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Determination of Operational Limit for a Conduction Cooled 6U Versa Module Eurocard

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Abstract: ***It is necessary that the heat generated whilst a Printed Circuit Board (PCB) is in operation must be dissipated away. Else it will trigger thermal throttling, which in turn slow down the processing speed or at its extreme, failure of circuit components. The conventional method involves convective cooling, which is established by means of convective heat transfer by the installation of fans or running coolants through channels. In the present work, conductive cooling is achieved by placing metallic blocks and keeping them in direct thermal contact with the heat source. In cases of convection cooling, flow rate, turbulence, and fluid properties can be varied to improve heat dissipation, whereas, for conduction cooling, no such control and modifications can be done. Thus, the maximum amount of heat that can be produced by the components assembly as a whole must be limited to a particular value. In the present study, we evaluate the operating limit of the conduction cooling system. In addition to that, the tests also evaluate and compare the thermal resistance of different material-based modules. The study is conducted for a 6U VME (Versa Module Euro-card) designed as per IEEE 1101.2 standards. This standard defines the dimensions of associated plug-in units for conduction cooling applications and connector-mounting details together with applicable detail dimensions of key sub-rack interfaces.***

Keywords*:* Printed Circuit Board (PCB), Versa Module Euro-card (VME), Wedge locks, Thermal Interface Material (TIM)

1. Introduction

Conduction cooling utilizes direct thermal contact to conduct the heat from the source to the outer walls of the enclosure. This makes the enclosure itself a heat radiator. Heat conduction, analogous to the flow of electricity, is the flow of internal energy from a region of higher temperature to one of lower temperature by the interaction of the microscopic particles (atoms, molecules, ions, electrons, etc.) close to one another, in the intervening space. To facilitate heat flow from one point to other, a thermal gradient must exist between the two points. From Fourier's law of heat conduction, it is evident that heat flux through a solid medium is proportional to thermal conductivity, however, we cannot depend entirely upon a fixed value of the same because thermal conductivity is a function of temperature.

VME (Versa Module Eurocard) is one of the early open-standard backplane architectures used for high volumetric data transmissions. Based on the Eurocard form factor, board size changes, where boards are typically 3U or 6U, the designs of these boards are quite rugged; with shrouded pins and rugged connectors, this form factor is widely used in military, aerospace, and industrial applications. VPX defines the `base line' specification of a circuit module, which defines the basic mechanical and electrical elements in a circuit module; together with a series of `dot level' specifications, it creates a functional unit by establishing serial connections between different modules. While VME was based on a bus, with signals daisy-chained at each slot, VPX is based on switched fabrics that enable significant system speed improvements, upgrading ability, and packaging for critical military applications.

The study focuses on the cooling limitations of a 6U VME by conduction. In order to facilitate conduction cooling, we make a thermal contact between the card (heat source) and the conducting blocks. Heat is carried away by the blocks, which consist of the top cover, bottom cover, and wedge locks, and then through the card cage to the outside. However, convective cooling has to be considered when the assembly operates in ambient air or any other fluid medium.

2. Conduction Cooling- Overview

As the heat is generated, the heat flux of the component increases, followed by a rise in temperature, and the heat tends to conduct along with the parts in direct contact. If the heat source is constant, the temperature within the component continues to rise until the rate of the heat generated is equal to the rate of the heat dissipated from the component, the system attains a steady state.

When electricity flows along the copper channels and components, heat is generated. Each element offers an effective resistance or impedance to the flow of charges, and this phenomenon reflects, causing heat to rise up according to the equation:

$$H = I^2Rt \qquad (1)$$

Where '*H*' represents the heat generated, '*R*' Electrical resistance and 't' is the time. The heat generated from the board escapes through the covers (Aluminium) that maintains contact with it and then through the wedge locks (Aluminium) and the chassis. Wedge lock ensures firm thermal contact for allowing heat transfer.

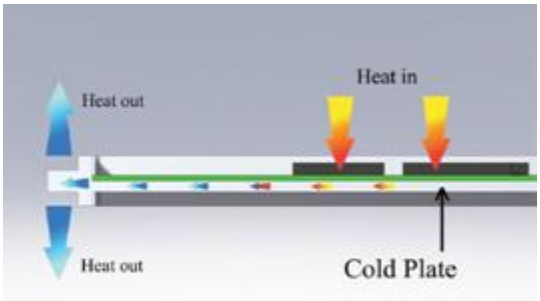

Figure 1: Conduction cooling pathway

The materials along the heat flow path greatly influence the temperature gradients. The ability of the heat to flow through any material is determined by the physical properties of the material and by the geometry of the structure. The relation for steady-state conduction from a single concentrated heat load is given by Fourier's law:

$$Q = -K\,A\,(dT/dx_i) \qquad (2)$$

Where 'Q' stands for the heat transferred, 'A' the cross-section area of flow, and (dT/dx_i) is the temperature gradient along the direction of heat transfer.

Under steady-state conditions, the equation that governs the distribution of temperature without heat generation is of the differential form:

$$K \;\nabla^2 T = 0 \qquad (3)$$

This expression reduces the only material property of interest to perform the analysis to ie, the thermal conductivity of the material. The temperature distribution will be defined as per expression (3).

3. Modelling Conduction Cooling Module

The conduction cooling module corresponds to the path along which heat is dissipated from its source to outside, or in other words, the conducting pathways. The heat from the board is dissipated by conduction through direct thermal contact with the primary and secondary covers, followed by the wedge lock and exits through the chassis.

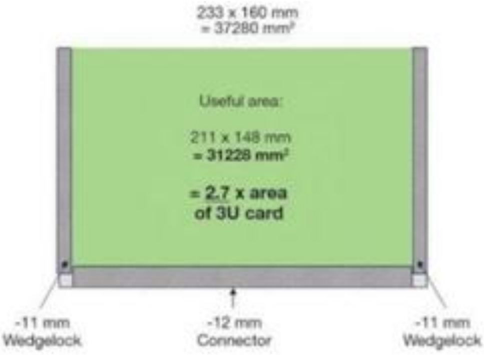

Figure 2: Components area in a 6U VME

The actual board area for a 6U VME is 233 X 160 mm. However in the assembled module, 211 X 148 mm of the area is only available for placing the electronic components, as the rest of the portions will be covered by backplane connectors and wedge locks.

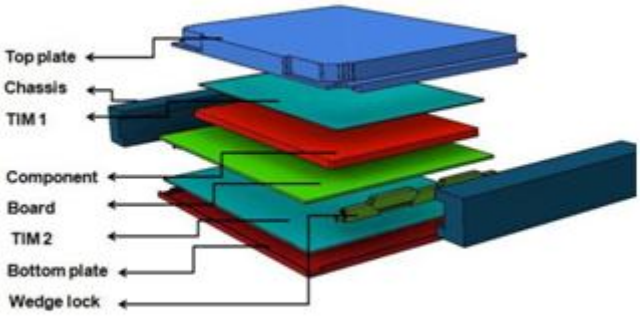

Figure 3: 3D Model (Exploded view) Autodesk inventor

The 3D model is generated using Autodesk inventor in compliance with IEEE 1101.2 standards and later exported to Ansys for thermal analysis. Components were assembled by setting mate and flush constraints and restricting certain degrees of freedom. Mating joints the faces and flushing sets the chosen male and female geometry to be parallel or maintain a parallel offset relative to one another. Surface constraints were added between the lower portion of the secondary cover and the upper surface of a mounting rack on the chassis.

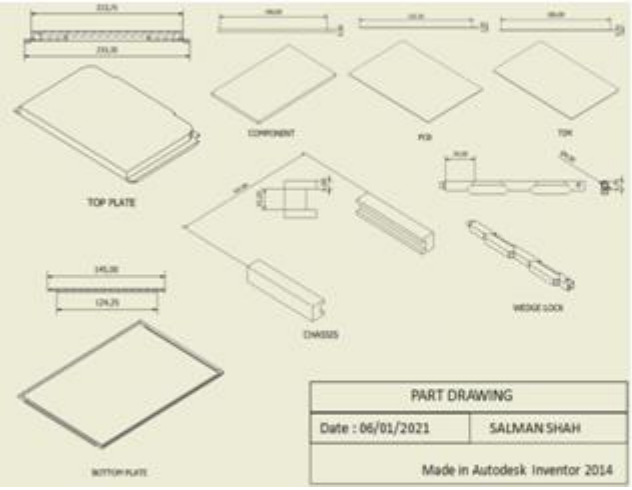

Figure 4: 2D drawings of models- Autodesk inventor

The card cage has many racks that allow us to fit cards of standard sizes. The cards are part of bus-based systems, and hence, in order to perform similar functions, there will be many VME boards in consecutive racks on a cage. To limit our study to a single VME card and its modules, we need to consider only one rack dimension in the present assembly. Hence for the analysis in the present study, we insert only one module. In most actual practices, this assembly is surrounded by air; hence, convective heat transfer occurs along with conduction cooling. Neglecting the convective heat transfer from the module implies a system operating in vacuum; in order to obtain a realistic heat transfer characteristic, we consider the convection effects from the module.

With 6U-VME conduction cooling, power dissipation per slot is limited by the cold plate on which the chassis is mounted. Heat is conducted away from the hot components on the card by a heat spreader which is then transferred out to aluminium wedge locks attached to the edges of the card. The wedge locks are seated in card slots on the chassis, which conducts the heat to the chassis walls. The mechanism of heat generation is electric components is as follows; when connected to a power supply, the components in operation will oppose the flow of charges due to impedance and thereby causes the component to generate heat. So proper channeling of this heat must be attained to prevent failure of the circuit. Hence each dimension in the design plays a vital role in realizing this concern.

4. Assigning Materials

In the preliminary analysis, we used pure aluminium, pure Copper and a newly defined Aluminium Nitride based thermal interface material was defined in the engineering data section of Ansys steady state thermal analytical system. Separate tests were carried out for aluminium based and copper-based plates under three different ambient conditions in five different heat input conditions. In the second set of simulations, aluminium 6061 exhibiting a thermal conductivity of 180 W/m-k, industrial Copper exhibiting a thermal conductivity of 394 W/m-k, and aluminium nitride-based thermal interface material having 0.3W/m-k as thermal conductivity value was defined in the engineering data section.

Table 1: Material Allocation and Cases of Simulation

Cases of Simulation	Material of Conduction plates	Thermal conductivity [W/m-K]	TIM	Thermal conductivity [W/m-K]
Case 1	a) Al b) Cu	238 400	AlN	0.3
Case 2	a) Al6061 b) Ind.Cu	180 394	AlN	0.3
Case 3	a) Al6061 b) Ind.Cu	166 394	TGP 1000 VOUS	1

In the final part, the TIM material was changed to Bergquist TGP 1000 VOUS, a TIM product exhibiting thermal conductivity of 1 W/m-k was used instead, and the property value of aluminum 6061 was changed to 166 W/m-k based on a known composition value of additives in the alloy. Also, a new material was defined in the engineering data for the PCB, considering that a single layer of 1 oz of Copper on an FR-4 Epoxy layer as the basic structure, exhibiting a thermal conductivity of 1.7W/m-k.

5. Methodology

The heat formed during the operation must be dissipated away to minimize thermal throttling of components in the circuit. Here we conduct thermal analysis in Steady-state thermal analytical package on Ansys software. The first step was to model the geometry right to the dimensions as per IEEE standards. In order to solve the differential equation for conduction in 3 dimensions for a steady-state case, the only property to be defined in the engineering data section is the thermal conductivity.

Once the engineering data are added, the model is loaded. In the geometry cell, we assign material for each component. Based on data gathered from sources, modifications were made in the engineering data of elements to improve the reliability. The current flows exactly through the copper channels over the board, and hence a material that shows an effective conductive behavior between fibre-glass, the actual board material, and Copper was defined for the VME card considering one layer of copper vias.

The analysis is performed at three different ambient conditions and same initial temperature of all solids considering thermal equilibrium prior to simulation. The ambient conditions tested were 25^{0}C, 30^{0}C and 55^{0}C. Heat flow is defined on the interface between component and TIM1. The calculations were carried out for 50W, 100W, 150W, 200W, and 250W. Grid Independence study has been conducted on the model prior to the running to ensure accuracy to the results.

6. Meshing

Element size in mesh section was gradually reduced to study fluctuations in results. The resultant values converged for a total discretization into around 5,30,000 elements. Adaptive meshing were used to improve the element quality at major mating faces. Although an error value less than 2.5% was achieved at around 0.3 billion of elements, considering an additional margin, the simulations were carried out using a grid size of 0.53 million elements.

In-order to perform simulation, the physics preference for meshing was set as mechanical, adaptive meshing with element size as 1.5 mm was chosen. The mesh method is chosen as hex dominant but with hex and tetra elements occurring in the domain to consider into account more nodal connections at complex geometries and turning junctions in the assembly.

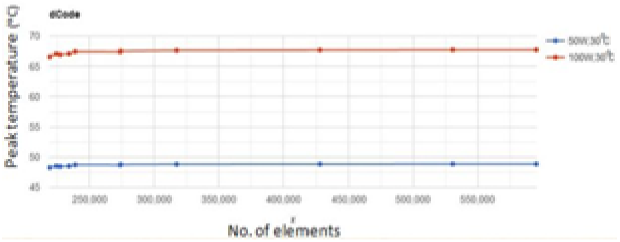

Figure 5: Grid independence graph

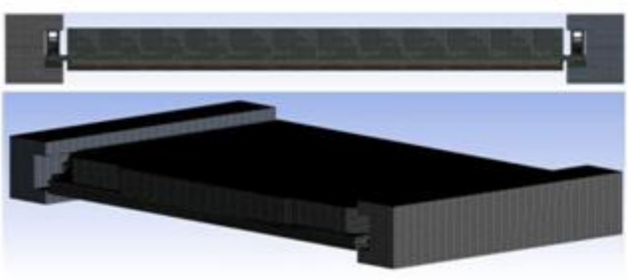

Figure 6: Computational mesh for the simulation

The mesh has an average element quality of 0.87 with 530641 elements and 1204622 nodes. The average skewness was found to be 0.19 and an aspect ratio of 1.7. Although the simulations could be performed at a relatively coarser mesh, this fine mesh was used to further improve reliability and accuracy. Adaptive meshing enabled automatic size reduction of elements at narrow geometries and curved sections in a smooth manner, yet enabling more nodal connections, this improves the overall quality of the grid.

6. Boundary Conditions

To simulate the operating environment, three different ambient temperature conditions were individually considered. In each case, the initial temperature of solids was set as the same as the ambient condition considering the system in thermal equilibrium with the surroundings prior to operation. Although the heat transfer in the system is fully governed by conduction, in practical cases, there will be surrounding air.

A Convection criterion at a film coefficient equal to 5W/m^2-k was defined at the indicated faces of chassis walls. This also acts as guidance for heat transfer in our simulation case. Heat flow values in watts were specified, originating from the component as in the Figure 7.

Walls that were left unchecked was automatically coupled for heat transfer and the posterior faces will be automatically set to faces with directional heat flux equal to zero in a direction perpendicular to the face as there is no medium to receive or give off heat. Since the enclosure has been restricted to the solid domain alone, the system will not have interaction with the surroundings unless otherwise any boundary conditions are defined.

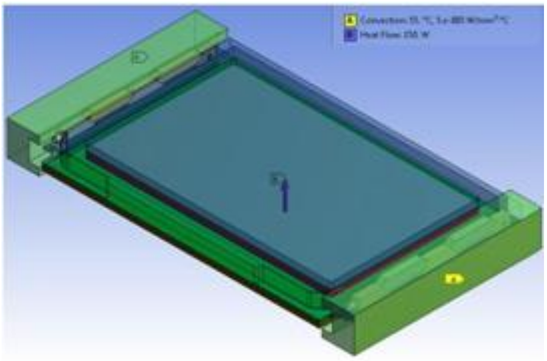

Figure 7: Boundary conditions applied for 30^0C 250W input – Ansys

The applied boundary conditions in Figure 7 is sufficient enough to simulate the close to real world operating environment. Ansys, by default has automatic contact detecting and hence the contacts between different components in the assembly need not be separately defined unless otherwise a relative motion exists between the contacting bodies.

The same conditions were repeated for different material based plates and different thermal interface materials operating in the above mentioned three operating thermal conditions under five different heat loads.

7. Result and discussion

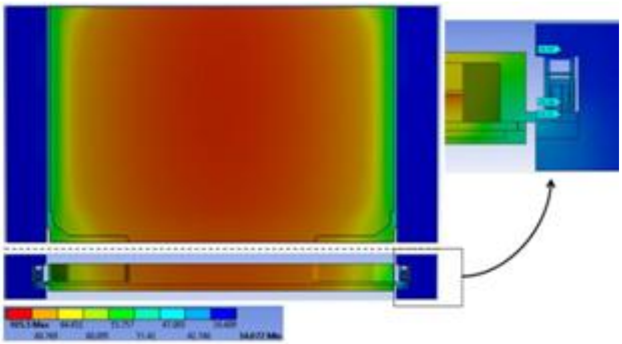

Figure 8: Temperature contour for 200W, 30^0C – Ansys

Figure 8 shows how temperature is distributed on the assembled module operating at 200W in a 30^0C ambient temperature for a pure aluminium based setup. The contours generated for other cases also follow the same trend with maximum value occurring at the midsection and decreasing towards the periphery.

The thermal distribution near the module-wedgelock-chassis interface is also shown in the Figure 8. The maximum value occurs in the the origin itself, the component, and the centre of the board in which it is assembled also exhibits similar temperature value. The minimum values are obtained at chassis walls. The results generated for the rest of all cases are as below.

Table 2: Maximum and Minimum Temperatures for 25^0c Ambient (Al Based, Cu Based, Aln Based Tim)

Heat Input	Al(min)^{o}C	Al(max)^{o}C	Cu(min)^{o}C	Cu(max)^{o}C
50 W	26.018	43.875	26.023	39.562
100 W	27.036	62.751	27.046	54.124
150 W	28.054	81.626	28.069	68.686
200W	29.072	100.5	29.091	83.248
250 W	30.09	119.38	30.114	97.809

Table 3: Maximum and Minimum Temperatures for 30^0c Ambient (Al Based, Cu Based, Aln Based Tim)

Heat Input	Al(min)^{o}C	Al(max)^{o}C	Cu(min)^{o}C	Cu(max)^{o}C
50 W	31.018	48.875	31.023	44.562
100 W	32.036	67.751	32.046	59.124
150 W	33.054	86.626	33.069	73.686
200W	34.072	105.5	34.091	88.248
250 W	35.09	124.38	35.114	102.81

Table 4: Maximum and Minimum Temperatures for 55^0c Ambient (Al Based, Cu Based, Aln Based Tim)

Heat Input	Al(min)^{o}C	Al(max)^{o}C	Cu(min)^{o}C	Cu(max)^{o}C
50 W	56.018	73.875	56.023	69.562
100 W	57.036	92.751	57.046	84.124
150 W	58.054	111.63	58.069	98.686
200W	59.072	130.5	59.091	113.25
250 W	60.09	149.38	60.114	127.81

The above results are generated for pure aluminium based and pure Copper based modules utilizing AlN based TIM at the interfaces. The thermal conductivity of each material were set at default value from Ansys engineering data at 238 W/m-k for aluminium, 400 W/m-k for Copper and 0.3 W/m-k for the TIM material

On observing the manner of progression from the tables below, which is linear, useful results could be obtained for intermediate heat inputs as well. The numerical figures for Copper in the tables are always below that of aluminium, indicating better performance.

This is due to their higher conductivity that aluminium. Aluminium based heat sinks are widely used because of their availability and light-weigh characteristics. Usually the printed circuit boards are said to be maintained under a temperature of 70- 80^{0}C , so all the cases in which the limit exceeds must be excluded or in those conditions, conduction cooling cannot provide sufficient cooling, this is the fundamental limitation of conduction cooling and beyond this point other modes of heat dissipation must be used.

This is remarked as the limitation for a conduction cooling module as compared to conventional modes of cooling utilising convection as the mode of heat transfer for heat dissipation. Since once setup, there are no further options or controlling parameters to externally influence heat transfer, the study of this limitation is important.

Table 5: Maximum and Minimum Temperatures For 25^{0}c Ambient (Al 6061based, Ind. Cu Based, Aln Based Tim)

Heat Input	Al(min)^{o}C	Al(max)^{o}C	Cu(min)^{o}C	Cu(max)^{o}C
50 W	25.976	47.493	25.984	39.89
100 W	26.953	69.987	26.967	54.781
150 W	27.929	92.48	27.951	69.671
200W	28.905	114.97	28.934	84.561
250 W	29.881	137.47	29.918	99.452

Table 6: Maximum and Minimum Temperatures For 30^{0}c Ambient (Al 6061based, Ind. Cu Based, Aln Based Tim)

Heat Input	Al(min)^{o}C	Al(max)^{o}C	Cu(min)^{o}C	Cu(max)^{o}C
50 W	30.976	52.493	39.984	44.89
100 W	31.953	74.987	31.967	59.781
150 W	32.929	97.48	32.951	74.671
200W	33.905	119.97	33.934	89.561
250 W	34.881	142.47	34.918	104.45

Table 7: Maximum and Minimum Temperatures For 55^{0}c Ambient (Al 6061based, Ind. Cu Based, Aln Based Tim)

Heat Input	Al(min)^{o}C	Al(max)^{o}C	Cu(min)^{o}C	Cu(max)^{o}C
50 W	55.976	77.493	55.984	69.89
100 W	56.953	99.987	56.967	84.781
150 W	57.929	122.48	57.951	99.671
200W	58.905	144.97	58.934	114.56
250 W	59.881	167.47	59.918	129.45

Al 6061 is an alloy of aluminium that exhibits very high corrosion resistance due to addition of zinc, and is easily formable and exhibits better mechanical properties and strength compared to its original parent element, due to this, even with its low thermal conductivity compared to pure aluminium, Al 6061 is widely used in many industrial applications.

The value of thermal conductivity varies from 151W/m-k to 204W/m-k depending upon the mass fraction of added elements in the alloy, and hence in the above generated results, an average of 180 W/m-k was chosen for simulations. Copper used in electrical industrial applications contains other additives which accounts for a minor drop in overall thermal conductivity of industrial copper. The value of "k" for copper was chosen to be 394W/m-k for the above cases.

However, there is a significant variation in temperature compared to the first set due to the drop in thermal conductivity; but still, the progression is linear and resultant rise of temperature for copper based plates marginally lesser than that of aluminium based. A maximum temperature difference of 40^{0}C change is observed between copper and aluminium based modules.

The differences in conductivities is the sole factor responsible for the unique results produced for each set of assigned modules. This is clearly evident from the differential form of conduction heat transfer for steady system. The only material data input required is “K” alone. The effective thermal resistance offered by each module is a fuction of length and area of heat transfer which is same for all modules.

Table 8: Maximum and Minimum Temperatures For 25^{0}c Ambient (Al 6061based, Ind.Cu Based, Tgp1000Vous Tim)

Heat Input	Al(min)^{o}C	Al(max)^{o}C	Cu(min)^{o}C	Cu(max)^{o}C
50 W	25.964	44.98	25.972	36.048
100 W	26.927	64.961	26.944	47.097
150 W	27.891	84.941	27.916	58.145
200W	28.855	104.92	28.888	69.193
250 W	29.819	124.9	29.86	80.242

Table 9: Maximum and Minimum Temperatures For 30^{0}c Ambient (Al 6061based, Ind.Cu Based, Tgp1000Vous Tim)

Heat Input	Al(min)^{o}C	Al(max)^{o}C	Cu(min)^{o}C	Cu(max)^{o}C
50 W	30.964	49.98	30.972	41.048
100 W	31.927	69.961	31.944	52.097
150 W	32.891	89.941	32.916	63.145
200W	33.855	109.92	33.888	74.193
250 W	34.819	129.9	34.86	85.242

Table 10: Maximum and Minimum Temperatures For 55^{0}c Ambient (Al 6061based, Ind.Cu Based, Tgp1000Vous Tim)

Heat Input	Al(min)^{o}C	Al(max)^{o}C	Cu(min)^{o}C	Cu(max)^{o}C
50 W	55.964	74.98	55.972	66.048
100 W	56.927	.94.961	56.944	77.097
150 W	57.891	114.94	57.916	88.145
200W	58.855	134.92	58.888	99.193
250 W	59.819	154.9	59.86	110.24

In case 3, the thermal conductivity (k) of Al 6061 was chosen to be 166W/m-k for a known composition of additives and industrial copper having same thermal conductivity value of 394W/m-k was defined. The thermal interface material was defined based on Bergquist thermal gap pad 1000 VOUS, a product from Bergquist used specifically for these applications. It exhibits a thermal conductivity of 1W/m-k and the layer thickness is about 0.91 mm only.

Comparing the charts with the initial results, there is a significant reduction in thermal resistance due to introduction of Bergquist thermal gap pad 1000 VOUS as TIM. The performance of Industrial copper based module utilizing Bergquist thermal gap pad 1000 VOUS is very appreciable and proven out to be performing the best of all other cases specified in Table 1.

The overall rise in temperature is minimum for the module with Bergquist thermal gap pad 1000 VOUS as TIM, in comparison with other material combination specified in Table 1, hence the use of Bergquist thermal gap pad 1000 VOUS as TIM is recommended for practical and industrial applications.

Table 11: Overall ΔT V/S Heat Input- (Al Based, Cu Based, Aln Based Tim)

Heat Input	ΔT *Al*(°C)	ΔT *Cu*(°C)
50 W	17.857	13.539
100 W	35.715	27.078
150 W	53.572	40.617
200 W	71.428	54.157
250 W	89.29	67.695

In Tables 11, 12 and 13, the variation of overall temperature difference (ΔT) attained in each module is plotted against respective heat inputs, in which ΔT exhibits a linear behaviour, and is independent of ambient condition. The slope is thus constant, and is of the units of ^{0}C / W; hence this directly gives us the value of thermal resistance offered by the module. The overall thermal resistance offered by aluminium based module in case 1(Table I) is 0.357165 ^{0}C/W and that by the Copper based module is 0.27078 ^{0}C/W.

Table 12: Overall ΔT V/S Heat Input- (Al 6061 Based, Ind. Cu Based, Aln Based Tim)

Heat Input	ΔT *Al*(°C)	ΔT *Cu*(°C)
50 W	21.517	13.906
100 W	43.034	27.814
150 W	64.551	41.72
200 W	86.065	55.627
250 W	107.589	69.534

There are an increase in the value of thermal resistance for aluminium and copper based modules respectively. This is due to decrease in thermal conductivity shown in Table 1.

Table 13: Overall ΔT V/S Heat Input- (Al 6061 Based, Ind. Cu Based, Aln Based Tim)

Heat Input	ΔT *Al*(°C)	ΔT *Cu*(°C)
50 W	19.016	10.076
100 W	38.034	20.153
150 W	57.05	30.229
200 W	76.065	40.305
250 W	95.081	50.382

A lowest value of thermal resistance of 0.20152 ^{0}C / W was achieved for Industrial Copper based conduction cooling module (Case 3 in Table 1) utilising Bergquist Thermal Gap Pad 1000 VOUS as the material of TIM. From the thermal analysis it can be inferred that, of all the material specified in Table 1, Bergquist Thermal Gap Pad 1000 VOUS module shows better thermal performance offering minimum thermal resistance.

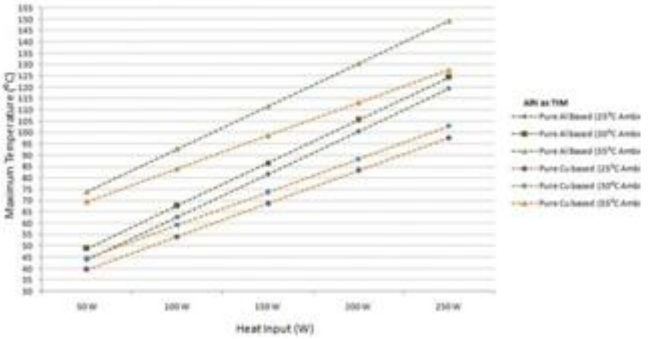

Figure 9: Peak Temperature V/S Heat input (Al based, Cu based, AlN based TIM)

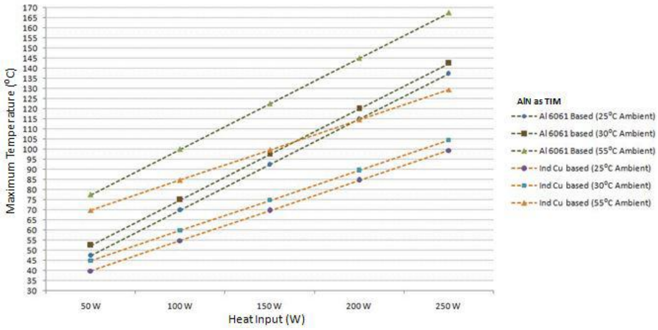

Figure 10: Peak Temperature V/S Heat input (Al 6061 based, Ind.Cu based, AlN based TIM)

Figure 9-11 corresponds to the plot of peak values of temperatures against respective heat inputs for the materials specified in Table 1. To evaluate the safe operating limit for each cases, for board temperature not to exceed 70 ^{0}C, a horizontal line from the horizontal line at y intercept equal to 70 can be projected to the characteristic line of each modules.

The maximum heat, that can be generated without exceeding the safety limit can be obtained by extrapolating the point of intersection of the projected line to the x axis for each cases, this defines the safe operating condition corresponding to the maximum allowed temperature rise.

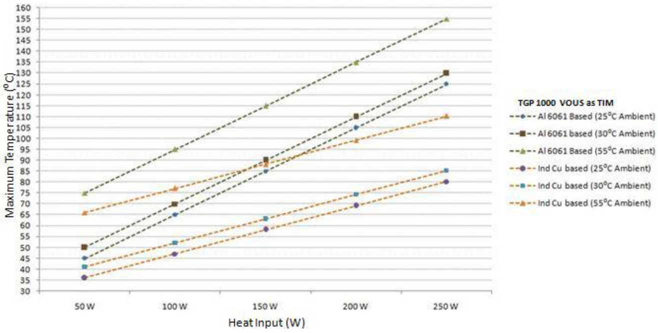

Figure 11: Peak Temperature V/S Heat input (Al 6061 based, Ind.Cu based, TGP 1000 VOUS TIM)

The performance of Industrial Copper based module in the Figure 11 is most appreciable, by observing the trend at an ambient condition of 25 ^{0}C, the maximum temperature corresponding to 250 watts reaches only around 80 ^{0}C, thus when compared to other modules mentioned in Table 1, copper based module is most suitable for high thermal load applications. Similarly, the above plot can be used to determine the operating limits of other modules mentioned in Table 1.

Therefore, depending upon the peak temperature specified for respective VME circuit assembly board, the corresponding characteristic curve can be used to determine which modules pass the safety check.

Table 14: Operating Limit For A Peak Temperature Of 70°C (Tamb=30°c)

Peak Temperature = 70°C	T_{amb}=30°C
Combination of materials according to:	Limit of Operation (Max. heat that can be produced by components array) [Watts]
Case 1 (a)	105.957
(b)	137.34
Case 2 (a)	88.91
(b)	134.315
Case 3 (a)	100.097
(b)	181.023

The limiting value of heat input from the circuit components array for each cases (Table 1) at an ambient temperature of 30°C and corresponding to a peak temperature of 70°C are specified in Table 14. This remarks the limitation for conduction cooling. Beyond this limit, high temperature can induce thermal throttling and thermal stress which could lead to failure of the component.

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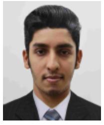
Author Profile



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