Heatsink Optimization

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Introduction

Optimal design of a heatsink, meeting program targets for cost, weight, size, and performance, is one of the more challenging activities within most electronics engineering teams. Without a dedicated solver, designers or thermal engineers can be involved in a game of 'opinioneering', which typically involves overdesign, or initiate an expensive and time-consuming physical design of experiments that provides limited results

In the case study below, DfR worked to optimize an extruded aluminum heat sink for an IGBT module in a low-cost, high-volume design. Reliability requirements (10-year life), harsh environments (vibration, elevated temperature), limited ability to perform maintenance (consumer household), and cost constraints eliminated forced air cooling as a practical solution. The focus was instead to optimize the design within the dimensional constraints provided by the end-user.

IGBT Module

Optimization was requested because the IGBT module starts to behave intermittently at 60°C and shuts down completely at 65°C. The module shutdowns due to a thermal cutoff limit of 100°C at the internal thermistor. The data sheet for the IGBT module indicates that the cutoff temperature of the IGBT junction temperature is 150°C. The module thermal resistances are supplied by the manufacturer and are shown in Figure 1.

The goal of this analysis was to reduce the thermistor temperature during operation such that the module achieves stable operation at 60°C and shutdown at or above 65°C. To achieve this goal, the case temperature of the IGBT must be decreased. This increase in the operating margin will be achieved by modifying the relevant heatsink parameters. The baseline heatsink dimensions are displayed in Figure 2.

Symbol	Parameter	Min	Typ	Max	Units	Conditions
$R_{th(j-c)}$	Thermal resistance, per IGBT	---	4.2	4.7	°C/W	Flat, greased surface. Heatsink compound thermal conductivity 1W/mK
$R_{th(j-c)}$	Thermal resistance, per Diode	---	5.5	6.5		
$R_{th(c-s)}$	Thermal resistance, C-S	---	0.1	---		

Figure 1: Thermal resistance of IGBT module

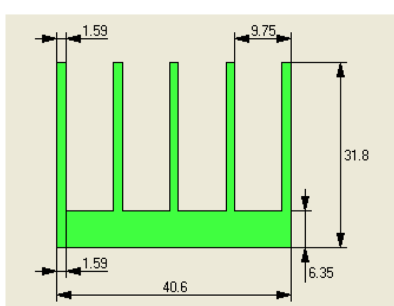
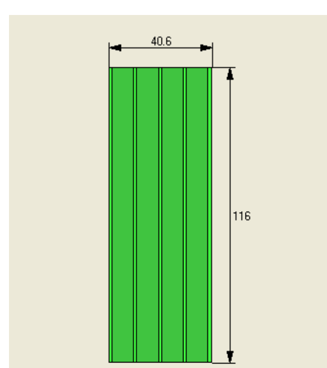


Figure 2: Dimensions of heatsink



Model Calibration

A thermal analysis of the original heatsink design was conducted to baseline the thermal model. A thermal image of the heatsink while the IGBT module is dissipating 40 watts at 20°C is shown in Figure 3 (left image). The maximum heat sink temperature is measured as 90.1C, or a 70.1C rise above ambient.

The results of thermal simulation at 40 watts at 20C are also shown in Figure 3 (right image). The maximum temperature rise was predicted to be 75.7C. The difference between measured and predicted is within 6%, which is a reasonable margin of error.

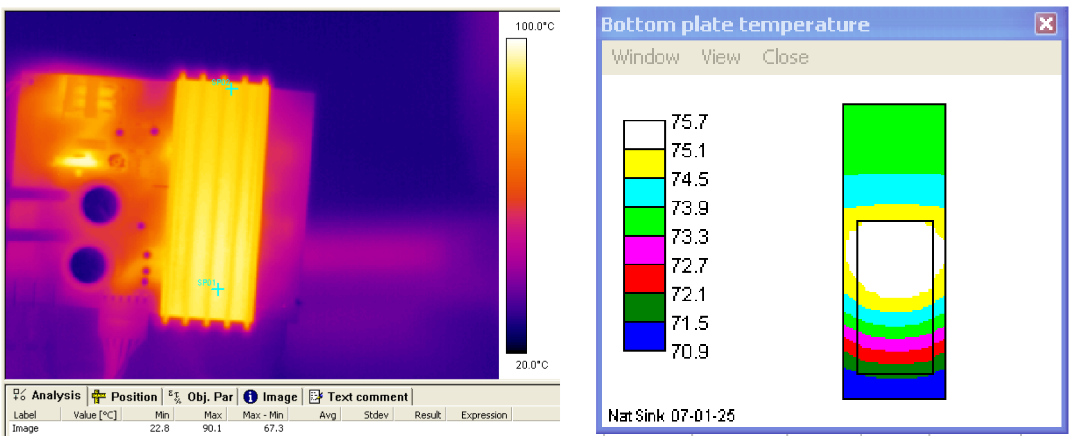


Figure 3: Heatsink temperatures at 20°C ambient

Design of Experiments

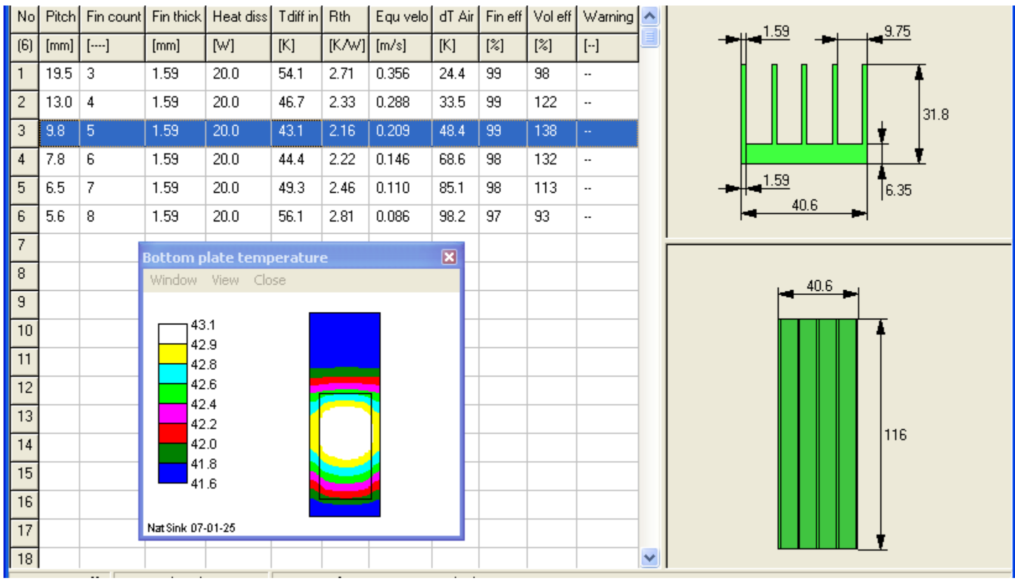
The heatsink parameters assessed in this design optimization study are presented in Table 1. Number of fins, fin height, location of heat source, and surface treatment were all assessed in terms of their ability to lower IGBT case temperature.

Table 1: Heatsink DoE Parameters

Base Thickness	Height	Width	Length	Fin Thickness	Fin Pitch	Fin #	Misc.
6.35 mm	31.8 mm	40.6 mm	116 mm	1.6 mm	9.75 mm	5	
6.35 mm	31.8 mm	40.6 mm	116 mm	1.6 mm	7.8 mm	**6**	
6.35 mm	**38.1 mm**	40.6 mm	116 mm	1.6 mm	9.75 mm	5	
6.35 mm	**44.5 mm**	40.6 mm	116 mm	1.6 mm	9.75 mm	5	
6.35 mm	31.8 mm	40.6 mm	116 mm	1.6 mm	9.75 mm	5	**Center IGBT**
6.35 mm	31.8 mm	40.6 mm	116 mm	1.6 mm	9.75 mm	5	**Annodized**

Results

When the calibrated model is run at the desired use condition of 20 watts at 60°C ambient, the case temperature rise is 43.1°C over ambient (see **Figure 4**). This clearly explains the intermittent operation of the IGBT under these conditions and indicates that for the heatsink optimization to be successful, the new heatsink design must reduce case temperatures by at least 5 and preferably 10C[1].



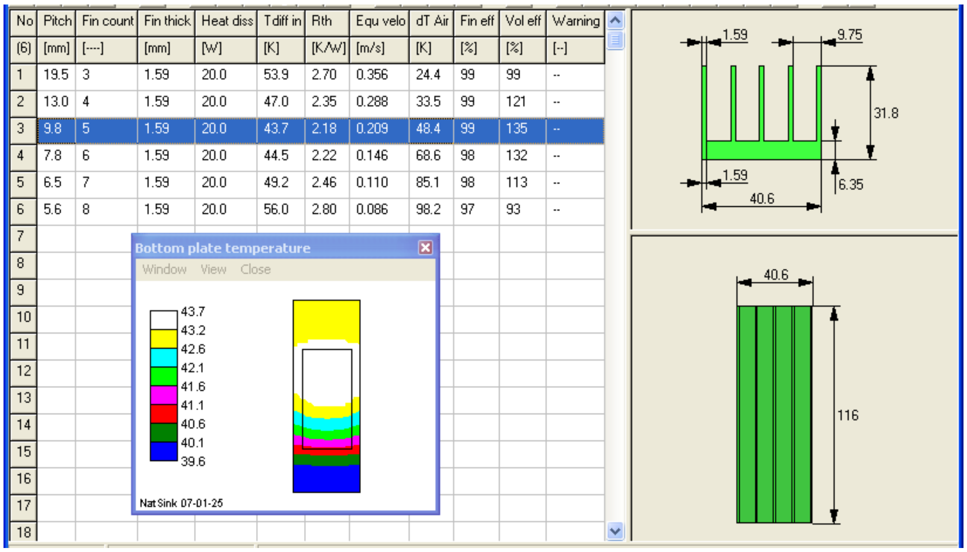
No	Pitch	Fin count	Fin thick	Heat diss	Tdiff in	Rth	Equ velo	dT Air	Fin eff	Vol eff	Warning
(6)	[mm]	[----]	[mm]	[W]	[K]	[K/W]	[m/s]	[K]	[%]	[%]	[--]
1	19.5	3	1.59	20.0	54.1	2.71	0.356	24.4	99	98	--
2	13.0	4	1.59	20.0	46.7	2.33	0.288	33.5	99	122	--
3	9.8	5	1.59	20.0	43.1	2.16	0.209	48.4	99	138	--
4	7.8	6	1.59	20.0	44.4	2.22	0.146	68.6	98	132	--
5	6.5	7	1.59	20.0	49.3	2.46	0.110	85.1	98	113	--
6	5.6	8	1.59	20.0	56.1	2.81	0.086	98.2	97	93	--

Figure 4: Baseline heatsink analysis at 20 watts, 60°C ambient, five fins optimal, 103°C

[1] Interesting finding within the DoE: At 20C and 40W, the optimum number of fins is six (6). However, when the ambient temperature is increased to 60C, but the power dissipation is lowered to 20W, the optimum number of fins drops to five (5).

Heat source location

The effect of moving the heat source was simulated at 60°C ambient conditions. Moving the heat source to the heatsink center had little effect on the performance (<1°C temperature change), as shown in **Figure 5**. Moving the heat source above the centerline increased the temperature by almost 3°C, as shown in **Figure 6**.



No	Pitch	Fin count	Fin thick	Heat diss	Tdiff in	Rth	Equ velo	dT Air	Fin eff	Vol eff	Warning
(6)	[mm]	[---]	[mm]	[W]	[K]	[K/W]	[m/s]	[K]	[%]	[%]	[-]
1	19.5	3	1.59	20.0	53.9	2.70	0.356	24.4	99	99	--
2	13.0	4	1.59	20.0	47.0	2.35	0.288	33.5	99	121	--
3	9.8	5	1.59	20.0	43.7	2.18	0.209	48.4	99	135	--
4	7.8	6	1.59	20.0	44.5	2.22	0.146	68.6	98	132	--
5	6.5	7	1.59	20.0	49.2	2.46	0.110	85.1	98	113	--
6	5.6	8	1.59	20.0	56.0	2.80	0.086	98.2	97	93	--
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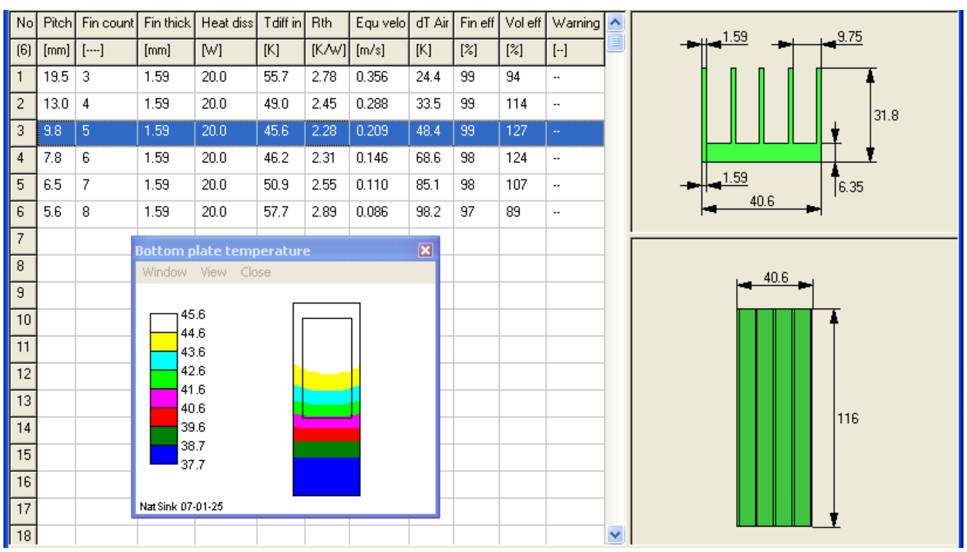
Figure 5: Heat source located at center



No	Pitch	Fin count	Fin thick	Heat diss	Tdiff in	Rth	Equ velo	dT Air	Fin eff	Vol eff	Warning
(6)	[mm]	[---]	[mm]	[W]	[K]	[K/W]	[m/s]	[K]	[%]	[%]	[-]
1	19.5	3	1.59	20.0	55.7	2.78	0.356	24.4	99	94	--
2	13.0	4	1.59	20.0	49.0	2.45	0.288	33.5	99	114	--
3	9.8	5	1.59	20.0	45.6	2.28	0.209	48.4	99	127	--
4	7.8	6	1.59	20.0	46.2	2.31	0.146	68.6	98	124	--
5	6.5	7	1.59	20.0	50.9	2.55	0.110	85.1	98	107	--
6	5.6	8	1.59	20.0	57.7	2.89	0.086	98.2	97	89	--
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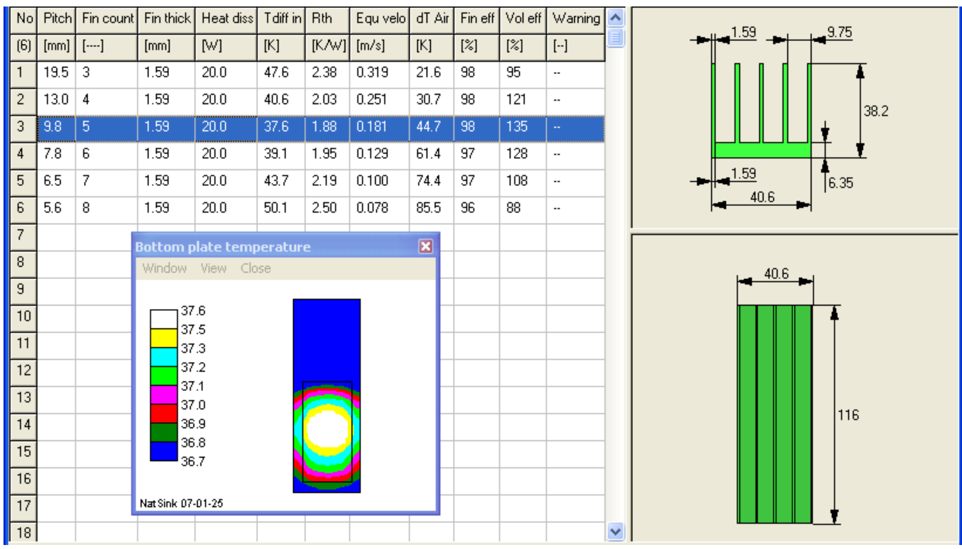
Figure 6: Heat source located near top

Heatsink Fin Height

The effect of changing the fin height was modeled at 60°C ambient conditions. Increasing the fin height by 0.25" decreased the temperatures by 5.5°C, as shown in **Figure 7**. Increasing the fin height by 0.5" decreased the operating temperature by 10°C. This indicates that the module will be running at 93.6°C.

Increasing the ambient temperature to 65°C has a minimal impact on the temperature rise. At 65°C the IGBT module will be operating at 98.7°C and should be at the limitations of its operating range. Further modifications of the heatsink should be done to increase this margin.



No	Pitch	Fin count	Fin thick	Heat diss	Tdiff in	Rth	Equ velo	dT Air	Fin eff	Vol eff	Warning
(6)	[mm]	[----]	[mm]	[W]	[K]	[K/W]	[m/s]	[K]	[%]	[%]	[--]
1	19.5	3	1.59	20.0	47.6	2.38	0.319	21.6	98	95	--
2	13.0	4	1.59	20.0	40.6	2.03	0.251	30.7	98	121	--
3	9.8	5	1.59	20.0	37.6	1.88	0.181	44.7	98	135	--
4	7.8	6	1.59	20.0	39.1	1.95	0.129	61.4	97	128	--
5	6.5	7	1.59	20.0	43.7	2.19	0.100	74.4	97	108	--
6	5.6	8	1.59	20.0	50.1	2.50	0.078	85.5	96	88	--
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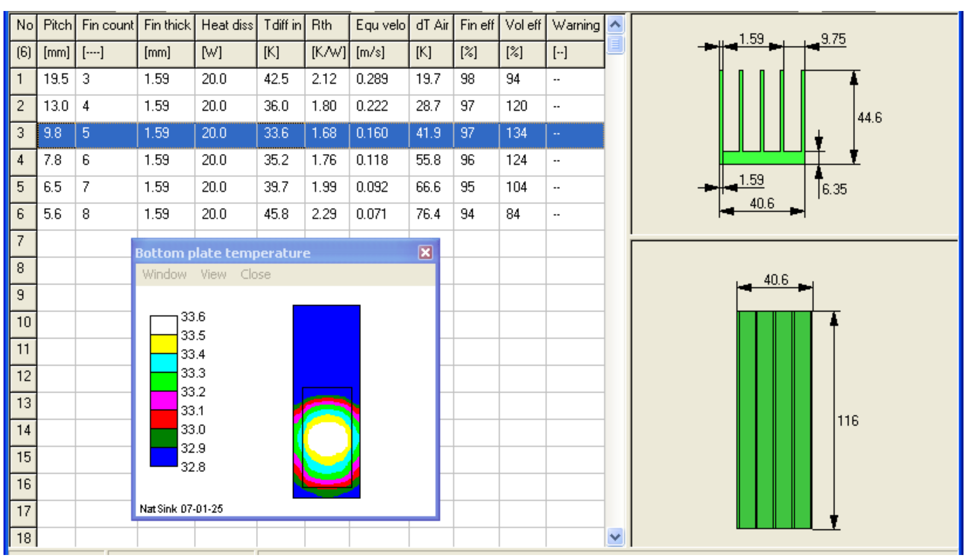
Figure 7: Heatsink fin height +0.25"



No	Pitch	Fin count	Fin thick	Heat diss	Tdiff in	Rth	Equ velo	dT Air	Fin eff	Vol eff	Warning
(6)	[mm]	[----]	[mm]	[W]	[K]	[K/W]	[m/s]	[K]	[%]	[%]	[--]
1	19.5	3	1.59	20.0	42.5	2.12	0.289	19.7	98	94	--
2	13.0	4	1.59	20.0	36.0	1.80	0.222	28.7	97	120	--
3	9.8	5	1.59	20.0	33.6	1.68	0.160	41.9	97	134	--
4	7.8	6	1.59	20.0	35.2	1.76	0.118	55.8	96	124	--
5	6.5	7	1.59	20.0	39.7	1.99	0.092	66.6	95	104	--
6	5.6	8	1.59	20.0	45.8	2.29	0.071	76.4	94	84	--
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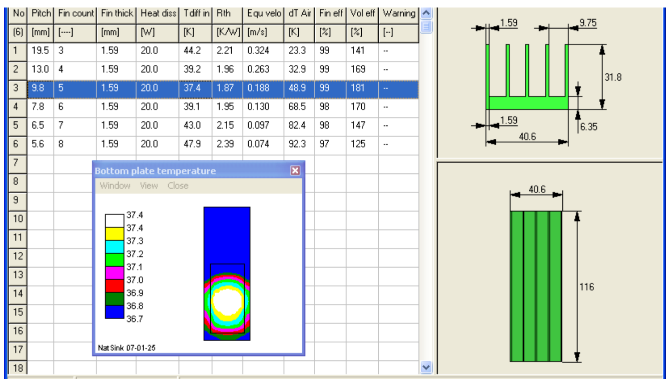
Figure 8: Heatsink fin height +0.50"

Effect of Anodized Surface

The effect of radiation heat transfer is very important in natural convection, as it can be responsible of up to 25% of the total heat dissipation[2]. The capability of a material to radiate heat is given by its emissivity. Extruded low-cost aluminum has a relatively low emissivity (0.02 to 0.2), which can impede its thermal performance.

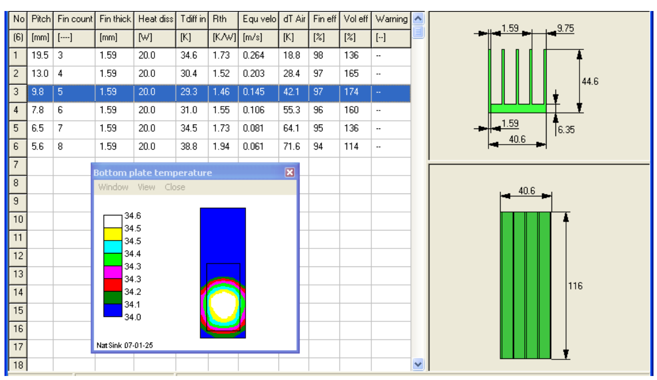
One way to improve emissivity of aluminum is through an anodization treatment. Anodization is an electrochemical treatment process that introduces a relatively thin layer of oxide. When the treatment is combined with a black dye[3], it can increase emissivity to almost 0.9.

To assess the impact of anodization, the emissivity was increased from 0.4 to 0.9 for the model with the as designed fin height. The model was then run with the 0.5" added to the fin height. The results are shown in **Figure 9** and **Figure 10**. Increasing the emissivity alone on the heatsink is not sufficient to drop the operating temperature below 100°C when operating at 65°C and should be combined with additional fin height which should place the operating temperature at about 94.3°C at 65°C ambient.



No	Pitch	Fin count	Fin thick	Heat diss	Tdiff in	Rth	Equ velo	dT Air	Fin eff	Vol eff	Warning
(6)	[mm]	[----]	[mm]	[W]	[K]	[K/W]	[m/s]	[K]	[%]	[%]	[--]
1	19.5	3	1.59	20.0	44.2	2.21	0.324	23.3	99	141	--
2	13.0	4	1.59	20.0	39.2	1.96	0.263	32.9	99	169	--
3	9.8	5	1.59	20.0	37.4	1.87	0.188	48.9	99	181	--
4	7.8	6	1.59	20.0	39.1	1.95	0.130	68.5	98	170	--
5	6.5	7	1.59	20.0	43.0	2.15	0.097	82.4	98	147	--
6	5.6	8	1.59	20.0	47.9	2.39	0.074	92.3	97	125	--

Figure 9: Emissivity increase, 5.7°C drop



No	Pitch	Fin count	Fin thick	Heat diss	Tdiff in	Rth	Equ velo	dT Air	Fin eff	Vol eff	Warning
(6)	[mm]	[----]	[mm]	[W]	[K]	[K/W]	[m/s]	[K]	[%]	[%]	[--]
1	19.5	3	1.59	20.0	34.6	1.73	0.264	18.8	98	136	--
2	13.0	4	1.59	20.0	30.4	1.52	0.203	28.4	97	165	--
3	9.8	5	1.59	20.0	29.3	1.46	0.145	42.1	97	174	--
4	7.8	6	1.59	20.0	31.0	1.55	0.106	55.3	96	160	--
5	6.5	7	1.59	20.0	34.5	1.73	0.081	64.1	95	136	--
6	5.6	8	1.59	20.0	38.8	1.94	0.061	71.6	94	114	--

Figure 10: Emissivity increase with +0.5" fins, 13.8°C drop

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[2] Aavid Thermalloy, Selecting a Heat Sink

[3] Anodized aluminum does not have to be black. It can be clear or one of many colors

Conclusions

Using more standardized optimization techniques, it was determined that fin height and anodization had the greatest ability to drop case temperatures below 100C when the IGBT was dissipating 20 watts at 65°C ambient. Orientation of the heat source and fin count had minimal effects.

Analysis Information

This white paper may include results obtained through analysis performed by DfR Solutions' Sherlock software. This comprehensive tool is capable of identifying design flaws and predicting product performance. For more information, please contact DfRSales@dfrsolutions.com.

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