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AN11113

LFPAK MOSFET thermal design guide - Part 2

Rev. 2 — 16 November 2011 Application note

Document information

Info	Content
Keywords	LFPAK, MOSFET, thermal analysis, design and performance, thermal considerations, thermal resistance, thermal vias, SMD, surface-mount, PCB design, enclosure, bottom-side cooling, top-side cooling
Abstract	Thermal aspects are an important concern when designing for power MOSFETs. Part 1 of this design guide (AN10874) describes the impact of various PCB and device configurations on thermal behavior in free air and at 20 °C ambient temperature. Part 2 discusses how the construction and configuration of an enclosure influences the operating temperatures of the power MOSFET devices within.

Revision history

Rev	Date	Description
v.2	20111116	improved quality of graphics and made cosmetic changes to text
v.1	20110906	initial version

Contact information

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1. Introduction

In the companion document, AN10874 the impact of various different PCB and device configurations on thermal behavior was considered. By analyzing and comparing multiple scenarios, it was possible to draw numerous conclusions regarding the optimum way to provide heatsink cooling of LFPAK MOSFETs.

All of the PCB configurations considered in AN10874 had one thing in common - they were situated in free air at an ambient temperature of 20 °C. No enclosures or housing were included in the scenarios. In most real-life applications, however, it is likely that we would not have an exposed PCB with no enclosure present. The need to protect the PCB from environmental factors, plus possible considerations for ElectroMagnetic Compatibility (EMC) would almost certainly dictate that the PCB would be mounted in an enclosure of some form. Inevitably the enclosure would interfere with the free flow of air around the PCB, and so would also have an impact on the thermal performance of the system.

In this document we will take a close look at how the construction and configuration of an enclosure can have an impact on the operating temperatures of the power MOSFET devices within. Factors which will be examined include:

- Enclosure material and surface finish
- Internal spacing above, below and around the PCB
- Bottom-side cooling of the PCB (i.e. PCB bottom surface in contact with an internal surface of the enclosure)
- Top-side cooling of the MOSFET devices (top of the device packages in contact with an internal surface of the enclosure)
- The role of encapsulation within the enclosure, where the air gap around the PCB is partially or completely filled with an encapsulation compound
- Proximity of the “module” to a bulkhead

In order to rationalize the number of possible variables, we will consider only one PCB configuration, taken from AN10874. The enclosure plus PCB will be referred to hereafter as the “module”.

As with AN10874, the thermal analyses presented in this document have been carried out using thermal simulation software. The simulations use MOSFET models which have been validated against empirical data and are known to accurately model the thermal behavior of real-life devices.

The thermal simulation software used to carry out the analyses is the Mentor Graphics (Flomerics) “FloTHERM” package. The device models used in the analysis are available for free download from the NXP web site, together with a selection of the scenarios used in the preparation of this document.

2. The module model

2.1 PCB characteristics

In the interests of minimizing the number of possible variables, we will consider only one PCB configuration, taken from Section 5.4 of AN10874. The PCB is shown in Figure 1.

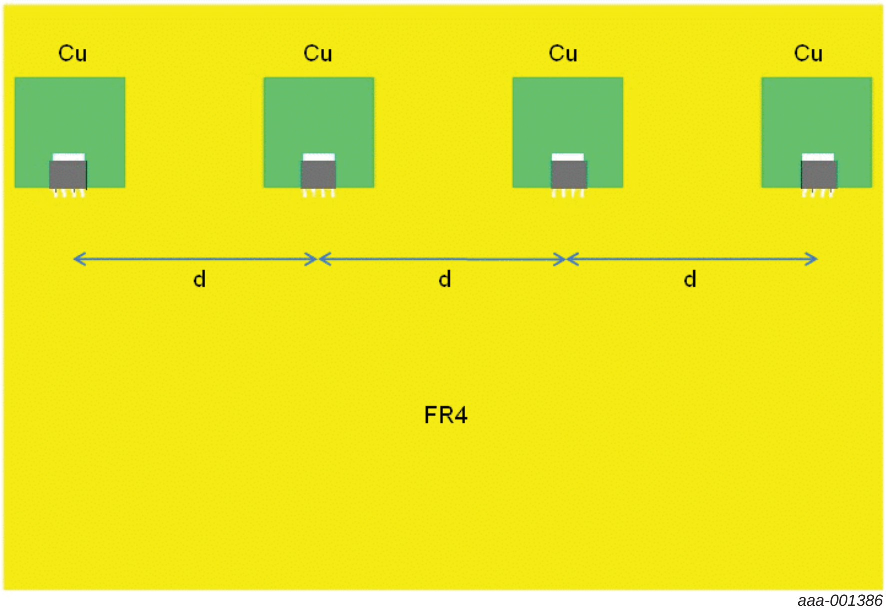


Fig 1. The PCB model

The main PCB characteristics are:

- Overall PCB size 80 mm × 120 mm, thickness 1.6 mm
- Standard FR4 PCB material
- All copper layers 1 oz/35 μm thickness
- Top copper - 15 mm × 15 mm area per device, attached to the device tab (as shown)
- Bottom copper - also 15 mm × 15 mm area per device, connected to the top copper by vias
- Internal layers - average 50 % area coverage
- Vias - under each device a pattern of 5 × 4 vias of 0.8 mm internal diameter
- Device spacing d = 25 mm
- Power dissipation is 0.5 W per device

AN10874 indicated that the placement of the individual MOSFETs actually had very little influence on their operating temperatures - varying by only around ±1 °C.

2.2 Enclosure characteristics

Several enclosure characteristics will be varied throughout the course of this document. However, some general features will remain the same throughout:

- The enclosure is completely sealed with no holes or cutouts.
- The walls of the enclosure are 2 mm thick, irrespective of enclosure material.
- The enclosure is able to lose heat energy to the outside environment by the mechanisms of convection, conduction and radiation.

There are potentially many different enclosure materials which could be considered in this Design Guide. To keep the number of variables to a manageable level, while also providing a usefully realistic analysis of typical materials, we will restrict ourselves to the following three variations as shown in Table 1.

Table 1. Enclosure materials and their properties summarized

Material	Thermal conductivity (W/m.K)	Surface emissivity
Black plastic	0.2	0.95
Polished aluminium	201	0.04
Anodized (black) aluminium	201	0.8

Surface emissivities apply to both inner and outer surfaces of the enclosure.

An example module is shown in Figure 2. Note that the enclosure top and one side have been made transparent so that the position of the PCB can be seen.

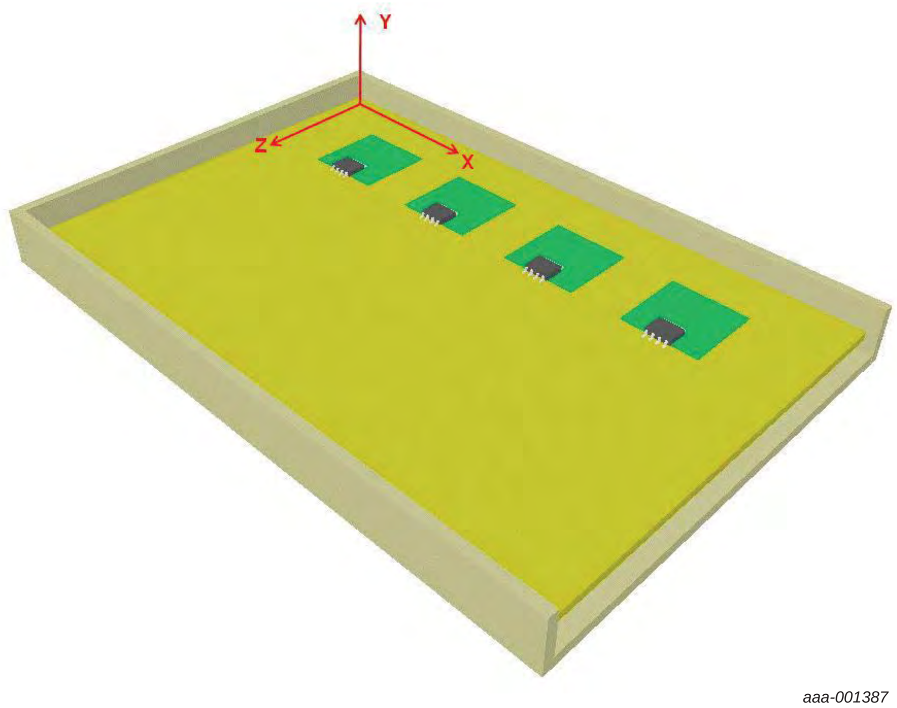


Fig 2. An example module

2.3 Axes naming convention

Throughout this document we will consider the effects of moving or resizing objects in the three spatial directions. We therefore need a convention for referring to these directions, as shown by the arrows in Figure 2.

So for example, when we are increasing the gap between the PCB and enclosure at the short edges of the PCB (the x-direction), this will be referred to as the “x-gap”. Similarly, the gaps above and below the PCB will be referred to as being in the “y-gap”, and so on.

2.4 The ambient environment

The module is situated in an environment with the following characteristics:

- The module is surrounded by free air at an ambient temperature of 20 °C
- There is no applied airflow, although the module is able to create airflow by the process of natural convection from its outer surfaces
- The environment is free to exchange heat energy with the module by the processes of convection, conduction and radiation

2.5 Potential heat paths

There are numerous possible paths along which the heat may travel from the PCB. These paths utilize the three heat transfer mechanisms of conduction, convection and radiation and are illustrated in Figure 3.

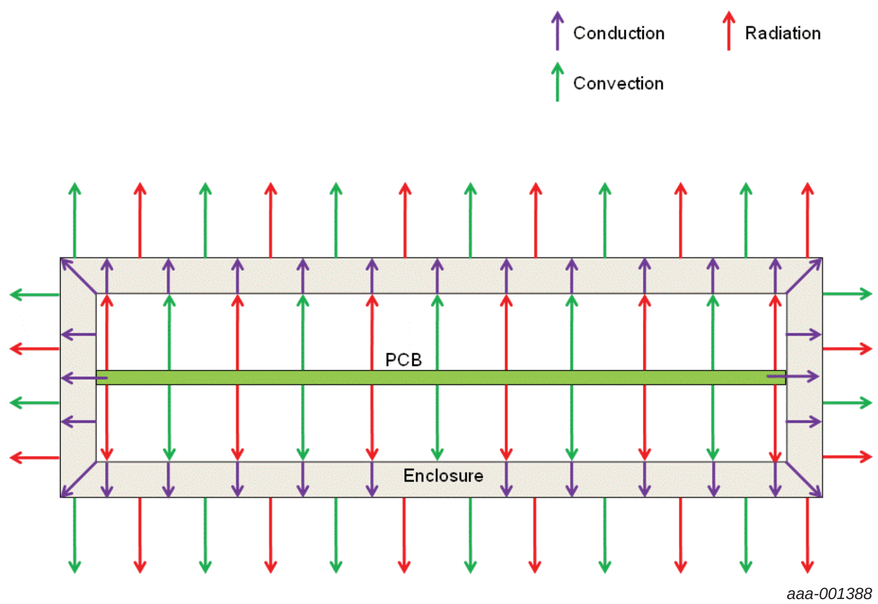


Fig 3. Potential heat paths

3. The influence of y-gap on T_j

3.1 Black plastic enclosure; x- and z-gaps = zero

In the first analysis, we will reduce the variables to the smallest number possible. The x- and z-gaps around the board will be set to zero, so the edges of the PCB will actually be in contact with the internal walls of the enclosure, and we will consider only the black plastic enclosure material. The y-gap above and below the PCB will be varied, as illustrated in Figure 4.

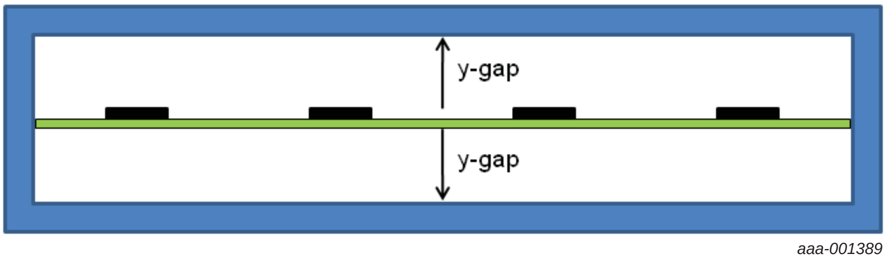
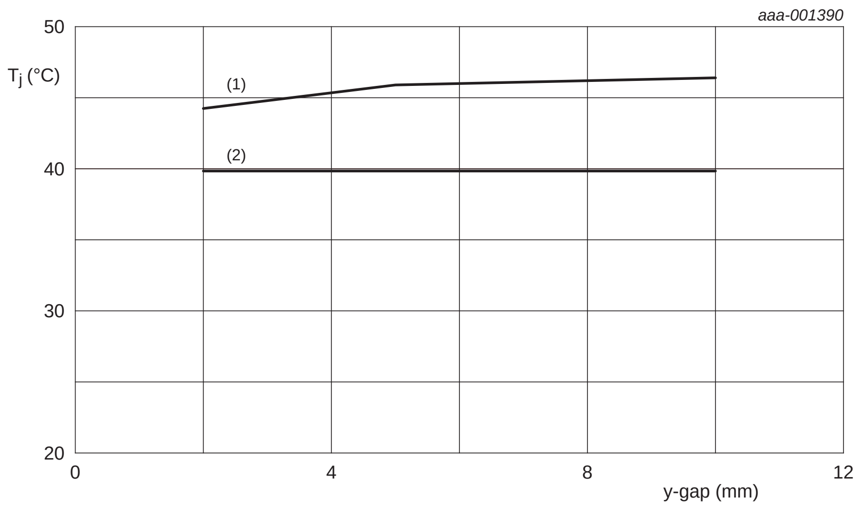


Fig 4. Varying the y-gap above and below the PCB

We will run the model for y-gap values of 2 mm, 5 mm and 10 mm and observe what happens to the device T_j. The results are shown in the graph of Figure 5, together with the temperature observed with no enclosure present. Temperatures shown are the average for the four devices.



(1) T_j (black plastic enclosure).

(2) T_j (no enclosure).

Fig 5. The variation of T_j with y-gap

The graph of Figure 5 has some interesting features:

- Surrounding the PCB with an enclosure has resulted in an elevated T_j compared to the case where no enclosure was present

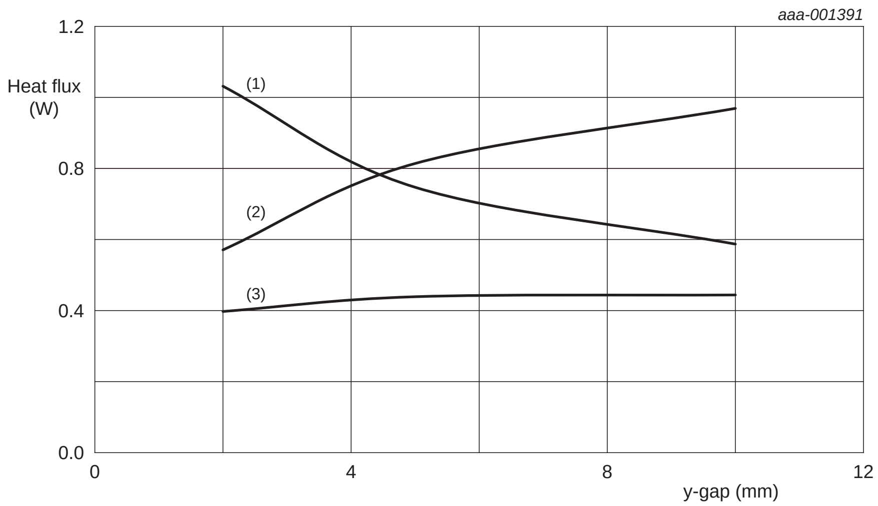
- As the y-gap increases, so T_j also increases slightly

The first of these observations is in keeping with the expectation expressed in the Introduction, as the enclosure tends to interfere with heat loss by natural convection from the surfaces of the PCB and devices. It is therefore reasonable to expect T_j to rise with the enclosure in place.

The second observation is a more counter-intuitive result! Surely as we add more air gap around the PCB, the cooling of the PCB should become more effective? In order to answer this question, we need to consider the various potential heat paths present within the module (Figure 3).

Altering the y-gap should increase the volume of air available to circulate around the PCB surfaces, even though the air cannot escape, and hence provide for better cooling. However, this is not the effect which we see. The reason is that air will only circulate under natural convection if there is sufficient room for it do so. The air experiences “drag” forces where it contacts solid surfaces, and if these forces are sufficiently dominant (because the volume is small) then natural convection cannot occur. The air is stationary and is said to be “stagnant”[1]. The simulations suggest this is exactly what is happening in this case, even when the y-gap is 10 mm, with reported air velocities within the enclosure being effectively zero. The end result is that the natural convection heat loss mechanism does not occur within the enclosure and instead we have only conduction heat loss through the air, whose conductivity is very low (typically 0.003 W/m.K for air at 20 °C).

FloTHERM allows us to examine the magnitude of the heat transfer mechanisms in a scenario, and applying this analysis to the scenario results in the graph of Figure 6.



(1) Conduction (through air).

(2) Radiation.

(3) Conduction (through solids).

Fig 6. Variation in heat loss mechanisms with y-gap

1. This is also the reason why, for instance, the air gap in double glazing is such an effective insulator. For a more detailed explanation of this phenomenon, the reader is encouraged to research the terms “Nusselt number” and “Rayleigh number”.

In Figure 6 we can see that conduction through the air does indeed decrease as the y-gap increases, while conduction from the edge of the PCB to the enclosure walls remains much more constant. At the same time, radiation loss from the PCB increases as the y-gap increases - why should this be?

Radiation heat exchange occurs between the PCB and inside walls of the enclosure. All the surfaces involved are radiating heat energy, but as the PCB is at a higher temperature than the enclosure walls, the net effect is the transfer of heat from the PCB to the enclosure. The amount of heat energy exchanged depends on several factors, including:

- The temperatures of the surfaces
- The emissivities of the surfaces (related to surface color, finish, etc.)
- The “view factor” existing between the surfaces

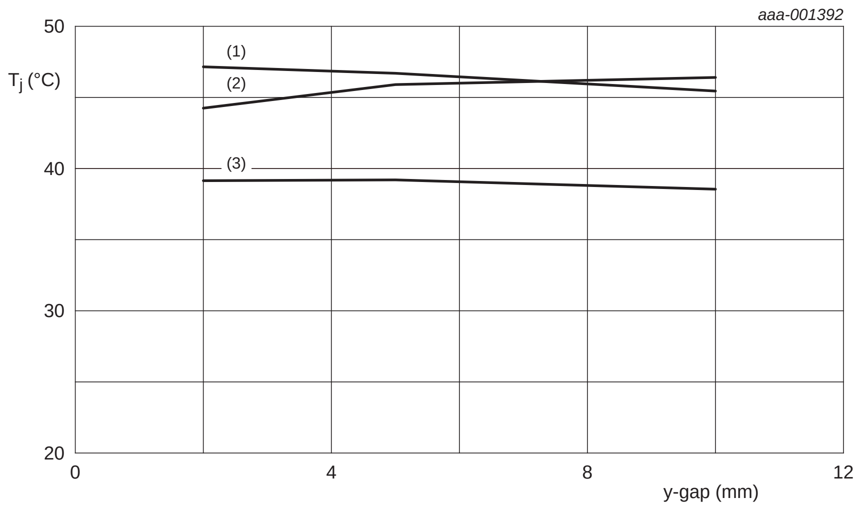
The “view factor” is a measure of how much of the receiving surface can be “seen” by the transmitting surface. In this case, as we increase the y-gap we also increase the surface area of the inside of the enclosure, and hence more area is made available to receive heat energy from the PCB by the process of radiation. Hence, in Figure 6, as the y-gap increases so the heat loss by radiation increases. Note also that for any value of y-gap, the total heat loss by the three mechanisms must always add up to the total dissipated within the enclosure, which is 4×0.5 W = 2 W in this case.

3.2 Two more enclosure materials

So far we have only considered the flow of heat within the enclosure. Of course, as illustrated in Figure 3, there are other heat paths through the enclosure walls and from the enclosure outer surfaces which will also have an impact on the overall module thermal performance. The nature of the heat flow will depend very much on the thermal properties of the enclosure material:

- Conduction through the enclosure walls, which will be influenced by the conductivity of the enclosure material.
- Radiation heat loss from the enclosure's outer surface, which will be influenced by the emissivity of the module surface.

In addition, the module dimensions (which vary as we vary the y-gap) will also determine the nature of heat flow within the enclosure, as we have already seen, plus heat loss through the enclosure walls and from the module outer surface both by convection and radiation. Clearly these factors are interlinked, and do not lend themselves to a simple, manual analysis. We have therefore re-run the simulations with the two new enclosure materials, and the results are shown in Figure 7.



(1) T_j (polished aluminium).

(2) T_j (black plastic).

(3) T_j (anodized aluminium).

Fig 7. Variation in T_j with y-gap for the three enclosure materials

We can summarize the properties of the three materials in a simple way, as shown in Table 2.

Table 2. A simple summary of the material properties

Material	Heat transfer by radiation	Heat transfer by conduction
Black plastic	good	bad
Polished aluminium	bad	good
Anodized aluminium	good	good

The black plastic and polished aluminium materials are both good in one respect and less good in another. Hence the temperatures for these two materials tend to be higher, although the property variations do not exactly cancel out. On the other hand, the anodized aluminium material has “the best of both worlds”, being both a good conductor and good for radiation exchange, so the temperature results for this material are lower.

3.3 Summary: the influence of y-gap on T_j

The following list is a summary of observations from this section:

1. The presence of the enclosure can cause an increase in device temperatures compared to the case where no enclosure is present - this was seen for the black plastic and polished aluminium materials.
2. However, an enclosure made from anodized aluminium was found to reduce device temperatures slightly.
3. Air inside the enclosure is “stagnant” and so the process of natural convection cannot occur.
4. The heat loss mechanisms inside the enclosure are therefore:
   a. conduction through the stagnant air
   b. direct conduction from the PCB edges to the enclosure
   c. radiation
5. Radiation heat exchange depends on the “view factor” between radiating surfaces and tends to increase as the enclosure internal dimensions increase.
6. The enclosure material influences overall module thermal performance. In particular, the material thermal conductivity and surface emissivity.
7. Of the three materials considered, anodized aluminium has the best combination of thermal conductivity and surface emissivity.

4. Adding x- and z-gaps around the PCB

So far, all the cases we have considered have had physical contact between the edges of the PCB and the enclosure walls. Although the area of contact was small, the graph of Figure 6 has shown that the amount of heat transferred through this path is significant, amounting to approximately 20 % of the total in the case of the black plastic enclosure.

It is probable, though, that some real-life configurations may have an air gap between the PCB edges and enclosure walls - perhaps to provide electrical isolation or for other mechanical reasons. Introducing such an air gap would alter the available heat paths within the module, and inevitably have an effect on the temperatures of the MOSFET devices mounted on the PCB.

To investigate the effect of the air gap around the PCB, the previous models were re-run, but this time with x- and z-gaps of 5 mm and 10 mm. See Figure 8.

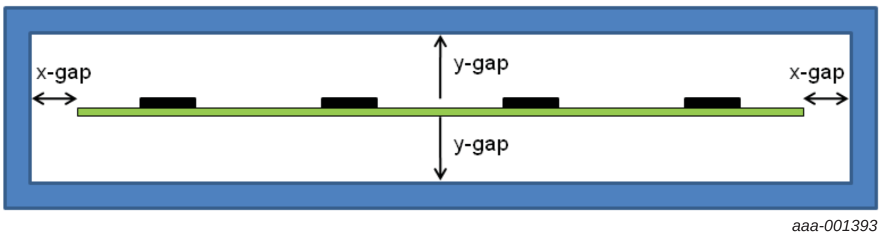
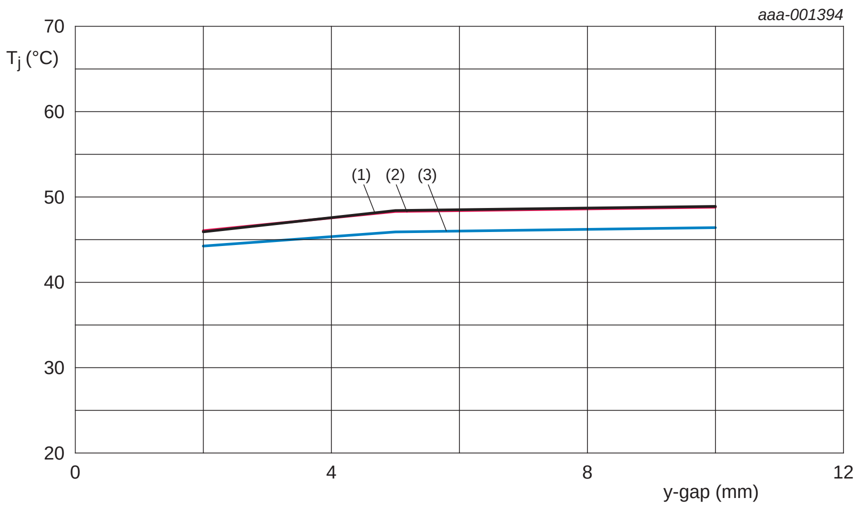


Fig 8. Gaps added around the PCB

4.1 The black plastic enclosure

The results for the black plastic enclosure are shown in Figure 9.



(1) T_j black plastic (5 mm gap).

(2) T_j black plastic (10 mm gap).

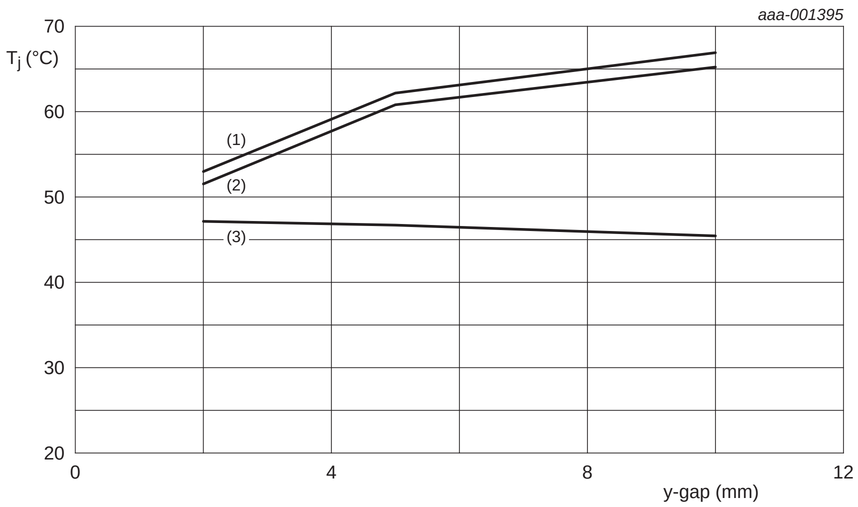
(3) T_j black plastic (no gap).

Fig 9. The effect of x- and z-gaps on T_j for the black plastic enclosure

Although we can see some difference when the gap is introduced, it could be argued that the effect is not dramatic - around 2.5 °C. This is because the plastic material is not a good conductor of heat energy, and so conduction into the enclosure is not a dominant heat path (see Figure 6). In addition, the increased view factor results in an improved transfer of heat by radiation. Hence removing the conduction heat path does not result in a dramatic change in temperatures.

4.2 The polished aluminium enclosure

We would expect to see a more significant effect for the aluminium enclosures, as aluminium is a better conductor of heat than plastic, and so removing this conduction path should have more effect on T_j. The results for the polished aluminium enclosure are shown in Figure 10.



(1) T_j polished aluminium (5 mm gap).

(2) T_j polished aluminium (10 mm gap).

(3) T_j polished aluminium (no gap).

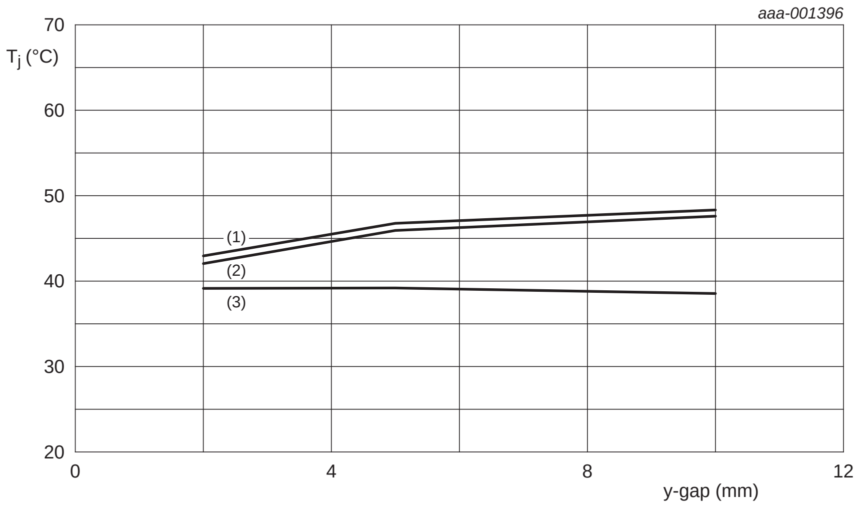
Fig 10. The effect of x- and z-gaps on T_j for the polished aluminium enclosure

The effect of adding the x- and z-gaps around the PCB is much more noticeable in this case, especially as the y-gap increases, resulting in a difference of ~20 °C when the y-gap is 10 mm. By removing the conduction path from the PCB edges we have increased the thermal isolation between the PCB and enclosure:

- Direct conduction between the PCB and enclosure is eliminated.
- Heat flow through the air remains poor as the air is still stagnant.
- Radiation heat exchange is also poor as the surface emissivity of the aluminium is very low.

4.3 The anodized aluminium enclosure

For the anodized aluminium enclosure, the effect of adding the x- and z-gaps is less pronounced. See Figure 11.



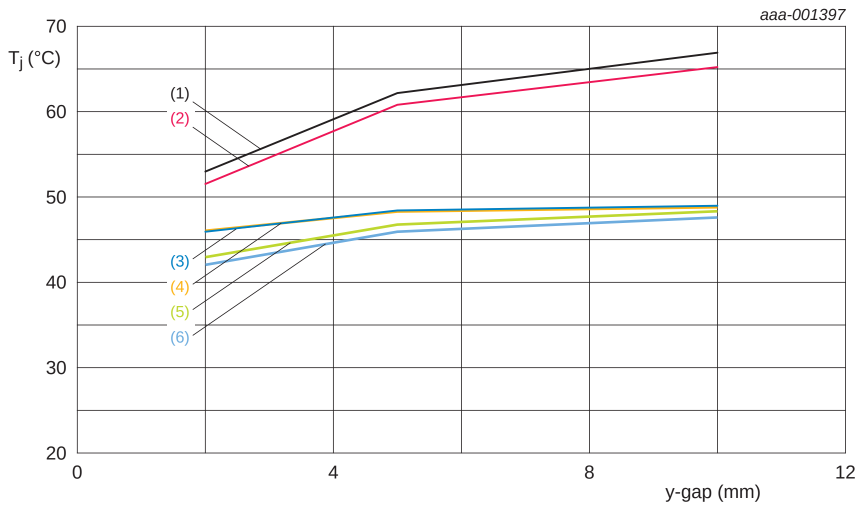
(1) T_j anodized aluminium (5 mm gap).
(2) T_j anodized aluminium (10 mm gap).
(3) T_j anodized aluminium (no gap).

Fig 11. The effect of x- and z-gaps on T_j for the anodized aluminium enclosure

Although in this case we have lost the direct conduction heat path within the module, the radiation heat path is still quite effective, owing to the surface finish of the enclosure material. Hence the variation in T_j is not as great as for the polished aluminium material.

4.4 The three enclosures side-by-side

The results for all three enclosure types are shown on the single graph of Figure 12. This graph enables us to compare the influence of the three material types when there is no direct conduction between the PCB and enclosure.



(1) T_j polished aluminium (5 mm gap).

(2) T_j polished aluminium (10 mm gap).

(3) T_j black plastic (5 mm gap).

(4) T_j black plastic (10 mm gap).

(5) T_j anodized aluminium (5 mm gap).

(6) T_j anodized aluminium (10 mm gap).

Fig 12. The effect of x- and z-gaps on T_j for the three enclosure materials

It should be remembered that the surface finish of the enclosure also influences how its outer surfaces will lose heat energy to the environment by the process of radiation. So for instance, the polished aluminium material will not only have poor radiation heat transfer between its inner surfaces and the PCB, but also between its outer surfaces and the local environment.

4.5 Summary: adding x- and z-gaps around the PCB

- Adding a gap between the PCB and enclosure removes the direct conduction heat path between these items
- For the black plastic enclosure, the effect on T_j of the air gap is not dramatic as plastic is a poor conductor of heat anyway, and radiation exchange between the surfaces is good
- For the polished aluminium enclosure with larger y-gap, the effect is more dramatic as aluminium is a good thermal conductor and radiation exchange is poor
- The change in temperatures for the anodized aluminium material lies somewhere between the previous two sets of results. This is because, although aluminium has good thermal conductivity, the surface properties of anodized aluminium allow for good heat exchange by radiation
- Viewed side-by-side, the temperatures observed for the anodized aluminium and black plastic materials are quite similar, while the polished aluminium results are higher - especially for the larger y-gap
- Enclosure thermal conductivity and emissivity also influence the heat paths through the enclosure and from the enclosure outer surface to ambient

5. Encapsulating the PCB

So far we have only considered cases where the PCB has been surrounded by air within the enclosure. However, it is sometimes the case that the interior of the enclosure may be partially or completely filled with an encapsulation (or “potting”) compound. This is generally done to provide the PCB with additional protection from dirt and moisture, as well as improving the mechanical reliability of the module as a whole.

Clearly, if we fill some or all of the enclosure with a solid material then we will alter the thermal behavior of the module. Even without carrying out any detailed analysis, it seems likely that the following aspects will be affected:

- Assuming that the encapsulant is opaque, some or all of the radiation paths will be eliminated
- Some or all of the conduction paths through the air within the enclosure will be improved, provided the encapsulant has a higher thermal conductivity than stagnant air

In the following analyses, we will examine the influence of a typical encapsulant with thermal conductivity of 0.55 W/m.K. For comparison purposes, the thermal conductivity of still air is around 0.003 W/m.K, so although the thermal conductivity of the encapsulant is not very high in absolute terms, it is considerably higher than the air which it may replace. We will consider two methods of encapsulation - one where the level of encapsulant just reaches the top surface of the PCB and one where the whole space within the enclosure is filled with encapsulant. See Figure 13.

We will only examine configurations where the x- and z-gaps are 5 mm. In other words, where the PCB edge is separated from the enclosure walls by a gap of 5 mm. The rationale for this is as follows:

- The need to keep the number of variables to a manageable level
- The likelihood that, in a real design, there would be a need to provide an electrical insulation gap between the PCB and enclosure, when an aluminium enclosure is utilized
- The further probability that, in the x- and z-directions, the PCB would be the largest single item in the module, and hence the enclosure would probably not be much larger than the PCB in these directions

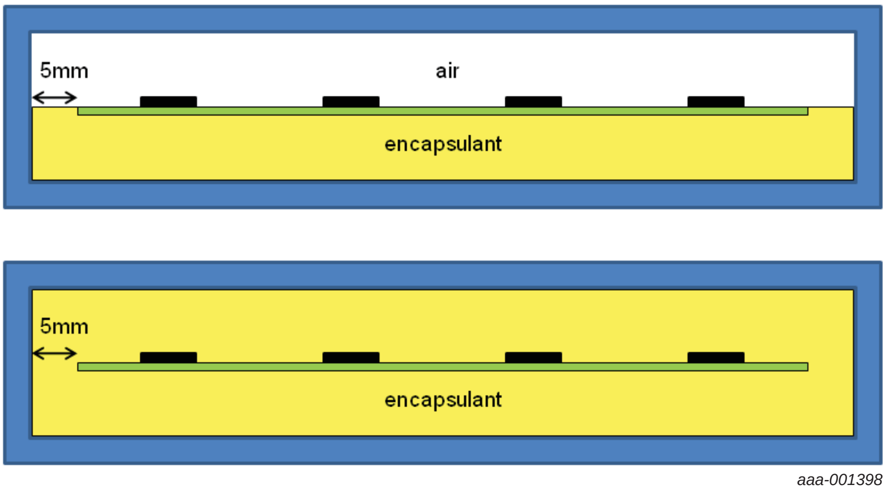
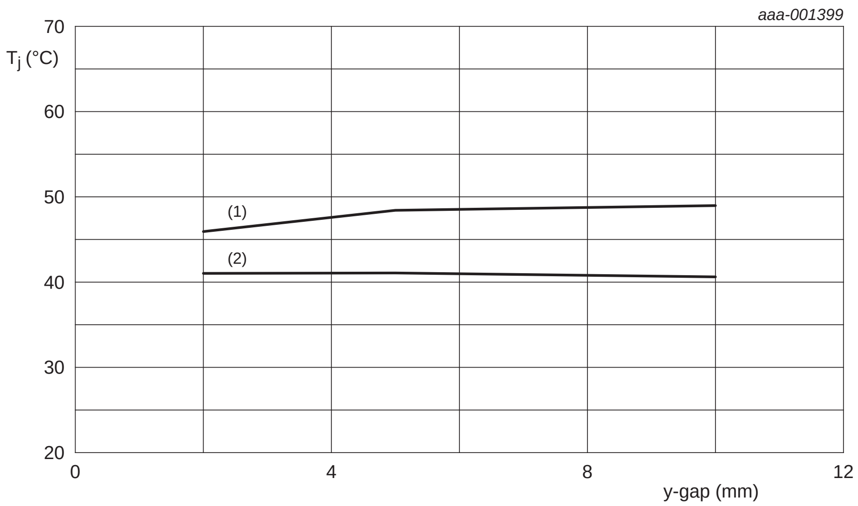


Fig 13. The enclosure partially filled with encapsulant (top) and completely filled (bottom)

5.1 Partial encapsulation

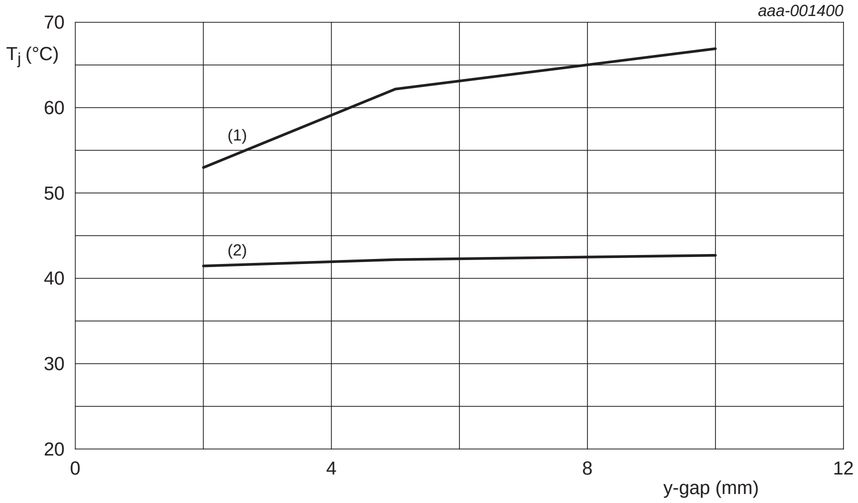
The results for the three enclosure types are shown in Figure 14, Figure 15 and Figure 16. Results without encapsulation are also shown in each graph, for the purpose of comparison.



(1) 5 mm gap, no encapsulation.

(2) 5 mm gap, partial encapsulation.

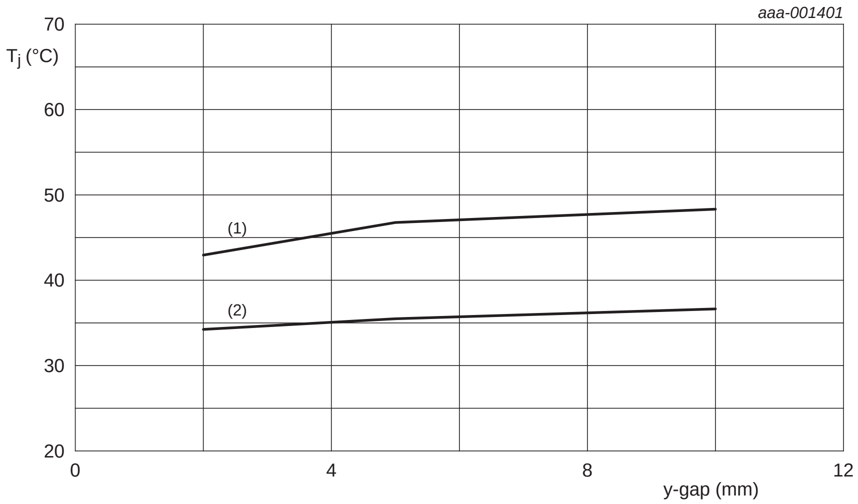
Fig 14. Partial encapsulation - black plastic enclosure



(1) 5 mm gap, no encapsulation.

(2) 5 mm gap, partial encapsulation.

Fig 15. Partial encapsulation - polished aluminium enclosure



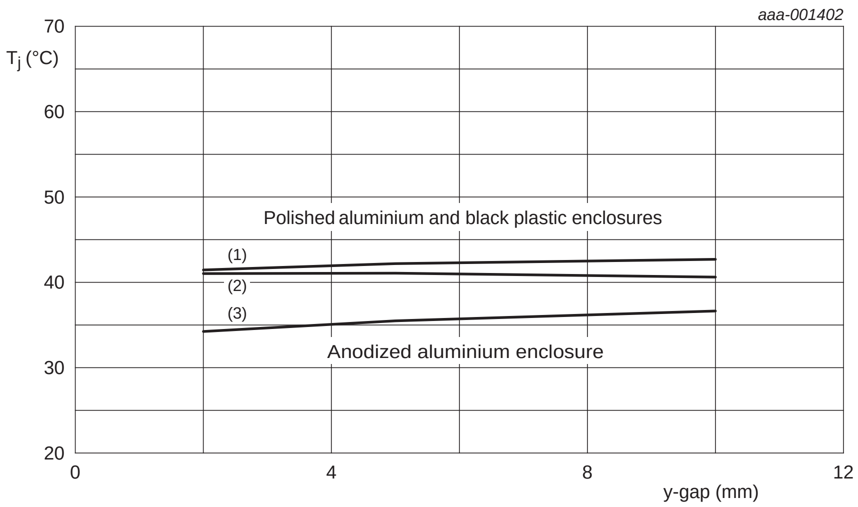
(1) 5 mm gap, no encapsulation.

(2) 5 mm gap, partial encapsulation.

Fig 16. Partial encapsulation - anodized aluminium enclosure

In all three cases, partial encapsulation results in major reductions in temperature. This strongly suggests that the new conduction paths introduced by the encapsulant are thermally better than those which it replaces. This is particularly noticeable for the polished aluminium material, where (relatively) poor radiation heat paths are replaced by more effective conduction paths.

The results are collated onto the single graph of Figure 17, again for the purpose of comparison.



(1) 5 mm gap, polished aluminium, partial encapsulation.

(2) 5 mm gap, black plastic, partial encapsulation.

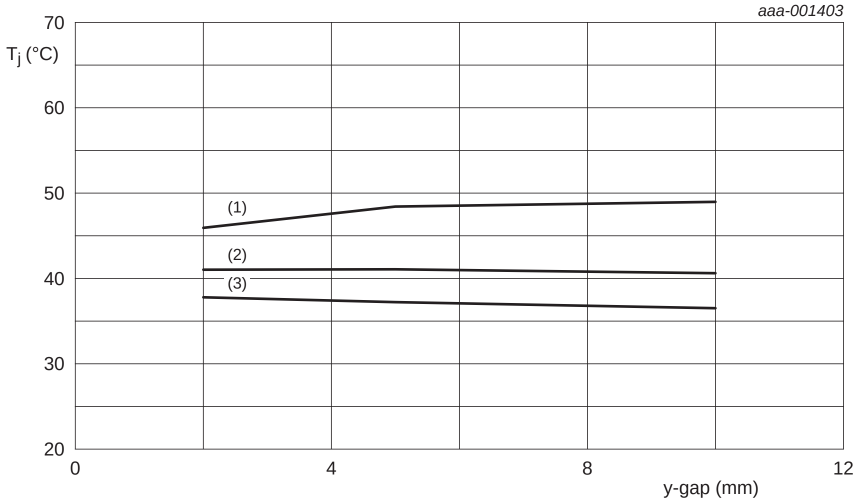
(3) 5 mm gap, anodized aluminium, partial encapsulation.

Fig 17. Partial encapsulation - the three enclosure types summarized

It is also interesting to note that the results have become largely independent of y-gap.

5.2 Full encapsulation

The results for the three enclosure types are shown in Figure 18, Figure 19 and Figure 20. Results with half- and no encapsulation are also shown on each graph, for the purpose of comparison.

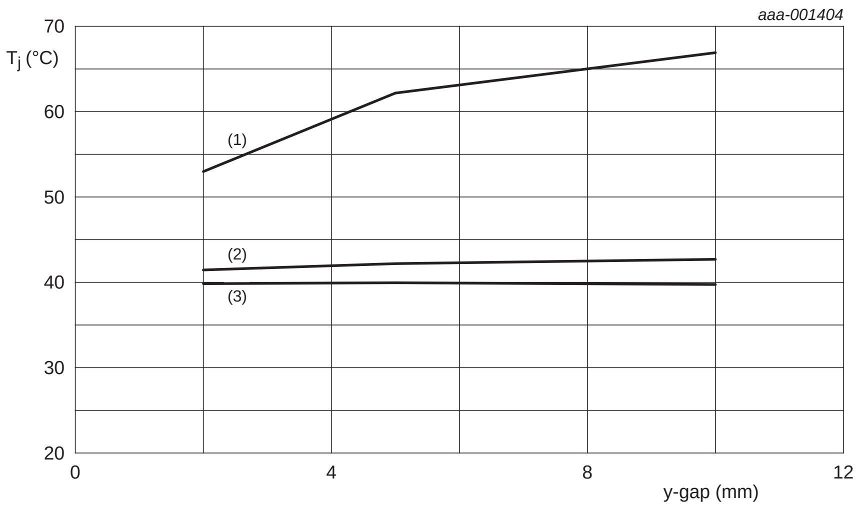


(1) 5 mm gap, no encapsulation.

(2) 5 mm gap, partial encapsulation.

(3) 5 mm gap, full encapsulation.

Fig 18. Full encapsulation - black plastic enclosure

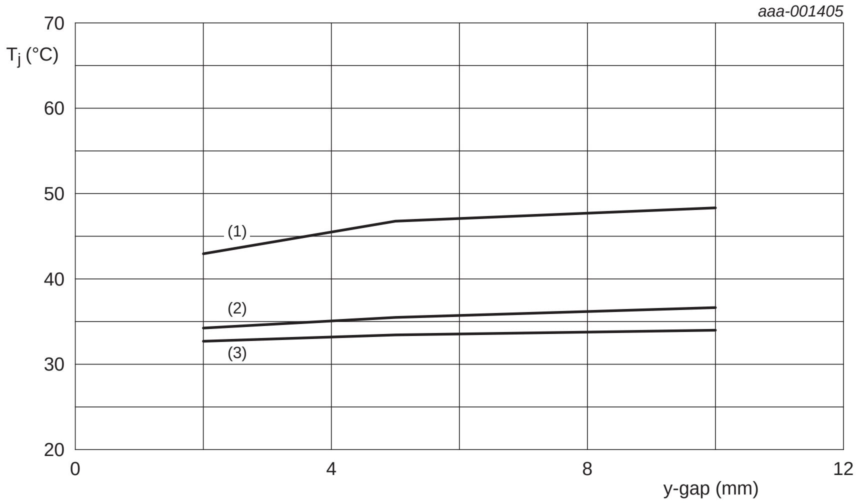


(1) 5 mm gap, no encapsulation.

(2) 5 mm gap, partial encapsulation.

(3) 5 mm gap, full encapsulation.

Fig 19. Full encapsulation - polished aluminium enclosure



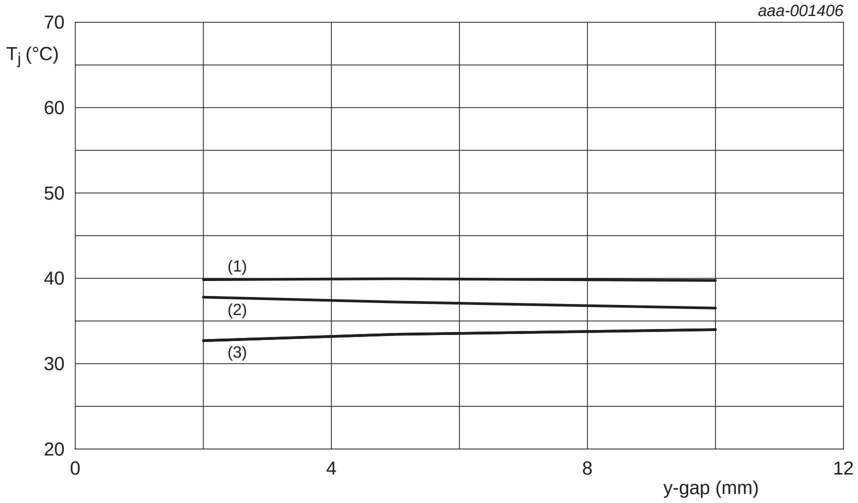
(1) 5 mm gap, no encapsulation.

(2) 5 mm gap, partial encapsulation.

(3) 5 mm gap, full encapsulation.

Fig 20. Full encapsulation - anodized aluminium enclosure

The results are very similar to those for partial encapsulation, with a general overall reduction in temperature, which is sometimes quite substantial, and a general independence of y-gap. The results are collated onto the single graph of Figure 21, again for the purpose of comparison.



(1) 5 mm gap, polished aluminium, full encapsulation.

(2) 5 mm gap, black plastic, full encapsulation.

(3) 5 mm gap, anodized aluminium, full encapsulation.

Fig 21. Full encapsulation - the three enclosure types summarized

By fully encapsulating the enclosure internal space we have made the thermal pathways identical, irrespective of enclosure material. However, we still see a difference in the thermal performance of enclosures of the same size but differing materials. This is because the thermal pathways within the enclosure are only part of the total path which the heat energy takes from source to ambient. The heat energy still has to travel through the walls of the enclosure by conduction, and then from the outside of the enclosure to ambient by convection and radiation. As these thermal pathways are heavily dependent on material properties, we still see differences in thermal performance for enclosures of the same size when fully encapsulated.

5.3 Summary: encapsulating the PCB

1. Encapsulation, whether partial or full, removes some or all of the radiation heat paths within the module and replaces still air with a more conductive material.
2. Both partial and full encapsulation result in a general decrease in device temperatures.
3. The results have become largely independent of y-gap.

6. Direct cooling through the enclosure

So far we have considered cases where the area of direct contact between PCB and enclosure has either been very small (only at the edges of the PCB) or non-existent. In this section, we will consider two cases where the contact between PCB and enclosure is much more direct.

6.1 Bottom-side cooling of the PCB

Bottom-side cooling (BSC) of the PCB is an arrangement whereby the underside of the PCB is brought close to the inner surface of the enclosure, separated by a thin insulating layer. See Figure 22.

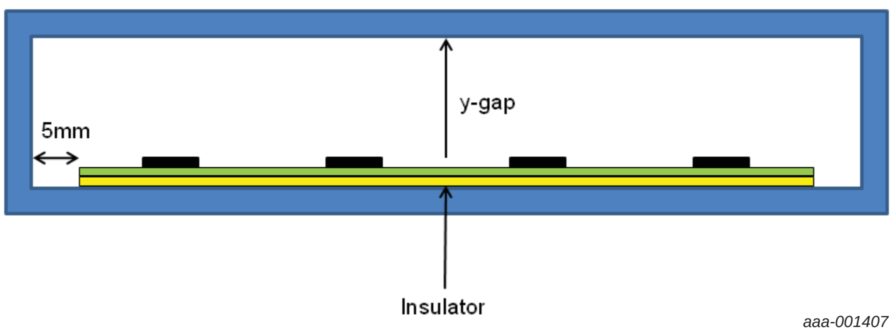
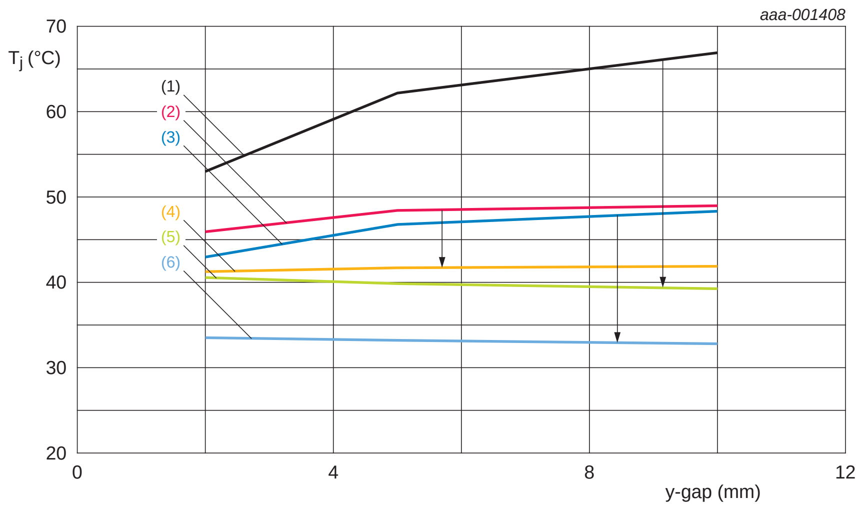


Fig 22. Bottom-side cooling of the PCB

The goal of bottom-side cooling is to channel the heat energy from the MOSFETs' die, through the bottom of the MOSFET device packages, through the PCB vias and into the enclosure. Within the enclosure the intention is to make conduction the primary heat transfer mechanism. Once the heat energy arrives at the enclosure it is dispersed to the local environment from the enclosure outer surface by convection and radiation in the usual way.

The insulator we have chosen has a thermal conductivity of 2.6 W/m.K and a thickness of 2.54 mm, and is representative of common insulating materials. The y-gap is now relevant to only one side of the PCB and, as in the previous section, we will only consider configurations where the PCB edge is separated from the enclosure walls by a gap of 5 mm. The results for all three enclosure types are shown in Figure 23, together with the corresponding results for non-bottom-side cooling, for comparison purposes.



(1) T_j polished aluminium.

(2) T_j black plastic.

(3) T_j anodized aluminium.

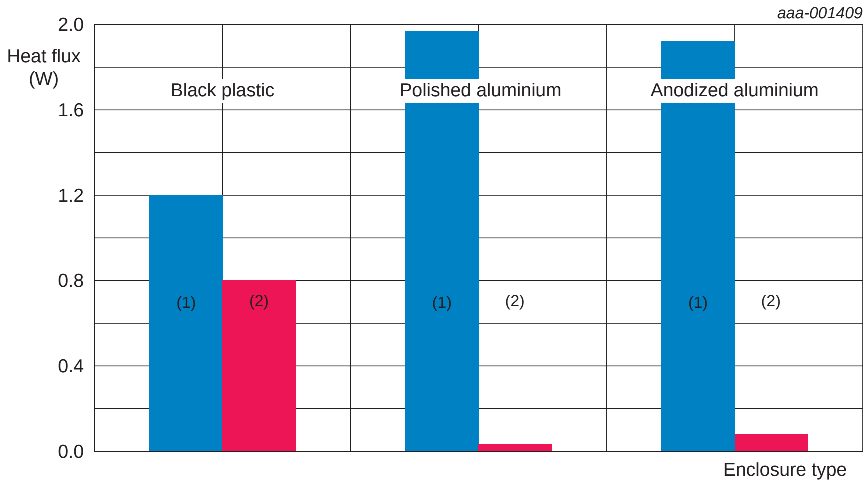
(4) T_j black plastic BSC.

(5) T_j polished aluminium BSC.

(6) T_j anodized aluminium BSC.

Fig 23. Bottom-side cooling (BSC) applied to the three enclosure types

The application of bottom-side cooling has resulted in a reduction in temperatures in all three cases, with results which are almost independent of y-gap. The extent to which we have succeeded in making conduction the dominant mechanism is shown in Figure 24. As T_j is now almost independent of y-gap, Figure 24 shows only the results for y = 10 mm. A 10 mm gap is considered reasonable to allow for other components (connectors, capacitors, etc.) on the top side of the PCB.



(1) Conduction.

(2) Other paths.

Fig 24. Comparison of conduction heat transfer for the three enclosure types with bottom-side cooling applied (y-gap = 10 mm)

For the two aluminium enclosures the amount of heat transferred by conduction within the enclosure is in every case greater than 95 %. This should not be a surprise as aluminium is a relatively good conductor of heat (see Table 1 and Table 2) and so does not present a significant barrier to the conduction of heat energy. Even for the plastic enclosure, the amount of heat transferred by conduction within the enclosure is still almost 60 %. When considered in conjunction with the graphs of Figure 23, this fact suggests that bottom-side cooling is an effective strategy for removing heat from the PCB. Finally, as we have seen before, the overall best performance is achieved with the anodized aluminium enclosure, which benefits both from good conduction and effective heat transfer by radiation.

6.2 Bottom-side cooling of the PCB, with encapsulation

For the final part of the bottom-side cooling analysis, we can also look at the effect of adding encapsulant to the inside of the enclosure. In Section 5 we saw that replacing some or all of the air space inside the enclosure with encapsulant tended to reduce device temperatures, as the encapsulant has a better thermal conductivity than stagnant air. In the first part of Section 6 we also saw that applying bottom-side cooling had a significant impact on device temperatures due to the presence of a direct conduction heat path through the wall of the enclosure. For the aluminium enclosure materials in particular, the majority of the heat was found to be passing through the enclosure wall by conduction (Figure 24). It will therefore be interesting to see, for instances when we already have good conduction through the enclosure wall, whether adding encapsulant will make any further significant difference to device temperatures. See Figure 25.

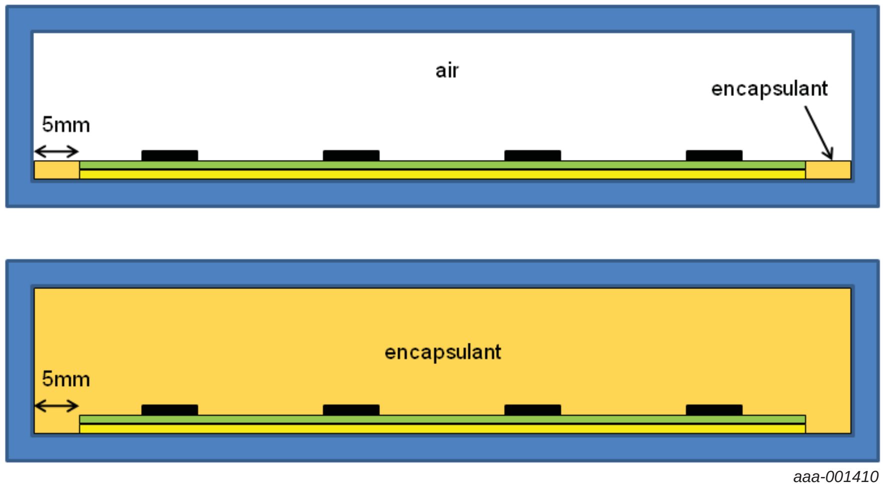
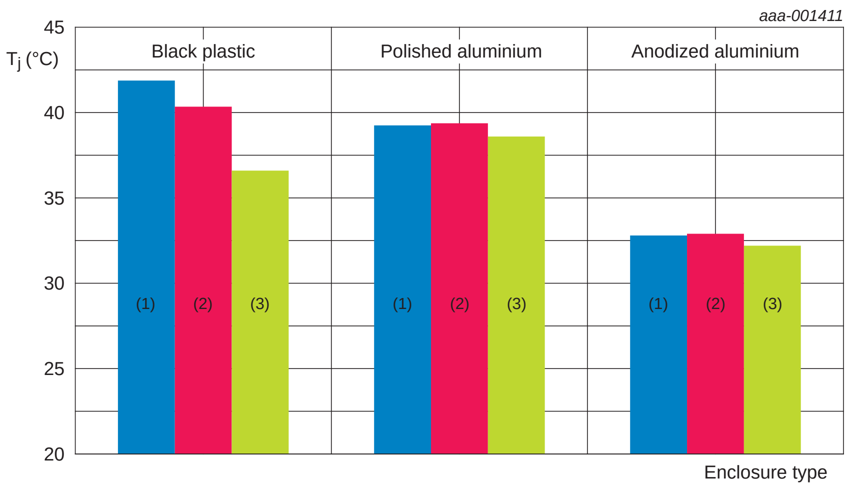


Fig 25. Bottom-side cooling with partial encapsulation (top) and full encapsulation (bottom)

The three bottom-side cooling scenarios from Section 6.1 have been simulated with partial- and full encapsulation, and the results are shown in the graph of Figure 26.



(1) No encapsulation.

(2) Partial encapsulation.

(3) Full encapsulation.

Fig 26. Bottom-side cooling, with and without encapsulation

For the aluminium enclosures, the presence of encapsulation has made almost no difference to device temperature. These results are not surprising, as most of the heat energy is being transferred from the PCB to the enclosure by direct conduction anyway, and so adding encapsulant makes little additional difference. In the case of the plastic enclosure, however, the presence of the encapsulant makes a more significant difference as less heat is being transferred to the enclosure by direct contact (Figure 24).

6.3 Top-side cooling of the PCB

Top-Side Cooling (TSC) is an arrangement whereby the tops of the device packages are brought close to the inner surface of the enclosure, separated by a thin insulating layer. See Figure 27. Although there is no need for an electrical insulator between the device packages and the enclosure, a thermal “gap filler” is usually employed to allow a consistent contact between all the devices and the enclosure surfaces. For the purposes of this exercise we will use the same insulating material as in the bottom-side cooling cases.

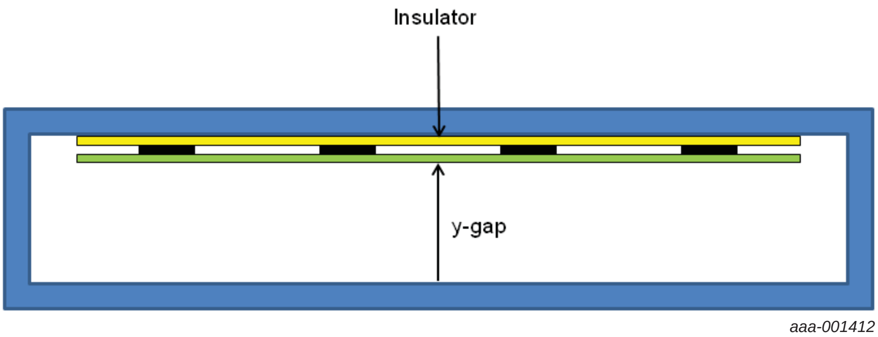
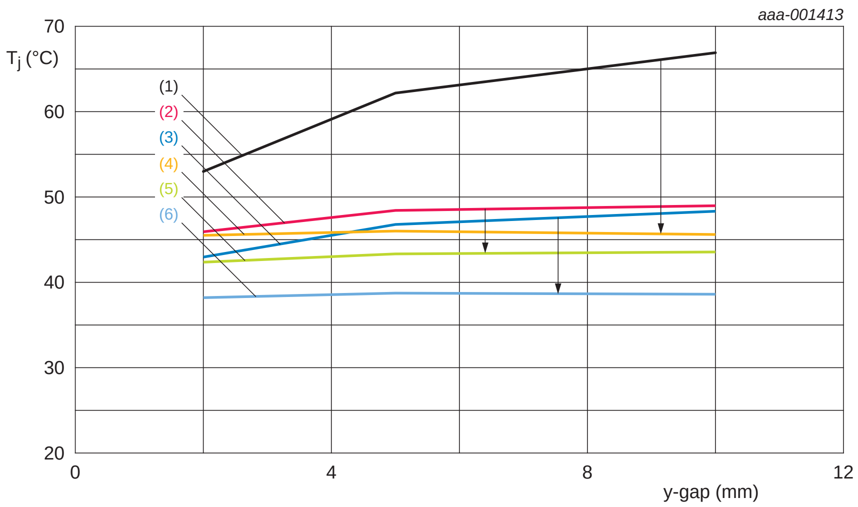


Fig 27. Top-side cooling of the devices

This arrangement is intended to channel the heat energy from the MOSFETs' die, through the top of the MOSFET device packages and into the enclosure.

The y-gap is again relevant to only one side of the PCB and, as in the previous section, we will only consider configurations where the PCB edge is separated from the enclosure walls by a gap of 5 mm. The results for all three enclosure types are shown in Figure 28, together with the corresponding results for non-top-side cooling, for comparison purposes.



(1) T_j polished aluminium.

(2) T_j black plastic.

(3) T_j anodized aluminium.

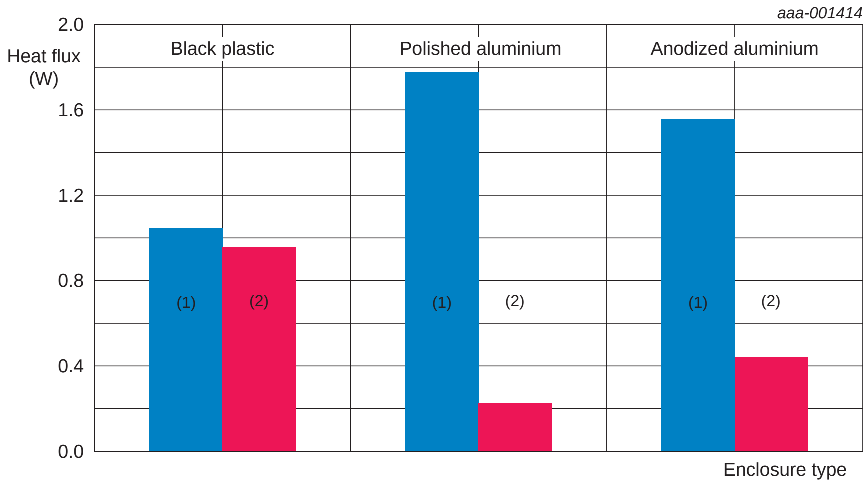
(4) T_j polished aluminium TSC.

(5) T_j black plastic TSC.

(6) T_j anodized aluminium TSC.

Fig 28. Top-side cooling applied to the three enclosure types

The results are strikingly similar to those for bottom-side cooling, shown in Section 6.2: the application of top-side cooling has again resulted in a reduction in temperatures in all three cases. Similarly, the results are also virtually independent of y-gap. The degree to which we have made conduction the dominant mechanism is shown in Figure 29. As before, T_j is now almost independent of y-gap, and so Figure 29 shows only the results for y = 10 mm.



(1) Conduction.

(2) Other paths.

Fig 29. Comparison of conduction heat transfer for the three enclosure types with top-side cooling applied (y-gap = 10 mm)

Compared to the figures for bottom-side cooling (Figure 24) we can see that, for the aluminium enclosures, conduction is not quite so dominant, and for the plastic enclosure the split is almost equal between conduction and the other paths combined. This is perhaps not surprising, as in the top-side cooling scheme the heat energy must pass through the (admittedly thin) layer of plastic on the package tops before reaching the insulator and enclosure, and as we have seen, plastic is a relatively poor conductor of heat energy. On the other hand, for the bottom-side cooling scheme, the heat energy has a relatively high conductivity path (solder, PCB planes, thermal vias) before reaching the insulator, and is not impeded by a layer of plastic.

6.4 Top-side cooling of the PCB, with encapsulation

Following the same progression as for bottom-side cooling, we will also look at the effect of adding encapsulant to the top-side cooling scheme. See Figure 30.

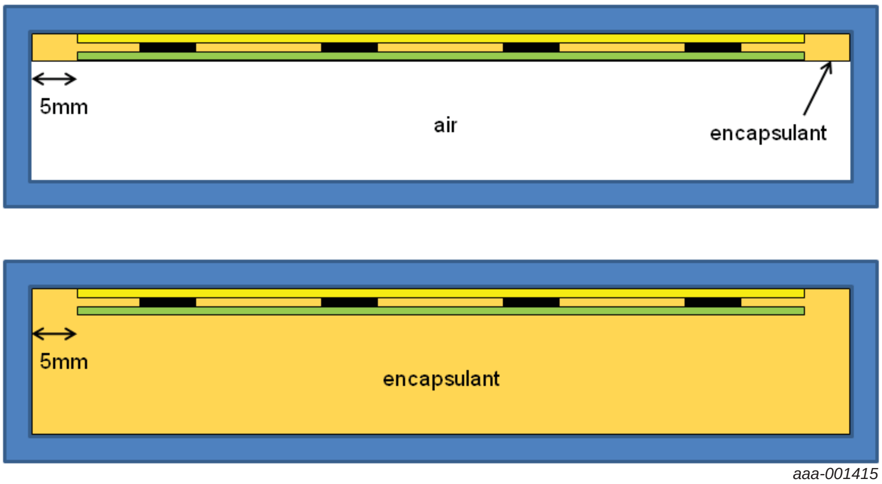
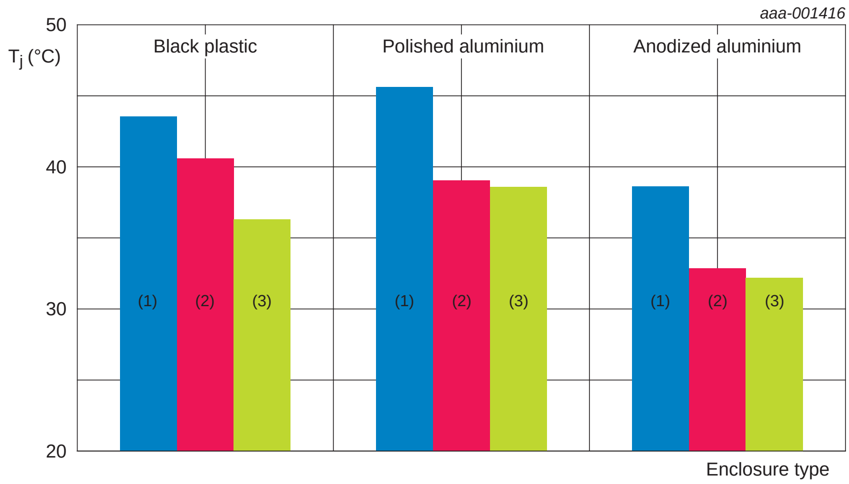


Fig 30. Top-side cooling with partial encapsulation (top) and full encapsulation (bottom)

In the bottom-side cooling scheme we saw that adding encapsulation tended to lower device temperatures for the plastic enclosure, but made little difference for the aluminium enclosures. This was because, for the aluminium enclosure material, the majority of the device heat energy was found to be passing through the PCB and enclosure wall by conduction, and so adding the encapsulant material made little difference to thermal pathways which were already very effective.

In the top-side cooling scheme we have already identified the device plastic as a potential barrier to the flow of heat energy, so it will therefore be interesting to see whether adding encapsulant will make any significant difference to device temperatures.

The three top-side cooling scenarios from Section 6.3 have been simulated with partial- and full encapsulation, and the results are shown in the graph of Figure 31.



(1) No encapsulation.
(2) Partial encapsulation.
(3) Full encapsulation.

Fig 31. Top-side cooling, with and without encapsulation

It is interesting to compare these results with those for bottom-side cooling (Figure 26). For the aluminium enclosures with bottom-side cooling, the presence of encapsulation made almost no difference to device temperatures. However, for top-side cooling, we see a notable decrease in temperature when encapsulation is applied. This is a reflection of the fact that the thermal pathway from the devices in a top-side cooling scheme is not as direct as it is for bottom-side cooling, and so improving the path from the bottom of the PCB (by replacing the air with encapsulant) results in a reduction in device temperature.

6.5 Summary: direct cooling through the enclosure

Bottom-side cooling:

- The application of bottom-side cooling results in a reduction in device temperature. The degree to which temperature is reduced is dependent on the enclosure material
- Results become almost independent of y-gap
- For the aluminium enclosures, the presence of encapsulation makes almost no difference to device temperatures. For the plastic enclosure, the encapsulant results in reduced device temperatures.

Top-side cooling:

- The application of top-side cooling also results in a reduction in device temperature. Again, the degree to which temperature is reduced is dependent on the enclosure material.
- However, top-side cooling is not as effective as bottom-side cooling
- Results become almost independent of y-gap
- For all three enclosure types, there is a notable decrease in device temperature when top-side cooling is applied

7. Mounting the enclosure on a bulkhead

All of the cases we have looked at so far have the module located horizontally in free air. In this last chapter we will consider the module's thermal performance when located in a manner more representative of actual usage i.e. mounted vertically, close to a steel bulkhead.

For the purposes of this exercise, we will consider the following module variations:

1. Module x- and z-gaps fixed at 5 mm.
2. Module y-gap(s) fixed at 10 mm.
3. Three enclosure materials (black plastic, polished aluminium, anodized aluminium).
4. PCB mounted centrally in the enclosure.
5. PCB with bottom-side cooling applied.
6. PCB with top-side cooling applied.

7.1 Vertical orientation of the module

Before considering the effect of the steel bulkhead, we will first examine what happens when we orientate the module vertically rather than horizontally. See Figure 32.

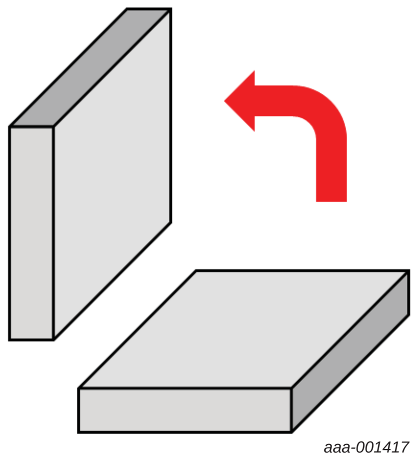
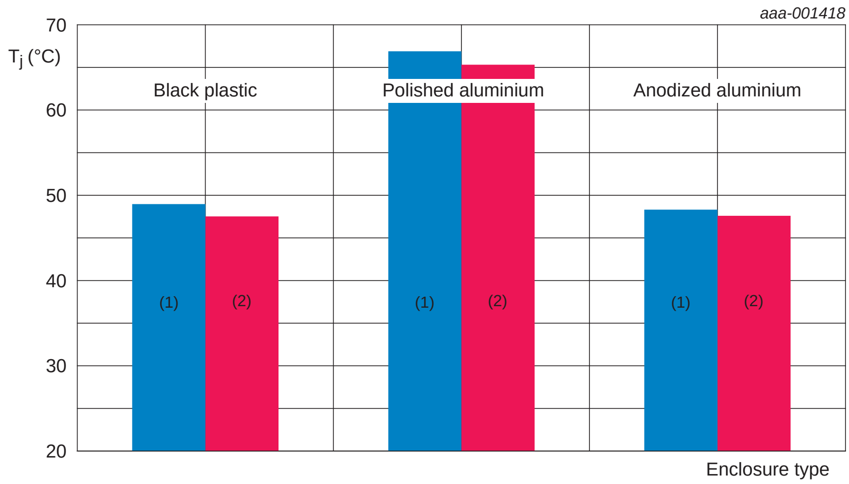


Fig 32. Orientating the module vertically

The effect on device temperatures is shown in the graph of Figure 33.



(1) Module horizontal.

(2) Module vertical.

Fig 33. The effect of module orientation on device temperature

At most, the change in orientation has resulted in a decrease in device temperature of 1.5 °C. Remember that at this stage the PCB is still mounted centrally within the enclosure i.e. the y-gaps above and below the PCB are 10 mm.

7.2 Adding the bulkhead

The next stage is to add the bulkhead to the scenario. Rather than mount the module directly against the bulkhead, with perfectly flat adjoining surfaces, we have instead chosen to mount the module using 5 mm plastic “standoffs”. This means that there is an air gap of 5 mm between the surface of the module and surface of the bulkhead. This is felt to better represent reality, as any real-life module would probably be mounted using some form of plastic clips. See Figure 34.

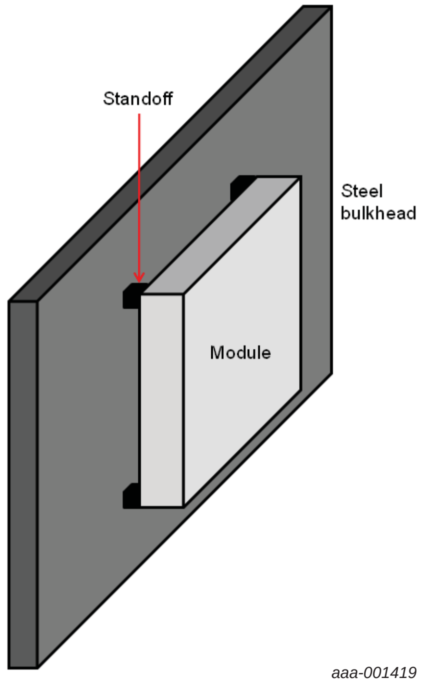


Fig 34. The module mounted on the bulkhead

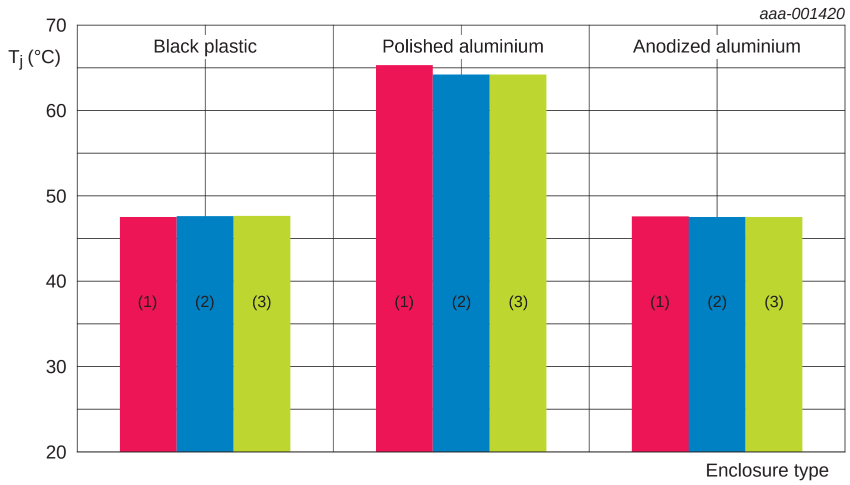
The bulkhead itself is modeled as a piece of steel measuring 220 mm × 170 mm × 5 mm. As the bulkhead is now a part of the overall thermal system, we have to decide how to model its thermal characteristics. On the one hand, we could model the bulkhead as a normal piece of conducting material which is capable of transferring heat by the processes of conduction, convection and radiation. However, if we take this approach then we have to consider how the section of bulkhead will itself lose heat energy to its surroundings, and the danger with this approach is that we could end up trying to model the entire vehicle!

An alternative approach, and the one adopted here, is to define the bulkhead as a fixed temperature block at the ambient temperature of 20 °C. This means that, no matter how much heat energy is passed into the bulkhead, its temperature will remain at a fixed, uniform 20 °C. The justification for this approach is that, in reality, the bodywork of the vehicle is so much more massive than the module that, for all practical purposes, the bulkhead is almost the “perfect heatsink” used in the model.

A final point which must be addressed is that of which of the two sides of the module should be nearest to the bulkhead. This could be an important consideration in scenarios where, for instance top-side or bottom-side cooling of the PCB is employed. We will therefore consider both cases, where both the bottom and top of the module are nearest to the bulkhead. The “bottom” of the module is considered to be the side nearest to the solder side of the PCB, and the “top” of the module is the side nearest to the component side of the PCB.

7.3 Results for the PCB mounted centrally in the module

The results for the module with PCB mounted centrally (y-gaps above and below the PCB are 10 mm) are shown in Figure 35. Results are shown for the module mounted bottom-side to the bulkhead, top-side to the bulkhead and without any bulkhead.



(1) No bulkhead.

(2) Module bottom side to bulkhead, with 5 mm gap.

(3) Module top side to bulkhead, with 5 mm gap.

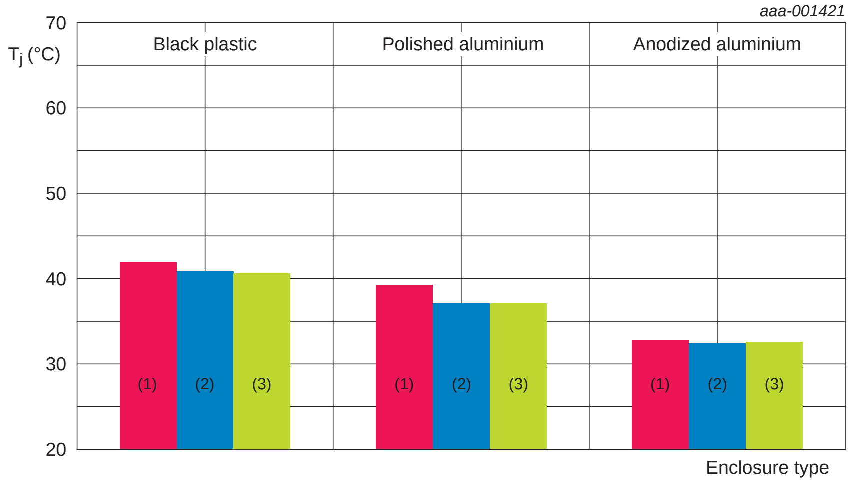
Fig 35. Results for the module mounted on the bulkhead (PCB central)

For a given enclosure material, there is little difference in temperature whether the module is mounted on the bulkhead or not, and also whether the bottom or top side of the module is nearest to the bulkhead.

We might consider this an unexpected result, as the presence of the bulkhead should be interfering with the process of natural convection occurring on one side of the module. While this is undoubtedly true, and the air on the affected sides remains “trapped” and stationary against the side of the module, the air (and hence the side of the module in contact with it) is maintained at a lower than normal temperature by the fixed-temperature bulkhead. We might think of this effect as “heat sinking at a distance”. Hence the lack of convection on one side is compensated for and there is almost no effect on device temperature.

7.4 Results for the PCB with bottom-side cooling

The results for the module with bottom-side cooling (y-gap above the PCB is 10 mm) are shown in Figure 36. The vertical scale in Figure 36 has been deliberately made the same as for Figure 35 in order to facilitate comparison of the results.



(1) Horizontal (no bulkhead).

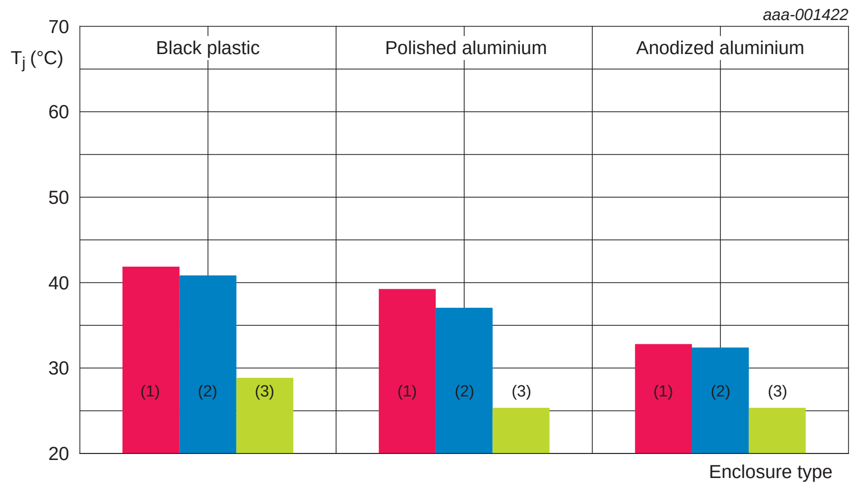
(2) Module bottom side to bulkhead, with 5 mm gap.

(3) Module top side to bulkhead, with 5 mm gap.

Fig 36. Results for the module mounted on the bulkhead (PCB utilizing bottom-side cooling)

Once again, for a given enclosure material, we do not see a dramatic difference when the module is mounted on the bulkhead. This might seem a little surprising as, inside the module, there is a good conduction path from the devices, through the PCB and into the enclosure material. However, the heat energy is still required to bridge the air gap between the module outer surface and the bulkhead, and so any heat sinking effect from the bulkhead is effectively eliminated.

In order to illustrate this point a little better, we will consider the same scenario once more (PCB bottom-side cooled within the module) except that this time we will attach the module face directly to the bulkhead. This will be a “perfect attachment” with no contact resistance and complete, uniform contact between the surfaces. Such a perfect arrangement could never be achieved in real life, and the results are shown here simply for interest (Figure 37).



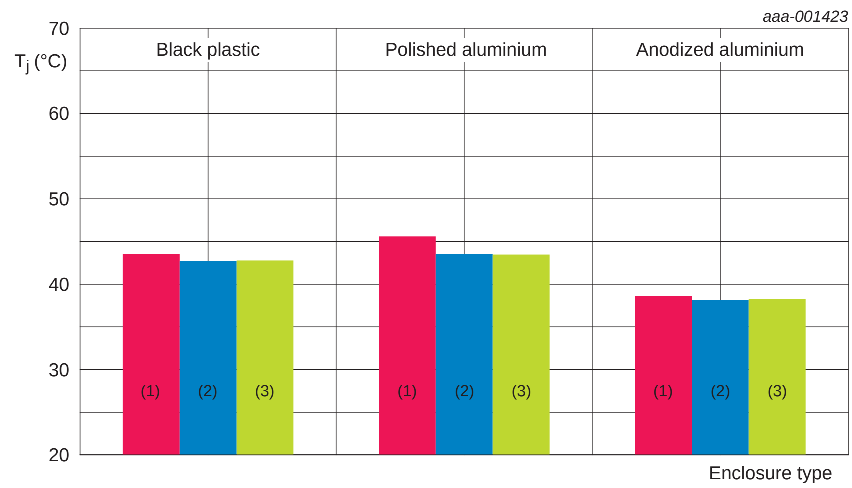
(1) Horizontal (no bulkhead).
(2) Module bottom side to bulkhead, with 5 mm gap.
(3) Module bottom side in contact with bulkhead.

Fig 37. Results for the module mounted “perfectly” on the bulkhead

As one might expect, with an uninterrupted conduction path between the module and the bulkhead, there is a significant reduction in device temperature.

7.5 Results for the PCB with top-side cooling

The results for the module with top-side cooling (y-gap below the PCB is 10 mm) are shown in Figure 38.



(1) Horizontal (no bulkhead).
(2) Module bottom side to bulkhead, with 5 mm gap.
(3) Module top side to bulkhead with 5 mm gap.

Fig 38. Results for the module mounted on the bulkhead (PCB utilizing top-side cooling)

The trend in results is very similar to that seen for the bottom-side cooled PCB i.e. the presence of the bulkhead actually makes little difference to the device temperatures.

7.6 Summary: mounting the enclosure on a bulkhead

- Altering the module orientation from horizontal to vertical has little effect on device temperatures - at most a decrease of 1.5 °C was observed
- Adding the bulkhead to the module with central PCB also makes little difference to device temperatures
- The bulkhead limits convection heat loss from the surface of the enclosure, but also provides an effect of “heat sinking at a distance”. These two phenomena tend to cancel each other out.
- The bottom-side cooling version of the module does not benefit from the presence of the bulkhead unless mounted directly on it with “perfect” thermal contact. This is an arrangement which is likely to be unachievable in practice.
- The top-side cooling version of the module also does not benefit from the close proximity of the bulkhead
- Overall, mounting the module vertically and close to a bulkhead does not make things dramatically better or worse

8. Summary

Thermal aspects are an important concern when designing with power MOSFETs. Both MOSFET junction temperature and PCB temperature must be kept within safe limits if reliable operation is to be ensured.

Application Note *AN10874 “LFPAK thermal design guide”* considered the impact of various different PCB and device configurations on thermal behavior. The factors considered included PCB layer count, the impact of thermal vias and the placement of multiple devices.

The scenarios considered in AN10874 utilized PCBs situated in free air, with no enclosures or housings included in the scenarios. The primary heat loss mechanism from the PCBs was therefore natural convection, unimpeded by the presence of any other physical structure.

This design guide has addressed the likelihood that, in most real-life applications, the need to protect the PCB from environmental factors, plus possible considerations for electromagnetic compatibility would almost certainly dictate that the PCB would be mounted in an enclosure of some form. The investigations have examined how the enclosure, and the bulkhead on which it may be mounted, have impacted on the thermal performance of the system.

The design guide has considered three enclosure materials with differing thermal properties and dimensions. Encapsulation within the enclosure, and the role of bottom- and top-side cooling has also been examined, as has the effect of locating the module in close proximity to a bulkhead. From this investigation we have been able to draw several interesting conclusions:

1. Adding an enclosure around the PCB may or may not increase device temperatures - this depends on several other factors.
2. The air within the enclosure is not able to move, and hence the normal process of heat loss by convection does not occur. Instead, the air behaves as a stationary conductor with low thermal conductivity.
3. In the absence of convection, heat loss by radiation becomes of more significance, and hence the surface finish of the materials employed also becomes significant.
4. Partially or completely filling the enclosure with encapsulant results in a lowering of temperatures, as the encapsulant has a higher thermal conductivity than the stationary air it replaces.
5. The use of bottom- and top-side cooling techniques can reduce device temperatures significantly. Of the two, bottom-side cooling is more effective.
6. Altering the module orientation from horizontal to vertical has almost no effect on device temperatures.
7. The presence of the bulkhead makes little difference to device temperatures.

While this document cannot hope to address all possible different module configurations, it is hoped that those presented here are representative of typical “real life” usage.

Finally, we should reiterate that the information contained within this design guide is presented as a starting point only. Any new design should of course be prototyped and its thermal behavior characterized before placing the design into production.

9. Abbreviations

Table 3. Abbreviations

Acronym	Description
EMC	ElectroMagnetic Compatibility
LFPAK	Loss-Free Package
MOSFET	Metal-Oxide Semiconductor Field-Effect Transistor
PCB	Printed-Circuit Board
SMD	Surface-Mounted Device

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11. Contents

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