TND6410/D
Rev. 3, July – 2023

Cooling Concept Assessment for High Power Step–Down Conversion

July, 2023 – Rev. 3
Publication Order Number:
TND6410/D

Cooling Concept Assessment for High Power Step−Down Conversion

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Introduction

In an era where autonomous driving is the next big thing for all automotive OEMs, the number of electronic control units (ECUs) within a vehicle has dramatically increased. These cover various applications such as driver assist cameras, data fusion ECU, as well as their respective power consumption. Depending on the application and the scope of operation, the output power of the pre−regulator can range from the single−digit watt range for a park assist ECU, to one hundred watts or more for a data fusion ECU. This white paper aims to convey the underlying significance of using a heat sink to reduce thermal stress on electronic devices and the dependency of system thermal performance on various factors such as the position and size of the heat sink.

We will first describe the setup used to perform the measurements, a brief overview of the test board, and the various heat sinks used for experimentation. We will present the measurements, highlighting the effects of using a heat sink when designing high−output power pre−regulators.

Setup

Figure 1 depicts the setup used in the thermal evaluation of the test board, consisting of the following instruments:

- Power Supply Toellner TOE8872
- Electronic Load Prodigit 3311C
- Power Analyzer Fluke Norma 5000
- Keysight Multichannel Data Logger 34970A
- Device Under Test (DUT)

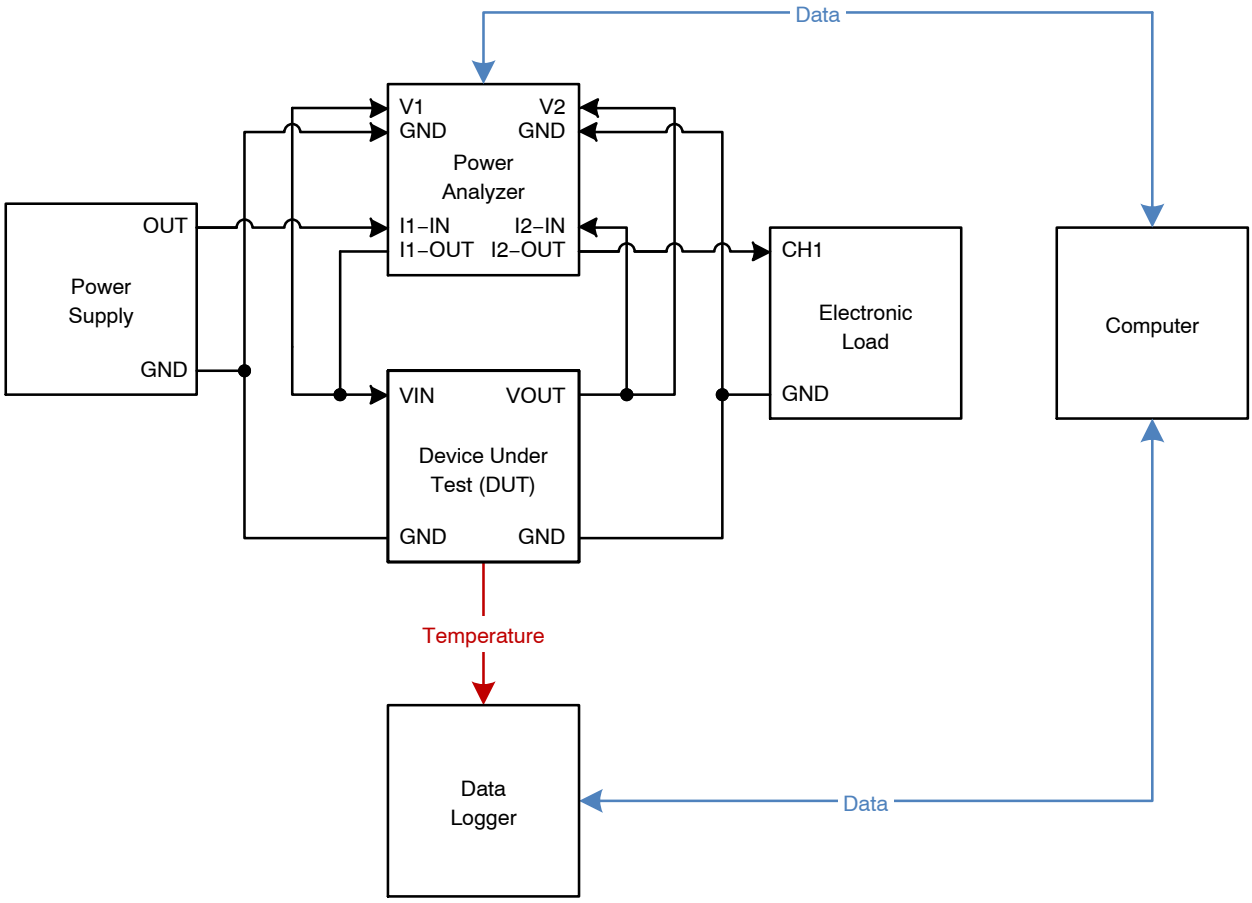


Figure 1. Test Setup

The current flows from the power supply OUT port to the power analyzer input current port I1−IN, where the power analyzer measures it. Then it flows out of the power analyzer through I1−OUT to the VIN port of the Device−Under−Test (DUT). The power analyzer V1 is connected to the DUT VIN port to measure the input voltage. The GND of the power supply connects to the GNDs of the DUT and power analyzer.

On the output side, the current flows from the DUT VOUT port to the power analyzer input current port I2−IN, where the power analyzer measures it. Then it flows out of the power analyzer through I2−OUT to the CH1 port of the DC Electronic Load, where the DUT load current is set. The power analyzer V2 is connected to the DUT VOUT port to measure the output voltage. The GND of the power analyzer connects to the GNDs of the DUT and DC electronic load.

The power supply has a sensing feature that keeps the voltage supplied to the DUT constant (compensates cable losses) and protects sensitive loads if there is a break in a sensor line. The data logger measures the temperature of different ICs components on the DUT.

The complete system is fully automated to ensure precise and reproducible results. Python−based software controls the entire setup, from setting the input voltage and the output load to measuring the component's temperature and calculating the overall system efficiency. Figure 2 shows the GUI of the software.

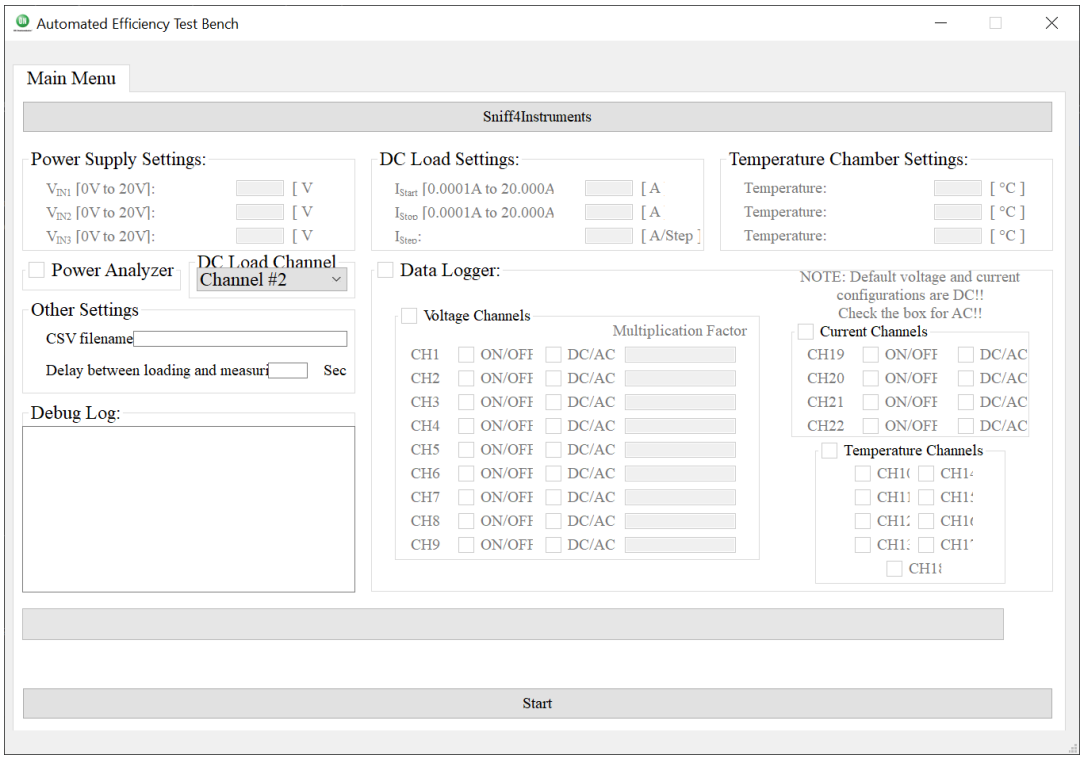


Figure 2. Software GUI

Test Board and Heat Sinks

To estimate the performance and impact of the different heat sinks, we designed a dedicated board based on the 100 W Automotive Pre−Regulator Design with the PCB optimized for thermal assessment. Figure 3 shows the schematic of the synchronous buck converter with an output voltage of 5 V and an output current capability of up to 20 A. The automotive buck controller NCV881930 has a fixed switching frequency of 410 kHz. It drives two automotive−qualified 40 V MOSFETs NVMFS5C460NL (SO−8FL with bottom side exposed pad) in parallel on the high−side (HS) as well as on the low−side (LS) of the buck converter to enable high output currents up to 20 A.

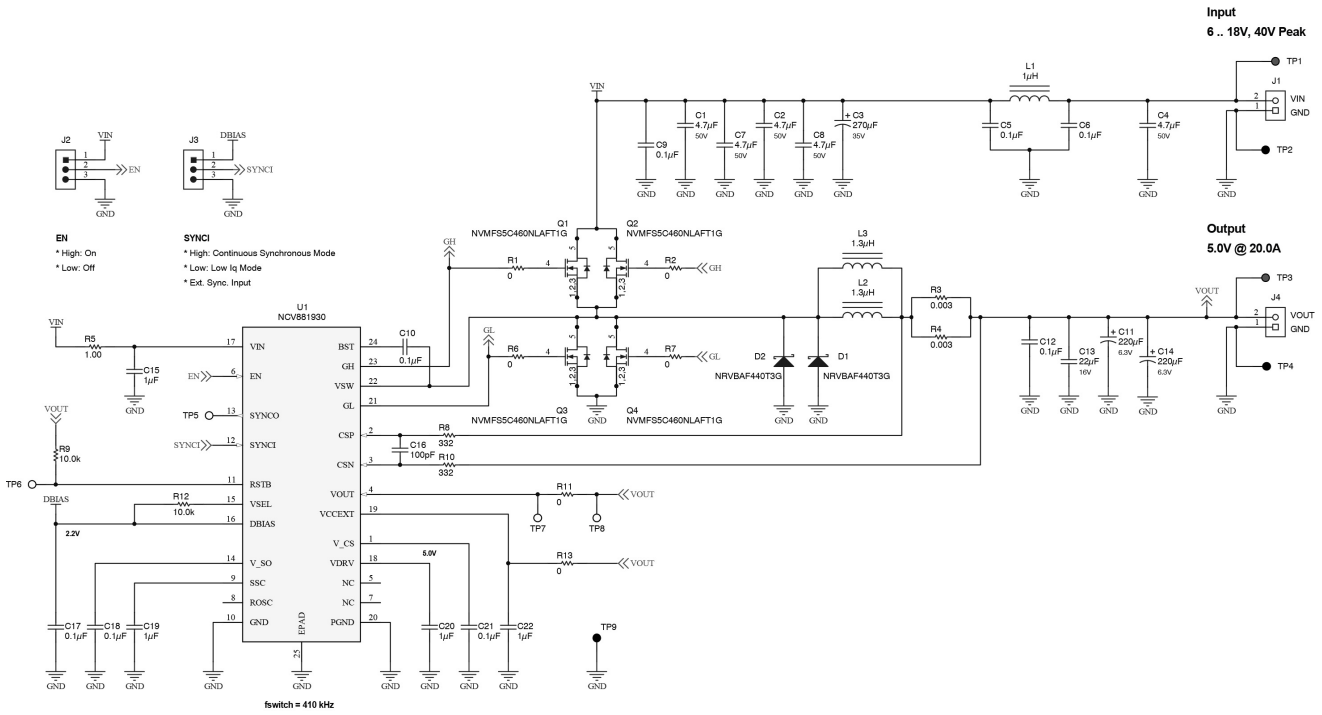


Figure 3. Test Board Schematic

The following implemented modifications of the layout enable the thermal evaluation of the board:

- Increased total PCB size to allow mounting of a 50 mm x 50 mm heat sink on the top and bottom sides of the PCB.
- Provided mounting holes for the heat sink.
- Provided an additional footprint for the inductor on the bottom side of the PCB.

Figure 4 and Figure 5 show the top and bottom sides with the possibility of mounting a heat sink on the top and bottom sides of the PCB.

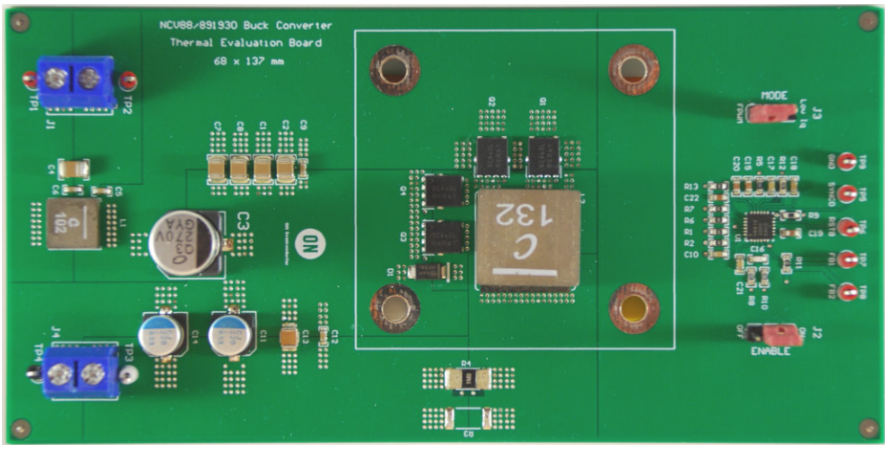


Figure 4. DUT Top Side

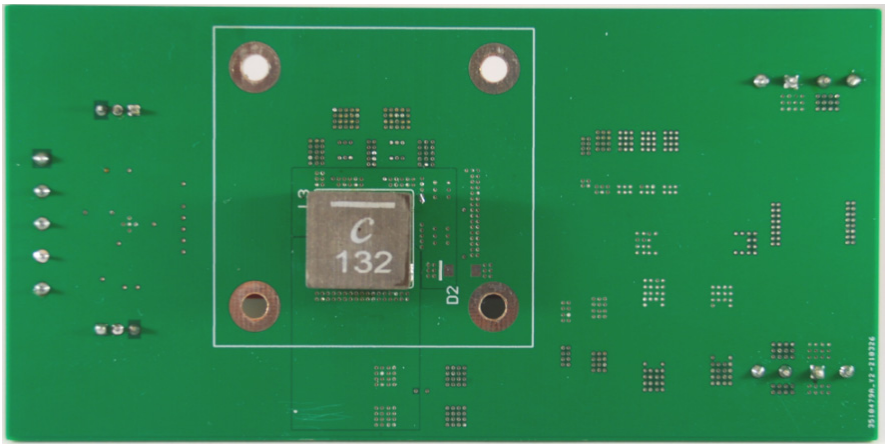


Figure 5. DUT Bottom Side

With the above configuration, three different test setups are possible and have been analyzed:

Table 1. TEST SETUPS

Setup	Placement MOSFETs	Placement Inductor	Placement Heat Sink
#1	Top	Top	No heat sink
#2	Top	Bottom	Top (on MOSFETs)
#3	Top	Top	Bottom (on PCB)

The proper and replaceable mounting of the heat sink to the PCB is the most challenging part from a mechanical perspective. For any configuration, it is essential to have a film gap pad between the heat sink and the heat−emitting surface to achieve good thermal conductivity. The emitting surface, like the PCB or the package of the MOSFET, is never perfectly flat and parallel to the heat sink, so the gap pad ensures a good and laminar interface between both. Material selection plays an important role, significantly impacting thermal performance. For example, a

material that needs to withstand a high voltage will always have a considerably higher thermal resistance than a material based on graphite, which is electrically conductive.

For the test setup KERAFOL “SOFTTHERM” material with a thickness of 0.5 mm is selected, see Table 2. All measurements are performed with the 3.0 W/(m·K) material, which has a thermal resistance of 0.41 K/W. The 6.0 W/(m·K) material (thermal resistance of 0.20 K/W) is used only once to compare of both materials at the end of this white paper.

Table 2. FILM GAP PADS

Material	Thermal Conductivity	Thermal Resistance	Thermal Impedance	Thickness	Breakdown Voltage
86/300 SOFTTHERM	3.0 W/(m·K)	0.41 K/W	164 (K·mm^2)/W	0.5 mm	7.0 kV
86/600 SOFTTHERM	6.0 W/(m·K)	0.20 K/W	80 (K·mm^2)/W	0.5 mm	1.5 kV

- Thermal conductivity is a material property and is not geometry dependent (i.e. shape or size). It describes internal heat conduction ability and is a helpful parameter when comparing different materials.
- Thermal resistance describes how a material with a certain thickness resists the heat flow. As the thickness is directly related to the thermal resistance, a thinner material has a better heat transfer than a thicker material.
- Thermal impedance depends on the shape or size, thickness, and pressure. It is a more realistic value as all variables, like the flatness of the surface, pressure, etc., are considered for a specific application.

The torque applied to attach the heat sink also contributes to the thermal impedance. Generally, the higher the compression, the lower the thermal resistance. This is because the compression reduces the overall thickness and increases the denseness of the material. Both factors improve heat conductivity. 86/300 SOFTTHERM material with 5 mm thickness has a thermal resistance of 4.1 K/W at zero pressure. A pressure of 30 N/cm^2 results in a thickness of 3.7 mm, and the thermal resistance is reduced to 3.0 K/W. The thinnest version of this material has a thickness of 0.5 mm. In that case, the material can be compressed to 0.3 mm when applying the maximum pressure of 30 N/cm^2. At the same time, the thermal resistance drops from 0.4 K/W to 0.25 K/W. Too high pressure can damage the film gap pad, e.g., leak out. For example, for the 86/300 SOFTTHERM, the compression should not exceed 30% of the original thickness.

For the test setup, the absolute value of the pressure is not essential as long as too high torque or pressure does not damage the film gap pad and the mechanical setup. The most crucial point is that the pressure must be the same for each heat sink and setup; otherwise, the results will not be comparable. As previously explained, the relationship between pressure and thermal resistance shows clearly that pressure significantly impacts the complete system’s thermal

performance. Considering a film gap pad with a thickness of 0.5 mm, the thermal resistance increases by 60% from the maximum pressure of 30 N/cm^2 down to zero pressure.

A relatively simple yet reliable setup, usually used for mounting heat sinks on computer's CPUs, is based on springs. In such a mechanical setup, the screws hold springs in place, which presses the heat sink onto the top of the CPU. The pressure depends on the elastic force of the springs, not on the torque of the screws, as those apply no pressure on the heat sink or CPU.

Figure 6 shows the setup with the heat sink mounted to the PCB. Inductor and MOSFETs are placed on the bottom side – the heat dissipates through the PCB to the heat sink. Numerous vias are placed around the hot spots of the PCB to reduce the thermal resistance of the PCB and improve the vertical heat flow in the PCB. The film gap pad between the heat sink and PCB levels out any roughness and unevenness to minimize the thermal resistance. The heat sink has threads for the screws that keep the heat sink and springs in place. The springs are gently pre−stressed by the screws that cause the heat sink to press onto the PCB. The length of the compressed spring is proportional to its force and all four springs need to have the same length to achieve the same pressure for each fixation. Using the same spring length and mechanical force for each setup ensures replicable and comparable results.

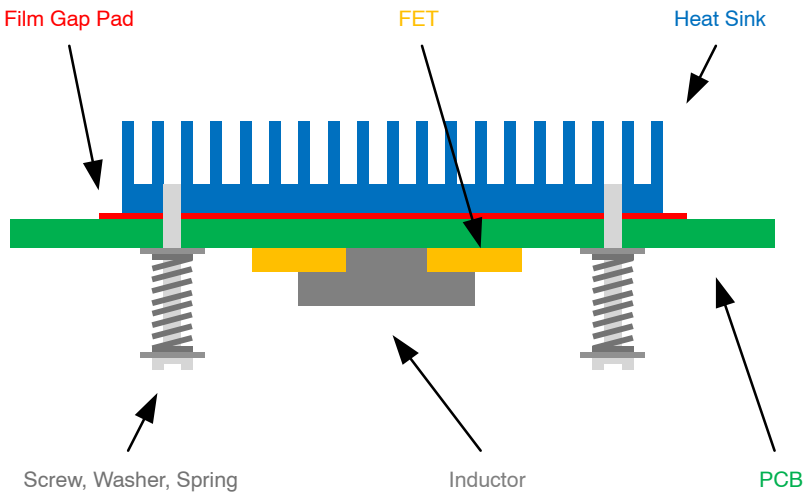


Figure 6. Heat Sink on PCB

Figure 7 shows the configuration with the heat sink on top of the MOSFETs. The setup is the same; just the inductor is placed on the bottom side to allow mounting the heat sink on top of the MOSFETs.

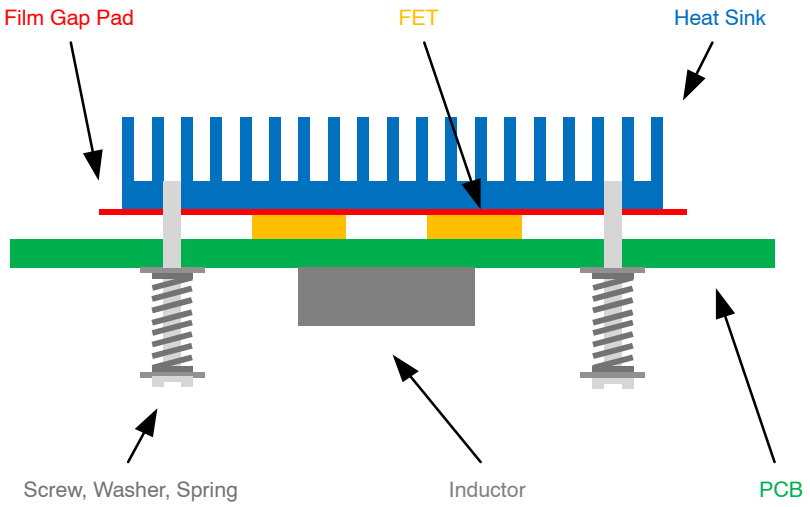
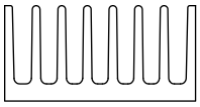
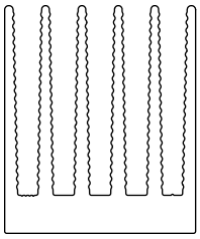


Figure 7. Heat Sink on MOSFETs

Three different heat sinks with a base area of 50 x 50 mm from Fischer Elektronik have been used for the measurements, see Table 3.

Table 3. HEAT SINK OVERVIEW

Part Number	Thermal Resistance	Height	Drawing
SK 548 50 SA	7.4 K/W	10 mm	
SK 567 50 SA	4.0 K/W	25 mm	
SK 527 50 SA	2.5 K/W	60 mm	

They have been selected such that there is a significant difference between their respective thermal resistances given their respective heights. With each increasing height, the thermal resistance becomes smaller by roughly a factor of two. This should help to clearly distinguish the thermal performance due to the different heat sinks.

Power Split Between the MOSFETs

It is crucial to understand the following measurements to bring the losses, and loss split distribution between the HS and LS MOSFETs into the proper context. Therefore, all MOSFET−related losses are calculated to get an understanding of the main contributors. Placing a Schottky diode parallel to the LS MOSFET prevents reverse recovery losses, and the dead time losses shift from the LS MOSFET to the Schottky diode.

Table 4 parameters used to calculate the losses.

Table 4. PARAMETERS FOR LOSS CALCULATION

Parameters	Value	Notes
U_{in}	12.0 V	Input voltage
U_{out}	5.0 V	Output voltage
I_{out}	20.0 A	Output current
$I_{L,min}$	19.83 A	Minimum inductor current at 20.0 A load
$I_{L,max}$	20.17 A	Maximum inductor current at 20.0 A load
η	92.2%	Efficiency
f_{sw}	410 kHz	Switching frequency
t_{dead}	20 ns	Typical dead time between HS and LS MOSFET switching of NCV881930 buck controller
R_{shunt}	1.5 mΩ	Current sense resistor
$R_{ds(on)}$	5.8 mΩ	Typical on−resistance at 4.5 V gate−source voltage
C_{oss}	800 pF	Typical output capacitance at 12.0 V drain−source voltage
$V_{f,SK}$	0.485 V	Forward voltage of the Schottky diode

Output Power

$$P_{out} = U_{out} \cdot I_{out} = 5.0\ V \cdot 20.0\ A = 100.000\ W \quad \text{(eq. 1)}$$

Input Power

$$P_{in} = \frac{P_{out}}{\eta} = \frac{100.0\ V}{0.922} = 108.500\ W \quad \text{(eq. 2)}$$

Total Losses

$$P_{loss,total} = P_{in} - P_{out} = 108.5\ W - 100.0\ W = 8.500\ W \quad \text{(eq. 3)}$$

Shunt Losses

$$P_{shunt} = I_{out}^2 \cdot R_{shunt} = (20.0\ A)^2 \cdot 1.5\ m\Omega = 0.600\ W \quad \text{(eq. 4)}$$

Inductor Losses

$P_{inductor}$ = 0.600 W (Coilcraft web tool for XAL1580−132ME)

HS MOSFET Conduction Losses

$I_{HS,RMS,single}$ = 6.5 A (for single MOSFET, 13.0 A for both MOSFETs in parallel)

$$P_{HS,conducted,single} = I_{HS,RMS,single}^2 \cdot R_{ds,on} = (6.5\ A)^2 \cdot 5.8\ m\Omega = 0.245\ W \quad \text{(eq. 5)}$$

$$P_{HS,conducted,total} = 2 \cdot P_{HS,conducted,single} = 2 \cdot 0.245\ W = 0.490\ W \quad \text{(eq. 6)}$$

LS MOSFET Conduction Losses

$I_{LS,RMS,single} = 7.7$ A (for single MOSFET, 15.4 A for both MOSFETs in parallel)

$$P_{LS,conducted,single} = I^2_{LS,RMS,single} \cdot R_{ds,on} = (7.7\ A)^2 \cdot 5.8\ m\Omega = 0.344\ W \quad \text{(eq. 7)}$$

$$P_{LS,conducted,total} = 2 \cdot P_{LS,conducted,single} = 2 \cdot 0.344\ W = 0.688\ W \quad \text{(eq. 8)}$$

Dead Time Losses with Schottky Diode

During the current transition from the HS to the LS MOSFETs and vice versa, all MOSFETs are off for a specific time called “dead time”. During this short time (20 ns typical), the current flows through the body diodes of the LS MOSFETs. If an additional Schottky diode is placed parallel to the LS MOSFETs, the current during the dead time flows through the Schottky diode due to its lower forward voltage (0.485 V typical) compared to the body diodes (0.86 V typical). The main benefit of an additional Schottky diode is to avoid the reverse recovery losses of the body diodes, as a Schottky diode has no reverse recovery losses. Dead time losses due to the forward voltage drop appear then on the Schottky diode and have to be considered for $I_{L,MIN}$ (switching LS MOSFET off) and $I_{L,MAX}$ (switching LS MOSFET on).

$$P_{LS,deadtime} = V_{f,SK} \cdot t_{dead} \cdot f_{sw} \cdot \left(I_{L,min} + I_{L,max}\right) = 0.485\ V \cdot 20\ ns \cdot 410kHz \cdot (19.83\ A + 20.17\ A) = 0.160\ W \quad \text{(eq. 9)}$$

Capacitive Losses

The HS MOSFET’s output capacitance is charged during toff to (V_{in} – V_f). By switching the MOSFET on, the on−resistance shortens the output capacitance; hence, the stored energy is converted into heat.

$$P_{COSS} = \frac{1}{2} \cdot C_{OSS} \cdot \left(V_{in} - V_{f,SK}\right)^2 \cdot f_{sw} = \frac{1}{2} \cdot 800 \cdot\ pF \cdot (12.0\ V - 0.485\ V)^2 \cdot 410\ kHz = 0.022\ W \quad \text{(eq. 10)}$$

Capacitive losses are minimal compared to the other losses and therefore neglected in the following calculations.

Switching Losses

Switching losses are hard to estimate as they depend on complex parameters, such as the parasitic inductance of the gate driver traces. Therefore a different approach is used in this case to determine them. The total switching losses are left if all the known and calculated losses are subtracted from the total losses. Of course, there are also some losses due to the copper resistance of the PCB, but as they are not known and not dominant, they will be neglected as well.

$$P_{switching,total} = P_{loss,total} - P_{shunt} - P_{inductor} - P_{HS,conducted,total} - P_{LS,conducted,total} - P_{dead}$$

$$P_{switching,total} = 8.500\ W - 0.600\ W - 0.600\ W - 0.490\ W - 0.688\ W - 0.160\ W = 5.962\ W \quad \text{(eq. 11)}$$

Due to the almost zero voltage switching of the LS MOSFET (drain−source voltage equals the diode forward voltage when the MOSFET switches on and off), most of the calculated switching losses are due to the HS MOSFET.

HS MOSFET Total Losses

$$P_{HS,total} = P_{HS,conducted,total} + P_{switching,total} = 0.490\ W + 5.962\ W = 6.452\ W \quad \text{(eq. 12)}$$

LS MOSFET Total Losses

$$P_{LS,total} = P_{LS,conducted,total} = 0.688\ W \quad \text{(eq. 13)}$$

The HS MOSFETs have tremendously higher total losses than the LS MOSFETs based on the calculations above, leading to the assumption that the temperature increase of the HS MOSFETs is much higher than the temperature increase of the LS MOSFETs. Figure 8 shows that the LS MOSFETs have less than 1.0 W losses at all load currents, whereas the HS MOSFETs have more than 6.0 W losses at 20.0 A load current.

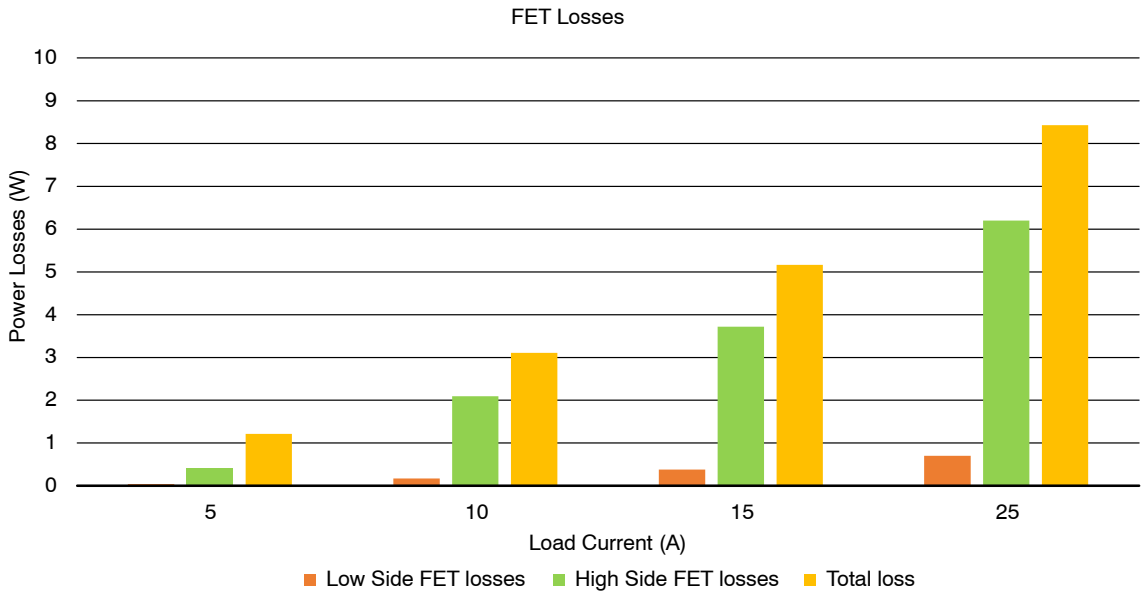


Figure 8. MOSFET Losses

Measurement Preparation

Three configurations are used to assess the thermal performance of the board:

- Setup #1: Without the heat sink
- Setup #2: Heat sink on the top
- Setup #3: Heat sink on the bottom

The board is tested with the below electrical parameters (Table 5) for all three configurations; additionally, efficiency and total losses are measured at the given operating points.

Table 5. OPERATION POINTS

Input Voltage	Output Voltage	Output Current	Total Losses	Efficiency
12.0 V	5.0 V	5.0 A	1.2 W	95.3%
12.0 V	5.0 V	10.0 A	3.1 W	94.1%
12.0 V	5.0 V	15.0 A	5.1 W	93.5%
12.0 V	5.0 V	20.0 A	8.4 W	92.2%

Figure 9 shows the efficiency plot up to 20.0 A load current.

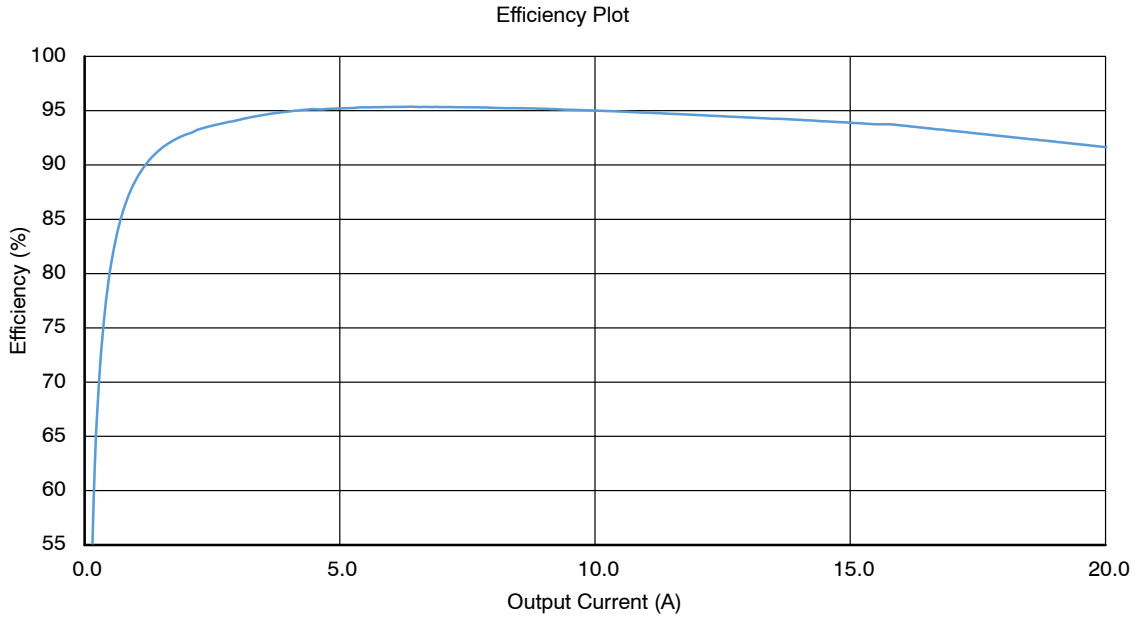


Figure 9. Efficiency Plot

Before performing the measurements, to ensure that the temperature across the MOSFETs is stable enough to get more accurate results, a few trial measurements are made to understand the time span after which the MOSFETs' temperature becomes steady. For all the measurements , the Type−K thermocouple and HERNON 746 SET−04 thermal adhesive are used to attach thermocouples to the MOSFETs and the PCB.

Additionally, before powering up the board, both thermocouples are attached to the MOSFETs and measured at room temperature to ensure they show the same temperature. At 24.0°C ambient temperature, the deviation between both sensors is less than 0.3°C, which is accurate enough for this evaluation.

Table 6 shows that the MOSFET's temperature settles to a stable value after around 20 to 25 minutes. Since the difference between 20 and 25 minutes is negligible, a time span of 20 minutes is chosen to compromise duration and accuracy in logging the temperature data between each measurement.

Table 6. TEMPERATURE PROFILE OVER TIME WITHOUT A HEAT SINK

Setup #1 – Without Heat Sink – V_{in} = 12 V, V_{out} = 5 V, I_{out} = 20 A		
Time−lapse	**Low−side MOSFET Temperature**	**High−side MOSFET Temperature**
5 minutes	71.3°C	79.5°C
10 minutes	77.8°C	85.0°C
15 minutes	80.7°C	85.1°C
20 minutes	81.6°C	86.6°C
25 minutes	81.8°C	87.0°C

Table 7 shows the temperatures with the 60 mm heat sink mounted on the bottom side of the PCB. The temperatures stabilize after around 25 minutes. As there is only a minimal temperature difference after 25, 30 and 35 minutes of measurement, 30 minutes is chosen to be the optimal time lapse between the measurements.

Table 7. TEMPERATURE PROFILE OVER TIME WITH 60 MM HEAT SINK

Setup #3 – With 60 mm Heat Sink on the Bottom Side – V_{in} = 12 V, V_{out} = 5 V, I_{out} = 20 A		
Time−lapse	**Low−side MOSFET Temperature**	**High−side MOSFET Temperature**
5 minutes	44.7°C	47.4°C
10 minutes	49.6°C	52.7°C
15 minutes	52.7°C	55.6°C
20 minutes	54.2°C	57.6°C
25 minutes	54.7°C	58.5°C
30 minutes	55.1°C	58.7°C
35 minutes	55.3°C	58.9°C

The previous section noted a significant difference between the losses of the HS and the LS MOSFETs. At 20.0 A load current, the power dissipation of the HS MOSFETs is around 6.5 W and approximately 0.7 W for the LS MOSFETs, basically one−tenth, leading to the assumption that the temperature difference between the HS and LS MOSFETs should also be significant. But as the measurements show, this isn't the case. The temperature of all MOSFETs is quite similar; the deviation is well below 10%.

The reason for that is the layout of the PCB, which is optimized for good thermal conductivity and dissipation. Numerous vias around the MOSFETs and large copper planes on the outer and inner layers (four−layer PCB, 35 μm copper thickness) effectively distribute the heat from the MOSFETs and spread it within the PCB. This leads to the effect that the LS MOSFETs with a very low power dissipation are heated up by the HS MOSFETs, which are the primary heat source of the board. The temperature difference between HS and LS MOSFETs indicates the different power loss levels. Still, as the difference isn't as large as one would expect, based on the loss estimation, this demonstrates the excellent thermal performance of the PCB.

Measurements

Setup #1 – Without a Heat Sink

No heat sink is mounted on the PCB and the thermocouples are placed on one of the HS and one of the LS MOSFETs using thermal glue as shown in Figure 10. The board has 5 A, 10 A, 15 A and 20 A load currents. After 20 minutes of loading the board with each load current, the data logger saves the temperature information from both thermocouples.

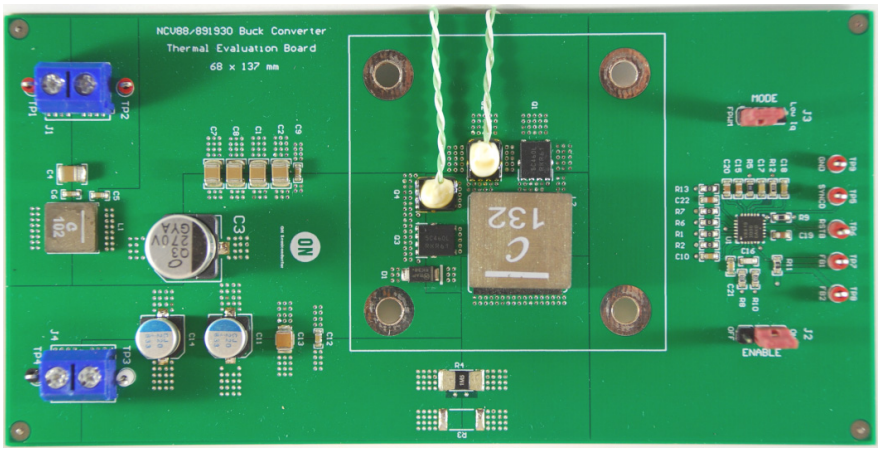


Figure 10. Setup #1 – Without Heat Sink

Table 8 shows the measurement results for the four different output currents.

Table 8. SETUP #1 – WITHOUT HEAT SINK

Output Current	Low−side MOSFET Temperature	High−side MOSFET Temperature
5.0 A	40.2°C	42.1°C
10.0 A	49.2°C	52.3°C
15.0 A	65.3°C	70.6°C
20.0 A	83.4°C	89.7°C

Figure 11 shows the graphical representation of the temperatures. Generally, the HS MOSFETs are getting slightly hotter than the LS MOSFETs. As the load current increases, also the temperature of both MOSFETs increase. The temperature increase from 5.0 A to 20.0 A is not linear, as the switching losses increase linearly but not the conduction losses ($P_{Conducted} = I_{RMS}^2 \cdot R_{DS,On}$).

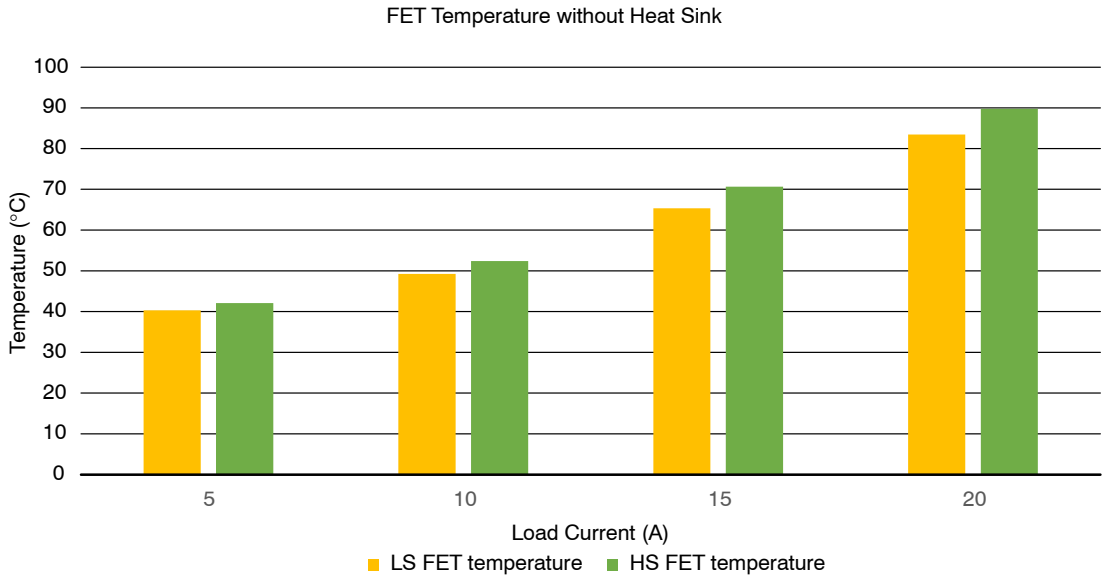


Figure 11. Setup #1 – Without Heat Sink

Setup #2 – Heat Sink on the Top Side

Figure 12 shows the board with a heat sink on the top side of the PCB. It is placed right on top of the HS and LS MOSFETs with a gap pad in between to avoid air gaps and compensate for any roughness to maximize the thermal conductivity. Measurements are done using 10 mm, 25 mm, and 60 mm fin height heat sinks with a 30−minute time lapse between each load current to understand the impact of thermal conductivity and heat dissipation. The heat sink is mounted using screws and springs from the bottom side of the PCB, as described in the previous section.

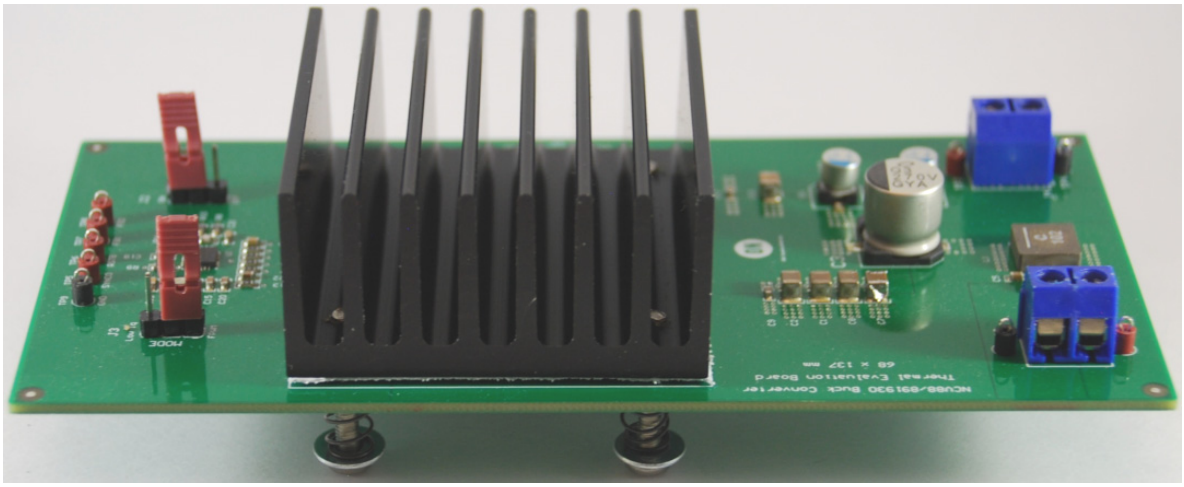


Figure 12. Setup #2 – Heat Sink on the Top Side

Placing the thermocouples on top of the MOSFETs would create an uneven surface for mounting the heat sink; hence they are placed between the HS and LS MOSFETs, as shown in Figure 13.

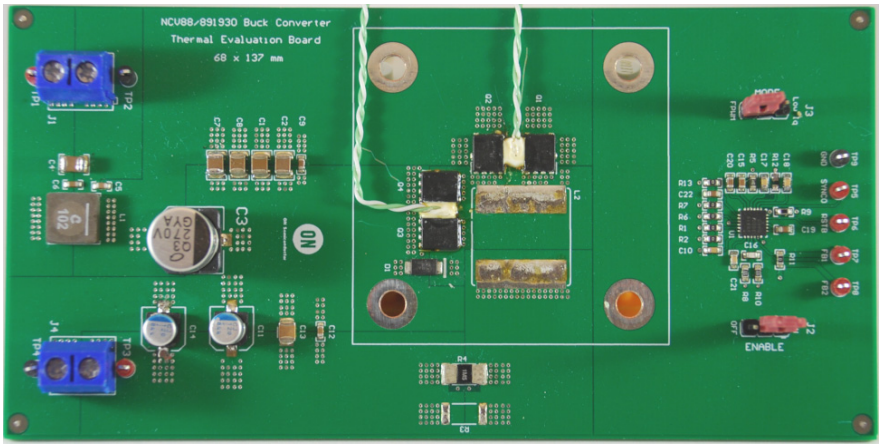


Figure 13. Placement of the Thermocouples

Table 9. SETUP #2 – 10 mm HEAT SINK ON THE TOP SIDE

Setup #2 – 10 mm Heat Sink on the Top−side – V_{in} = 12 V, V_{out} = 5 V		
Output Current	**Low−side MOSFET Temperature**	**High−side MOSFET Temperature**
5.0 A	37.0°C	37.5°C
10.0 A	45.9°C	46.0°C
15.0 A	58.0°C	58.1°C
20.0 A	75.1°C	75.2°C

Table 10. SETUP #2 – 25 mm HEAT SINK ON THE TOP SIDE

Setup #2 – 25 mm Heat Sink on the Top−side – V_{in} = 12 V, V_{out} = 5 V		
Output Current	**Low−side MOSFET Temperature**	**High−side MOSFET Temperature**
5.0 A	34.3°C	35.2°C
10.0 A	40.0°C	40.8°C
15.0 A	49.5°C	50.9°C
20.0 A	61.0°C	63.6°C

Table 11. SETUP #2 – 60 mm HEAT SINK ON THE TOP SIDE

Setup #2 – 60 mm Heat Sink on the Top−side – V_{in} = 12 V, V_{out} = 5 V		
Output Current	**Low−side MOSFET Temperature**	**High−side MOSFET Temperature**
5.0 A	34.1°C	34.7°C
10.0 A	39.1°C	40.2°C
15.0 A	45.7°C	47.4°C
20.0 A	53.8°C	57.1°C

With the 10 mm heat sink there is not much difference in the temperature between the HS and LS MOSFETs. But with the 25 mm and 60 mm heat sinks, a small but noticeable temperature difference between HS and LS MOSFETs can be observed. This difference increases with the height of the heat sink. The explanation for that behavior is that smaller heat sinks have a lower mass and higher thermal resistance. This leads to thermal saturation of the heat sink and the HS MOSFETs with the higher losses heat up the LS MOSFETs via the PCB due to its excellent thermal conductivity. This effect is also seen in the measurements in the previous section without a heat sink (Table 8).

By increasing the height of the heat sink and lowering the thermal resistance, the impact of one MOSFET on the other is reduced due to the better thermal conductivity of the heat sink. The heat takes the path of least resistance – the heat sink – and then dissipates to the ambient. Without a small heat sink, the heat is mainly distributed through the PCB, leading to similar temperatures for all MOSFETs, even though the power dissipation is different.

Figure 14 and Figure 15 show the significant impact of the heat sinks, especially at higher load currents. The LS MOSFETs at 20.0 A load current are around 30°C cooler with a 60 mm heat sink compared to the measurement without a heat sink. The HS MOSFETs are about 32°C cooler with a 60 mm heat sink compared to the measure without a heat sink.

For low load currents like 5.0 A, the thermal difference between the four setups is relatively low, with a maximum of 6°C, which makes the additional cost of a heat sink appear questionable.

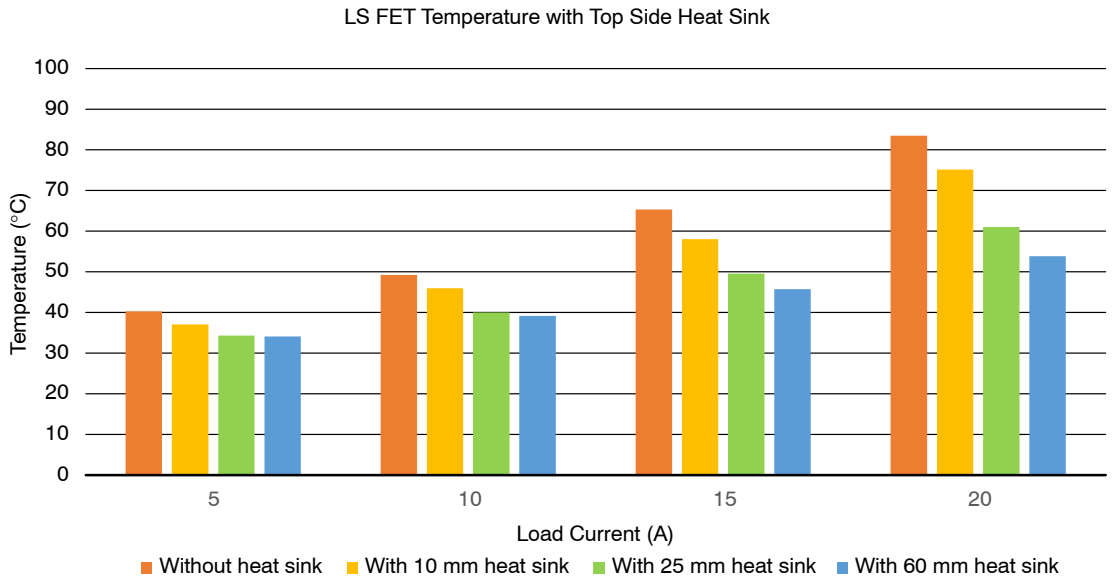


Figure 14. Setup #2 – LS MOSFET Temperature with Top−Side Heat Sink

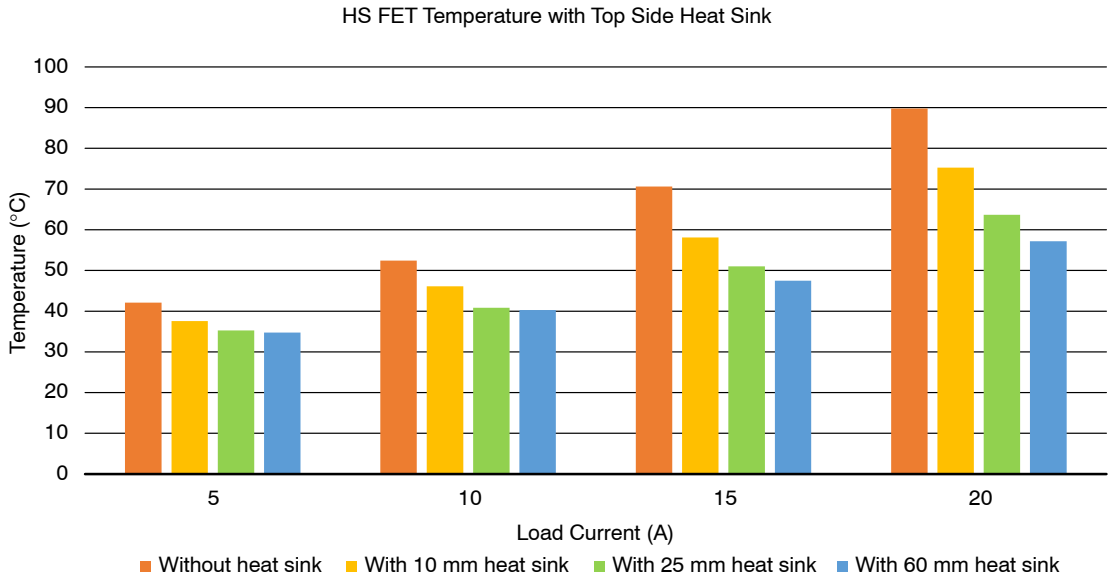


Figure 15. Setup #2 – HS MOSFET Temperature with Top−Side Heat Sink

Figure 16 and Figure 17 show the variation in temperatures of the HS and LS MOSFETs with different heat sinks at various load currents. There is a significant reduction in temperatures using a 60 mm heat sink compared to a 10 mm heat sink visible. A temperature reduction of approximately 22°C at the LS MOSFETs can be noticed at 20.0 A load current, around 14°C cooler LS MOSFETs with 25 mm than 10 mm heat sink can be observed. A similar pattern can also be noticed at lower load currents, but the impact of the heat sink is not that noticeable.

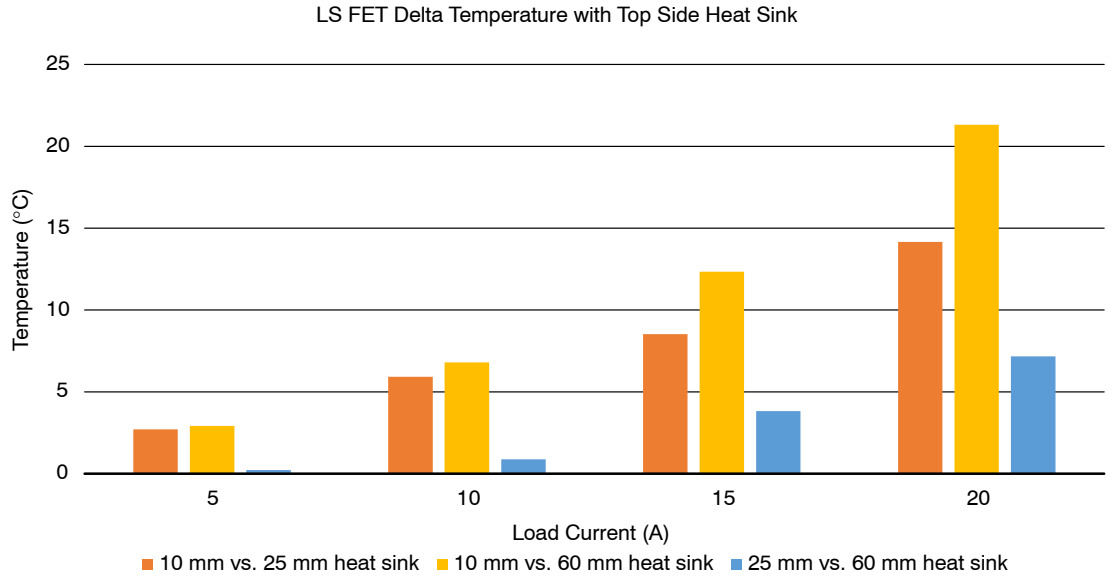


Figure 16. Setup #2 – LS MOSFET Delta Temperature with Top−Side Heat Sink

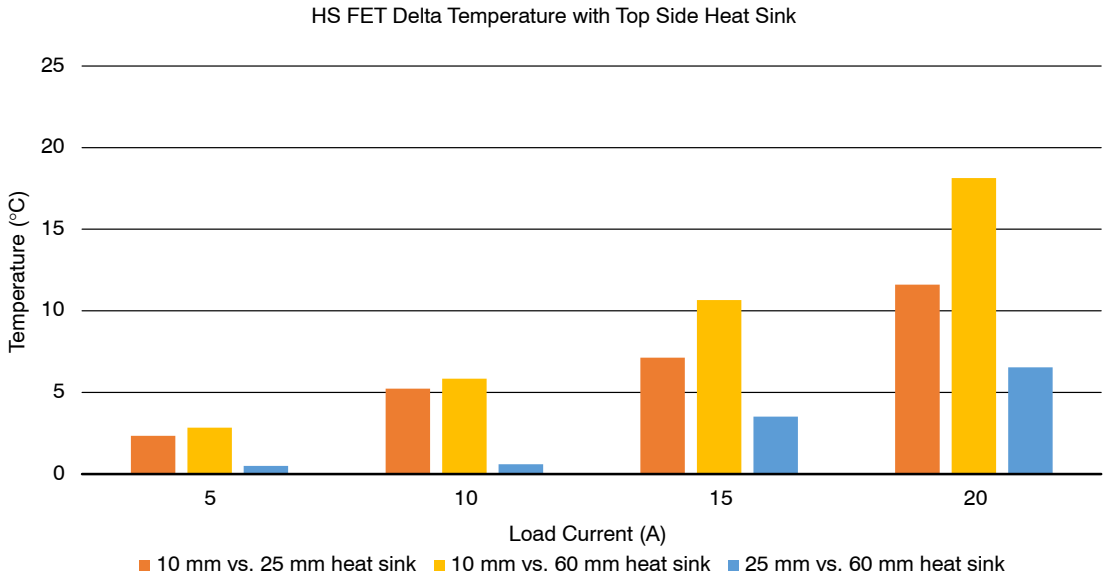


Figure 17. Setup #2 – HS MOSFET Delta Temperature with Top−Side Heat Sink

The same measurements show the variation in temperatures of the HS MOSFETs with different heat sinks at various load currents. Similar results can also be seen here: HS MOSFETs are around 18°C cooler with 60 mm than 10 mm heat sink at 20.0 A load current. Approximately around 12°C cooler HS MOSFETs with 25 mm compared to 10 mm heat sink can be observed.

Setup #3 – Heat Sink on the Bottom Side

The inductor needs to be soldered on the top side of the PCB to mount the heat sink on the bottom side. As shown in Figure 19, the thermocouples are glued on the top side of the HS and LS MOSFETs using heat conductive glue. The heat sink is mounted on the bottom side using the same springs and screws used for the top−side mounted setup. Also, this configuration places a gap pad between the heat sink and the board to optimize the thermal interface. Similar to the previous section, three different heat sinks are used to analyze the thermal performance.

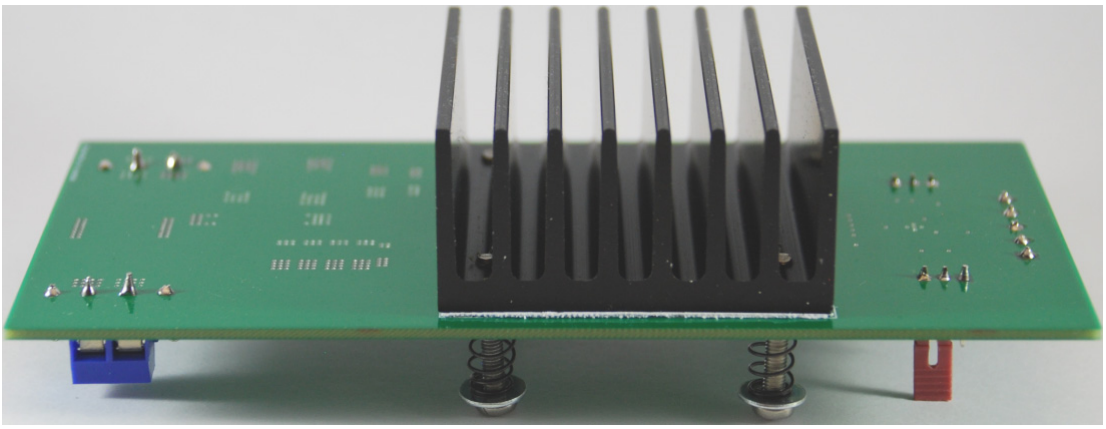


Figure 18. Setup #3 – Heat Sink on the Bottom Side

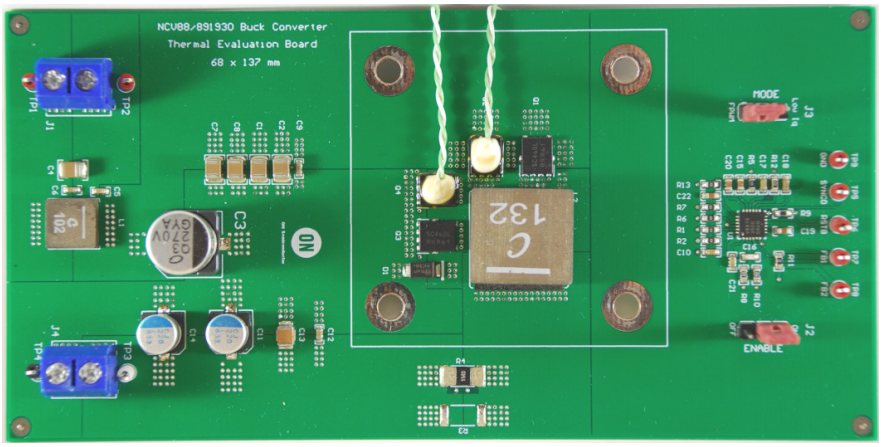


Figure 19. Placement of the Thermocouples

Table 12. SETUP #3 – 10 mm HEAT SINK ON THE BOTTOM SIDE

Setup #3 – 10 mm Heat Sink on the Bottom−side – V_{in} = 12 V, V_{out} = 5 V		
Output Current	**Low−side MOSFET Temperature**	**High−side MOSFET Temperature**
5.0 A	37.3°C	38.7°C
10.0 A	43.9°C	47.2°C
15.0 A	53.9°C	59.2°C
20.0 A	70.6°C	77.7°C

Table 13. SETUP #3 – 25 mm HEAT SINK ON THE BOTTOM SIDE

Setup #3 – 25 mm Heat Sink on the Bottom−side – V_{in} = 12 V, V_{out} = 5 V		
Output Current	**Low−side MOSFET Temperature**	**High−side MOSFET Temperature**
5.0 A	35.4°C	36.1°C
10.0 A	39.9°C	41.6°C
15.0 A	47.2°C	50.0°C
20.0 A	60.2°C	64.3°C

Table 14. SETUP #3 – 60 mm HEAT SINK ON THE BOTTOM SIDE

Setup #3 – 60 mm Heat Sink on the Bottom−side – V_{in} = 12 V, V_{out} = 5 V		
Output Current	**Low−side MOSFET Temperature**	**High−side MOSFET Temperature**
5.0 A	34.5°C	34.9°C
10.0 A	39.2°C	40.6°C
15.0 A	45.5°C	48.0°C
20.0 A	54.8°C	58.6°C

With all three heat sinks, there is a discernable pattern of the HS MOSFETs warming up more than the LS MOSFETs at the given load current. A similar pattern is noticed in the previous measurements without a heat sink and with a heat sink mounted on the top side of the PCB.

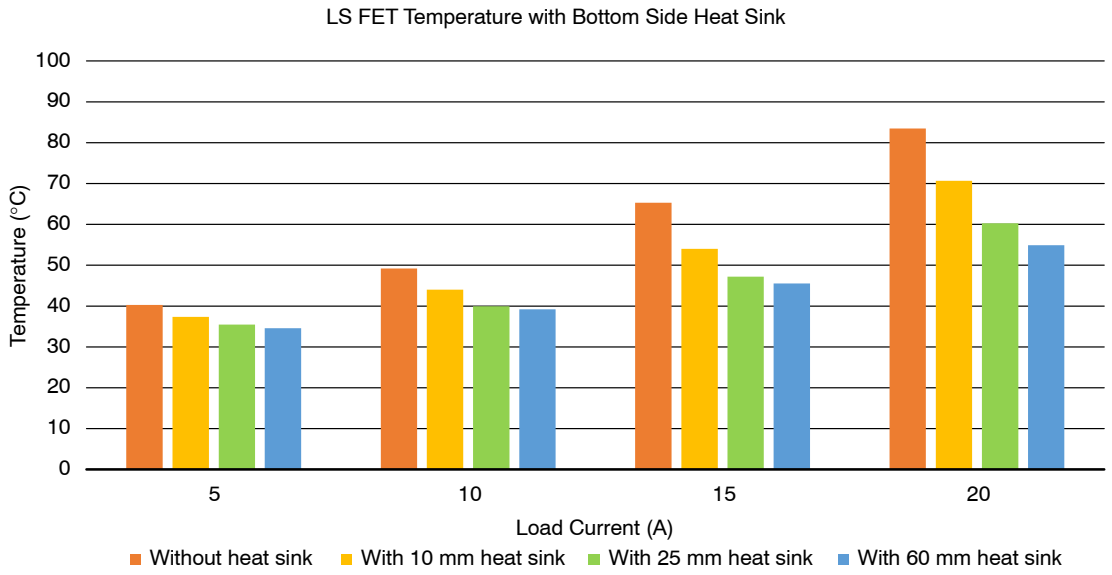


Figure 20. Setup #3 – LS MOSFET Temperature with Bottom−Side Heat Sink

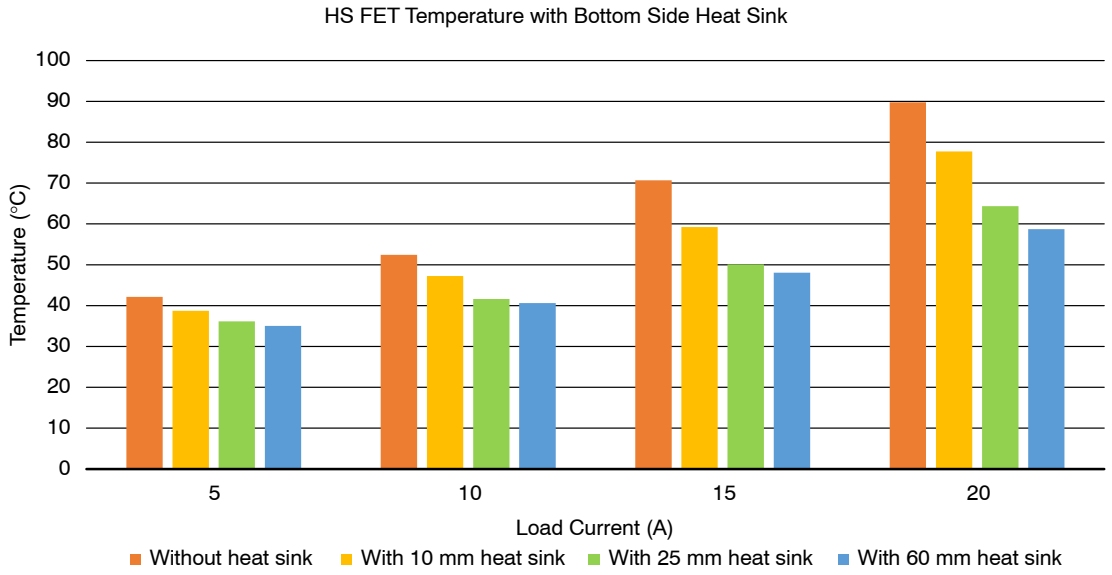


Figure 21. Setup #3 – HS MOSFET Temperature with Bottom−Side Heat Sink

Figures 20 and 21 show the improvement in heat dissipation at both LS and HS MOSFETs using different heat sinks than the configuration without a heat sink. The LS MOSFETs at 20.0 A load current are around 29°C cooler with the 60 mm heat sink than without a heat sink. The HS MOSFETs are about 31°C cooler with a 60 mm heat sink than without a heat sink.

Similarly to the previous test setup, the temperature difference at low load currents is relatively low.

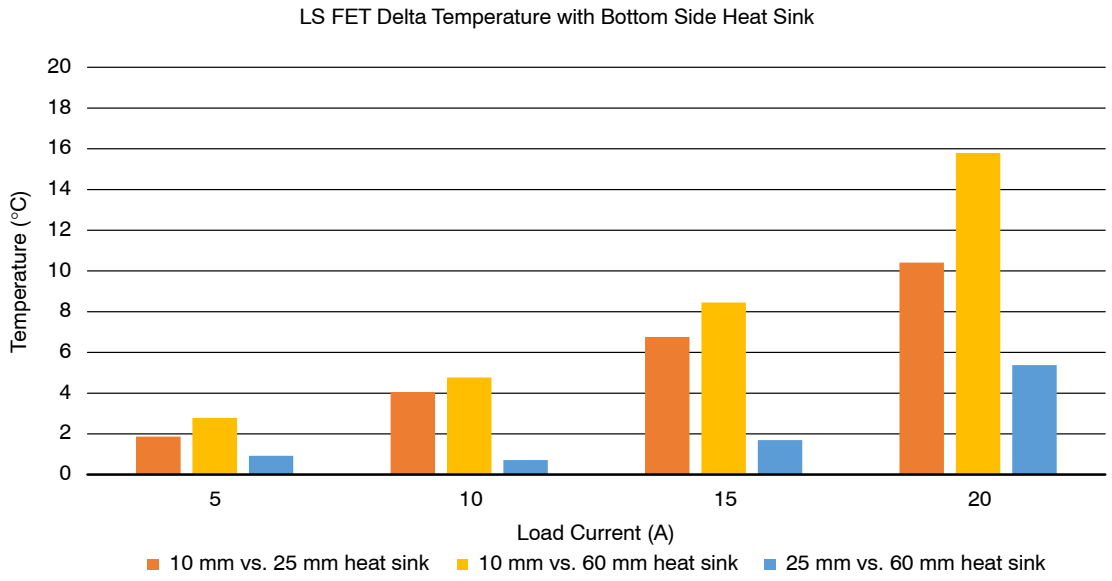


Figure 22. Setup #3 – LS MOSFET Delta Temperature with Bottom−Side Heat Sink

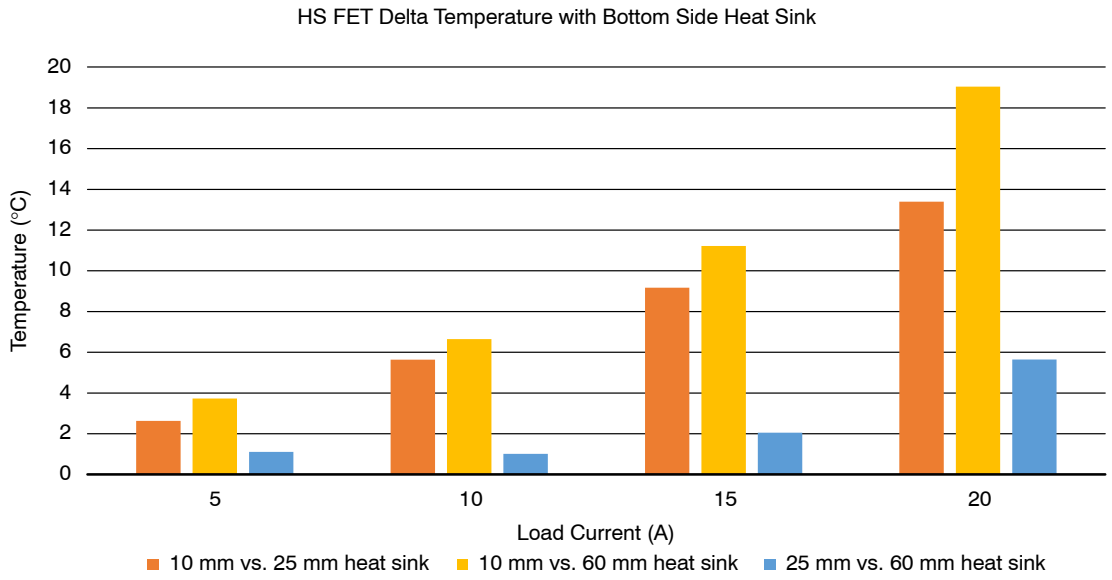


Figure 23. Setup #3 – HS MOSFET Delta Temperature with Bottom−Side Heat Sink

Figures 22 and 23 show the variation in temperatures at the HS and LS MOSFETs using different heat sinks on the bottom side. Like with the previous configuration having the heat sink on the top side, there is a significant reduction in the temperature of about 19°C at the HS MOSFET with the 60 mm heat sink compared to the 10 mm heat sink. A similar pattern can be seen for the LS MOSFETs as well. But the temperature difference between the 25 mm and the 60 mm heat sink is less significant than between 10 mm and 25 mm. Additionally, the difference is more important at higher than at lower load currents.

Comparison Between With and Without Heat Sink

Figures 24 and 25 show the delta in temperature of the MOSFETs without and with the top side heat sink. At higher currents, the LS MOSFETs without a heat sink are hotter than those with a top−side heat sink. The LS MOSFETs are approximately 30°C cooler at 20.0 A with a 60 mm heat sink than without a heat sink. Similarly, with a 25 mm heat sink, the MOSFETs are 22°C cooler compared to those without a heat sink.

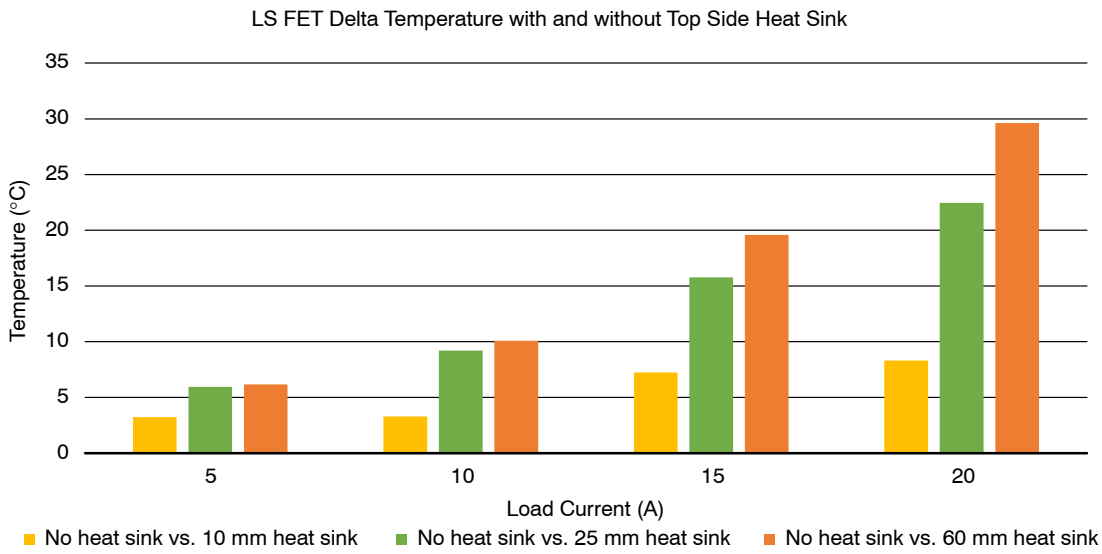


Figure 24. LS MOSFET Delta Temperature without and with a Top−Side Heat Sink

The HS MOSFETs are approximately 33°C cooler at 20.0 A with a 60 mm heat sink than without a heat sink. Similarly, with a 25 mm heat sink, the MOSFETs are 26°C cooler compared to those without a sink.

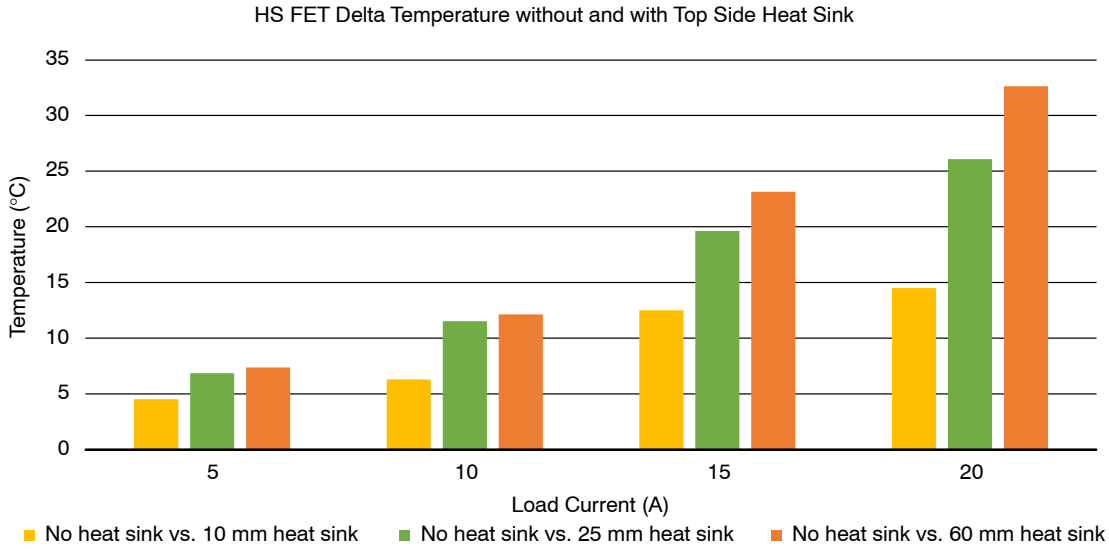


Figure 25. HS MOSFET Delta Temperature without and with a Top−Side Heat Sink

Figures 26 and 27 show the delta in temperature of the MOSFETs without and with the bottom side heat sink. At higher currents, the LS MOSFETs without a heat sink are hotter than those with a bottom−side heat sink. The LS MOSFETs are approximately 29°C cooler at 20.0 A with a 60 mm heat sink than without a heat sink. Similarly, with a 25 mm heat sink, the MOSFETs are 23°C cooler compared to those without a heat sink.

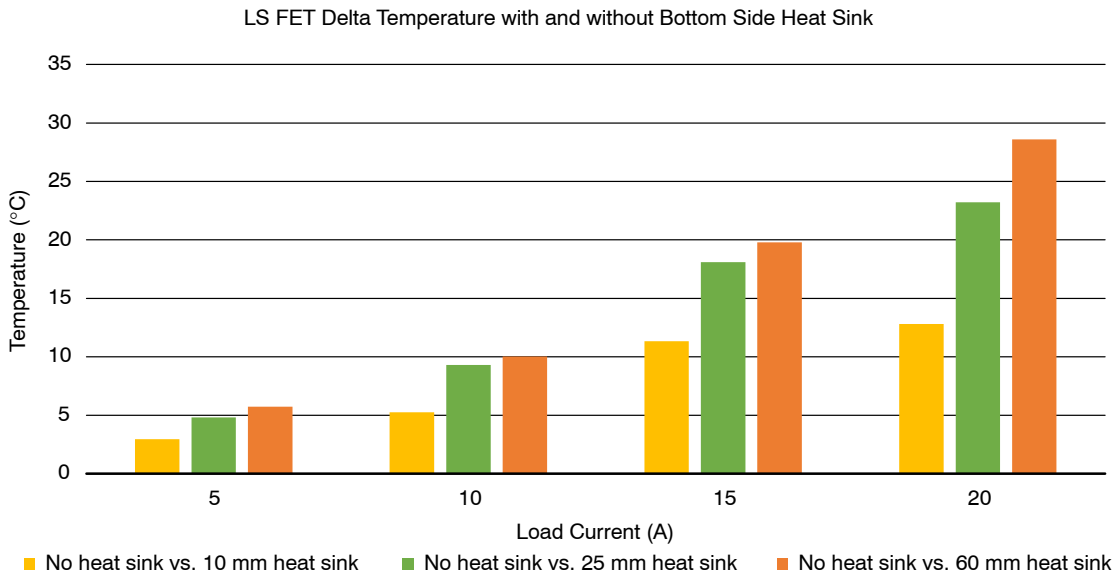


Figure 26. LS MOSFET Delta Temperature without and with a Bottom−Side Heat Sink

The HS MOSFETs are approximately 31°C cooler at 20.0 A with a 60 mm heat sink than without a heat sink. Similarly, with a 25 mm heat sink MOSFETs are 25°C cooler compared to no heat sink.

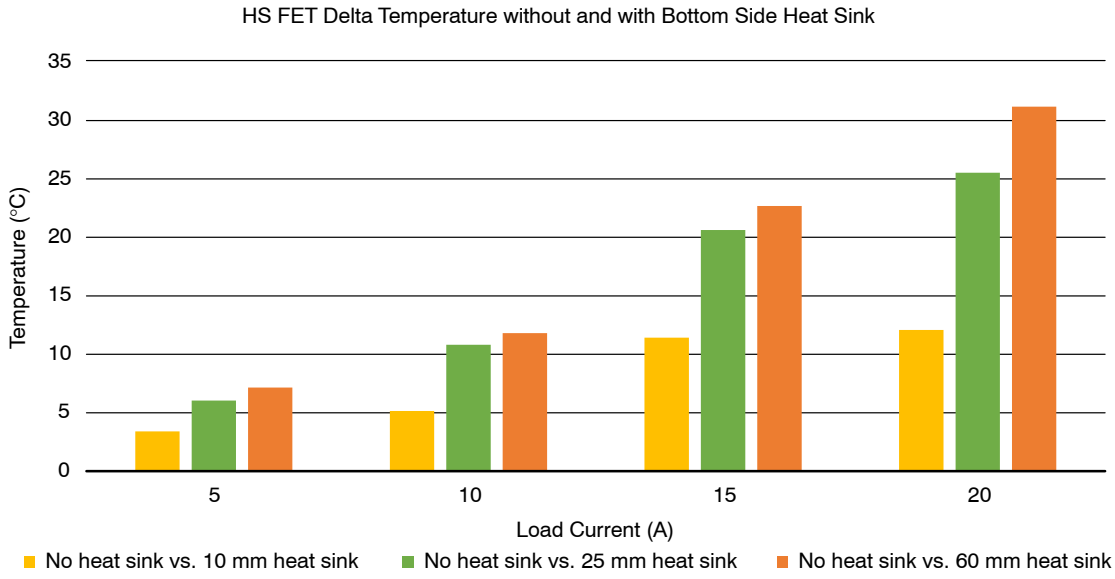


Figure 27. HS MOSFET Delta Temperature without and with a Bottom−Side Heat Sink

Impact of Gap Pad

With the 60 mm heat sink, the measurement results below are recorded using 3 W/(m·K) and 6 W/(m·K) gap pads at 20.0 A load current to understand the impact of the gap pad thickness on the thermal performance. The two different gap pads are KERAFOL 86/300 SOFTTHERM and 86/600 SOFTTHERM, shown in Table 2 at the beginning of this white paper.

With a top−side heat sink, a reduction of 1.6% in temperature at the LS MOSFETs and 3.5% at the HS MOSFETs were observed (Table 15), when switching from the gap pad with 3 W/(m·K) to the one with 6 W/(m·K), which has about half the thermal resistance.

Table 15. GAP PADS WITH A TOP−SIDE HEAT SINK

60 mm Heat Sink on the Top−side − V_{in} = 12 V, V_{out} = 5 V, I_{out} = 20 A			
	3 W/(m·K)	**6 W/(m·K)**	**Difference**
Low−side MOSFET Temperature	53.8°C	52.9°C	−1.6%
High−side MOSFET Temperature	57.1°C	55.1°C	−3.5%

With a bottom−side heat sink, around 7.6% temperature reduction for the LS MOSFET and 6.6% for the HS MOSFET is measured (Table 16).

Table 16. GAP PADS WITH A BOTTOM−SIDE HEAT SINK

60 mm Heat Sink on the Bottom−side − V_{in} = 12 V, V_{out} = 5 V, I_{out} = 20 A			
	3 W/(m·K)	**6 W/(m·K)**	**Difference**
Low−side MOSFET Temperature	54.8°C	50.6°C	−7.6%
High−side MOSFET Temperature	58.6°C	54.7°C	−6.6%

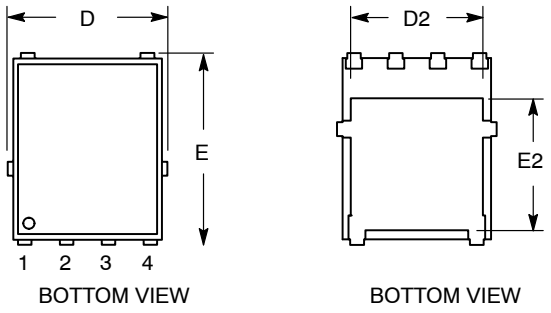
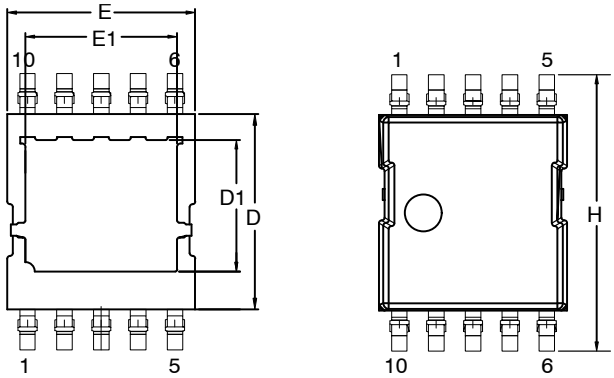
Top Side Exposed Pad vs. Bottom Side Exposed Pad

As highlighted, the PCB is optimized for good thermal conductivity and dissipation, acting as a very effective heat sink for the MOSFETs. This approach is often not desirable in an actual application where multiple heat sources are present, and the thermal dissipation capabilities of the PCB are limited. The preferred cooling method is to dissipate the heat by the housing of the ECU, which is thermally connected to the PCB. MOSFETs with a “Top Cool” package achieve the lowest thermal resistance between the heat source (MOSFETs) and heat sink (housing), allowing a direct thermal connection between the exposed pad of the MOSFET on the top side and the heat sink while minimizing the heat flow into the PCB.

MOSFETs with the same die but different packages are needed to compare the thermal performance directly. All previous measurements use NVMFS5C460NL, but this MOSFET is unavailable in a “Top Cool” package variant. Therefore NVMFS5C450N (SO−8FL with bottom side exposed pad) and NVMJST3D3N04C (“Top Cool” package with top side exposed pad) are chosen for the following measurements.

NVMJST3D3N04C is only available as a standard−level device, whereas NVMFS5C460NL is a logic−level device. A standard−level device is expected to have slightly lower efficiency than a logic−level device in this kind of application. Still, as the losses are not substantial, only the difference in thermal performance, NVMFS5C450N, and NVMJST3D3N04C can be compared.

Table 17. PACKAGE OVERVIEW

NVMFS5C450N	NVMJST3D3N04C
40 V, 1.2 mΩ max. @ 10.0 V	40 V, 1.2 mΩ max. @ 10.0 V
SO−8FL (Case 488AA)	TCPAK57 (Case 760AG)
	
Dimensions: • D: 5.15 mm (nom.) • E: 6.15 mm (nom.) • D2: 4.00 mm (nom.) • E2: 3.65 mm (nom.) • Plastic case surface area: approximately 31.7 mm^2 • Exposed pad surface area: approximately 14.6 mm^2	Dimensions: • D: 5.30 mm (nom.) • E: 5.10 mm (nom.) • D1: 3.57 mm (nom.) • E1: 4.12 mm (nom.) • H: 7.50 mm (nom.) • Plastic case surface area: approximately 27.0 mm^2 • Exposed pad surface area: approximately 14.7 mm^2

The plastic surface area of the top side of NVMFS5C450N in SO−8FL with 31.7 mm^2 is a bit larger compared to the plastic surface of the bottom side of NVMJST3D3N04C in TCPAK57 with 27.0 mm^2. The size of the exposed pad of both devices is approximately the same.

The heat sink with a height of 25 mm is used for the following measurements to avoid any limitations of the heat sink and maximize the thermal performance to optimize any differences in heating.

Bottom Side Exposed Pad MOSFET Measurements (NVMFS5C450N)

Tables 18 and 19 show the temperature of the high− and low−side MOSFETs (NVMFS5C450N) with and without a heat sink. The heat sink is mounted on the MOSFETs' top side (plastic housing).

Table 18. NVMFS5C450N − NO HEAT SINK

NVMFS5C450N − No Heat Sink − V_{in} = 12 V, V_{out} = 5 V		
Output Current	**Low−side MOSFET Temperature**	**High−side MOSFET Temperature**
5.0 A	46.3°C	50.2°C
10.0 A	65.9°C	69.6°C
15.0 A	86.3°C	88.4°C
20.0 A	109.4°C	109.6°C

Table 19. NVMFS5C450N − 25 mm HEAT SINK ON THE TOP SIDE

NVMFS5C450N − 25 mm Heat Sink on the Top Side − V_{in} = 12 V, V_{out} = 5 V		
Output Current	**Low−side MOSFET Temperature**	**High−side MOSFET Temperature**
5.0 A	40.0°C	41.9°C
10.0 A	47.9°C	50.8°C
15.0 A	58.7°C	62.0°C
20.0 A	69.5°C	73.0°C

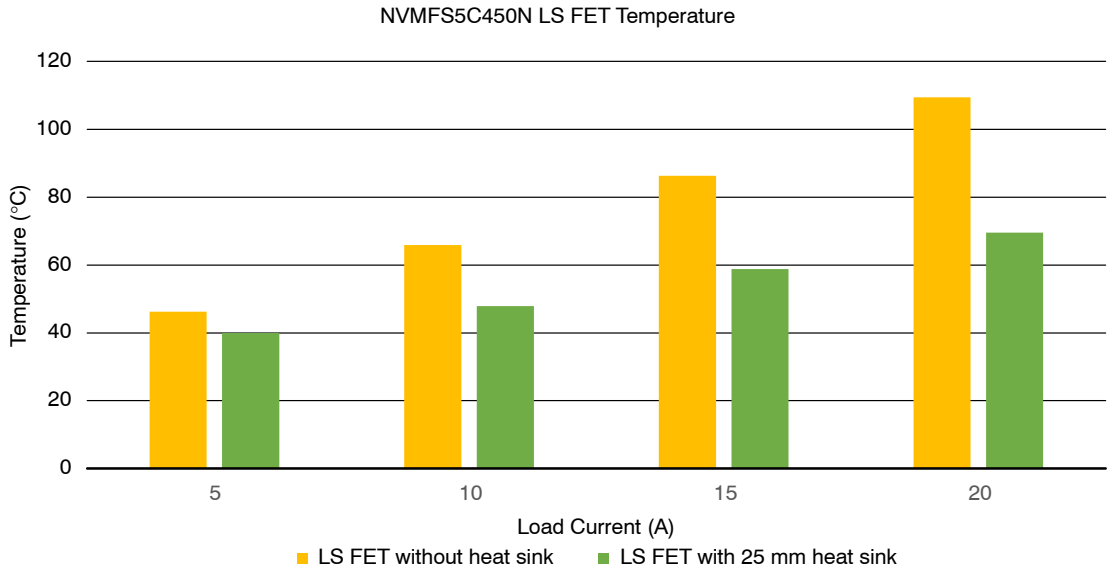


Figure 28. NVMFS5C450N − LS MOSFET Temperature with and without Heatsink

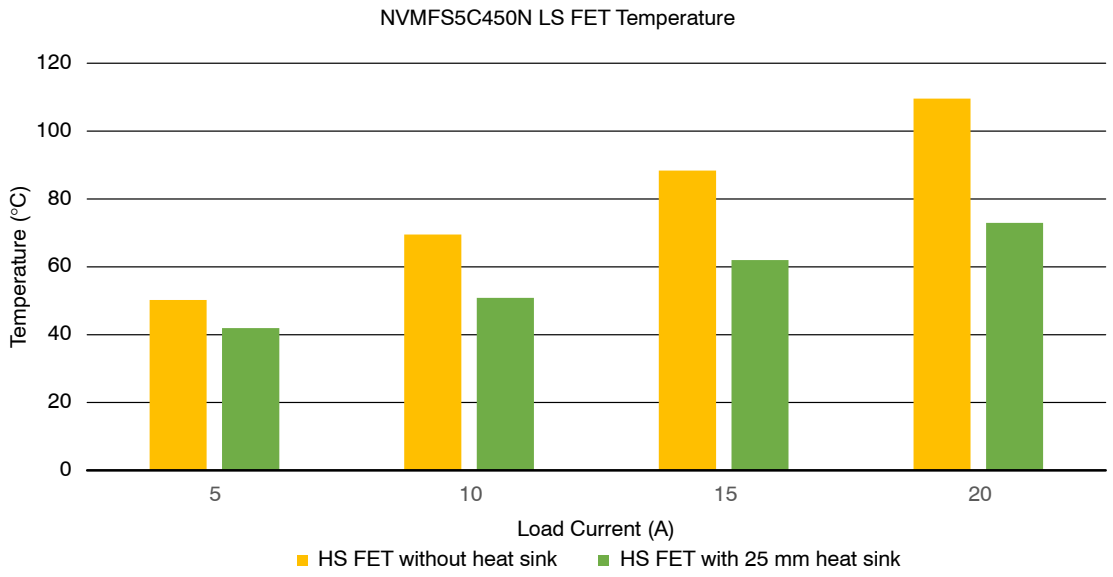


Figure 29. NVMFS5C450N – HS MOSFET Temperature with and without Heatsink

Figures 28 and 29 show the improvement in heat dissipation at both LS and HS MOSFETs using a heat sink mounted on the plastic top surface of the MOSFETs.

At 5.0 A load current, the LS MOSFETs are around 6°C cooler, and the HS MOSFETs are about 8°C cooler than without a heat sink. Whereas at 20.0 A load current, the LS MOSFETs are approximately 40°C cooler, and the HS MOSFETs are around 37°C cooler than without heat sink.

The thermal performance for both measurements is within the expected range, and a heat sink reduces the MOSFET temperature significantly. Generally, the temperatures are higher than the previous measurements using NVMFS5C460NL due to the higher gate charge and, therefore, slower switching speed of NVMFS5C450N. Even the on−resistance is slightly lower.

Top Side Exposed Pad MOSFET Measurements (NVMJST3D3N04C)

Tables 20 and 21 show the temperature of the high− and low−side MOSFETs (NVMJST3D3N04C) with and without a heat sink. The heat sink is mounted on the MOSFETs' top side (exposed pad).

Table 20. NVMJST3D3N04C – NO HEAT SINK

NVMJST3D3N04C – No Heat Sink – V_{in} = 12 V, V_{out} = 5 V		
Output Current	**Low−side MOSFET Temperature**	**High−side MOSFET Temperature**
5.0 A	45.2°C	47.1°C
10.0 A	60.5°C	61.0°C
15.0 A	82.7°C	78.4°C
20.0 A	113.1°C	103.7°C

Table 21. NVMJST3D3N04C – 25 mm HEAT SINK ON THE TOP SIDE

NVMJST3D3N04C – 25 mm Heat Sink on the Top Side – V_{in} = 12 V, V_{out} = 5 V		
Output Current	**Low−side MOSFET Temperature**	**High−side MOSFET Temperature**
5.0 A	37.6°C	37.1°C
10.0 A	49.7°C	48.3°C
15.0 A	61.3°C	57.0°C
20.0 A	73.5°C	66.9°C

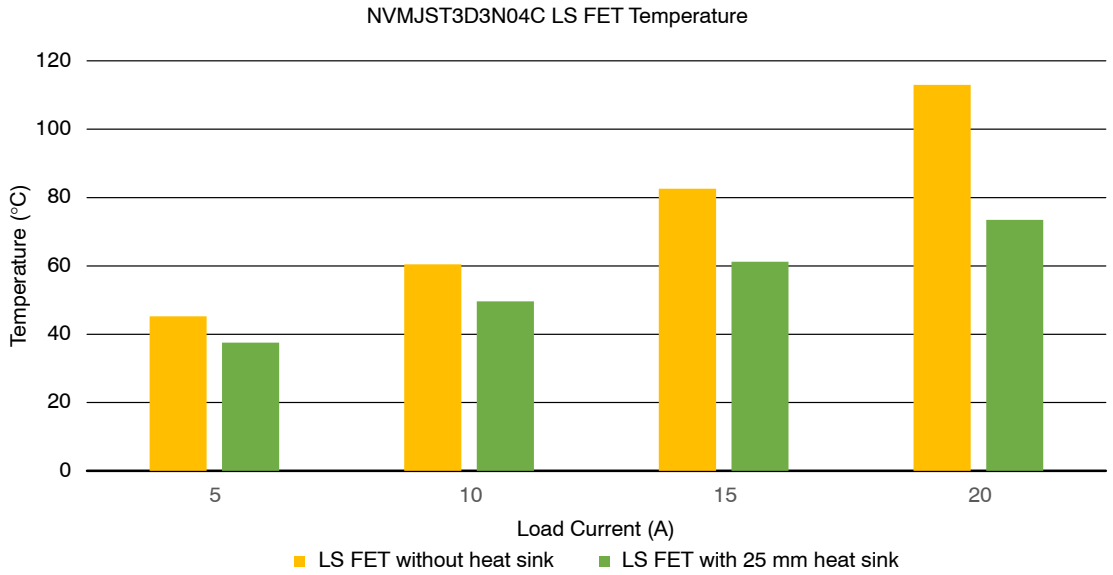


Figure 30. NVMJST3D3N04C – LS MOSFET Temperature with and without Heatsink

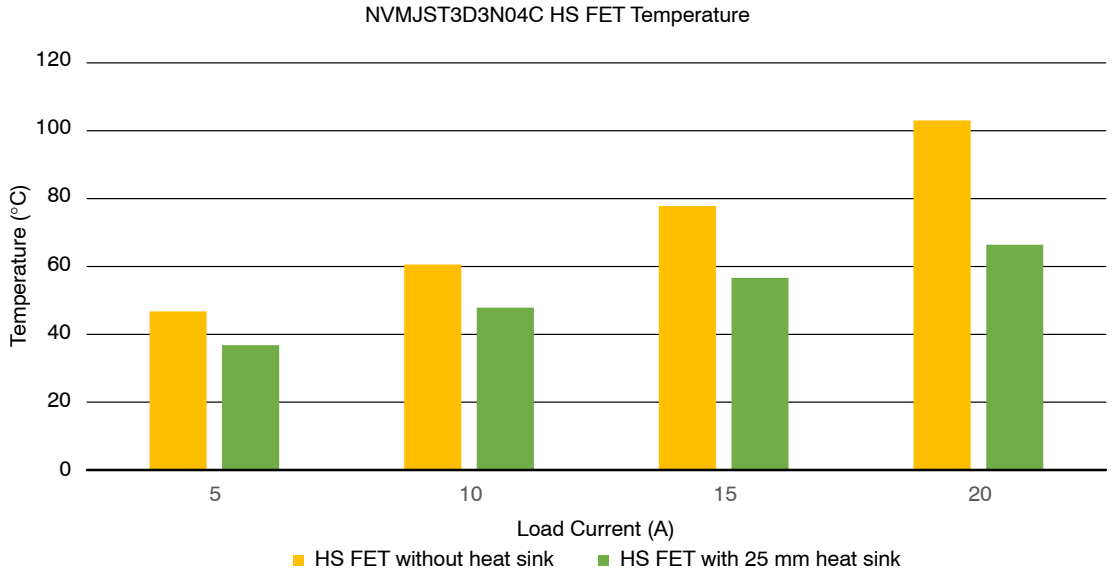


Figure 31. NVMJST3D3N04C – HS MOSFET Temperature with and without Heatsink

Figures 30 and 31 show the improvement in heat dissipation at both LS and HS MOSFETs using a heat sink mounted on the exposed pad on the top surface of the MOSFETs.

At 5.0 A load current the LS MOSFETs are around 8°C cooler, and the HS MOSFETs are approximately 10°C cooler than without a heat sink. Whereas at 20.0 A load current, the LS MOSFETs are about 40°C cooler, and the HS MOSFETs are about 37°C cooler than without heat sink.

Also, in this measurement, the thermal performance is as expected. As NVMJST3D3N04C and NVMFS5C450N use the same die, losses and heating are higher than previous measurements using NVMFS5C460NL due to higher gate charger and, therefore, higher switching losses.

Comparison Between Bottom and Top Side Exposed Pad

Figure 32 compares of the LS MOSFET temperature for the bottom (NVMFS5C450N) and top side (NVMJST3D3N04C) exposed pad with a heat sink on the top side.

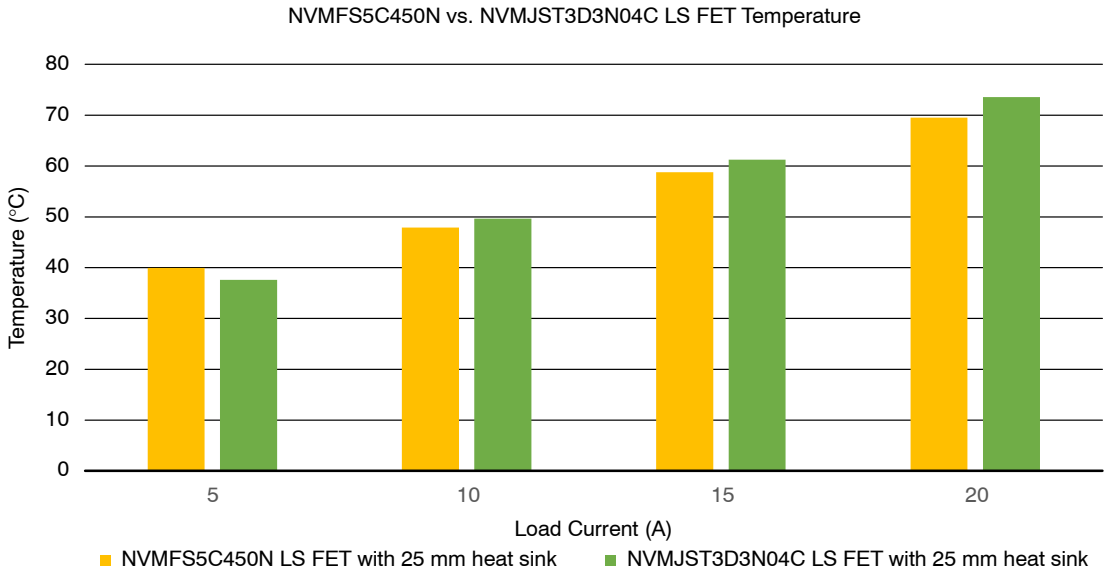


Figure 32. NVMFS5C450N vs. NVMJST3D3N04C – LS MOSFET Temperature with Heat Sink

Figure 33 compares the HS MOSFET temperature for the bottom (NVMFS5C450N) and top side (NVMJST3D3N04C) exposed pad with a heat sink on the top side.

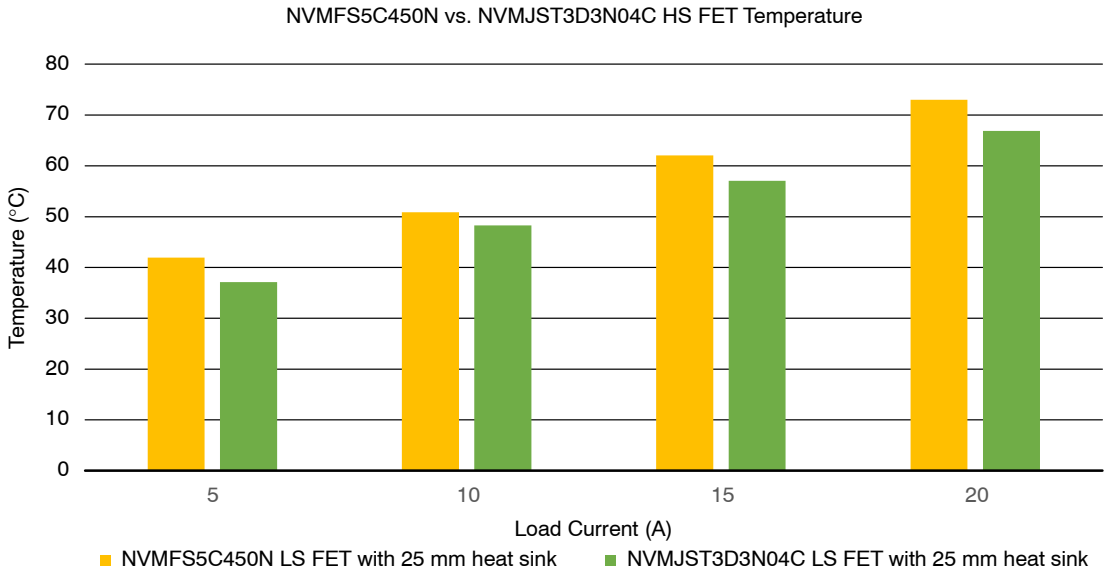


Figure 33. NVMFS5C450N vs. NVMJST3D3N04C – HS MOSFET Temperature with Heat Sink

Generally, the thermal performance is quite similar for this specific PCB and setup, independent of whether a MOSFET with a bottom or top side exposed pad and a heat sink on the top of the MOSFET package is used. The bottom side exposed pad package performs slightly better than the top side exposed pad for the LS MOSFET, and for the HS MOSFET, it is vice versa.

For MOSFETs with a bottom side exposed pad, a large amount of heat flows into the PCB, optimized as an effective heat sink. The heat sink on the plastic surface of the MOSFET top side also helps reduce the MOSFET temperature.

The MOSFETs with the top side exposed pad have relatively poor thermal coupling between the PCB and the plastic surface of the bottom side. However, the leads soldered to the PCB also allow heat to flow into the PCB. The exposed pad on the MOSFET top side is connected to the heat sink and effectively distributes the heat.

Both configurations dissipate heat via the bottom and top sides of the MOSFET package. For the bottom side exposed package, the thermal resistance between MOSFET and PCB is lower compared to MOSFET and heat sink. For the top side exposed package, it is vice versa; the thermal resistance between MOSFET and heat sink is lower. This leads to similar thermal performance being achievable with quite different configurations, and an effective cooling concept can be implemented for both types of packages.

Conclusion

The different measurements and comparisons showed the impact of a heat sink attached to a power supply on the MOSFET temperature. Based on the results the following statements can be concluded to be valid for the given setup:

- There is only a little difference of less than 3°C in the MOSFET temperature if the heat sink is either mounted on the bottom side of the PCB or the top side of the MOSFETs, using a thermally optimized PCB for heat conduction and dissipation as well as a MOSFET with bottom side exposed pad.
- The MOSFET temperature depends on the heat sink size.
  - At 20.0 A load current the MOSFET temperature is about 30°C lower with the 60 mm heat sink compared to a setup without any heat sink.
  - With the 25 mm heat sinks the MOSFETs are approximately 15 to 20°C cooler compared to a setup without any heat sink.
  - With the 10 mm heat sinks the MOSFETs are less than 10°C cooler than a setup without any heat sink.
  - This graduation is quite proportional to the thermal resistance of the three heat sinks. It also shows that a heat sink needs a certain mass and thermal conductivity to significantly reduce the temperature if a thermally optimized PCB layout is used.
- The difference in MOSFET temperature of 6°C at 20.0 A load current for the 25 mm and 60 mm heat sink is lower than initially expected.
- Up to 15.0 A load current, the MOSFET temperature difference between the 25 mm and 60 mm heat sink is relatively low, with around 2°C only. Above 15.0 A, load current the temperature difference increases to a maximum of about 6°C.
  This shows that the heat sink needs to be selected well to achieve the optimum between cost and thermal improvement.
- MOSFETs with a top−side exposed pad and heat sink enable similar thermal performance to MOSFETs with a bottom−side exposed pad mounted on a thermally optimized PCB and heat sink on the top side of the package. If the heat flows into the PCB should be minimized, MOSFETs with top side exposed pad are the right choice as they have a minimized thermal resistance to the heat sink mounted on the top side of the package.
- All measurements are consistent, reproducible, and in line with the general theoretical expectations. This proves that the electrical and mechanical setup works correctly and is reliable.

Of course, this test setup is far from an actual application, such as a power supply as part of a complex ECU inside a custom aluminum housing with cooling fins. However, it explains the different parameters' impact, like the heat sink's thermal resistance or gap pad thickness on the MOSFET temperature. It also clearly shows that mounting the heat sink on top of the heat source (the MOSFETs in this case) or the other side of the PCB (presuming the PCB layout is thermally optimized with thermal vias and larger copper areas on all layers to allow thermal flow through the PCB) can achieve similar performance.

If the heat flows into the PCB should be minimized, MOSFETs with top side exposed pad connected to a heat sink should be used.

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