction temperature. This will either be 90°C or 105°C.
3. Choose the best-fit thermal test platform for comparison (select between AM335x EVM and BeagleBone data, based on the thermal management similarities with your system).
4. Interpolate your system’s thermal behavior based on system power consumption and operating ambient temperature.
5. Review data to determine if additional thermal management techniques are required for your system.

If your system has already been prototyped, it is recommended to perform power/temperature measurements to evaluate your system’s thermal performance and ensure the maximum operating specifications are met. Measuring the AM335x case temperature will give you a good idea of the junction temperature, as it is always within a few degrees.

If your system is capable of measuring power on all AM335x supplies, the junction temperature can be estimated using the Ψ_{jb} equation. Measuring the system’s total power consumption while running the same applications as the experiment (OS Idle, continuous Dhrystone benchmark) would provide a useful data point for comparing the thermal performance of your system.

Measuring Case Temperature[edit]

Once the system has been finalized and manufactured, a case temperature measurement may be performed to ensure that the maximum junction temperature specification has not been exceeded. The greatest difficulty we face in order to achieve this target is that there is no direct way to measure junction temperature by using a thermocouple or infrared thermometer, because the IC is covered with a mold compound and the actual junction is not exposed. The AM335x features a built-in bandgap sensor to estimate junction temperature and facilitate thermal shutdown. The sensor can measure temperatures between -50°C and 150°C, but the low-resolution 8-bit ADC gives the sensor a poor accuracy of ±10.8°C. A much easier way to estimate junction temperature is by using the relationships between Ψ_{jt}, Ψ_{jb}, power, and case/board temperature.

Case temperature is a function of the local ambient and internal temperatures of the component. It is defined as the hottest temperature on the top of the device and should be measured at the geometric center of the package top. The case temperature measurement can be performed with (in order of accuracy) an IR camera, a fluoroptic probe, a thermocouple, or IR gun (maximum field view of 4mm diameter) just to name a few techniques.

When a thermocouple is chosen as the technique to perform the measurement, a fine gauge wire (36 to 40 gauge, J or K wire) should be used to minimize the local cooling from the thermocouple. If the case temperature is measured by a gauge thermocouple larger than 36, the thermocouple sinks heat away from the surface, cooling the spot that is being measured. The thermocouple should be attached to the center of the package surface (±1mm) with a bead of thermally conductive epoxy no larger than 2x2mm on a side. Taping the thermocouple to the package surface is not recommended. To minimize the heat sinking nature of the thermocouple, the wire should be dressed along the diagonal of the package, down to the PCB surface, and over a minimum distance of 25mm before lifting from the PCB. The thermocouple wire can be tacked to the PCB for this routing purpose with tape. When using an IR camera or IR gun, be sure to correct the reading for the emissivity of the surface being investigated. See your instrument's documentation for details.

Measuring Board Temperature[edit]

The board temperature should be measured using a fine gauge thermocouple (36 to 40 gauge, J or K wire). The thermocouple should be attached to the PCB with a bead of thermally conductive epoxy no larger than 2x2mm on a side, 1mm away from the center of one of the AM335x package's four edges. To minimize the heat sinking nature of the thermocouple, the wire should be dressed along the PCB surface over a minimum distance of 25mm before lifting from the PCB. The thermocouple wire can be tacked to the PCB for this routing purpose with tape.

Estimating Junction Temperature[edit]

Using case/board temperature, device power consumption, and Ψ_{jb}, the AM335x processor junction temperature can be estimated. The relationship between these parameters is discussed here, and is:

$T_{junction} = T_{PCB} + (Power * \Psi_{jb})$

For example:
In a ZCZ AM335x system with no air flow, the AM335x case and board temperatures are measured to be 45°C and 33°C, respectively. The AM335x is running the Dhrystone benchmark, with a total device power consumption measured at 1W. Listed in Thermal Metrics, Ψ_{jb} is equal to 12.7 for this package. Plugging these values into the junction temperature equation…

$T_{junction} = T_{PCB} + (Power * \Psi_{jb})$

$T_{junction} = 33 + (1 * 12.7)$

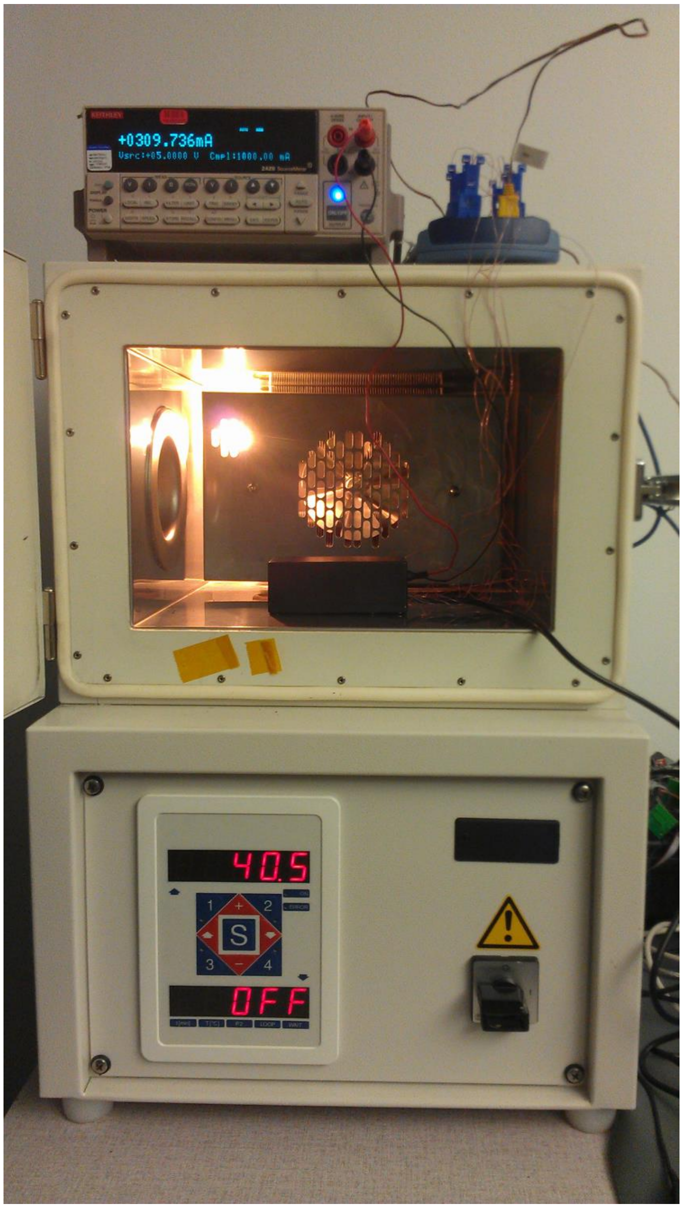
$T_{junction} = 45.7°C$

This estimated junction temperature of 45.7°C is very close to the measured case temperature of 45°C. In fact, the AM335x case temperature is always within a few degrees of the junction temperature.

Thermal Analysis of Chamber Experiments[edit]

Overview[edit]

This experiment is still ongoing! Additional data will be updated periodically.



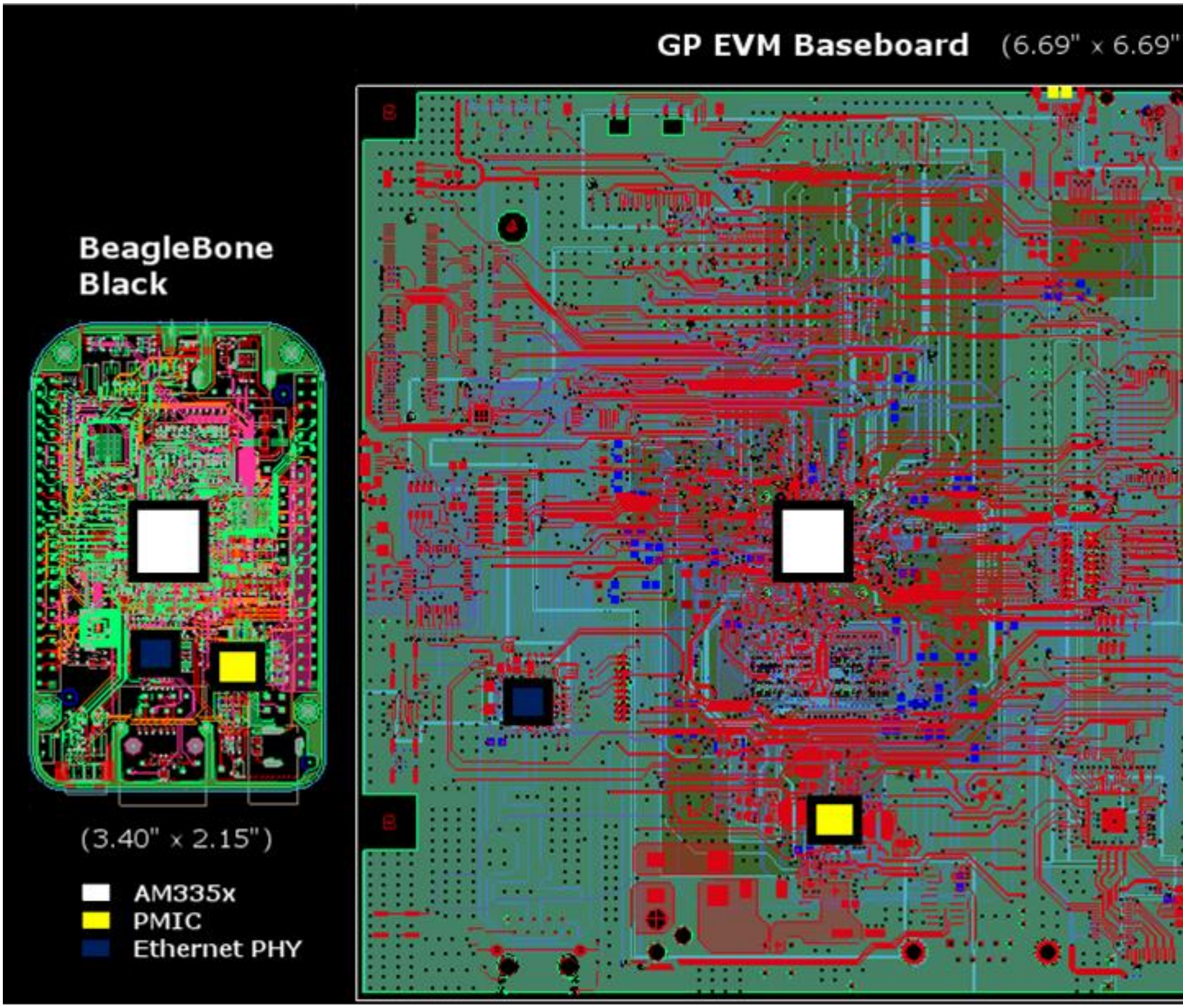
An experiment was completed to analyze the thermal behavior of the AM335x on real systems in a controlled environment. Using a thermal test chamber to manipulate external environmental conditions, such as ambient temperature and air flow, we simulated a range of temperature scenarios to model common customer use cases. By altering thermal management variables like board size, MPU frequency, and application intensity, we can create an operating thermal profile for each AM335x system tested. These thermal profiles are intended to serve as example use cases for users to evaluate during their thermal design process. Users can utilize the collected data to interpolate an approximation of their system's thermal behavior, and estimate the risk of exceeding the maximum operating junction temperature in their system—and consequently, determine the need for improved thermal management.

The example AM335x systems chosen for this experiment do not contain any complex cooling systems; they are both heat sink-less and fan-less. Both boards were enclosed and populated with worst-case hot silicon to account for the additional leakage power incurred at high temperatures. The systems were placed inside a thermal chamber to simulate a spectrum of ambient temperatures with no air flow. For each temperature test point, an application was run while monitoring the power consumption and case/board temperature. Starting at 25°C, this test procedure continued until the maximum operating junction temperature was exceeded. For more details on this experiment setup, please refer to AM335x Thermal Chamber Experiment.

System Comparison[edit]

In this experiment, two evaluation boards were tested to represent two types of systems with contrasting thermal efficiencies:

- Rev 1.5A General Purpose EVM baseboard
    - 6.69” x 6.69”
    - 6 layers (4 signal, 2 power)
    - Components are placed in spacious design to fit in mini-ITX form factor
- BeagleBone Black
    - 3.4” x 2.15”
    - 6 layers (4 signal, 2 power)
    - Components are densely populated and tightly routed to fit on a credit-card sized board



Having over 6 times the board area, the EVM baseboard represents a more thermally effective system solution than the BeagleBone. This means more copper and board space for spreading and dissipating heat. The EVM also has a better component placement in terms of thermal management, as the major sources of heat (processor, PMIC, Ethernet PHY, etc.) are placed spaciously apart on the PCB. The extra room also allows select traces to be wider on the EVM.

Both test systems were enclosed in ABS plastic cases to remove any airflow from the system. The EVM was enclosed in a B&W Type 10 Outdoor case, and the BeagleBone was enclosed in a Twin Industries B10-7100 ABS project box. These enclosures further reduce the thermal efficiency of the test systems, as heat must be dissipated from the processor/PCB through the internal ambient air, through the ABS plastic enclosure, and through the external ambient air of the thermal chamber. One goal of this experiment was to create a thermally-poor system (within reason) running an MPU-intensive application, with the hopes of achieving a worst-case to give users an extreme example for assessment; here, this is the enclosed BeagleBone.

Data and Results[edit]

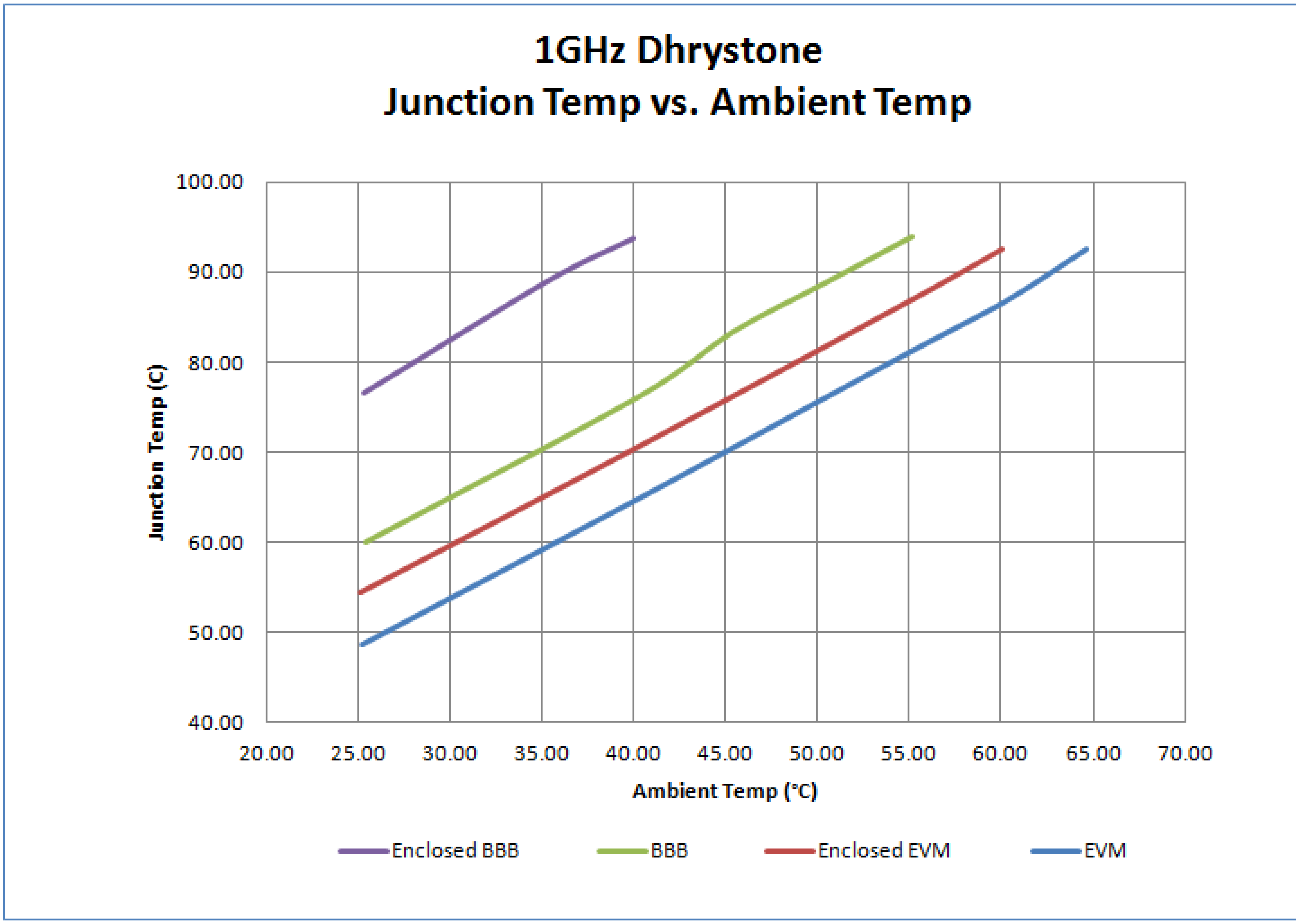
The following data was collected after running several use cases on 4 different systems: BeagleBone Black, EVM baseboard, enclosed BeagleBone Black, and enclosed EVM baseboard. For each system, power and temperature measurements were captured over combinations of 2 applications and 4 operating performance points (OPP), which are fixed voltage and frequency targets.

The applications selected were “OS Idle” and “Dhrystone.” OS Idle is the use case where the AM335x processor is idling at the Linux Matrix GUI, waiting for a command. Here, the processor is active, but consumes minimal power. Dhrystone, on the other hand, is the use case of running the Dhrystone benchmark continuously. This application was selected to represent a computationally-intensive use case, as it exhausts 100% of the MPU and consumes a significant amount of power. Both of these applications are available in the Linux EZSDK for Sitara ARM Microprocessors.

Certainly, more power-hungry applications exist, but they are beyond the scope of this experiment. Dhrystone was chosen because of its effect on the MPU power domain. As the MPU frequency is scaled up to 1GHz, thermal issues become more prevalent with the increased processor power consumption. Your system may be significantly different than the ones described in this experiment! Your application may consume more power than Dhrystone, and your system may be worse at dissipating the generated heat. Please be cautious when comparing the following results and conclusions with your system.

System Comparison at 1GHz, Dhrystone[edit]

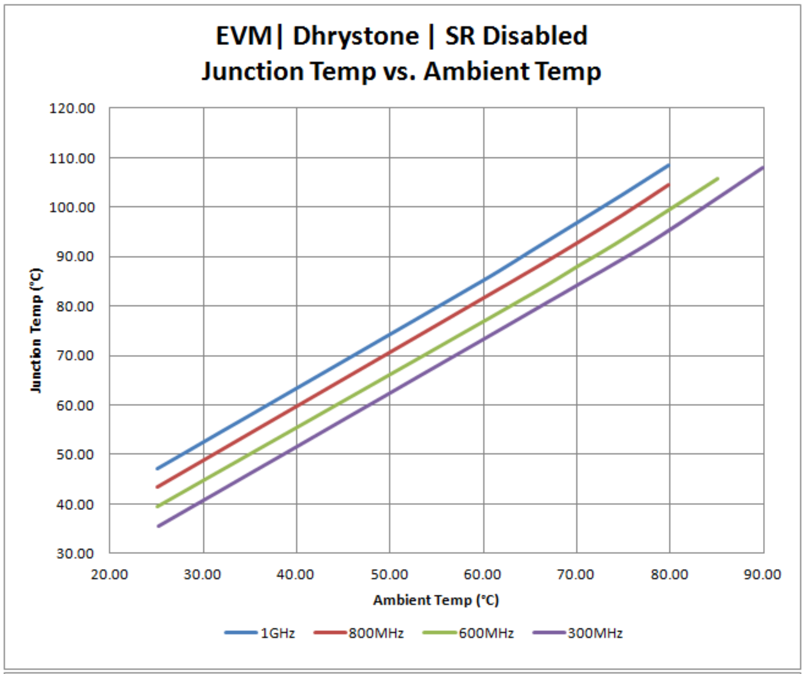
Note: the results of this test are currently under speculation.

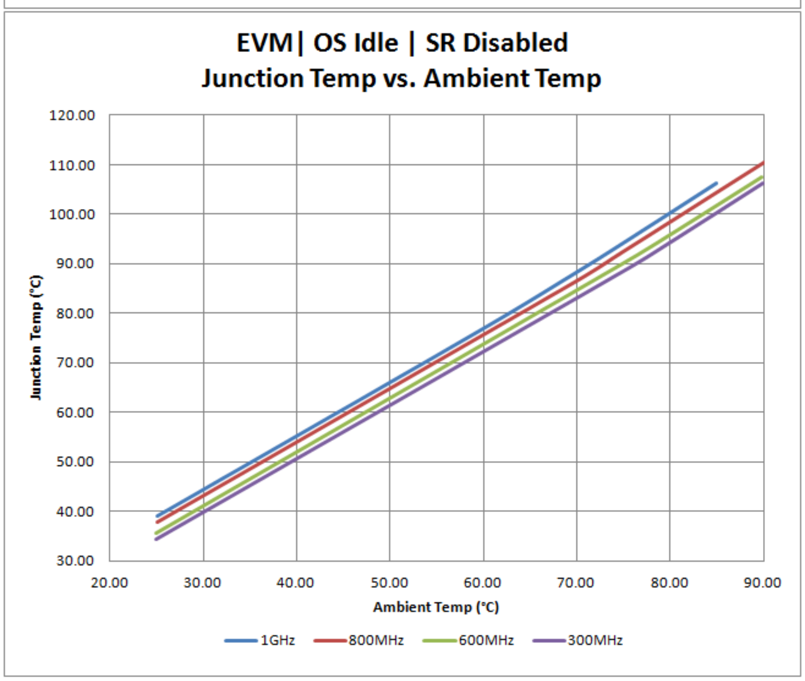


As expected, the enclosed BeagleBone performed the worst and the more thermally-efficient EVM performed the best. The EVM was able to withstand an ambient temperature of 60°C (140°F) before exceeding the 90°C maximum operating junction temperature. However, the enclosed BeagleBone exceeded this at just over 35°C (95°F) ambient.

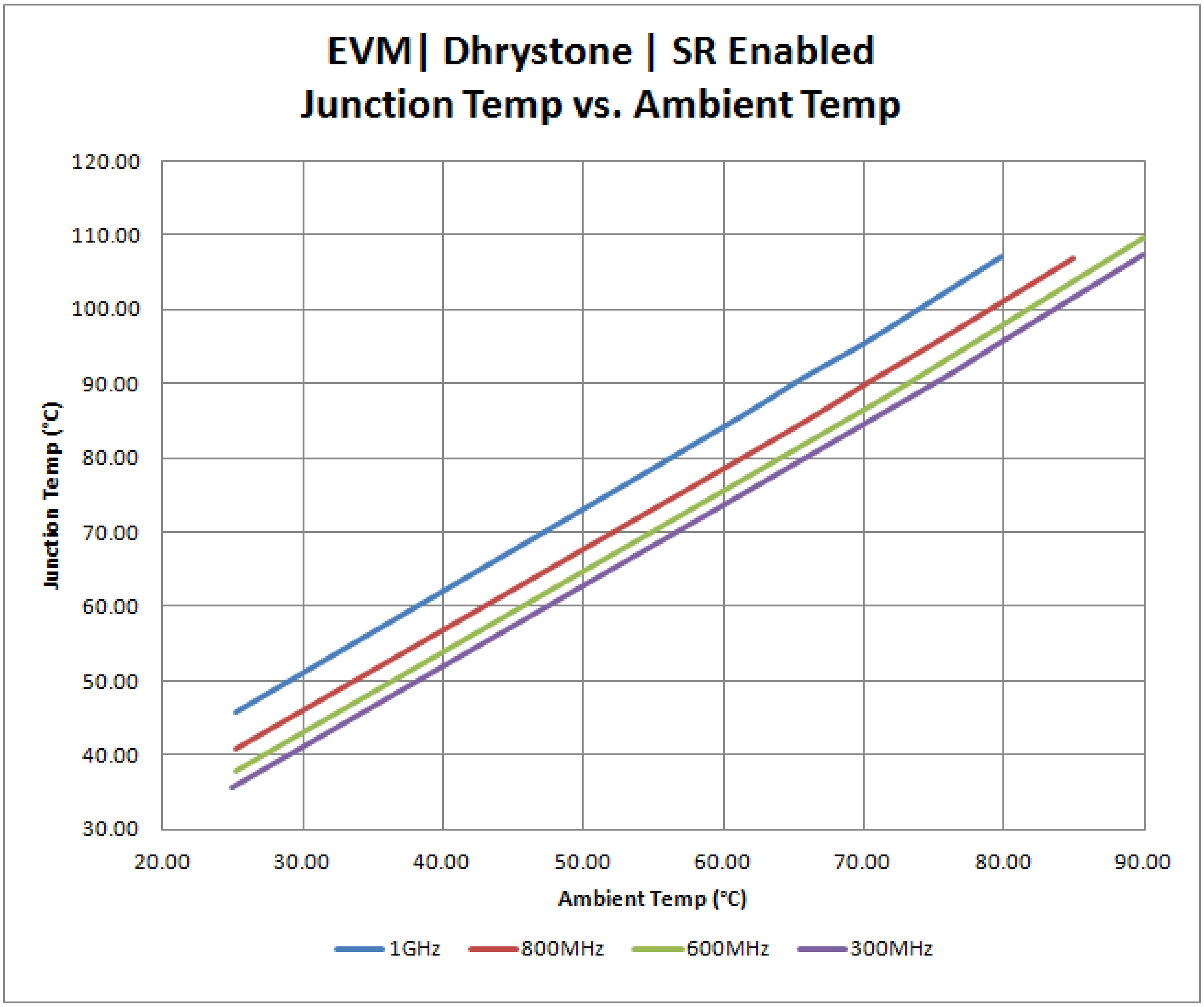
EVM[edit]

Running the Dhrystone application at 1GHz causes the junction temperature to exceed 105°C at an ambient temperature of 75°C. By scaling down the MPU frequency to 300MHz, the maximum operating ambient temperature is extended to 85°C. In the OS Idle application, the ambient temperatures can exceed 85°C before the junction temperature gets too hot.

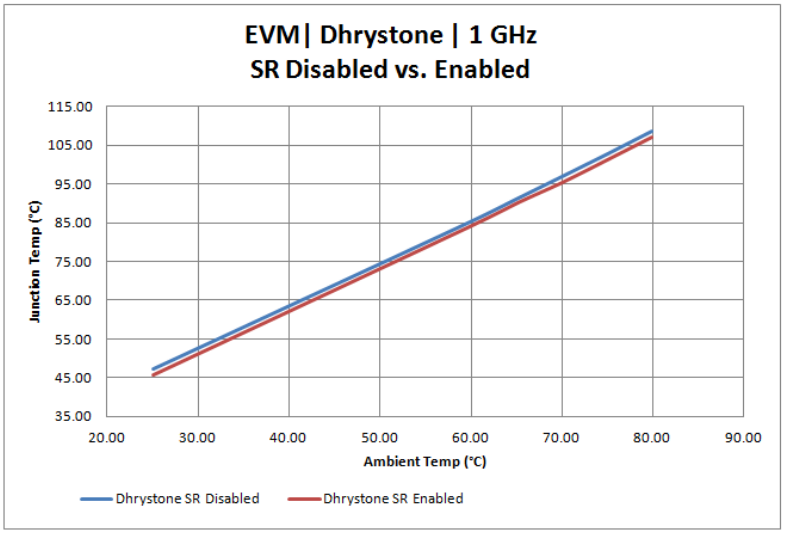


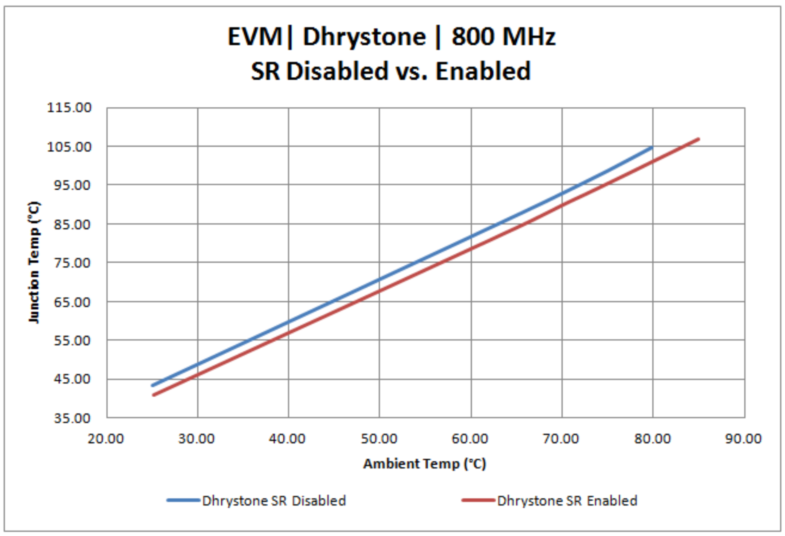


SmartReflex is an active power management technique which optimizes voltage based on silicon process. Because these test systems use a worst-case hot silicon process, we can use SmartReflex to reduce active power—and as a byproduct, reduce heat. In this test, we investigate the thermal management effect with SmartReflex enabled at different frequencies.

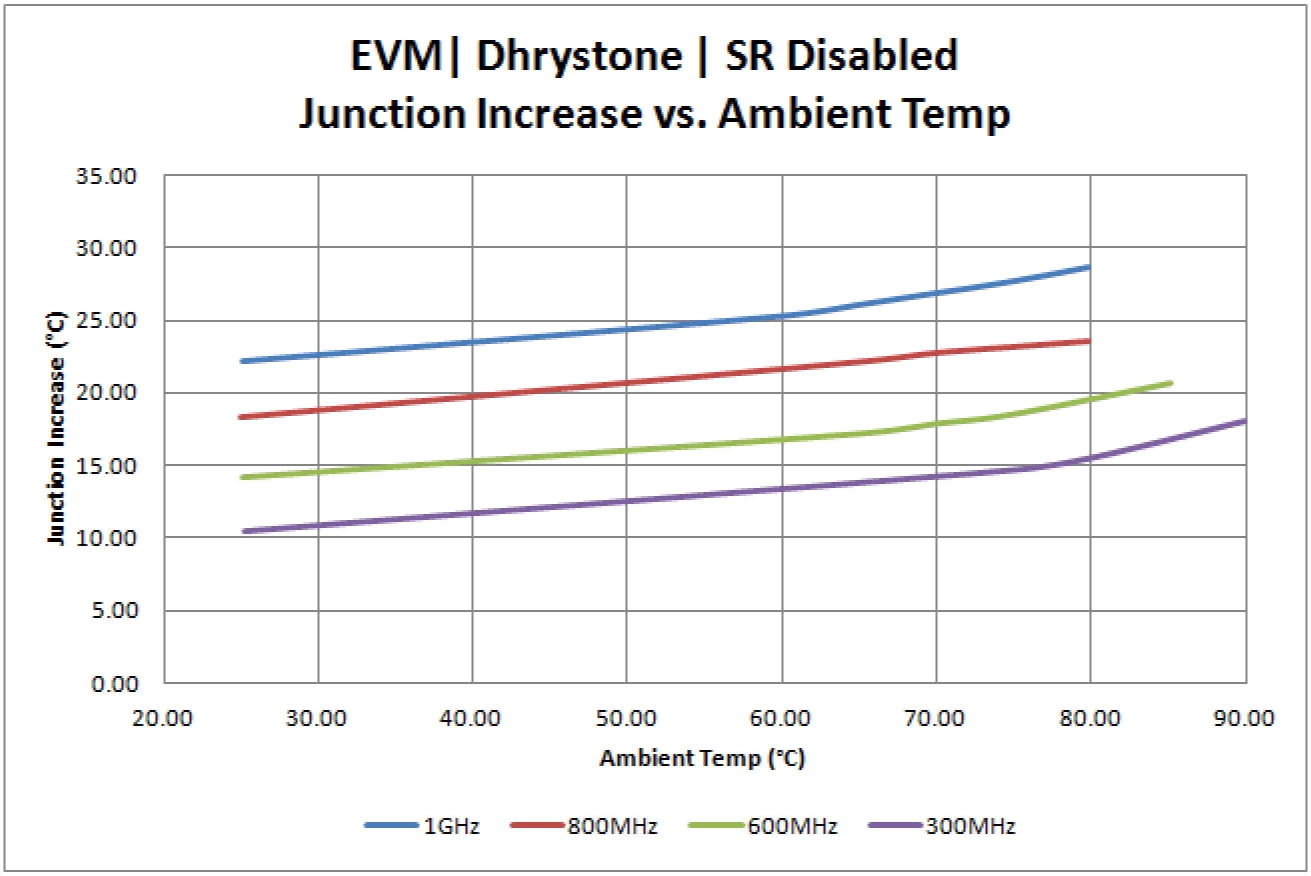


On the EVM baseboard with a worst-case silicon unit, SmartReflex reduces the operating junction temperature by 1-3°C, depending on frequency.





The thermal effect of MPU frequency is significant. At an ambient room temperature of 25°C, the AM335x junction temperature heats up ~10°C while running the Dhrystone application at 300MHz. Operating at 1GHz, the junction temperature increase from ambient is ~22°C! This effect increases as ambient temperature increases.



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