Application Report
SLPA015–January 2020

Accurate Thermal Calculations on the Back of a Napkin

Keith James Keller – Analog Field Applications

ABSTRACT

Since power circuit design has existed, the age old thermal engineering question has persisted: how much PCB copper is really enough to cool my device? It turns out that these calculations can be made with reasonable accuracy very easily, specifically for heat transfer from a part mounted on a PCB with only convection cooling. In fact, this method is so simple that you will be able to write it down on the back of a napkin.

Contents

List of Figures

Trademarks

All trademarks are the property of their respective owners.

1 Introduction

The simple thermal rule states that one Watt of power dissipated in one square inch of two-ounce copper generates a 100ºC temperature rise. Were you to know that your IC will dissipate 0.5 W and you have about 1 square inch of combined copper cooling area top and bottom side, you can expect around a 50ºC temperature rise (100ºC/W × 0.5 W / 1 sq inch = 50ºC). Considering metric units: 2.54 cm = 1 inch, therefore, 1 sq-in of copper is 6.45 sq-cm. So, 1 W dissipated into 1 sq-cm of 2-oz copper causes a 645ºC temp rise. Of course this is not realistic temperature rise in a system and would require additional heatsinking techniques beyond simple convection cooling.

Copyright © 2020, Texas Instruments Incorporated

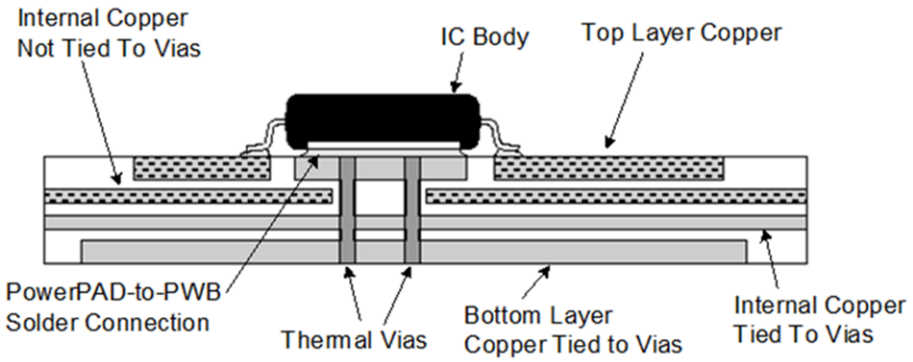

Figure 1. Example Cross Sectional Area of IC Body and 4-layer FR4 Board Showing Planes and Thermal Vias

2 Back of a Napkin Assumptions

You always need to know the assumptions for the equations. These are listed below and discussed in more detail in *Section 2.1*.

- 1 W into 1 sq-in copper generates a 100°C temperature rise.
- Thermal impedance through PCB is 10°C/W (this is from top side to bottom side).
- Thermal impedance of a via is 100°C/W.
- 1-oz copper, 25% higher temperature is 125°C/W.
- As an example, if you have 0.5 W of power in an IC, then you can expect a 50°C temperature rise to be 100°C/W × 0.5 W / 1 sq inch.

The Printed Circuit Board (PCB) is assumed to have 2-oz copper layers, however, for 1-oz copper, the calculation changes from 100ºC/W to 125ºC/W [1]. If you consider a 4-layer PCB, the effective cooling area is essentially the same as a 2-layer board (top and bottom). Where the internal layers really help you out is the ability to very effectively spread the heat across the PCB.

You want to have full copper pours across the PCB wherever possible since heat moves very efficiently through the FR4 material between overlapping copper pours. It turns out that these overlapping internal pours do *not* have to be electrically connected for good power flow (see *Section 3.2*). The PCB in Figure 1 would have excellent thermal performance using thermal vias and with full copper pours on all four layers. Heat easily moves vertically and horizontally.

Thermal vias have relatively high thermal impedance (100ºC/W), so you need to use many of them in your design for effective heat transfer. Consider four to six thermal vias under a thermal pad (or as many as will fit). In some cases, you do not have an option to use thermal vias (as the LM5069 AN-1522 eval kit demonstrates).

Finally, the effectiveness of a copper pour to dissipate power decreases at an exponential rate (see Figure 2). Therefore, you do not get much more benefit by having more than approximately one inch of copper in any direction from the IC in a circular pattern. This equates to about four square inches of copper using a 1.2-inch radius equal to $\pi \times \text{Radius}^2 = 3.14 \times 1.2^2 = 4.5$ square inches of copper.

2.1 Thermal Rule Summary

- PCB is 2- or 4-layer constructed of 2-oz copper with 100ºC/W thermal impedance. Otherwise, if you are using 1-oz copper, then thermal impedance is estimated at 125ºC/W.
- The thermal impedance from the package to the PCB is low (assuming no losses). Generally, this would require an IC with a thermal pad for conducting heat. In the case of ultra-small packages, you need thick copper pours at each pin conducting heat away from the IC.
- The thermal impedance between copper planes in a PCB is very low. Heat easily transfers between all layers if the copper pours overlap each other.
- The thermal impedance between cut copper pours on the same layer is very high. Heat is

Copyright © 2020, Texas Instruments Incorporated

concentrated to the area right under the IC. See Figure 8 with the TPS25942 Evaluation Kit example.

- Thermal vias have about 100ºC/W thermal impedance. To make an impact, you need to use many of these in parallel (10+ to get thermal impedance of approximately 10ºC/W). These need to connect to the bottom side-layer with large copper pour to dissipate the power.
- The temperature distribution decreases at an exponential rate (shown in Figure 2). You will not get much benefit beyond approximately 4.5 square inches of copper pour on either side (9.0 square inches of copper for both top and bottom side).
- Four-layer boards certainly help dissipate power across the PCB (if internal layers are completely poured and overlap with top and bottom side pours) versus two layer boards [2].

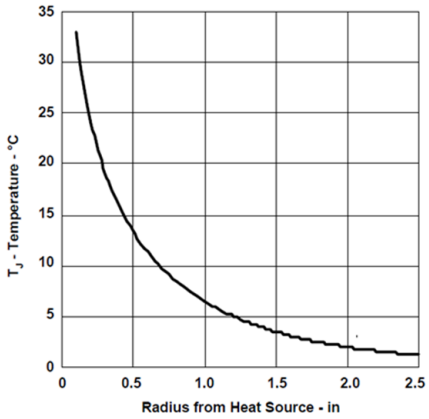

Figure 2. Temperature Distribution Laterally from IC Decreases Exponentially

3 Examples Showing Heat Flow on Top and Bottom Side of PCB

Nothing helps more than some examples and pictures to solidify a new concept. See the following sections for several examples:

- Two linear regulators
- Hot-swap controller with two different PCBs
- E-fuse device
- Power module

Each example shows different PCB thermal considerations. These particular devices were chosen since you can easily calculate the approximate power dissipated in the IC. This method can extend to discrete switching converters as well, but you need to consider power dissipation in other components on the board like the inductor and external MOSFETs.

NOTE: A caliper was used to take exact measurements of copper pour areas. These measurements were taken in the winter time, so please forgive the colder than normal ambient temperatures.

- TLV713P Linear Regulator (miniature 1-mm × 1-mm plastic package)
- LP5907 Linear Regulator (miniature 0.675-mm × 0.675-mm BGA package)
- First LM5069 Eval Board (AN-1522) thermal impedance estimation for high-side pass MOSFET
- Second LM5069 Eval Board (LM5069EVM-627)
  - This eval board shows the thermal performance with a different layout.
- TPS25942 Electronic Fuse (or E-fuse) device with integrated back-to-back MOSFETs (in a 3-mm × 3-mm QFN package)
- LMZM23601 36-V, 1-A Step-Down DC-DC Power Module (miniature 3.8-mm × 3-mm package)

Copyright © 2020, Texas Instruments Incorporated

3.1 Linear Regulator Evaluation Kit Examples

Both of these linear regulators were configured to dissipate 0.5 W and both have approximately the same copper area for cooling. The IC package is outlined in red in the following figures. The TLV713P layout can be improved by extending the top side copper pours all the way to the IC instead of using short traces to copper pours. The LP5907UV layout can perform even better if traces did not cut through the bottom layer (a combined bottom side region of the rectangle and triangle is shown marked up in blue).

3.1.1 TLV71312PEVM-171 Evaluation Kit

- Power dissipation is (5 Vin – 1.2 Vout) × 125 mA = 475 mW.
- Bottom side is 0.9 × 1.4 = 1.26 sq in (assume a little less than full bottom side for the cut in bottom side ground plane).
- Top side area is 1.26 / 2 = 0.63 sq in. The top side is estimated to be about half the bottom side since the VIN and VOUT planes do not extend to the IC itself.
- Total area is approximately 1.9 sq in.
- 1-oz copper
- 125ºC/W × 0.475W / 1.9 = 31.3ºC temperature rise
- Ambient temperature is 13.6ºC.
- IC temperature is 31.3 + 13.6, which is equal to approximately 44.9ºC (thermal camera is showing 45.4ºC max).

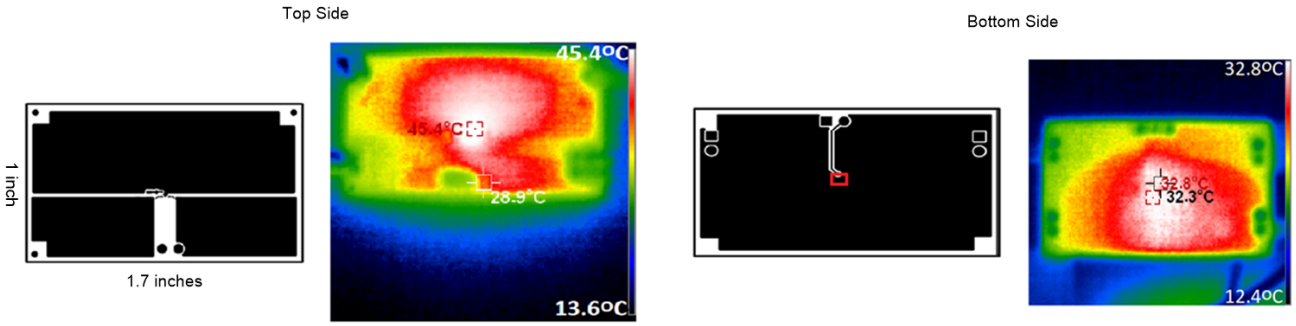

Figure 3. TLV71312PEVM-171 Linear Regulator Evaluation Kit Thermal Performance

Copyright © 2020, Texas Instruments Incorporated

3.1.2 LP5907UV-1.2EVM Evaluation Kit

- Power dissipation is (5 Vin – 1.2 Vout) × 125 mA = 475 mW.
- Bottom side is 1.0 x 0.7 (blue rectangle) + ½(0.75 × 0.7)(blue triangle) = 1.0 sq in.
- Top side area is 0.6 x 1.5 = 0.9 sq in.
- Total area is approximately 1.9 sq in.
- 1-oz copper
- 125ºC/W × 0.475 W / 1.9 = 31.2ºC temperature rise
- Ambient temperature is 13.5ºC.
- IC temperature is 31.2 + 13.5, which is equal to approximately 44.7ºC (thermal camera is showing 44.5ºC max).

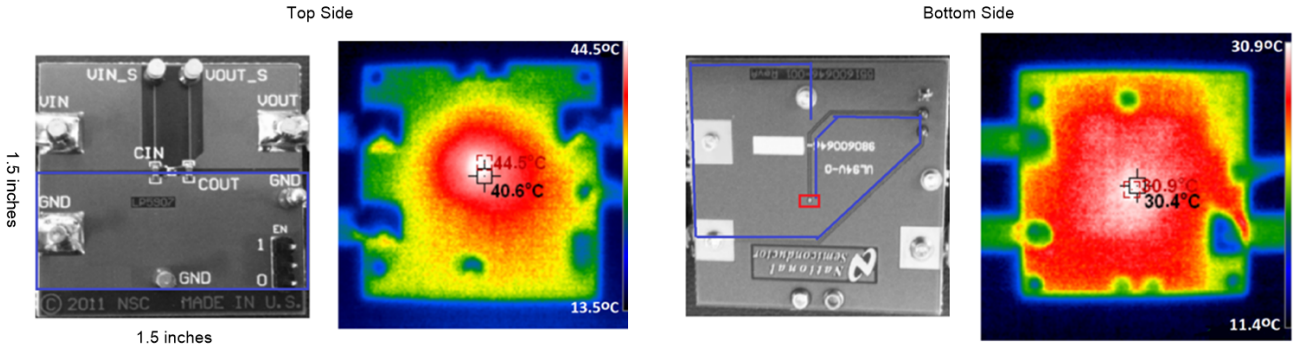

Figure 4. LP5907UV-1.2EVM Linear Regulator Evaluation Kit Thermal Performance

These two examples have fairly simple PCB shape and show good correlation to the equations. Section 3.2 shows some more complicated board construction.

It makes sense at this time to look closer at a cut in a copper pour. Figure 5 shows an example of a 1-inch wide pour with a 0.030-inch gap (which is equal to half the thickness of the PCB). Heat must flow through the FR4 material in this case. From the following calculations, you get a whopping 72°C/W from just this small cut in the plane [1].

$R = l / (\sigma \times w \times t)$

where

- R = thermal resistance
- l = length
- σ = thermal resistivity constant, FR4 = 0.007
- w = width, t = thickness (1)

$R = 0.030 / (0.007 \times 1 \times 0.060) = 72°C/W$ (2)

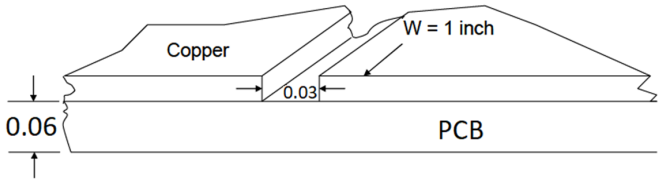

Figure 5. Gap Thermal Resistance Significantly Adds to Temperature Rise Due to Heat Flowing Through PCB Material

Copyright © 2020, Texas Instruments Incorporated

3.2 LM5069 Evaluation Kits

The LM5069 is a hot swap controller. As you can see in Figure 6, layer 2 has as much ground pour as possible, and in this case, the engineer is not able to directly connect the MOSFET thermal pad to ground. Instead, the engineer made the smart decision to rely on the thermal transfer through the PCB to the bottom layer. In this case, you need to add in a 10ºC/W temperature difference from the top side to the bottom side. The blue rectangular box on the bottom side shows the effective thermal relief in relation to the IC.

- Power dissipation is (31.15 Vin – 30.86 Vout) × 6 A = 1.74 W.
- Bottom side is 1.3 × 2.3 = 3.0 sq in.
- Top side area is 1.4 × 0.2 = 0.28 sq in.
- Total area is approximately 3.3 sq in.
- 2-oz copper
- 100ºC/W × 1.74W / 3.3 equals a 47.0ºC temperature rise.
- Ambient temperature is 15.8ºC.
- +10ºC/W power transfer to the back side of board is 10ºC/W × 1.74 W = 17.4ºC temperature rise.
- IC temperature is 52.7 + 15.8 + 17.4, equal to approximately 86ºC (thermal camera is showing 84.1ºC max).

Considering Figure 6, the calculations are similar to the results you see on the thermal camera.

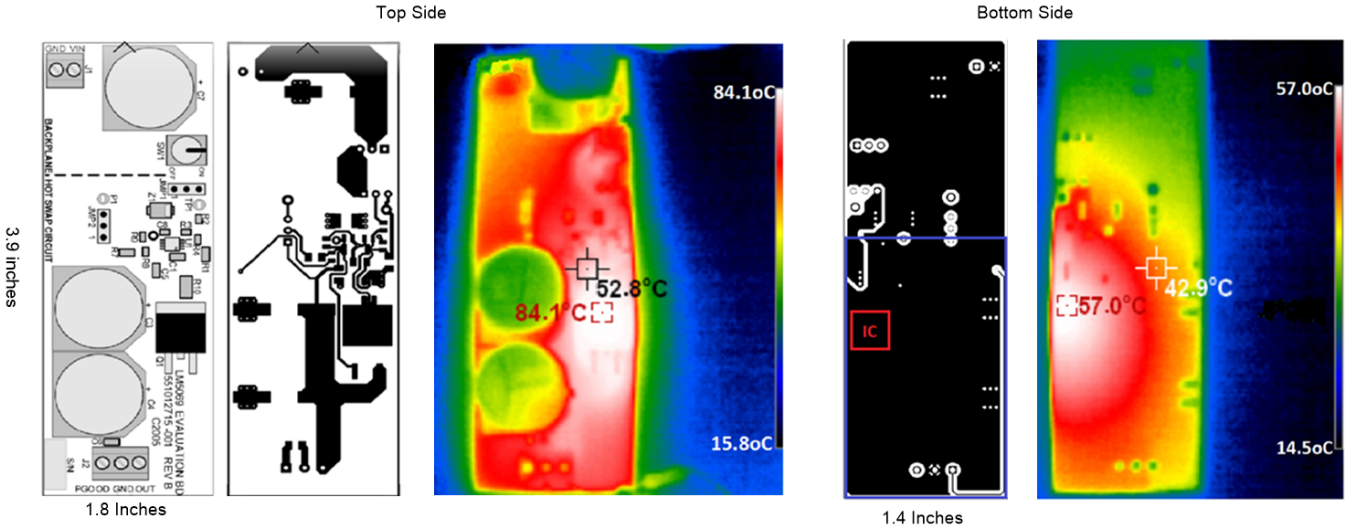

Figure 6. LM5069 (AN-1522) Hot-swap Controller Evaluation Kit Thermal Performance

Copyright © 2020, Texas Instruments Incorporated

3.2.1 LM5069EVM-627 Evaluation Kit

Take a look at a different version of the LM5069 evaluation kit with a different layout. In this case, the bottom side copper pour is cut by traces, limiting the cooling area for the IC (outlined in blue).

- Power dissipation is (29.94 Vin – 29.60 Vout) × 4 A = 1.36 W (note MOSFET Q2 was shorted to only have power dissipated in the main MOSFET Q1).
- Bottom side is 1.4 × 2 = 2.8 sq in.
- Top side area is 0.5 sq in.
- Total area is 3.3 sq in.
- 1-oz copper
- 125ºC/W × 1.36W / 3.8 = 45ºC temperature rise
- Ambient temperature is 18.3ºC.
- +10ºC/W power transfer to the back side of board is equal to 10ºC/W × 1.36 W = 13.6ºC temp rise. Since approximately 20% of PCB area is top side, you would expect 80% × 13ºC = 11ºC.
- IC temperature is 44.7 + 18.3 + 11, which is equal to approximately 74ºC (thermal camera is showing 73.8ºC max).

Looking at Figure 7, the calculations are similar to the results you see on the thermal camera.

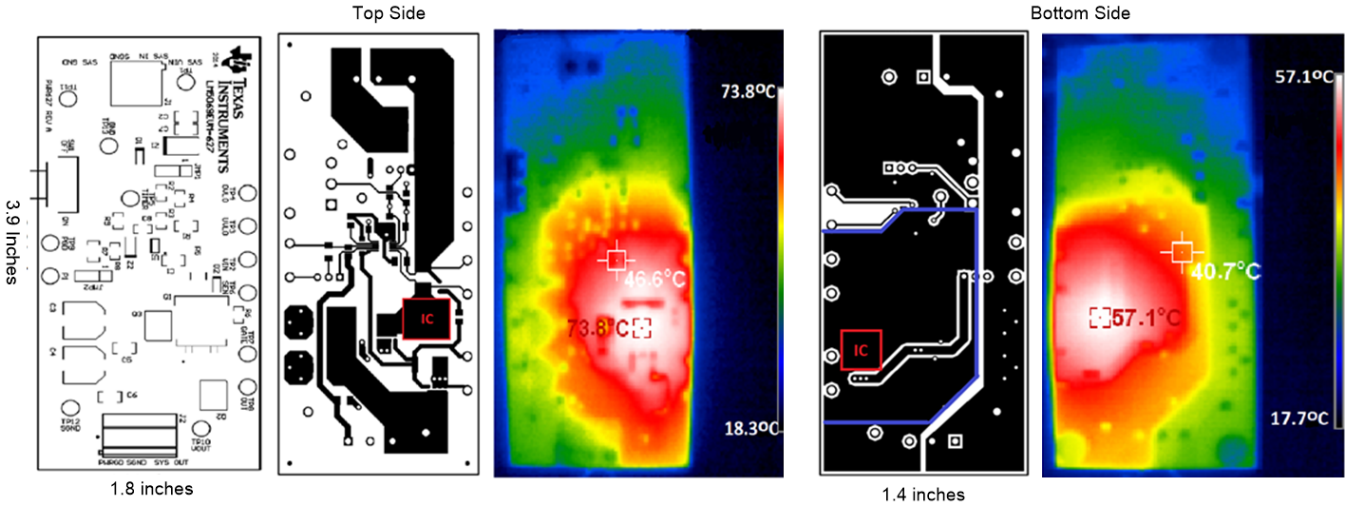

Figure 7. LM5069EVM-627 Hot-swap Controller Evaluation Kit Thermal Performance

Copyright © 2020, Texas Instruments Incorporated

3.3 TPS25942EVM-635 Evaluation Kit

Take a look at an E-fuse device which integrates high-side back-to-back MOSFETs. In this example, you see even more how the heat is trapped by the small copper pour island on the bottom side. Additionally, there is minimal overlapping of copper pours so heat does not spread across the PCB.

- Power dissipation is (14.67 Vin – 14.41 Vout) × 5 A = 1.3 W.
- Bottom side is 1.2 × 1.2 = 1.5 sq-in (estimated slightly larger than the pour directly under the IC).
- Top side area is 0.9 × 2.0 = 1.8 sq in.
- Total area is 3.3 sq in.
- 2-oz copper
- 100ºC/W × 1.30W / 3.3 = 39ºC temperature rise
- Ambient temperature is 24.4ºC.
- +10ºC/W power transfer to the back side of board is equal to 10ºC/W × 1.30 W = 13.0ºC temperature rise. Since approximately 50% of PCB area is top side, you would only expect 50% × 13ºC = 6.5ºC.
- IC temp is 39 + 24.4 + 6.5, equal to approximately 70ºC (thermal camera is showing 63.8ºC max).

Looking at Figure 8, it is very difficult to estimate the thermal dissipation area of this evaluation module. One thing you can see is how concentrated the heat is under the IC due to cuts in the bottom layer.

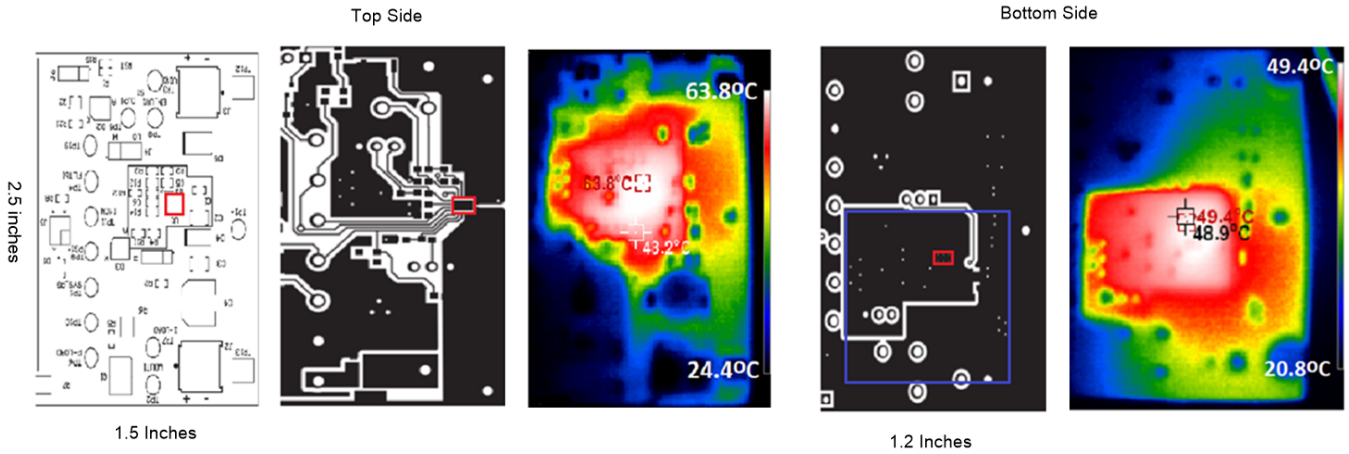

Figure 8. TPS25942EVM-635 Electronic Fuse Evaluation Kit Thermal Performance

Copyright © 2020, Texas Instruments Incorporated

3.4 LMZM23601V3EVM Evaluation Kit

As your final example, take a look at a power module. The LMZM23601 is a 36-Vin DC/DC buck module with integrated inductor in a 3-mm× 3.8-mm package. This was tested at 24 Vin and 3.3 Vout fixed voltage with 1 A of output current, since the data sheet had an efficiency estimate of 79% in this operation condition. These calculations are easy since you do not have to estimate power loss in discrete components like the MOSFETs, diodes, or inductor. Take a look at how the heat transfers to the PCB in this case.

- Power delivered is 3.3 V × 1 A = 3.3 W.
- Bottom side is 2.4 x 1.7 in = 4.1 sq in.
- Top side area is 1.5 x 1.1 in = 1.65 sq in.
- Power in is 3.3 W / 0.79 = 4.2 W input.
- Power dissipation is Pin – Pout = 0.9 W.
- 4-layer board with 1-oz copper on each layer
- Total area is 5.7 sq-in on PCB, so once you get your 0.9 W to the top side of the PCB, you only have a 19.7ºC temp rise equal to 125ºC/W × 0.9 W / 5.7 sq-in.
- +10ºC/W power transfer to back side of board equals 10ºC/W × 0.9 W, which is equal to a 9.0ºC temperature rise. Since approximately 70% of PCB area is bottom side, you would expect 70% × 9ºC = 6.3ºC (thermal camera is showing 4.0ºC temperature rise = 42.0ºC – 38.0ºC).
- Three thermal vias are connected, PCB (100ºC/W / 3_VIAs = 33ºC/W × 0.9 W = 29.7ºC) yields an expected 29.7ºC temperature rise. Thermal camera displays a 20.9ºC temperature rise = 62.9ºC IC temperature – 42ºC PCB temperature next to module. Actually, there are three vias on either side of the IC thermal pad (six total) that help transfer heat as well. From these equations, you can see that these six outside vias equate to approximately two additional thermal via directly under the package itself.
- Ambient temperature is 16.1ºC.
- IC temp is 29.7 +19.7 + 6.3 + 16.1, which is equal to approximately 71.9ºC (thermal camera is showing 65.8ºC max.)

Looking at Figure 9, you can see you get effective heat spreading across the PCB due to layer 2 and the bottom layer being complete GND copper pours. The top side can use copper pours as well, but there are cuts in the plane pours to connect Vin, Vout, and GND to the right. You can see how the heat gets trapped at those interfaces. On the bottom side, you can see heat spreading to all edges of the board.

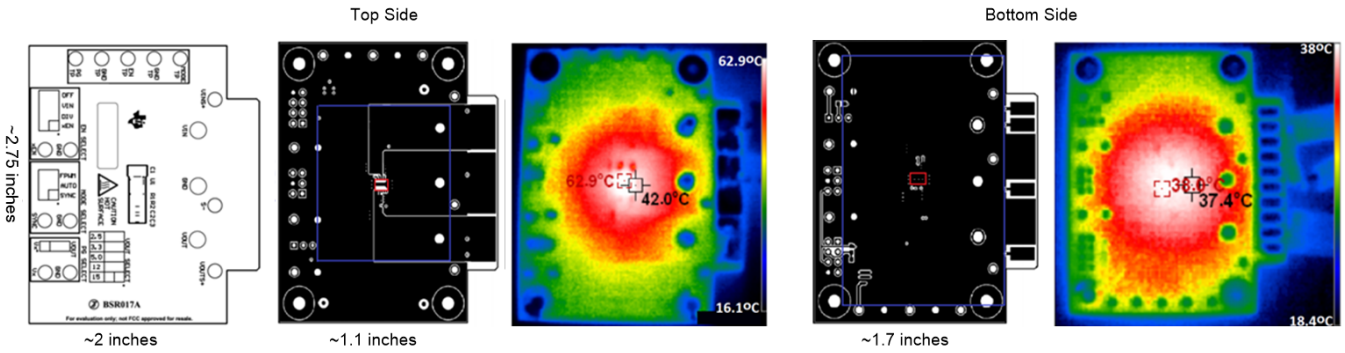

Figure 9. LMZM23601V3EVM DC/DC Module Evaluation Kit Thermal Performance

Copyright © 2020, Texas Instruments Incorporated

4 Conclusion

There are many times in an engineer's career where they need a simple way to estimate temperature rise in a circuit. The back of the napkin thermal rule is simple to remember: 1 watt dissipated in 1 square inch of 2-oz copper causes a 100ºC temperature rise (specifically for heat transfer from a part mounted on a PCB with only convection cooling). From this discussion on estimating the PCB cooling as well as showing thermal camera images, you can make an informed decision on how much copper pour area you need in your system and how best to use it.

5 References

1. Texas Instruments, *Constructing Your Power Supply — Layout Considerations Application Report*
2. *EE Times, Power Tip #9: Estimating Surface Mounted Semiconductor Temperature Rise*

Copyright © 2020, Texas Instruments Incorporated

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATA SHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, regulatory or other requirements.

These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI’s products are provided subject to TI’s Terms of Sale or other applicable terms available either on ti.com or provided in conjunction with such TI products. TI’s provision of these resources does not expand or otherwise alter TI’s applicable warranties or warranty disclaimers for TI products.

TI objects to and rejects any additional or different terms you may have proposed.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2022, Texas Instruments Incorporated