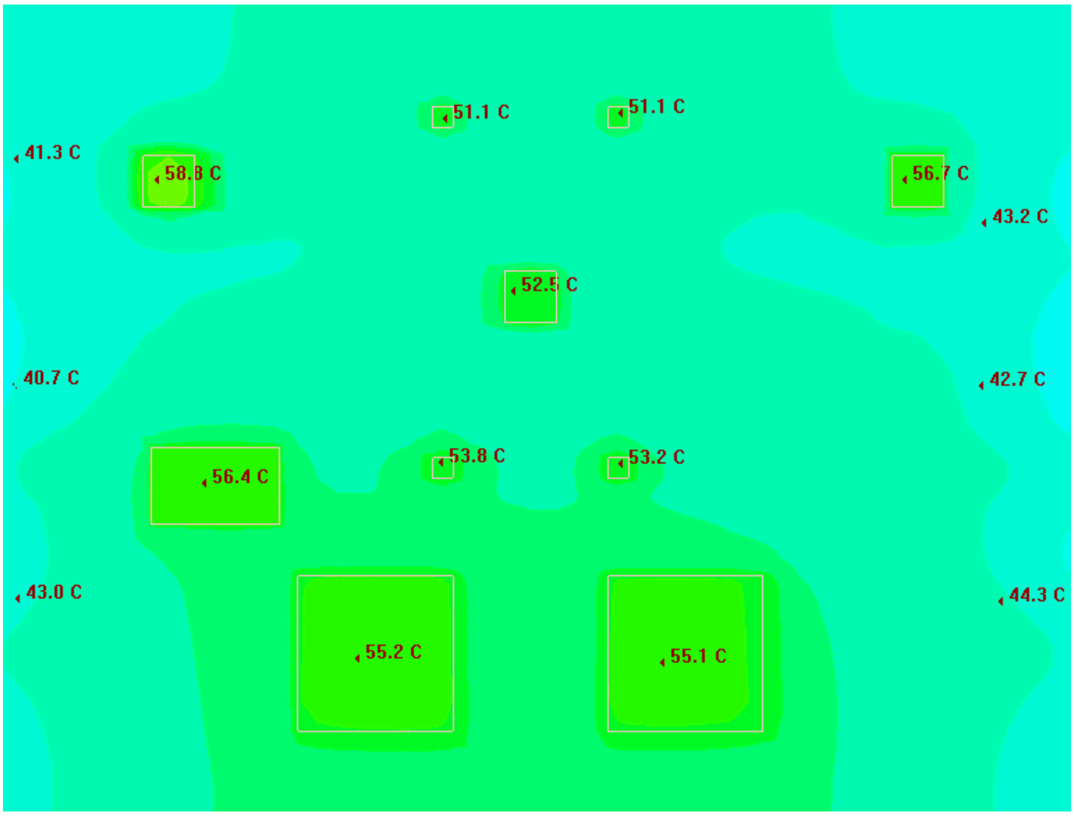

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Electronic cooling for radar equipment using advanced thermal technologies

Examensarbete inom högskoleingenjörsprogrammet Maskinteknik

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Examensarbete 2016:03 ISSN 1652-9901
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Omslag:
Simuleringsbild över hot spot-kortet

Tryckeri /Institutionen för Tillämpad Mekanik
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Abstract

This thesis work is a result of studies done at Saab Surveillance, with the objective to evaluate cooling technologies and find out which of them that are or are not suited to be implemented on a generic house and plug-in units, meeting the higher thermal demands of the future.

This task includes five products, all with their own pros and cons created by Thermacore, a company of advanced cooling technologies with its European head office located in Ashington, England.

First up was to realize under which circumstances these products were supposed to operate. This included application areas like land, sea and air which all have different grades of requirements set for today’s generic houses and plug-in units.

To find the answers for these factors a trip to England and Thermacore was made and together with their engineers, hypothetical thermal simulations could be developed but also gather a wide understanding of each technology´s possibilities and limits.

When all the information was assembled an extended evaluation process could be completed. The result showed that the superior cooling technology differed depending on mainly two things. The first one was taken in regard of which application area it was supposed to operate in but also where it is being implemented either in a generic house or on a plug-in unit.

In conclusion of this report it showed that for the plug-in unit the recommended technology for land and sea units was to be a heat pipe assembly. The construction contains four flattened heat pipes encapsulated in an aluminum plate. Regarding air applications and foremost the fighter jets, the most suited technology was the k-Core. It will endure the exposure of both high vibrations and shocks but above all in an effective way cool the system.

For the generic houses and those operating on land and sea it would once again be a heat pipe assembly that is the optimal solution, though those working in air applications the loop heat pipe is the better fit. These results will be discussed and visualized in the report.

Keywords: Thermacore, cooling technologies, simulations, application area, generic house, plug-in units, temperatures.

Acknowledgements

We would like to thank everyone that have been supporting us during our thesis work at Saab, sharing their knowledge, helping us through the process and giving us the equipment and recourses necessary to accomplish our assignment. An especially thank to our supervisor Torbjörn Nilsson for his commitment and sharing of expertise during this time but also to Ulrika Svahn who enabled this work to happen. Additional thanks to our examiner Karin Munch.

We would also like to thank Thermacore and especially Geoff Thompson, Elvedin Halimic and Peter Buddee for their much appreciated hospitality during our visit making it a rewarding and memorable experience. We are truly grateful for their commitment by contributing their knowledge and helping us throughout this project.

Special thanks to Hans Falk and Joel Lundh for their advice and patience regarding the thermal simulations. We want to give a final recognition to Mikael Schmid for answering all of our questions about the products at Saab and to Maria Thorngren for the assistance with the everyday problems.

Abbreviations

HP - Heat pipe

VC - Vapour chamber

KC - k-Core

WF – Working fluid

TIM - Thermal interface material

PCB - Printed circuit board

LHP - Loop heat pipe

CP - Cold plate

CPL - Capillary pumped loops

HS - Hot spot

TC - The combined

TSO - Temperature spread out

Table of Contents

1. INTRODUCTION

1.1 Background

The technology stands before a never-ending development to not become outdated. This applies to everything from improving one or more product features, to minimize its manufactory cost. Saab uses so-called “road maps” where thoughts and visions of the future are defined, both in a long and in a short time period, telling how to solve future challenges and problems, not least in those cases where today’s technology will not be sufficient. Everything to enable a progressive engineering technology which is at the leading edge.

Because of that the generic house and the plug-in units is part of a larger system, no major changes in volume can be made. Products from Saab are often based and operate in exposed environment. This demands that the construction is robust and well adapted to these circumstances.

In the future, Saabs equipment will need to be able to withstand an even higher power density and power output in order to continuously be a competitive company on the market.

1.1.1 Saab AB

Saab is a high technology company with main focus on the military industry. Saab was founded in 1937 in purpose to protect the borders and human population of Sweden. Today Saab has 14 700 employees stationed in 35 different countries all over the world. The largest part of the company is located in Sweden with the main office in Stockholm. The company is divided into five different business areas, “Aeronautics”, “Dynamics”, “Surveillance”, “Industrial Product and Services” and lastly “Support and Services”. Saab has costumers in approximately 100 countries, their biggest costumer is the Swedish defense department.

1.1.1.1 Saab Surveillance

The site in Gothenburg’s main focus is on Surveillance operations, there are approximately 1400 employees working at the facility in Gothenburg. At this location Saabs ground, naval and air radar systems are developed and constructed, for example the “Giraffe” and “Arthur” systems and the radar systems for the fighter jet “JAS Gripen”. On the mechanical department at the surveillance division there are 126 employees, which in turn some of these engineers are primarily working with thermal solutions and evaluation. (Saabgroup, 2016)

1.1.2 Thermacore

Thermacore is a company that manufactures advanced custom designed thermal solutions. Thermacore was founded 1970 in United States of America and is today located in 4 offices around North America and their European headquarters in Ashington, United Kingdom. Thermacore is working on the frontier of advanced cooling technologies, providing complex cooling solutions to several market sectors, from essential electronic cooling components in the F-35 joint strike fighter to cooling solutions on satellites orbiting around earth.

In order to solve thermal problems Thermacore has knowledge in five specific areas including, thermal analysis, mechanical design, prototyping, testing and production. Thermacore offers a portfolio of cooling technologies divided into three sectors, liquid cooling, solid conductance and two phase systems. Thermacore is specialized on solving each costumers needs, the production is costumer driven and therefore they do not have any “on the shelf” products. Thermacore is providing thermal solutions to many different markets including military industry, aerospace/avionics, hospital, computer, communications etc. More in-depth information about Thermacores portfolio and products can be found in chapter 5 (Thermacore, 2016).

1.2 Objective

In the future Saabs equipment must handle a higher heat output but there is also a request for both a lower manufacturing cost and a lower weight. Thermacore Ltd. (UK) is a company specialized in advanced cooling technologies, their portfolio contains a great variation of interesting cooling technologies that shall be evaluated to find a suitable option for Saabs equipment.

This task shall generate a matrix that consist of the chosen technologies and how well they fulfill the sought requirements and requests. The purpose of the matrix is to visualize which technology has the most potential to be applied in future equipment.

1.3 Limitation

- Limited equipment volume, no dimensional changes can be done on the casing
- Only treat Thermacores cooling technologies
- Limitation to a few of Saabs devices

1.4 Formulation of question

- Is it possible to apply the cooling technology into Saabs equipment?
- How well do each technology handle heat output and power density?
- Which of the cooling technologies are the most cost efficient?
- How much do the technologies affect the weight of the device?
- How much will the respectively technology cost?
- Which technology is best suited for future use based on this research?

2. METHOD

2.1 Literature studies

The project started up by collecting necessary information to understand the principles of thermodynamics and later on a more advanced thermal knowledge. Further on a more in-depth research was made about the products from Saab that were relevant to the assignment. This gathering of knowledge included for example reading several reports with detailed information about dimension limitations and environmental requirements. Tours at Saab´s facilities were given to look at actual hardware existing of plug-in units, generic houses but also entire radar system. These were ways to broader the overall knowledge about their products and understanding the system in whole, the functions and the possibilities.

The last part of the literature study was focused on Thermacore´s own portfolio of cooling technologies, that included for example heat pipe, vapour chamber and k-Core. The basic data could be found at the company website, (Thermacore, 2016) but a more in-depth information was received by meetings with their Swedish representative Peter Buddee and later on during the trip to Thermacore´s European office.

2.2 Post literature studies

After the basic knowledge had been acquired and a more understanding about the extent of the problem was revealed, the assignment´s two pivotal elements could be created, the requirement and request specification and our in-house circuit boards. The factors in the specification are categorized in the headings including technology, environment, human and economic aspects. Factors that could be interesting for Saab were included.

Three circuit boards were created, this was done because of three main reasons. The first one was due to the generically aspect, every card was built up in the same way with fixed values, which therefore meant that it was easier to compare the effect from the cooling technologies with each other. The second reason was to avoid the confidentiality censorship factor at Saab. The finale reason was the possibility to evaluate different kinds of extreme cases.

When the requirement and request specification and the circuit boards had been generated, a clearer problem definition was shaped and the foundation for the further comparison of Thermacore´s cooling technologies was established.

2.3 Trip to Thermacore

The problem was brought on by a trip to Thermacore in Ashington, England. Three days of meetings, discussions and tours around their facilities was held with several of their engineers. The visit gave a deeper knowledge about the technologies possibilities and limitations, insight in how the company reasons and solves thermal problems but also information about the manufacturing processes for each specific technology. Discussions and answers for each specific technology regarding the requirement and request specification were done. Lastly, hypothetical solutions to the given assignment could be made, focusing on how the simulations structure should be created.

2.4 Simulations

During this stage of the work there was enough information and knowledge to begin the necessary thermal simulations. The purpose was to both visualize and numerically show the possible temperature decrease for every cooling technology on each of the circuit boards. The simulations were made using a software program called Icepak 17.0. The simulations were done in several steps, where different dimensions, placements and combinations of technologies were tested to find the best possible solution.

2.5 Cost estimation and weight estimation

When dimensions and design of every technology was decided a cost and weight estimation for every specific solution could be made. This was done with the help from Thermacore´s vice president Geoff Thompson.

Further on could indexes be calculated including the relation between temperature decrease and the price for each technology, but also temperature decrease divided by its weight.

2.6 Evaluation

At this stage of the work all necessary information had been collected and a compilation of the simulations, cost estimation and all the given information from Saab and Thermacore could be put together. Based on this information and the answers for the requirement and request specification an evaluation matrix could be generated which shows how well each technology answers towards these factors. A second matrix was created that displays the suitability for the technologies in different application areas.

These matrixes are the standpoint for the upcoming discussion and conclusions.

2.7 Discussion and conclusions

Based on the evaluation part and continued discussion with Thermacore a final result matrix could be made. The matrix shows each specific cooling technology´s possibility to be applied on each specific circuit board and the generic house. This matrix stands as the result for the given assignment.

3. FRAME OF REFERENCE

For the purpose of this thesis work it is important to understand the basic science of thermodynamics and this chapter will take a closer look in just that. Heat transfer is energy that is transferred between two systems, from a hotter to a colder medium as a result of a temperature difference. It is an ongoing process until both sources has reached equal temperature. In other words, the amount of heat transported from a system to another in order to acquire equilibrium.

The three basic mechanisms of heat transfer are conduction, convection and radiation. (Çenge, et al., 2012)

3.1 Conduction

Conduction is energy that is transferred through a medium as a result of the interactions between the molecules. This phenomenon takes place in both solids and fluids. Where in the solids it is because of vibrations of the molecules in the lattice and the energy gained by free moving electrons, compared to the interaction in gases and liquids, where it is due to collisions of the moving particles.

The important factors when determine the rate of heat transferred are the temperature differences, the geometry, the thickness and the choice of material. Every material has its own ability to conduct heat, which is called thermal conductivity [W/m*K].

3.2 Convection

The second mode in which heat is transferred is called convection where energy is transferred between a solid surface and adjacent fluids that are in motion. Worth mentioning is that the phenomenon convection is a combination of conduction and the effect of movement created by liquids and gases. Convection is divided into two categories, natural and forced convection. Natural convection occurs due to density differences in the fluid which in turn is caused by its temperature differences. Forced convection is instead when an external source sets the fluid in motion. The most common sources are including pumps, fans etc.

3.3 Radiation

Radiation is the emission of energy in form of electromagnetic waves. This type of heat transfer does not require any specific medium to produce it. Though, everything with a temperature over the absolute zero emits, absorb and transmit thermal radiation which is the type of radiation affected by temperature.

3.4 Thermal resistance

Thermal resistance is a well-known phenomenon in the thermal science which slows down heat from moving between layers of materials. This problem is a result of the surface roughness between two opposing surfaces which reduces the contact area, which in turn directly correlates to a lesser amount of conduction. In addition to lower conduction, air pockets arises in these spots where material is missing creating high thermal resistance due to the air´s high isolation ability. The thermal contact resistance creates a temperature difference which leads to a corresponding temperature increase.

To solve this problem, a thermal interface material (TIM) has been developed which applies in between the materials, filling the empty spaces and removing the air pockets to increase the conduction. There is a lot of different TIM on the market with a wide variety of properties, pros and cons.

4. The design standardization

The design standardization consists of one generic house and several plug-in units. These constructions are the true backbones in a radar system. Depending on how the generic house is designed and which plug-in units are used, the standardization will receive different function in the system. This is an introduction of the generic house and the plug-in units and how they are composed. In Saabs case this is sensitive information and because of that the information below is more general than specific, (Saab, 2014).

4.1 Generic house

This assignment will only deal with a house where the transmission of heat happens by conduction in the side walls. The side walls of the generic house can be cooled by either air or liquid. A generic house consists of a front-, back-wall, two side walls, a top and a bottom wall. The side walls are milled, creating racks to control the placing of the plug-in units see figure 1. The material for all these elements is aluminum.

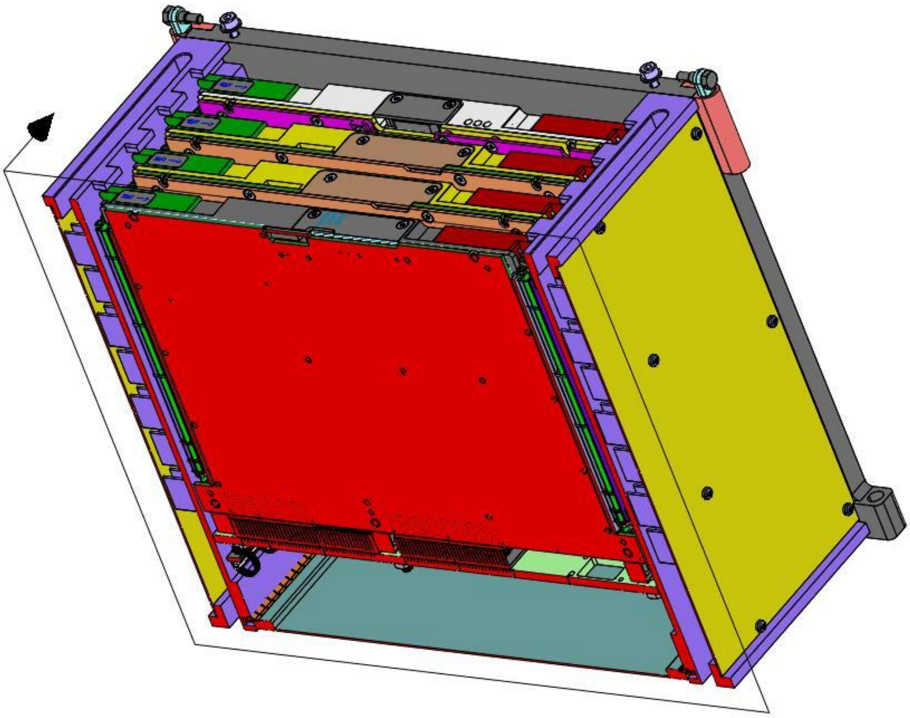

Figure 1 the generic house including plug-in units

The heat generated by the components in the plug-in unit is conducted through its own front wall or back wall which leads the heat to the cooled side walls. Here is where the conduction cooling happens, conducting the heat from the plug-in units through the connected areas with the generic house and towards its air cooled sides which can be seen in the purple areas.

On the bottom wall there is contacts for the plug-in units to be placed in. Shape, environment and other mechanical requirements on the generic house is controlled by standards from Saab, these requirements will be discussed later on (Saab, 2014).

4.2 Plug-in unit

Easily described, a plug-in unit consists of a front- and back wall, a TIM, two wedge locks and a circuit board in the middle. The variation of the design and which electric components are used on the circuit board is great. This variation is important to acquire the specific function demanded by the system.

The plug-in unit slides inside the milled racks located in the side walls of the housing, connecting with the contacts on the generic house´s bottom surface. Finally the unit is locked in to place with the two wedge locks. Dimensions can be found in VITA 48,2. (VITA, 2010).

As said before the heat is transported from the plug-in unit to the generic house through the edges of the plug-in unit to the cooled side walls of the house. A more detailed heat transport in the plug-in unit can be described like this. The electric components generate heat which is conducted either downwards alternatively upwards. If downwards cooling, the heat transports through the circuit board and the TIM into the back wall of the unit. The heat then spreads to the edges of the plug-in unit, conducting the heat to the housing´s side walls. If upwards cooling, the heat doesn’t go through the PCB but instead directly to the front plate, furthermore direct the heat to the sides. To improve the thermal conductivity through the circuit board several thermal vias are often implemented, a common material to use is copper.

5. COOLING TECHNOLOGIES

5.1 Heat pipe

Heat pipe [HP] is a passive two phase system with great cooling capabilities (K_{hp}=5000 W/m*k) where thermal energy is transferred by a vaporized working fluid to the condenser due to capillary force. It is a low cost, low weight technology without any moving parts that can be created in many different shapes, sizes and it is a very reliably long life thermal solution. Basic knowledge about heat pipes can be found in (Thermacore, 2016) and (Nilsson, 2012).

5.1.1 Construction

The pipe consists of primarily three components, a shell, a working fluid and a wick structure. The outer shell is vacuum tight and is often made of highly conductive copper. On the inner surface of the tube there is a capillary wick structure which is saturated by the later added working fluid and moves it from the condenser section back to the evaporator zone. There are several wick structures to choose from, most common are axial grooved wick, screen wick and sintered powder wick, all with different pros and cons.

The heat pipe is divided into three sections called evaporator section, adiabatic section and condenser section. The adiabatic zone is only a transport distance for the fluid to move between the two other sections.

Lastly, the common heat pipe has the shape of a cylinder, though there is a possibility to flatten them making it better fit for certain applications. However, there are limits on how much you can do this because all deformation of the HP will lower its total heat load capacity. The benefit received by this adjustment is the improved connection between the pipe and the PCB or components. Too even further enhance the thermal capabilities of the HP but also protect them they can be embedded into a solid, for example an aluminum plate.

5.1.2 Process

The process starts in the evaporator zone which is connected near the heat generated by the components. The amount of energy absorbed by the heat pipe, leads the working fluid to vaporize which creates increased pressure inside the vessel moving the fluid towards the colder end. The working fluid transport through the adiabatic zone to the condenser section where heat leaves the pipe and the vapour once again becomes liquid. The wick structure, due to capillary force, pumps the working fluid back to the evaporation zone. The system is therefore a counter flow system. By increasing the effective area of the evaporator and condenser sections the performance of the heat pipe will improve and will therefore be able to carry more power (Nilsson, 2012).

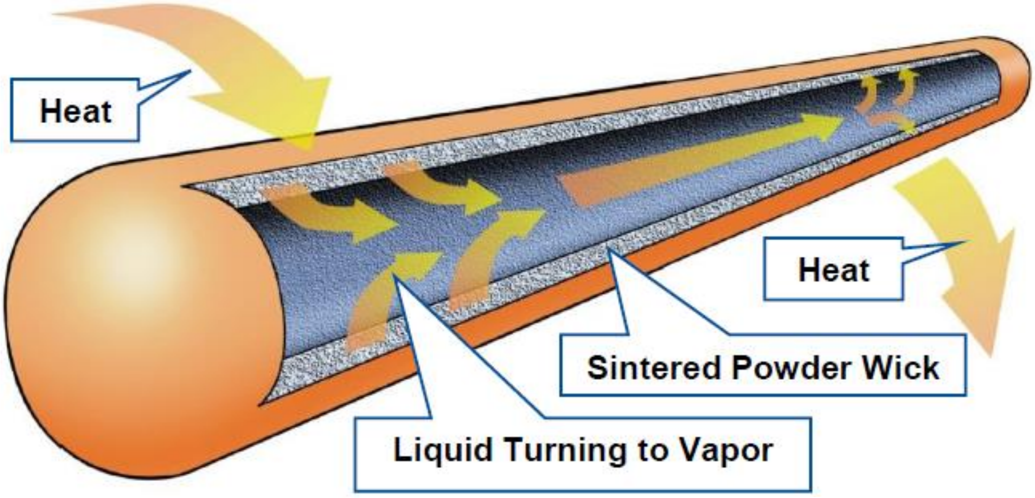

Figure 2 Construction of a heat pipe

5.1.3 Casing

When choosing the material of the casing there are a lot of different options out there but primarily used is copper because of its favorable thermal properties. Other containment materials that can be used are aluminum, titanium or stainless steel. The most important factor when deciding the material is its compatibility with the working fluid (Thermacore, 2016).

5.1.4 Wick structure

The wick structure in the pipe is used to transport the liquid back to the evaporation zone with the assistance of the forced capillary action created inside the wick. As previously said there are several types of wick structures, all providing the pipe with different properties. Furthermore only the three most common will be discussed, starting with screen wick (Thermacore, 2016).

5.1.4.1 Screen wick

This type of wick has one big strength, it has a very high heat flux capability when the heat pipe is working in the same direction as the gravity, though this is at the same time its weakness because it can only operate when working “with” the gravity. The screen wicks are also sensitive towards freezing and dry out. It also requires a larger evaporator section to work efficiently compared to the other two. In summary, the screen wick has a lot of limitations and requirements that needs to be taking in consideration before used but if met, it will work effectively.

5.1.4.2 Axial grooved wick

The axial grooved wick is a circle of grooves inside and along the mantel of the HP, enabling the system to carry heat further than its two competitors with a length of up to three meters. In addition, the axial grooved HP weight less because of the lesser amount of total material needed. The drawback is however its inability to efficiently work when affected by gravity and therefore axial grooved HP is often used and works best in space applications or if restricted to horizontal usage only.

5.1.4.3 Sintered powder wick

The sintered powder wick neglects a lot of the disadvantages the other two have. It enables the heat pipe to efficiently operate in all types of orientations and attitudes regardless of the gravity. It can also recover from both dry out and freezing situations which enables the HP to work in a wider variety of environmental situations. Interesting to know about the sintered powder is that the capillary force is inversely proportional to the pore size of the powder wick were smaller pores increases the HP´s capacity, though by decreasing the size of the powder pores it limits the permeability in longer pipes. This is a critical factor to take into consideration when creating the HP and deciding its length.

5.1.5 Working fluid

There is a large amount of different working fluids that can be used inside a heat pipe, all with their own pros and cons which thereby enable the heat pipe to operate in a variety of environment and temperatures. The most common working fluid is water. Water has a very wide operation temperature from 1°C to 325 °C but also has a high heat flux capability. Another often used fluid is methanol which can operate at lower temperatures where water otherwise would freeze and making the heat pipe to not function. The downside of methanol is that it carries less energy compared to water. The amount of fluid can also have a negative impact, too much causing problems when freezing and too little can make the pipe dry out. You want to saturate the wick structure. The amount of fluid needed varies depending on the size of the heat pipe and the amount of power it needs to carry away (Thermacore, 2016).

5.1.5.1 Freezing

When the temperature gets too cold for the active fluid to work it starts to freeze, preventing anymore liquid to vaporize and no more heat can be transferred, the heat pipe in this stage stops to work. Though, during such circumstances the aluminum plate will be cold enough to cool the components without the heat pipes. When the temperature once again rises to working temperature the ice will melt and the heat pipe starts to operate as usual without taking any damage.

5.1.5.2 Dry out

Another type of problem that can occur is called dry out. This implies that there is no longer any liquid in the evaporator section to vaporize, the rate of which liquid pumps back through the wick, from the condenser zone is to slow. The result of dry out is due to several reasons, the first one being that a too small quantity of liquid has been added in the process making, the other one is due to that the heat flux of which the heat pipe is supposed to carry is too high. To counteract this phenomenon, add the exact amount fluid needed and don’t expose the pipe to more than a maximum of 350 W/cm^2, (Thermacore, 2010).

5.2 Vapour chamber

The vapour chamber [VC] is a two phase heat transfer solution designed to replace traditional heat sinks. It can be described as a very wide flattened HP, the difference between VC and HP is that the VC transfer heat in three dimensions. It´s main purpose is the same as a traditional heat sink, spreading heat in all directions and in that way cooling electrical components. It is most commonly used in hospital applications but it can also be used in computers, power electronics and military industries. Information about the VC can be found in (Thermacore, 2016) and (Thermacore, 2012).

5.2.1 Construction

The VC consists of a shell, an inner wick structure and a vacuum. The shell is often made out of copper, titanium or other acceptable material that are compatible with the chosen working fluid. The shape can be made in a wide variation depending on the application. If needed vias and screw holes can be inserted through the structure. The whole construction is sealed by either welding or brazing. The thickness of the construction can be made from 1 mm to 10 mm, most commonly one use 3-4 mm.

The VC cannot withstand high internal pressure, the construction can expand and be damaged, though this can be solved by strengthen the construction often by internal pillars. Because of that the maximum working temperature is around 100^{o}C. Due to the location of the condenser zone and the evaporator zone the VC can work in any orientation without the effect of gravity. It can handle heat fluxes up to 350 W/cm^2 and often operates when the total power is between 50 – 500 watts (Thermacore, 2012).

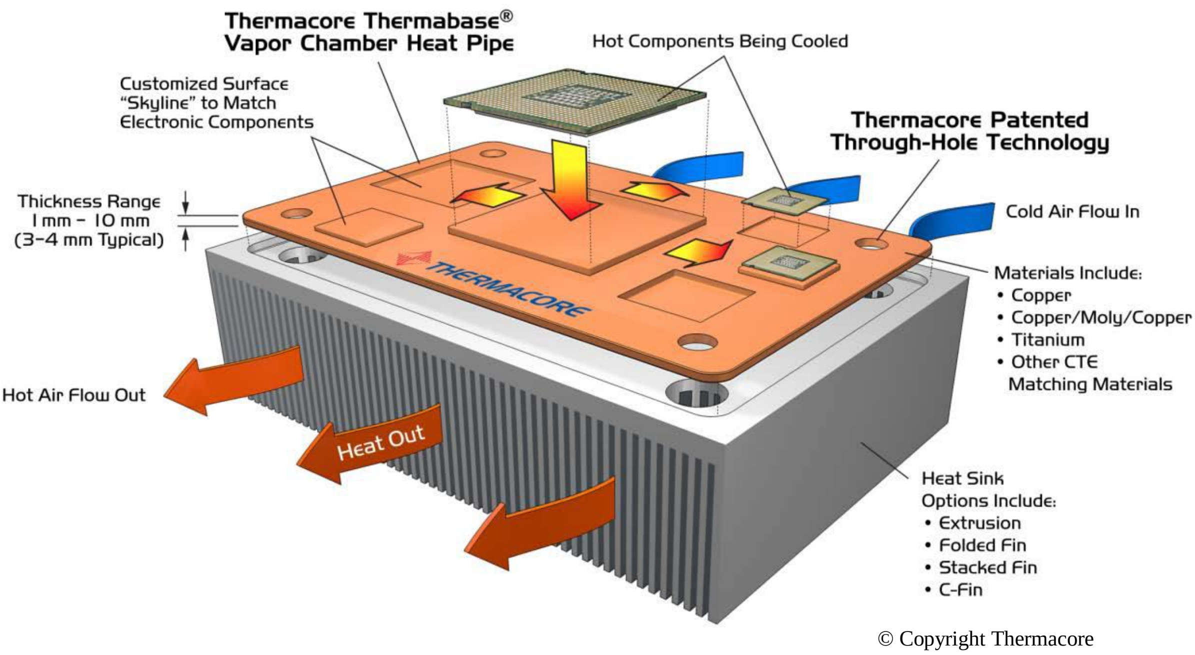

Figure 3 construction of a vapour chamber

5.2.2 Process

On the inside of the casing there is a wick structure saturated with a working fluid. The VC uses a sintered copper powder or a screen wick, see 5.1.4 wick structure for more information about wick structures. Choice of working fluid depends on where the VC is operating and the amount of heat necessary to be dissipated, but the most common working fluid used is water. See 5.1.5 Working fluid for more information.

When heat is transferred through the case into the wick structure, the working fluid will start to vaporize. The vapour will go into the vacuum section. When the vapour gets into contact with a cooler surface the latent heat from the vaporization will be released. The condensed fluid will then return to the original heat source by the capillary action of the wick structure. The condenser zone surface can be attached with fin stacks for a higher cooling performance. This cycle will repeat as long as heat is attached and enough to vaporize the working fluid.

The overall thermal conductivity for the VC is approximately K_{VC}=5000 W/m*K. The thermal conductivity is affected by the case material´s thermal resistance, the conductivity between the case material and the wick structure and finally the thermal conductivity of the inner section.

As previously mentioned for the effects of hot spots and freezing for the HP, the VC is affected in the same way, see 5.1.5.1 Freezing and 5.1.5.2 Dry out. Even if several heat sources are attached to the VC it will still work effectively dissipating heat.

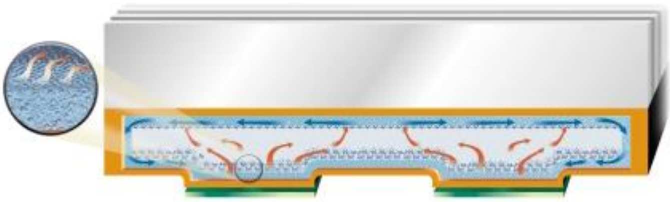

Figure 4 showing the internal fluid moments

5.3 k-Core

The k-Core is easily described as a multi material solid heat sink. The purpose of the k-Core is to spread heat effectively from high-power electronic components to a cooler area. The k-Core uses the mechanical strengths of the encapsulating material and the high thermal conductivity of graphite making it a thermal effective and mechanical robust product. Data about the k-Core can be found in (Thermacore, 2010), (Thermacore, 2016) and (Thermacore, 2016).

5.3.1 Construction

The k-Core is designed and constructed out of the costumers' problem and needs. Screws and vias have to be taken into consideration during the design process, because you cannot drill through the annealed pyrolytic graphite (APG). It is constructed by two materials, the encapsulating material and the annealed pyrolytic graphite. The encapsulated material is milled so that the APG can be inserted and then sealed by using vacuum brazing.

The encapsulating material can be different depending on the application and costumers need, often it is aluminum, copper or beryllium. The difference in properties using various materials can be seen in table 1.

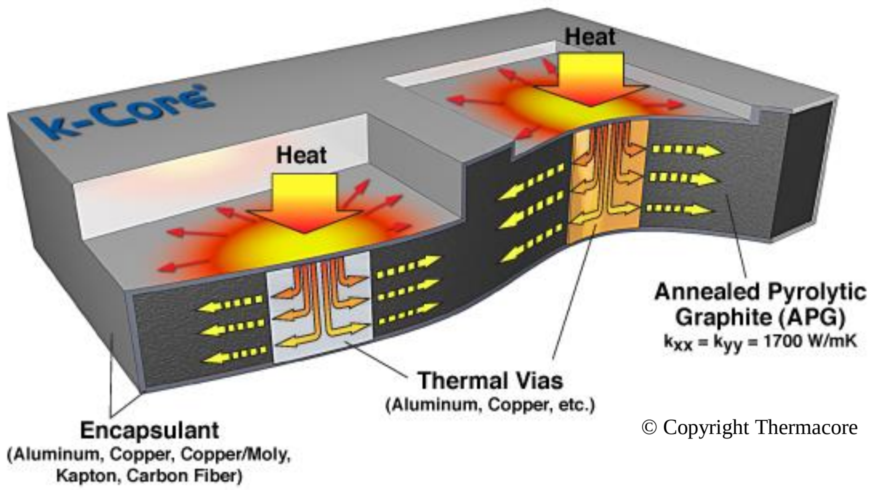

Figure 5 construction of a k-Core

Annealed pyrolytic graphite has high thermal conductivity of 1700 W/m*K in X- and Y-direction (in the plane). The thermal conductivity in Z-direction, through the thickness of the plane is not that good therefore you often use thermal vias. The APG has poor mechanical properties due to the weak van der Waal bonding and that is why the k-Core uses an encapsulated material. APG has lower density (ρ=2,2 g/cm^3) than most traditional materials and because of that the k-Core has a lower mass then a traditional one material solid heat sinks. The k-Core consists of solid materials without any moving parts and is therefore independent of gravitation (Thermacore, 2016).

The smallest thickness one can use is 2 mm (1 mm aluminum and 1 mm APG) but the smallest recommended thickness is 3 mm (2 mm aluminum and 1 mm APG).[1]

The k-Core is a high cost product due to the expensive manufacturing process of the APG. It is mostly used by the space and military industry. The k-core is a patented product by Thermacore.

Material	Thermal Conductivity (W/mK)		Density (g/cm^3)		Coefficient of Thermal Expansion (CTE) (ppm/K)	Specific Conductivity (conductivity/ density) (W/m·K/g/cm^3)	
	w/o APG insert	with k-Core	w/o APG insert	with k-Core		w/o APG insert	with k-Core
Copper (OFHC)	390.0	1176.0	8.90	4.92	16.9	43.8	239.2
Beryllium	220.0	1108.0	1.80	2.08	13.5	122.2	533.7
Aluminum Beryllium (62% Be)	210.0	1104.0	2.10	2.20	13.9	100.0	502.7
Aluminum (6061)	180.0	1092.0	2.80	2.48	23.6	64.3`	441.0
AlSi (40% Si)	126.0	1070.4	2.53	2.37	15.0	49.8	452.0
Magnesium (AZM)	79.0	1051.6	1.80	2.08	27.3	43.9	506.6
Kovar	14.0	1025.6	8.40	4.72	5.9	1.7	217.5

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Table 1 data over various encapsulated

[1] Elvedin Halimic Research engineer Thermacore Europe 16 March 2016

5.4 Cold plates

When an air cooled system cannot manage the heat that has to be dissipated from the electric components one often replaces the system with a liquid cooling system. Liquid cooling or cold plates as it is sometimes called is often used in the computer industry, but due to higher demand of greater heat loads and heat fluxes liquid cooling is spreading to several markets.

Cold plate systems consists of an enclosed system where liquid is circulated through the channels by a pump. The liquid absorbs the heat and transport it to a cooler section. The system is built up by tubes, pumps, a working fluid and a cooling section. (Thermacore, 2013) and (Thermacore, 2016).

5.4.1 Construction

The placement and the design of the channels and pipes are determined by the designer and the demand from the costumer. To enhance the performance of the system there is the possibility to apply other cooling technologies in the system, for example heat pipes or k-Core.

Thermacore delivers three different kinds of cold plates solutions. The first one is called Tube-in-plate which have tubes integrated within an aluminum or copper plate. The second one is called Aluminum vacuum brazed, which is an aluminum based structure with machined channels and fins, the plates are sealed together using manufacturing process called vacuum brazing. The last one is the micro-channel solution consisting of an aluminum or copper construction that uses the micro-channel technology to create internal flow.

The largest cold plate system that Thermacore can deliver is 1m*3,6 m in area. Their cold plate solutions have a shock resistance of 40 G when operating. All of these mentioned options are in need of an external pump, a cooling section and in some cases a heat exchanger (Thermacore, 2013).

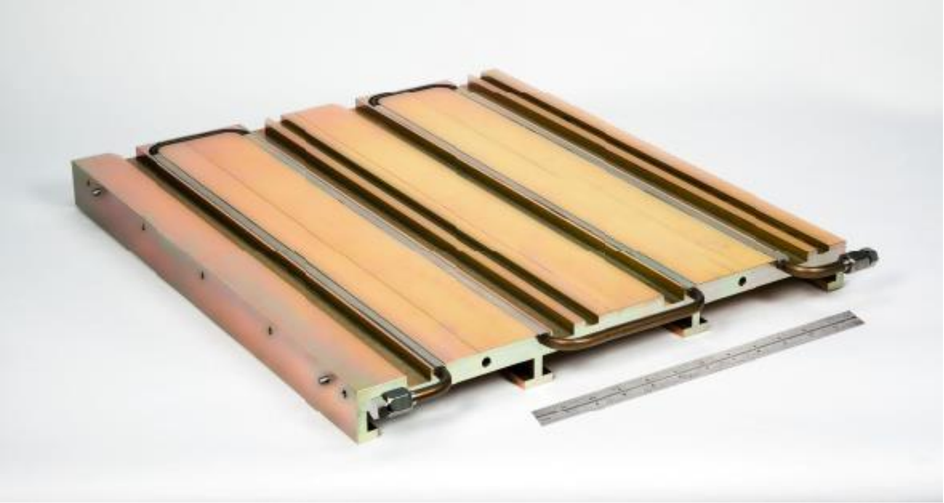


Figure 6 Cold plate system tube-in-plate

5.4.2 Process

The heat is transferred from the component through the plate, pipes and into the liquid by conduction and then transported along with the working fluid by convection. Higher turbulence in the liquid increases its possibility to absorb heat, due to the increased amount of cold liquid that is in contact with the warm pipe. The liquid is transported around the system with the help from pumps. Cooler fluid is pumped into the system, pushing the already warmer fluid forward. The liquid is either cooled by a heat exchanger, natural convection or forced convection by a fan.

The whole system is what we call an active cooling system because of the external pumps and cooling section for the fluid. Therefore you have moving parts that are in need of a consistently power input and service.

5.4.3 Working fluid

The most common used liquids are water, glycol-water mix and different kinds of oil. The choice of working fluid is determined by the costumers need and the system's working environment. The purpose of the liquid is to manage the heat and transport it away from the warmer areas. If the quality of the fluid is poor for example due to particles or bacterial contamination it might damage the pipes, heat exchangers or inlet and outlet.

When having a circulated liquid system around electrical components one always have to be aware about the risk of leakage damaging the electronic. In some cases leak detection systems have been used, with sensors detecting liquid leakage (Thermacore, 2013).

5.5 Loop heat pipe

Loop heat pipe is a two phase cooling technology which takes use of the advantages from both an ordinary heat pipe and capillary pumped loops (CPL) but at the same time avoiding their respective drawbacks. The LHP has the ability to transport high amount of heat over long distances, it is flexible, unaffected by gravity and can withstand both high shock and vibrations. Lastly, it is a totally passive and self-priming system. (Thermacore, 2016).

5.5.1 Construction

A LHP is more complicated than all the earlier mentioned technologies. It consist of, like an HP both an evaporator zone and a condenser zone but also contains similarities with the CPL which uses series connected transport zones in between, called vapour pipe and liquid pipe, in addition to this it also includes a reservoir of working fluid. Inside the evaporator there is a capillary wick consisting of sintered powder. It also contains small vapour passages located near the edges of the vessel which in turn consist of grooves and headers (see figure 9).[2]

To understand which advantages the LHP have inherited and which disadvantages it has eliminated, a short description of the heat pipe´s and CPL´s pros and cons is presented below.

A heat pipe´s two most beneficial abilities is that it can carry high amount of heat from one place to another very effectively and is totally passive. Though, the HP inherent two primarily drawbacks, the first one is its inability to carry heat over a longer distance and the second one is the counterflow aspect between the liquid and the vapour inside of the tube. The counterflow generates an inner counteraction between the fluids creating a risk of liquid entrainment into the vapour. The other one is due to the flow losses created when the liquid goes through the wick back to the evaporator, the capillary force have its limitations which in turn becomes a deciding factor for the length of the HP. How the capillary force is affected by the pores of the sintered powder, se chapter 5.1.3.3 Sintered powder wick. [3]

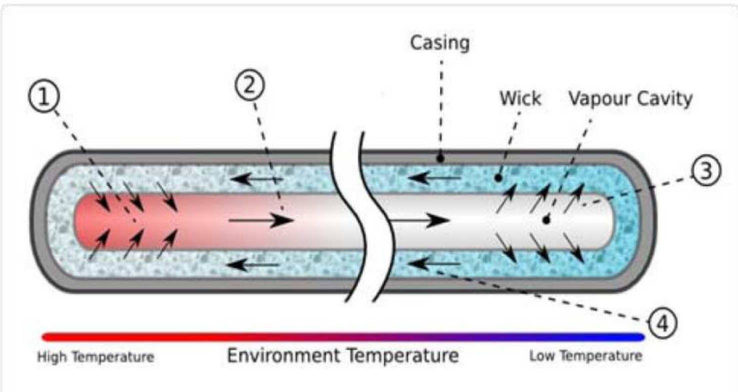


Figure 7 showcases the conunterflow inside of a heat pipe (Figure got from Wikipedia https://en.wikipedia.org/wiki/File:Heat_Pipe_Mechanism.png).

[2,3] (Ernst & Phillips, 1993)

The CPL is a series connected system where only the evaporator contains a wick (see figure 8) and by combining these two technologies it overcomes the negative aspects earlier mentioned above.

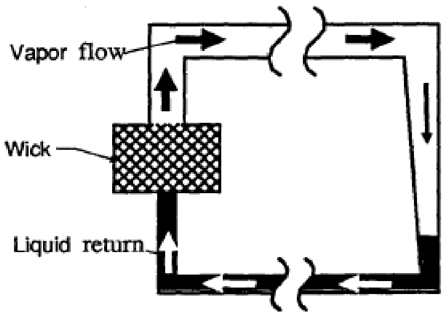


Figure 8 showing a capillary pumped loops (Taken from "LOOP HEAT PIPES- THEIR POTENTIAL" See list of reference)

Due to that the LHP is taking the advantage of the CPL's series connected lines, the vapour and liquid flows in the same direction, neglecting the drawbacks from counterflow effects. The benefits of only use wick structure in a small part of the system, in this case the evaporator, the LHP overcomes the flow losses that otherwise rapidly increases with a longer wick and also gives the opportunity to implement finer pores increasing the wick capacity. The result of this is a system with high performance, long distance heat transport that is totally passive (Ernst & Phillips, 1993).

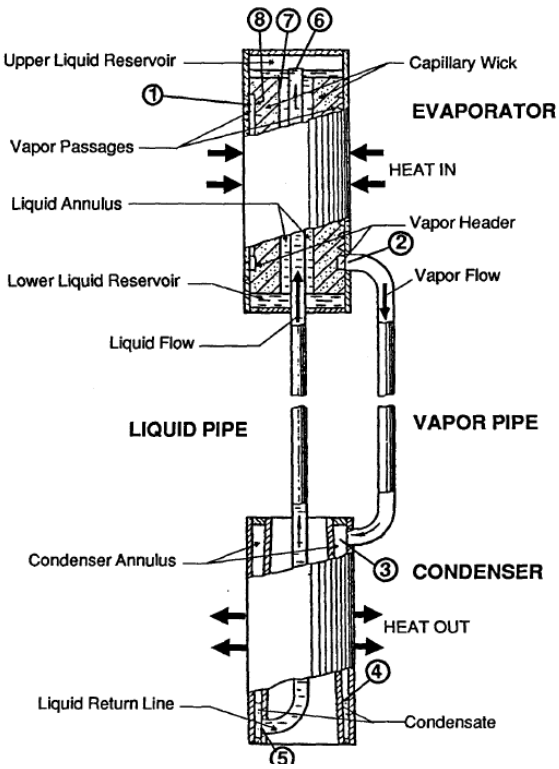


Figure 9 Construction of a LHP (Taken from "LOOP HEAT PIPES- THEIR POTENTIAL" See list of reference)

5.5.2 Process

Heat is absorbed in the vapour passages, it is important that the vaporization starts here and that the reservoir has a lower temperature when this happens for the system to insure self-priming. The vapour is directed towards the vapour pipe by the grooves and headers inside of the passages which then flow to the condenser where heat is dissipated and a phase transformation occurs once more. By the created vapour pressure liquid is forced back towards the evaporator and is collected inside of the reservoir which replenishes the wick structure inside of the evaporator and the cycle is completed, (Ernst & Phillips, 1993).

6. Product analysis

To be able to evaluate Thermacores products an extended analysis was made. This product analysis will stand as a base for the later evaluation part. During this chapter, information about the requirements and request specification, thermal simulations, cost estimations and choice of free variables for the technologies can be found. This information will then be evaluated and the technologies will later on be compared against each other. Data for this analysis is based on the earlier mentioned literature studies and the knowledge gathered on the trip at Thermacore. In this chapter the main focus will be on the cooling capabilities for the plug-in units but information about cooling options for the generic house will also be included.

6.1 Requirement and request matrix

When the literature study had been completed the next step was to put together all the relevant factors regarding performance, environmental effects, maintenance and economic for the plug-in units and generic house into a matrix. This gives an overview of what challenges the technologies must overcome to be suitable for the task. It is important that the requirements in the matrix are measurable and that the target values are not deviated from.

The factors in the matrix are divided into four categories called: technology, environment, human and economy which includes elements like cooling capacity, weight and pressure alternation, see figure 10. The matrix and the target values are mainly based on VITA-standard 47 and VITA 48.2 which both takes in consideration the dimension limitations of the plug-in units but also the environmental aspects for the whole system respectively. (VITA, 2010) (VITA47, 2007).

The application areas for radars are divided into three groups: land, sea and air, though due to vast difference in the level of requirements for applications in the air section a further breakdown of this group were needed, resulting into two new divisions: civil aircraft and fighter jet. All of the four areas above demands different kinds and levels of requirements and the values seen in the matrix are the absolute highest needed and takes the most demanding, the fighter jets in regards. Furthermore about this will be taken in consideration in the evaluation matrix in the evaluation chapter. Lastly, the verification methods that will be used are “simulation”, “calculation”, “testing on prototype” and “estimation”. Where “simulations” refers to the results from the thermal simulations made in Icepak, how the integrated technologies operates. “Testing on prototype” is the verification method for most of the requirements in the matrix, to be able to get accurate numbers testing on full sized prototypes needs to be made.

Because of the different application areas some requirements and request are more important to a specific area than to the others.

For example, on the sea division, the cost factor is a more important request compared to the other areas and this is due to a tougher price driven market and to be a competitive contender the cost of the product have to be low. On the other hand, weight is a less important request due to the proportionality, the predicted weight gain any of the technologies will have is small compare to the whole system.

On land there aren't any requirement or request that sticks out from the rest, all of them are somewhat equally important. Though the requirements for land units are generally tough, for example the vibration spectra on land are much wider than that for the civil aircraft and therefore are a tougher requirement to meet.

For the civil aircraft the requirement are generally a little bit nicer than for land and sea, but because it is a flying application other factors also have to be taken in consideration.

Lastly is the fighter jet which has the hardest requirements and requests, most important are the weight, the affect by g-force and the resistance of vibration. For the fighter jet application the prize factor becomes less important, it is a more expensive market then the other three.

The plug-in units are considered to be sheltered and therefore requirements like resistance to sand, wind, rain and dust have not been included in specification. For further evaluation these factors may have to be taken into consideration.

Requirement and request				
Technology	**Requirement/Request**	**Index**	**Target value**	**Verification**
Temperature decrease	Request	°C/comp	Compare temperature decrease	Simulation
max Heat load for tech	Request	W	Highest	Simulation
Cooling capacity/ thermal conductivity	Request	W/m*K	Highest	Simulation
Weight	Request	kg	Lowest	Calculation
Reliability	Request	-	Highest	Testing on prototype
Life span	Request	Years	Highest	Testing on prototype
Flexibility	Request	-	-	Testing on prototype
alowed maximum area	Requirement	m^2	See VITA48,2	Calculation
max Temperature in the soldering joints	Requirement	°C	85°c	Simulation
alowed maximum volume	Requirement	m^3	See VITA48,2	Calculation
Environment	**Requirement/Request**	**Index**	**Target value**	**Verification**
Vibration resistance	Requirement	g	See VITA47	Testing on prototype
Shock resistance	Requirement	g	See VITA47	Testing on prototype
ΔTsurrounding	Requirement	°C	See VITA47	Testing on prototype
Pressure alternation	Requirement	Δm	See VITA47	Testing on prototype
Corrosion resistance	Requirement	-	See VITA47	Testing on prototype
Humidity	Requirement	-	See VITA47	Testing on prototype
Frost resistance	Requirement	-	Recover	Testing on prototype
Dryout	Requirement	-	Recover	Testing on prototype
Effect by gravitation	Requirement	g	See VITA47	Testing on prototype
Attitude	Requirement	-	See VITA47	Testing on prototype
Human	**Requirement/Request**	**Index**	**Target value**	**Verification**
Maintenance	Request	-	applicable	Yes
Generically	Request	-	applicable	Yes
Economy	**Requirement/Request**	**Index**	**Target value**	**Verification**
Total cost	Request	SEK	Lowest	Estimation
Cost effiency	Request	ΔT/SEK	Lowest	Calculation
Cost effiency	Request	ΔT/Kg	Lowest	Calculation

Table 2 Requirement and request matrix illustrating important factors for the products. Most of the target values are taken from the VITA standards and therefore cannot be shown due to confidential information.

6.2 Choice of free variables for Thermacore products

As listed before there are many ways to design and a large amount of free variables to change for the interesting Thermacore products. How the structure is chosen is effected by the listed factors in the requirement and request specification, the technologies compatibility with other materials and working fluids, finally the possibility to enhance the heat transferring solution. Important to know is that the dimensions for every technology will affect their possibility to transfer heat and is limited by the maximum allowed volume and the products minimum volume. Mentioned below are how the technologies will be designed and what variables that will be used, for the simulations and further evaluation and discussion. These have all been choosen together with Elvedin Halimic[4]

6.2.1 Free variables for the HP

The heat pipe that will be used in the simulations and further on throughout this assignment will consist of a copper vessel, sintered powder wick and water as working fluid.

Copper is the material for the vessel that will be used. Copper is compatible with both water and methanol which is desirable. It also have a very high thermal conductivity compared to other possible materials, the thermal conductivity of copper will improve the performance of the HP. Copper heat pipes is the most common and most proven material used by Thermacore.

Water will be used as working fluid due to the earlier mentioned advantages like wide operation temperature, high heat flux capability and compatible with copper, see champter 5.1.5 Working fluid.

Sintered powder wick will be used as wick structure for the HP. Sintered powder can work in every orientation and when used it will be unaffected by gravitation. In applications that involves flying the effect of g-force on the HP will be great but when using powder the effect of g-forces will be smaller compare to the other mentioned wick structures. When using a powder wick structure the HP can recover from freezing and dry out without being damaged.

The heat pipes used further on in this assignment will be flattened and embedded in an aluminum plate. When flattened the contact area towards the component will be greater which enhance the possibility for heat to be transferred into to the HP. By embedding the HP the construction becomes more robust and they will be protected within the plate. The plate will be made in aluminum due to the preferable mechanical properties like weight and strength. When embedded the contact area between the aluminum plate and the HP will be greater and because of that heat will also be transferred into the plate and can then be further spread into the vessel. Therefore positioning becomes more easily chosen because the HP necessarily does not have to be in contact with the component to transfer heat. When embedded the performance for the existing heatsink will be enhanced with minimal design changes.

[4] Elvedin Halimic Research engineer Thermacore Europe 16 March 2016

6.2.2 Free variables for the VC

For the vapour chamber, the free variables that will be used further on, because of the same reason as for the heat pipe will include a containment vessel of copper, sintered powder wick and water as working fluid. Due to that a VC in general is a wider flattened HP, the possibility of using the same variables for the two technologies exists.

6.2.3 Free variables for the KC

The k-Core that will be used will have a structure consisting of aluminum as encapsulated material. Aluminum is chosen mostly due to its low density and cheap prize. Aluminum is the most common material used for the k-Core by Thermacore and it is also a commonly used material at Saab.

Finally, due to lack of knowledge regarding the complexity of the LHP and the CP systems, no detailed choices of variables could be done.

6.3 Own made circuit boards

Three circuit boards were made because a variety of extreme cases should be included and visualized. The two main extreme cases are high temperature spread out all over the circuit board that often exist because of a high total power and a high amount of components. The second one is high temperatures concentrated on smaller area so called hot spots that arises due to high power density. The third circuit board was a combination of the first two, including both high total power and hot spots. Therefore three boards named "Hot-spot" (HS), "Temperature spread out" (TSO) and "The combined" (TC) were made, all of them generates one of these cases. The main parts of the circuit boards are the PCB, TIM, back plate and components.

The circuit boards were first made in the CAD program Creo in order to decide were the components on each specific card should be placed.

The three cards all have the same basic structure and dimensions. The PCB is 2 mm thick, after that a 0,15 mm thick TIM is added, and on the bottom there is an aluminum back plate with a thickness of 1,6 mm or 4 mm, simulations were done using both thicknesses. It is on this back plate the evaluated technologies will be integrated. The boards have an area of 160*214,3 mm^2. These are all recommended dimensions received from discussions together with our supervisor Torbjörn Nilsson.[5]

As mentioned above all of the three circuit boards are created in the same way and has the same dimension. The only thing that is different between them is the amount, sizes and power losses of the components which have been decided when studying real circuit boards and reports at Saab (Saab, 2013). The dimensions and placements of the components are only used for illustrating the problem, they cannot be found in real Saab products, however due to possible sensitive information for Saab, all the power and power densities have been taken out. Picture of the other two cards can be found in figure 1 and figure 2 in appendix A.

[5] Torbjörn Nilsson Adj. professor Electronic Packaging Saab 3 March 2016

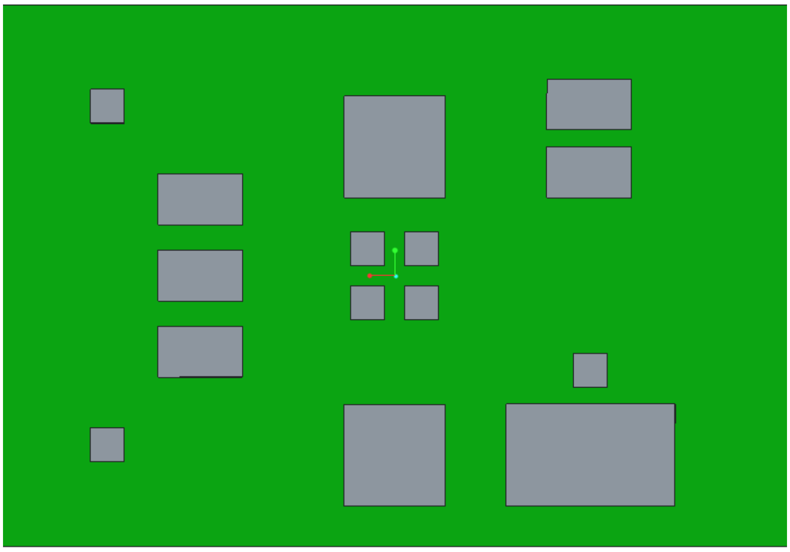


Figure 10 position of the components for the TC card

6.3.1 Details about the circuit boards

The "Temperature spread out" consists of 14 components with three different types of dimensions, it has a high total power loss of - W and maximum power density of - W/mm^2.

Circuit board: Temperature spread out			
Dimensions on the components (mm)	10x10	30x30	25x15
Height of components	7 mm	7 mm	7 mm
Powerloss on the component	-	-	-
Number of components	4 st	2 st	8 st
Temperature on component	125-130	147,5	147/105
Power density (W/mm^2)	-	-	-
Total powerloss on circuit board	-		

Table 3 detailed information about the TSO

The "Hot-Spot" circuit board consists of eleven components with a variation of five types of components. What sticks out for this card is its very high power density. The "Hot-Spot" card has one type of component that has a power density of - W/mm^2. It also has a total power loss of - W which is the lowest compared with the other circuit boards.

Circuit board: Hot-Spot					
Dimensions on the components (mm^2)	25x15	30x50	10x10	30x30	4x4
Powerloss on the component	-	-	-	-	-
Number of components	1 st	1 st	1/2 st	2 st	4 st
Temperature on component	101,3	-	(90,9/84,6) / (110,1)	116,7/112,6	(144,2-155,6)
Height of component	7 mm	"surface"	7 mm	7 mm	7 mm
Power density (W/mm^2)	-	-	-	-	-
Total powerloss on circuit board	-				

Table 4 detailed information about the HS

"The combined" circuit board have a total of 15 components with four different types. TC has the highest total power loss of all the cards. Overall the power density throughout the board is low compare to the earlier mentioned card "Hot-Spot".

Circuit board: The Combined				
Dimensions on the components (mm)	25x15	30x50	10x10	30x30
Powerloss on the component	-	-	-	-
Number of components	5 st	1 st	2/1/4 st	2 st
Temperature on component	150,3-154,9		(163,8-170,0)/(131,6-140,2)	157,5/169,6
Power density (W/mm^2)	-	-	-	-
Height of component	7 mm	"surface"	7 mm	7 mm
Total powerloss on circuit board	-			

Table 5 detailed information about the TC

Finally, it is important to understand that only heat generating components have been included on these cards, in reality circuit boards consist of many additional components but for the simplicity only the heat generating components have been included. It is also important to understand that these boards don't have any real function, they were made to visualize where the heat is generated and how it will be spread.

6.4 Weight estimation

When all of the free variables had been decided a weight calculation for the HP assembly, VC and KC could be made. This calculation is based on the dimensions from table 6 and the chosen material densities.

k-Core	[mm]	Heat pipe (flattened)	[mm]	Vapor chamber	[mm]
Length	214,3	Length	214,3	Length	214,3
Width	160	Width	7,86	Width	160
Height	4	Height	3	Height	3
APG length	212,3	Coppar vessel thickness	0,5	Copper vessel thickness	0,5
APG width	158	Capillary section thickness	0,4	Capillary section thickness	0,4
APG height	2	Thickness of Aluminium plate	4	Working fluid	Water
Size of Al-vias	10*10*2	Working fluid	Water		

Table 6 dimensions for the technologies

The heat pipes embedded in the aluminum plate will have a total weight approximately of 514 gram. This assembly includes four HP that weighed 46,714 gram each and this value was given by Thermacore[6]. The plate alone weighed 327 gram.

This estimation for the HP was based on the dimensions used in the simulations, but the aluminum plate does not have to be that thick. Therefor this estimation could be said to be the maximum weight of the assembly. The possibility of strip off some of the aluminum plate between each HP would therefor decrease the total weight of the heat pipe assembly.

The k-Core will have a weight of approximately 326 gram. Dimensions for the aluminum casing and the APG layer can be seen above.

For the Vapour chamber a weight for an already existing product was given by Thermacore, the dimensions of that VC were not the same as the one used in the simulations therefore calculations were done and resulted in an approximate weight of 588 gram.

For information about the calculations regarding all technologies see appendix G.

[6] Elvedin Halimic Research engineer Thermacore Europe 17 March 2016

This weight estimation will later be used to create interesting index for comparison work between the technologies.

6.5 Simulations

With the help from Thermacore´s engineers, instructions on how to create realistic models of the technologies were given. Making it possible to visualize and numerically show the improvement of the cooling technologies. The simulations gave a hypothetic solution of how the technologies are built up and how they should be placed for better efficiency. The simulations were made in Icepak.

In all simulations the simplified circuit boards earlier mentioned in chapter 6.3 were used and recreated in Icepak. Because of this only downwards cooling was taken into consideration. This created high temperatures in the solder joint which should not be acceptable in reality but it makes good reference values of what the cooling technologies are capable of.

The result from the simulations will be displayed by two figures for each card, some of them can be found in the text and the remaining ones in the appendix B. The first one shows the temperature in the solder joint and this is due to the set requirement of a maximal temperature of 85,0°C located there, see table 2. The second one shows the temperature in the aluminum plate and later on displaying the heat on the cooling technologies, showing the variation in degrees Celsius [ΔT] throughout the area where a value as low or homogenous as possible is desirable.

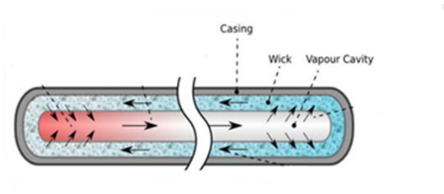
The simulations will also include two different temperature intervals. The first one ranging from 20,0°C to 170,0°C which was used to display the high temperature result from the 1.6 mm back plate simulations. The tests henceforth will be using an interval between 20,0°C-85,0°C due to the lower generated heat results and because that 85,0°C is the maximum temperature allowed. Because of the two different intervals the colour scheme changes alongside with it. The red colour shown in the figures will in the later mentioned alternative visualize a not acceptable solution.

Worth noticing is that the LHP and the CP will not be included in this part due to the complexity of each technology and their inapplicability to be integrated on a circuit board level. Nor have simulations of the generic house been made and this because the primarily focus at this stage was aimed at the plug-in units.

6.5.1 Input data

Data for all the simulations can be seen in the table 7. A more in depth information about these numbers will be explain in the subtitles below. Worth noticing is that the HP and the VC has the same built up structure, material and thicknesses, containing an outer casing, a vapour cavity and a wick structure. Throughout the simulations, the thicknesses of the PCB, the TIM and also the ambient temperature are constants. All the data describing the technologies is realistically chosen together with employees from Thermacore. Specific data about the components can be found in table 3, 4 and 5.

	Thinkness (mm)	Thermal conductivity (W/m*K)
PCB	2	8 through plane/22 in plane
TIM	0.15	6
Backplate (Al-plate)	1.6/4	164
APG	2	8 through plane/ 1700 in plane
Casing (HP and VC)	0,5	387,6
Vapour Cavity (HP)	1,2	50000
Wick (HP)	0,4	40



k-Core	[mm]	Heat pipe (flattened)	[mm]	Vapor chamber	[mm]
Length	214,3	Length	204,3	Length	214,3
Width	160	Width	7,86	Width	160
Height	4	Height	3	Height	3
APG length	212,3	Coppar vessel thickness	0,5	Copper vessel thickness	0,5
APG width	158	Capillary section thickness	0,4	Capillary section thickness	0,4
APG height	2	Thickness of Aluminium plate	4	Working fluid	Water
Size of Al-vias	10*10*2	Working fluid	Water		

Ambient temperature	25 °C

Table 7 dimensions for the simulations

Figure 11 shows how the circuit boards were built up in Icepak. The components are placed on the top of the PCB, which in turn is connected with a thin TIM and lastly the Aluminum back plate. Going forward, all the circuit boards are created in this way, and as earlier mentioned in chapter 6.3 only the placement of the components was changed and the thickness of the Al-back plate varies between 1,6 mm and 4,0 mm.

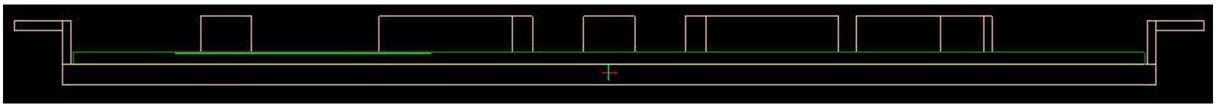


Figure 11 Showing the construction of the HS circuit board in Icepak, with a 1,6 mm back plate

6.5.2 Al-back plate 1.6 mm

The first simulations were made with a 1,6 mm thick Al- back plate. This number was chosen because it is the thinnest allowed dimension for cooling purposes. This resulted in high temperatures consistently throughout the circuit boards and gives reference values for upcoming tests. The Temperature interval is 20,0°C-170,0°C.

6.5.2.1 HS

As seen in figure 12 the temperature varies vastly between 44,5°C in the edges of the plug-in unit up to 142,2°C in the smallest components near the center of the PCB. The temperature in these four components is directly correlating to its high power density.

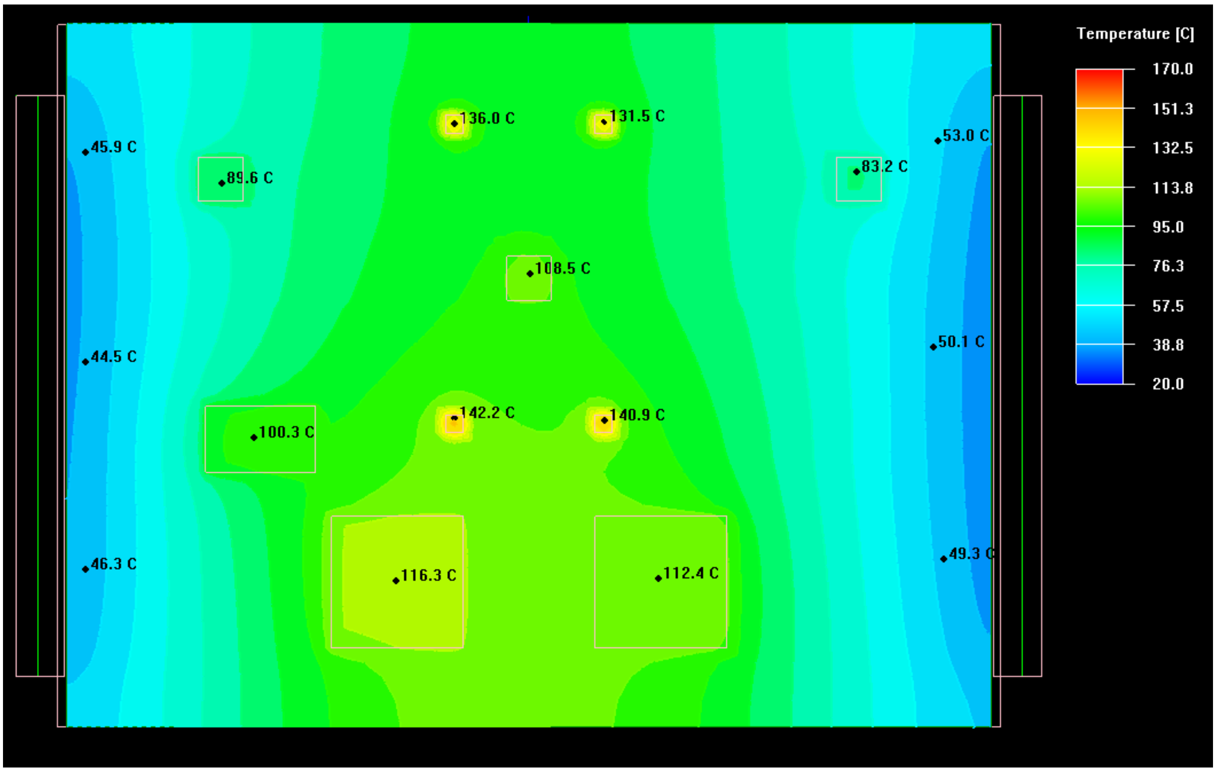


Figure 12 Temperature on the solder joint for HS

6.5.2.2 TC

The components have generated a temperature interval between 54,0°C up to 169,3°C where the hottest section is in the center of the PCB. This circuit board contains more components with higher total power which affect a wider area than the earlier mentioned HS-card. This resulted in a higher total temperature but also an increased temperature spread on the PCB, reaching closer to the edges.

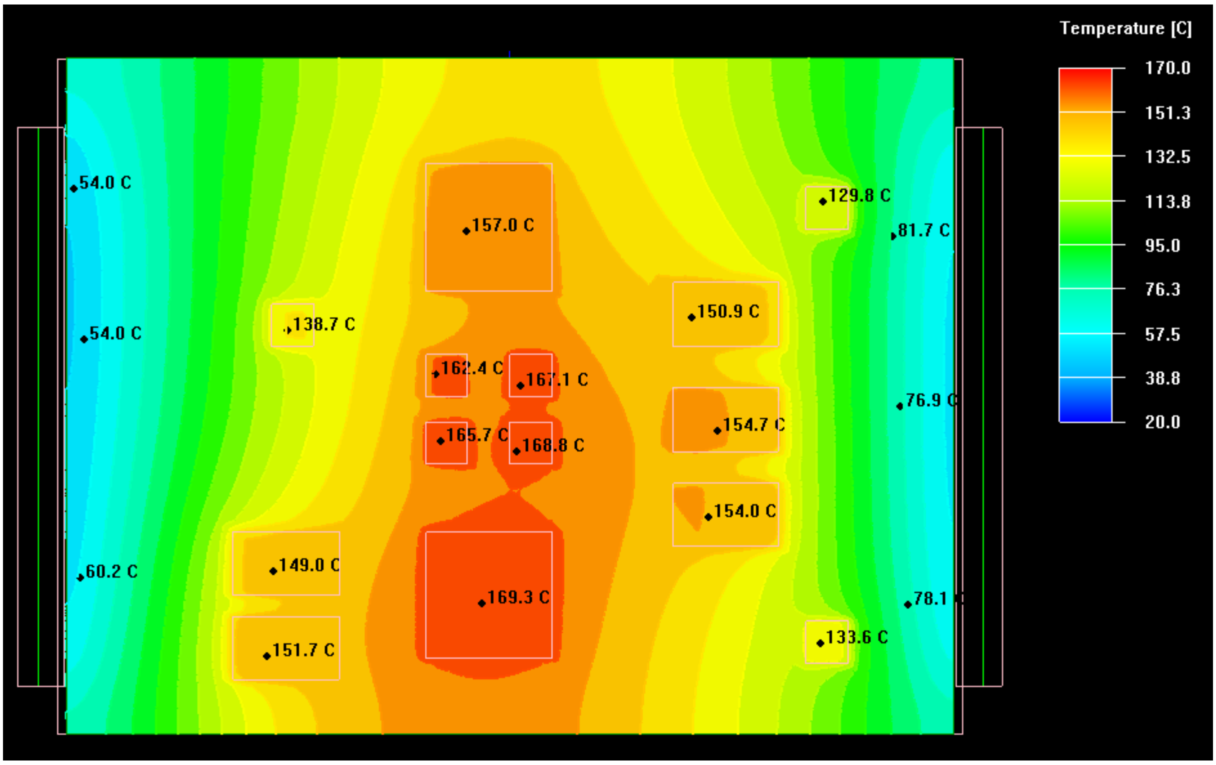


Figure 13 Temperature in the solder joint for TC

Looking at the temperature on top of the back plate (figure 14) there is three major things to take notice of. Firstly, the almost similar temperatures between those in the solder joint and the Al-plate where the generated heat in the back plate is stretching between 57,2°C up to 165,3°C. The second thing being the very high ΔT=108,0°C.

The two results from the simulations regarding the aluminum back plate for the HS and TSO card can be found in figure 3 and 4 in appendix B and this is due to similar result as in the one for the TC card.

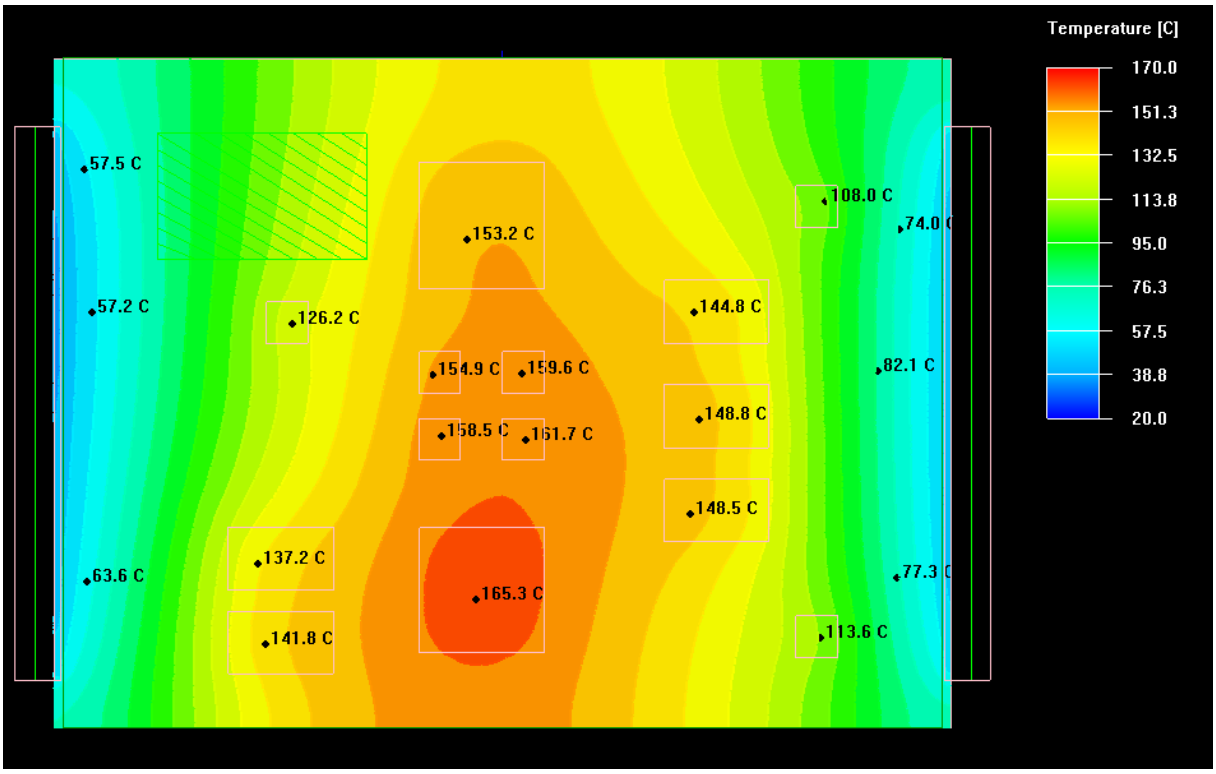


Figure 14 Temperature in the Al- back plate for TC

6.5.2.3 TSO

The generated temperatures are a bit lower compared to the ones generated in the TC card and no specific hot spot can be found, this is due to larger, more spread out components. The overall generated heat in the center of the PCB is fairly similar with a maximum of 148,5°C.

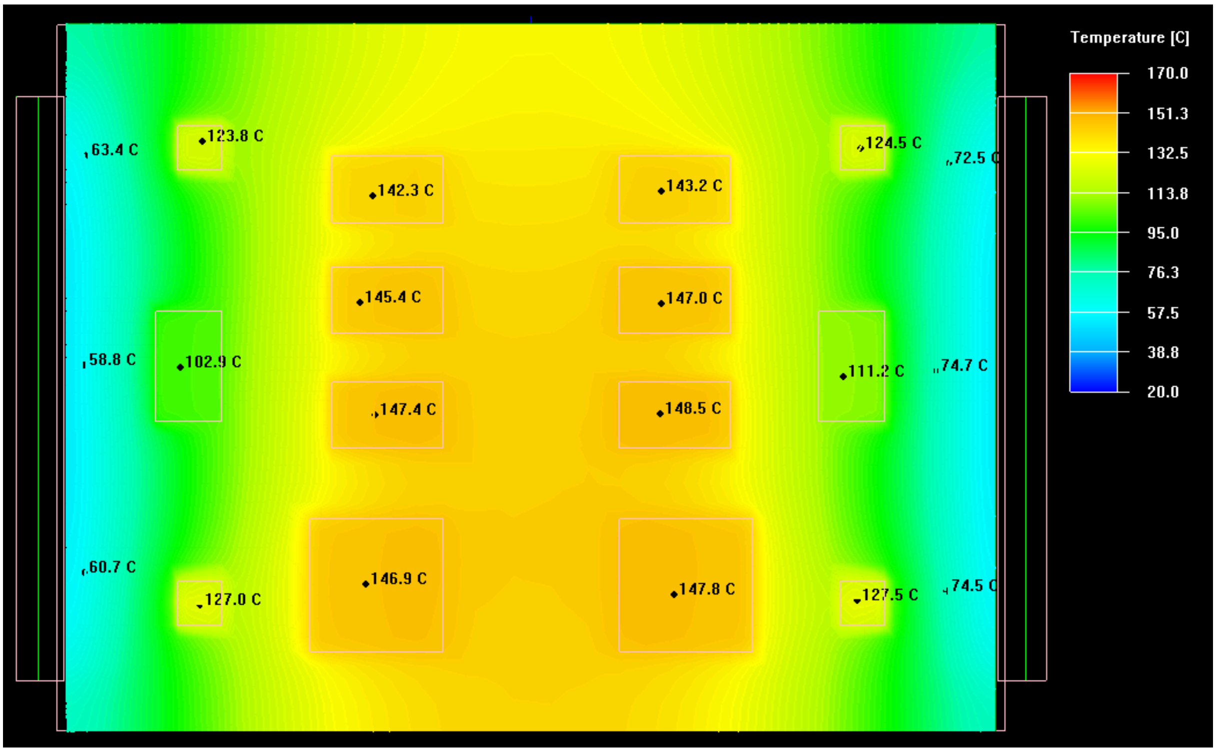


Figure 15 Temperature in the solder joint for TSO

6.5.3 Al-back plate 4.0 mm

The next step was to increase the back plate size to 4,0 mm think which henceforth is the standard total thickness for all the upcoming simulations. This specific value was chosen due to it enables all the technologies to be implemented but also makes the upcoming evaluation process easier if the dimensions is fixed. By increasing the volume and adding more material to the back plate it will be able to absorb and distribute more heat than before, resulting in lower temperatures compared to the 1,6 mm back plate.

In the continuance of the simulations the temperature interval will be set to 20,0°C-85,0°C where a red colour indicates a non-acceptable answer.

6.5.3.1 TSO

The overall temperature in the solder joint has decreased compared to the maximal temperature in the same circuit board with 1,6 mm back plate due to the thicker back plate. The maximum temperature is in this case almost 100,0°C which is an decrease of 48,2°C. However, a large red area can be seen in figure below visualizing temperatures over 85°C, further improvements needs to be done.

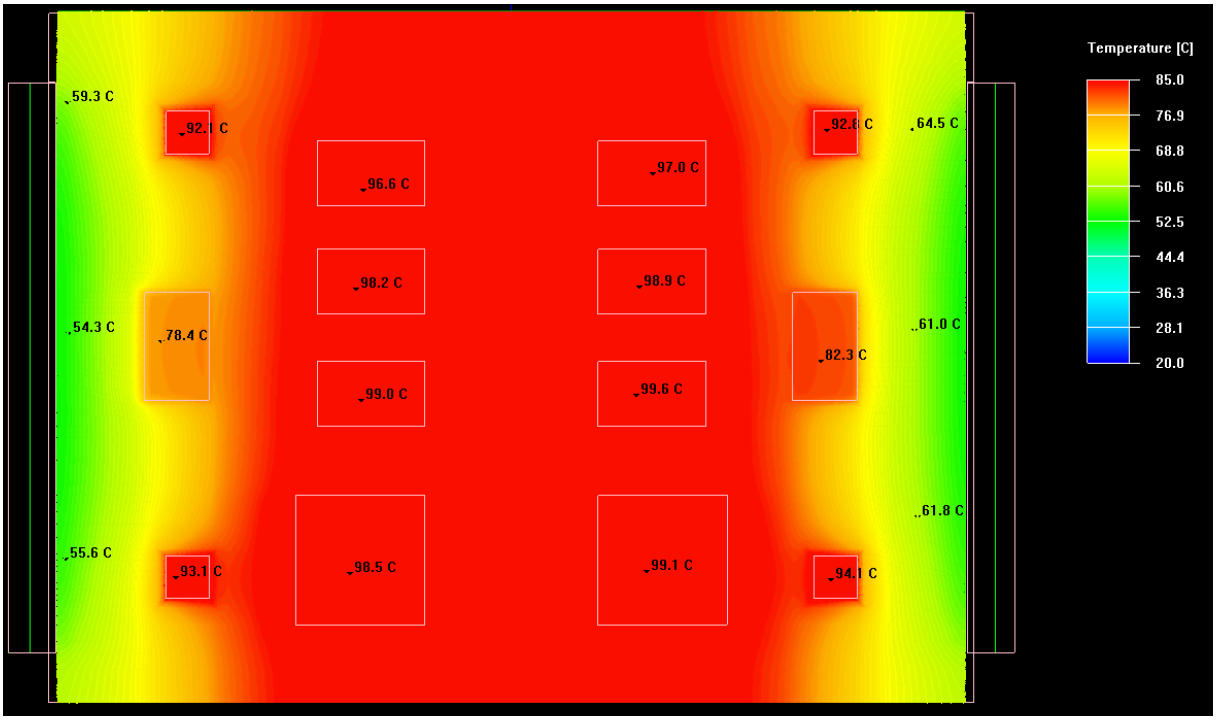


Figure 16 Temperature in the solder joint for the TSO

Looking at the back plate in figure 17 a decrease with nearly half in ΔT can be seen, now with an approximately value of ΔT=42,0°C which once again is an improvement compared to the 1,6 mm card with a value of 86,7°C. The highest temperature can be found in the bigger components placed near the center of the PCB with a T=94,2°C.

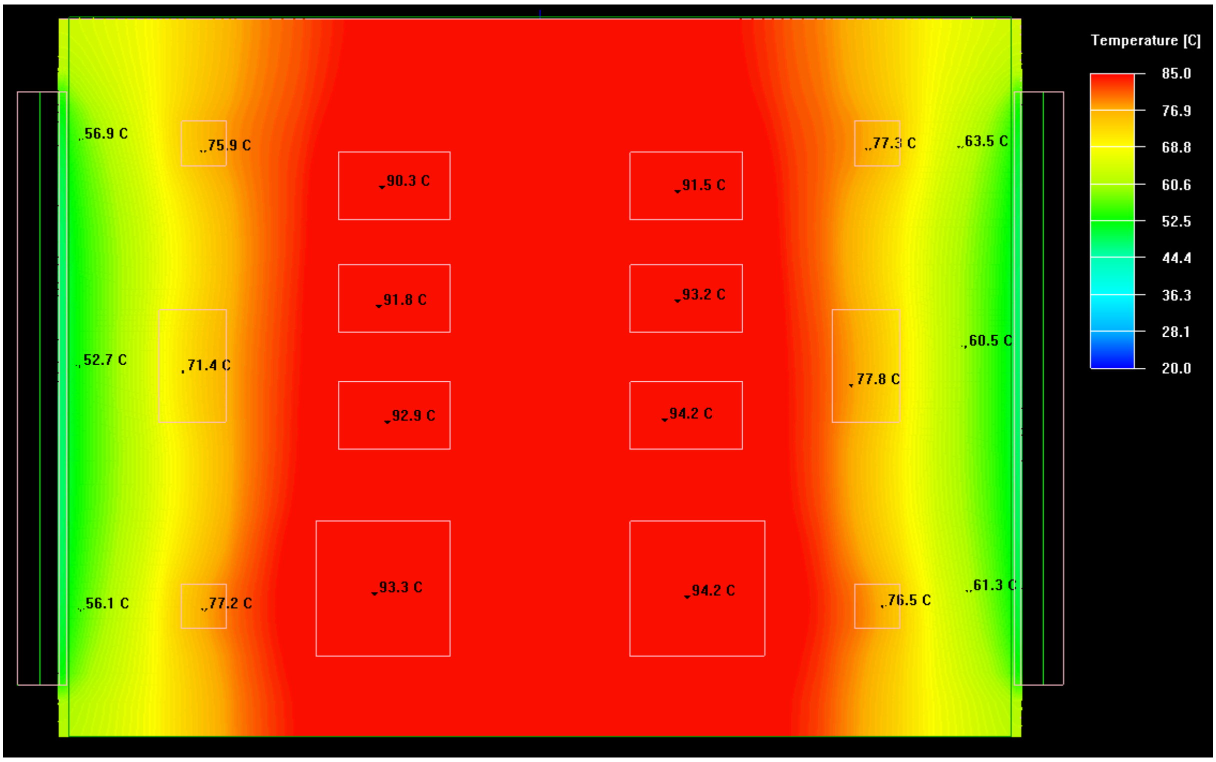


Figure 17 Temperature in the Al-plate for TSO

6.5.4 Integration of flattened heat pipes

The first cooling technology that was tested was the implementation of heat pipes. The heat pipes are flattened and embedded into the aluminum plate surface, still making contact to the TIM. The placement of the pipes for the HS card can be seen in figure 18 and figure 20 and it is worth noticing that they are placed directly under the smaller components with the highest power density for better effectiveness.

The heat pipe consists of three sections called casing, vapour cavity and wick. Each layer was given the properties to replicate a copper heat pipe containing sintered copper powder and water as the working fluid, see table 7 for exact data.

The chosen lengths of the HP´s made in Icepak are ten millimeters shorter than its corresponding "real" heat pipes. This was made due to the so called "dead zones" affecting approximately five millimeters from each end of the pipe which is non-function sections. This gave therefore more realistic simulations.

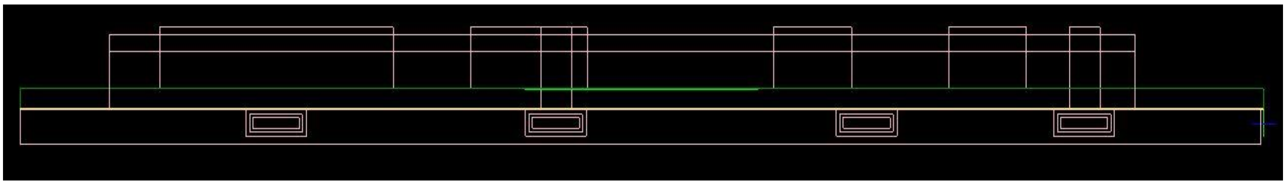


Figure 18 The three layers of the heat pipe

6.5.4.1 HS

The figure below displaces a greenish area with a low overall temperature on the PCB and most of the components have had a reasonable temperature decrease. Though, the generated heat in the smallest components surpassed the maximum temperature range of 85,0°C. A further researched was needed to find a solution to this problem.

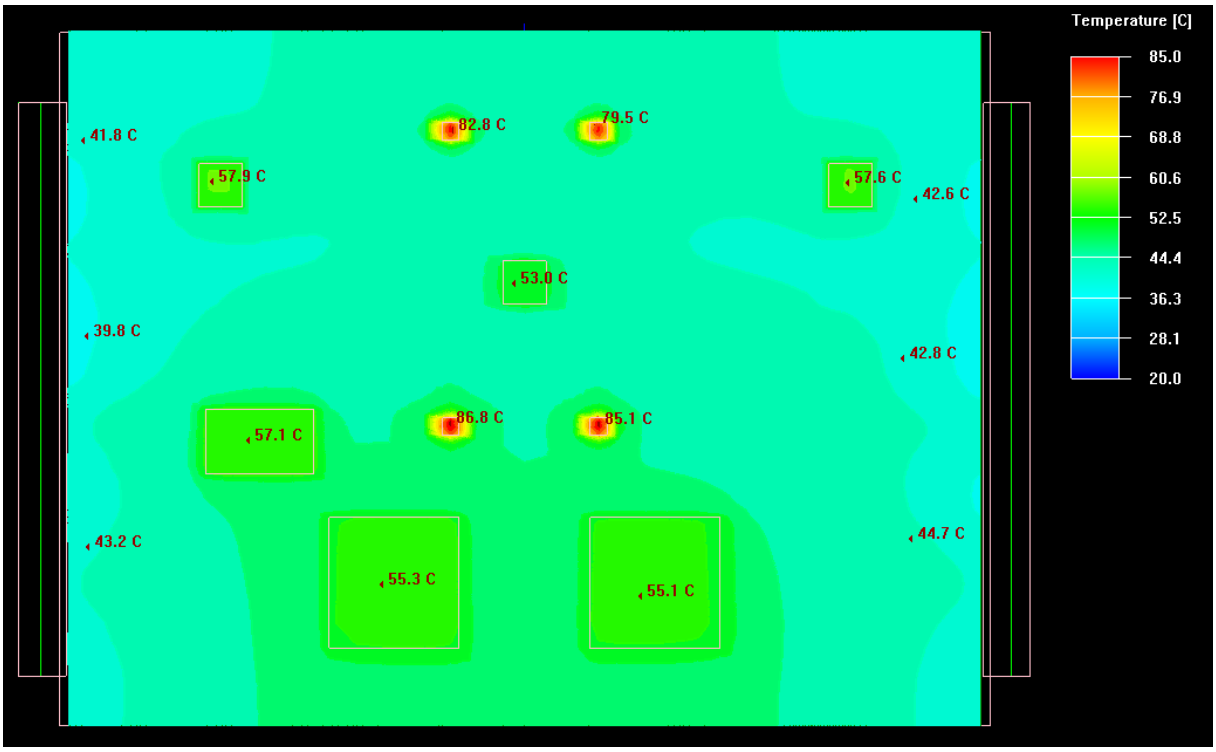


Figure 19 Temperature in the solder joint for the HS card with heat pipes

The global temperature over the back plate area has a ΔT of 9,1°C compared to the corresponding circuit board with 4,0 back plate with a temperature interval of 28,8°C. Focusing only on the heat affecting the heap pipes the ΔT is approximately between 3,0-4,5°C which is an acceptable result.

Interesting when analyzing figure 19 and 20 is the vastly differences in temperature, were the warmest spot in solder joint was 86,8°C compared to the 46,8°C located in the same spot heat pipe, a difference of 40,0°C.

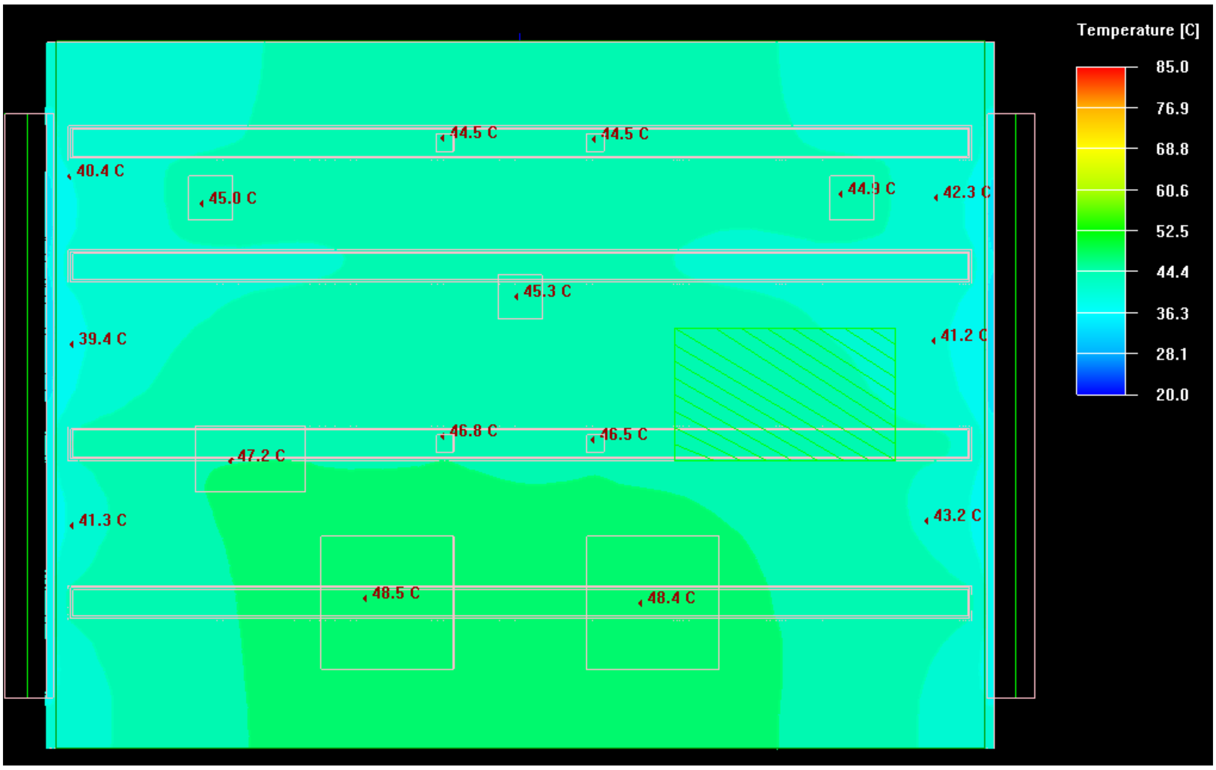


Figure 20 Temperatures on the cooling technology for the HS card

6.5.4.2 Extended testing by implementing copper coins on the HS circuit board

When analyzing the result from all the heat pipe simulations it showed that a too small temperature decrease had occurred, but especially on the HS card which consists of components with the highest power density. Because of that, a further investigation was made on that card.

As recently mentioned, it was a large temperature difference between the solder joint and cooling technology. What this means is that there is a lot of heat having issue getting through the PCB and TIM down to the cooling technology and this is due to its low thermal conductivity (see table 7), creating a bottleneck. This makes the heat pipe not working at its full potential because a heat pipe work more efficiently when the temperature differences between the evaporator and condenser section is high. The next step in this process was to find a solution of how to remove these bottlenecks which came to be a so called “copper coin”.

A copper coin is very simple explained, a thermal via in form of a small copper cylinder that implements in the PCB. They are often placed under the components with the highest power density, this increases the thermal conductivity through the plane and making it easier for the heat to travel to the cooling section. The conductivity increases from the PCB´s 8 W/m*K to that of copper 387,6 W/m*K.

After implementing copper coins under the components with the highest power density a huge difference could be seen. Firstly, the red areas are completely gone and the highest temperatures in these parts are now 53,8°C. The maximal temperature have now been moved and can now be found in the bigger component located in the top left of the PCB with a temperature of 58,8°C. This is a decrease of the max temperature with 28°C compared to the highest temperature prior to the changes of 86,8°C, see figure 19.

Going back to the smallest components and comparing the new gained temperatures with the ones from the 4,0 mm back plate (see appendix B, figure 3 and figure 12) the improvement would generate a difference of 53,8°C.

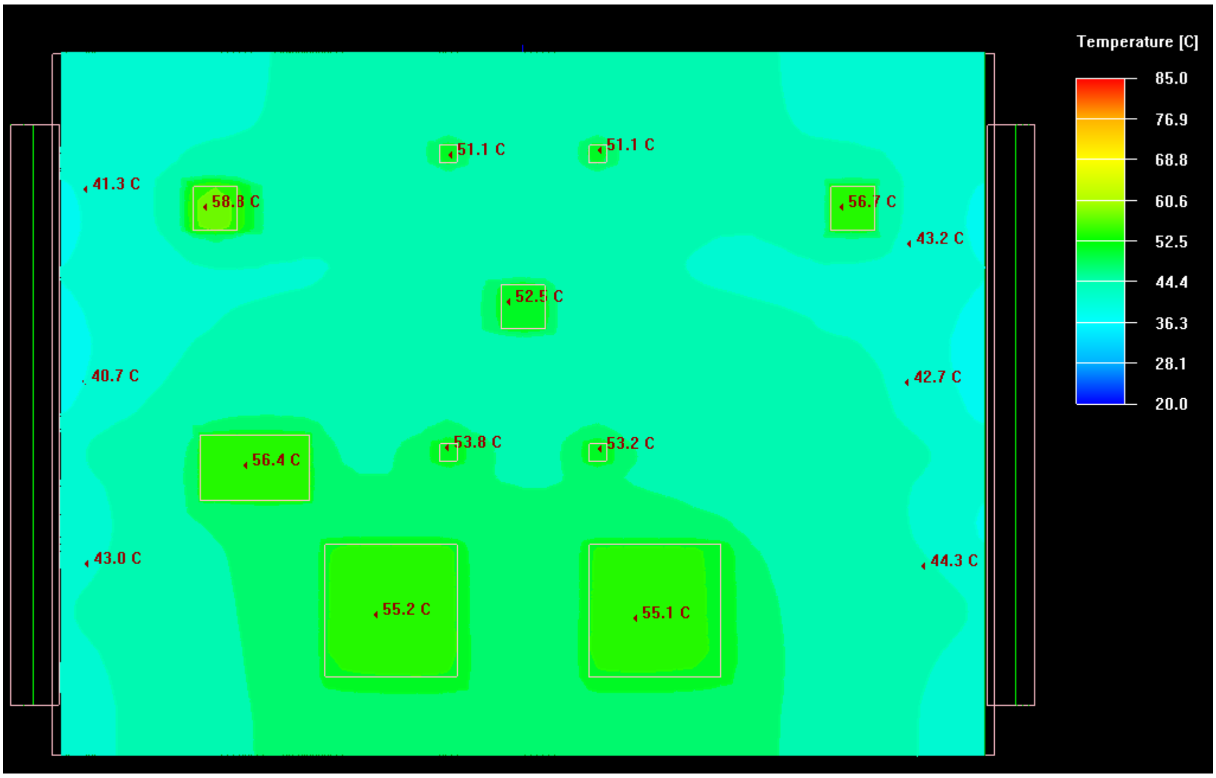


Figure 21 Temperature in the solder joint when using copper coins on the HS card

The temperature in the back plate became fairly unchanged compared to the pre changes (see figure 22). But the differences in temperature between the PCB and the back plate (figure 21 and 22) were now only 10,36°C which is a decrease of 29,6°C.

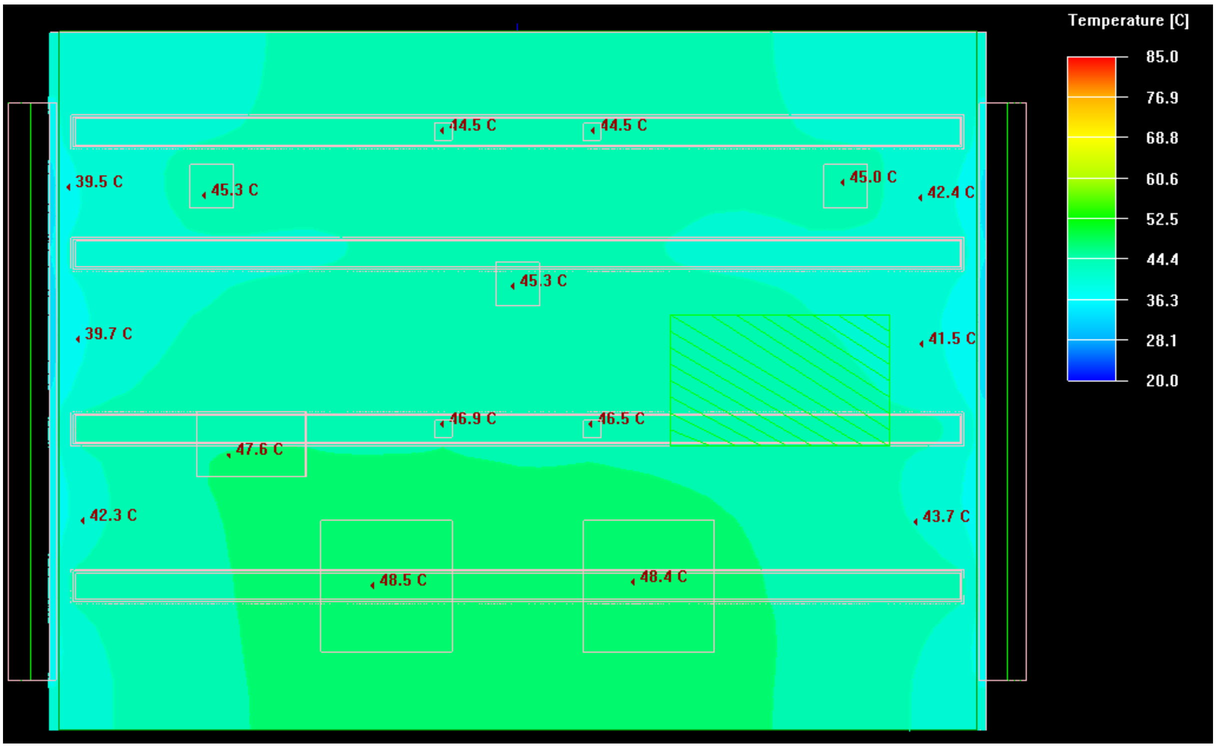


Figure 22 Temperature on the cooling technology for the HS card

6.5.5 k-Core

The k-Core was mainly created out of two layers, one encapsulating the other. The outer part was giving the properties of aluminum and the inner one was given the properties of APG. Aluminum thermal vias were lastly implemented inside of the APG under each component for the same reason as mentioned above about the "copper coins", to increase the thermal conductivity through the plane but this time, through the APG. See figure 23 for the construction of the simulation and table 7 for dimensions and thermal conductivity for each part.

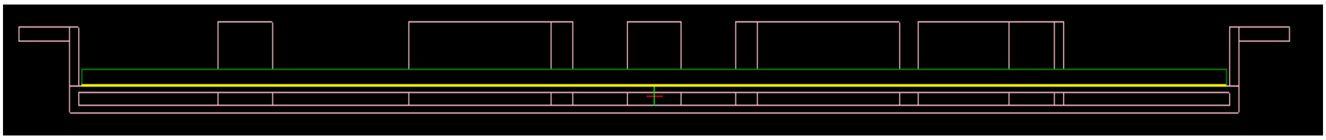


Figure 23 Construction of the k-Core and the thermal vias

6.5.5.1 TSO

The k-Core is very good at spreading heat and therefor works better on circuit boards having components with less power density and rather affecting a larger area. This makes it especially effective on the TSO card. Highest temperature can be found in the smaller components with a temperature of 74,9°C located in the edges of the PCB. This showcases the technology´s somewhat poor effectiveness against more power density units even though they are placed near the cooled sides. The k-Core has lowered the temperatures on the component with values ranging between 19 to 31°C throughout the PCB compared to the ones of the 4,0 mm back plate (figure 16). In addition, the large red area is now gone (see figure 24).

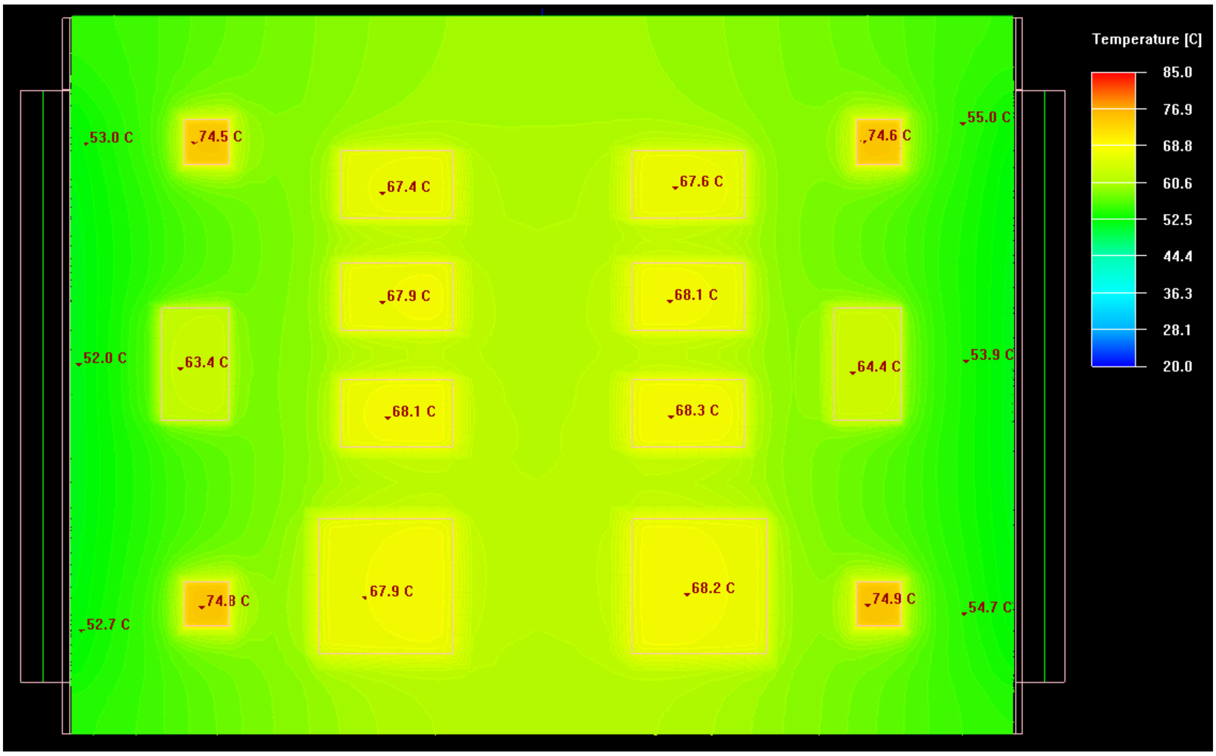


Figure 24 Temperature on the solder joint for k-Core TSO card

When looking specifically at the k-Core the red area is gone and the temperature difference over the whole area has decreased to 11,1°C compared to the 40 °C seen in figure 17. The temperature difference between the ones in the solder joint and the cooling plate was largest under the smallest components. This, once again, is due the lower thermal conductivity of the PCB and TIM.

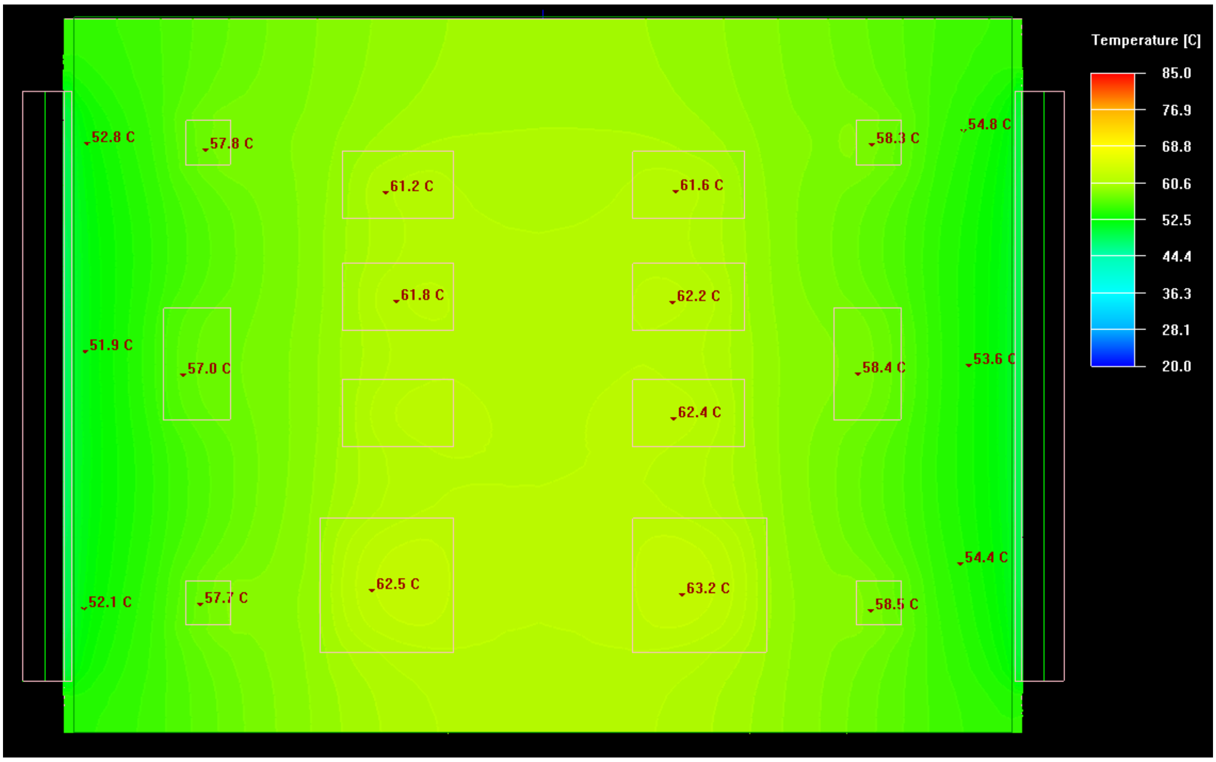


Figure 25 Temperature on the k-Core on the TSO card

6.5.6 Vapour chamber

The last technology that was simulated was the vapour chamber. The VC is basically the same as a flattened HP, just wider and therefor it is created in the same way, with three layers which has the same properties, see table 7.

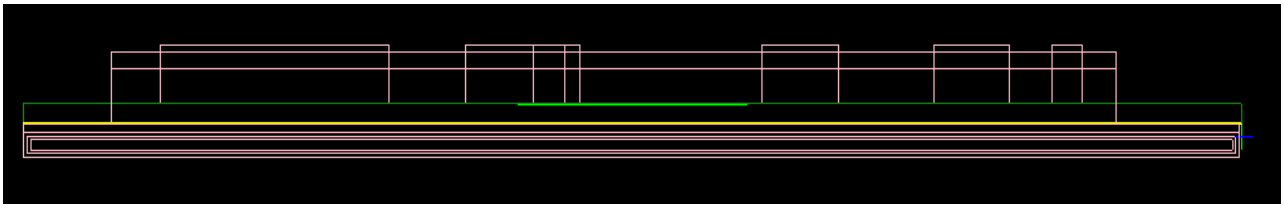


Figure 26 Structure of the VC

6.5.6.1 TC

A greenish colour can be seen between the components in figure 27, indicating a temperature around 55,0°C. Looking at the components, the heat that has been generated is for the most part good but sticking out are the two components once again having the highest power density and therefore reaching temperatures up to 74,8°C. The VC has lowered the temperatures in the middle section including the four tightly packed components with 48,2°C compared to the result for the 4.0 mm back plate.

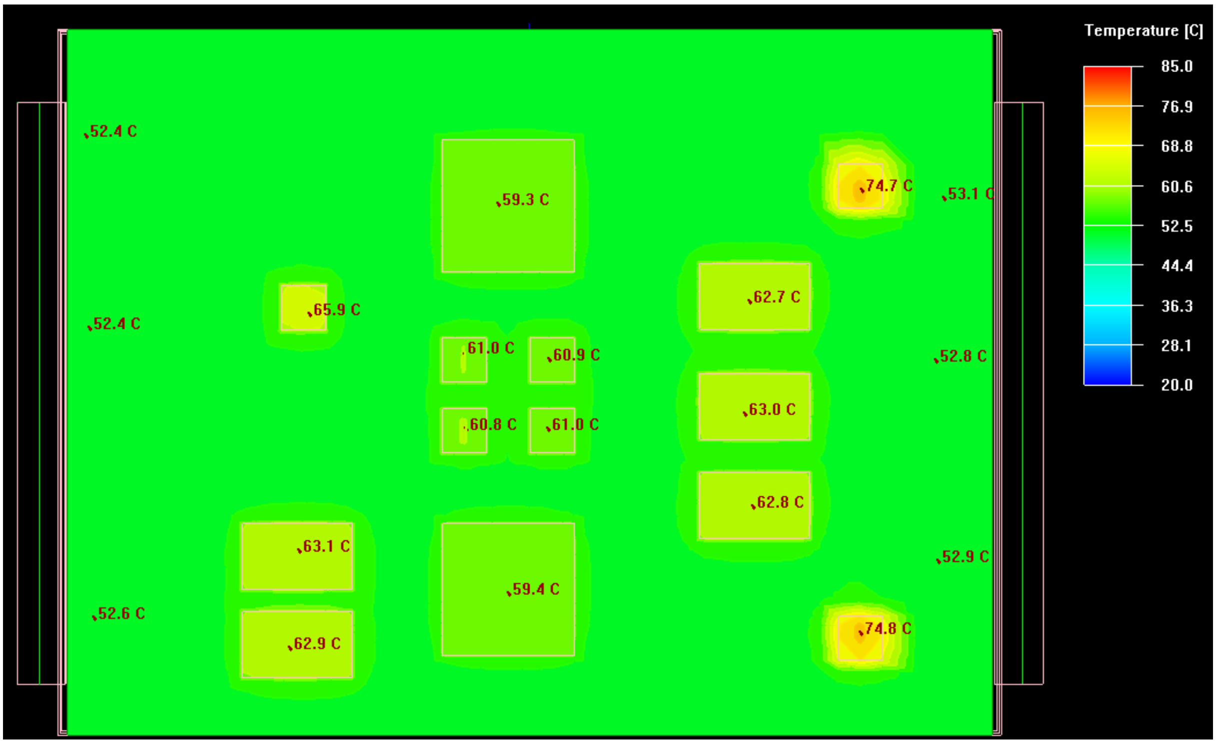


Figure 27 Temperatures in the solder joint for the TC

This final figure showcases a complete greenish area visualizing an almost total homogenous temperature throughout the vapour chamber. The ΔT of the VC is approximately 2°C compared to the 49,3°C of the 4,0 mm back plate.

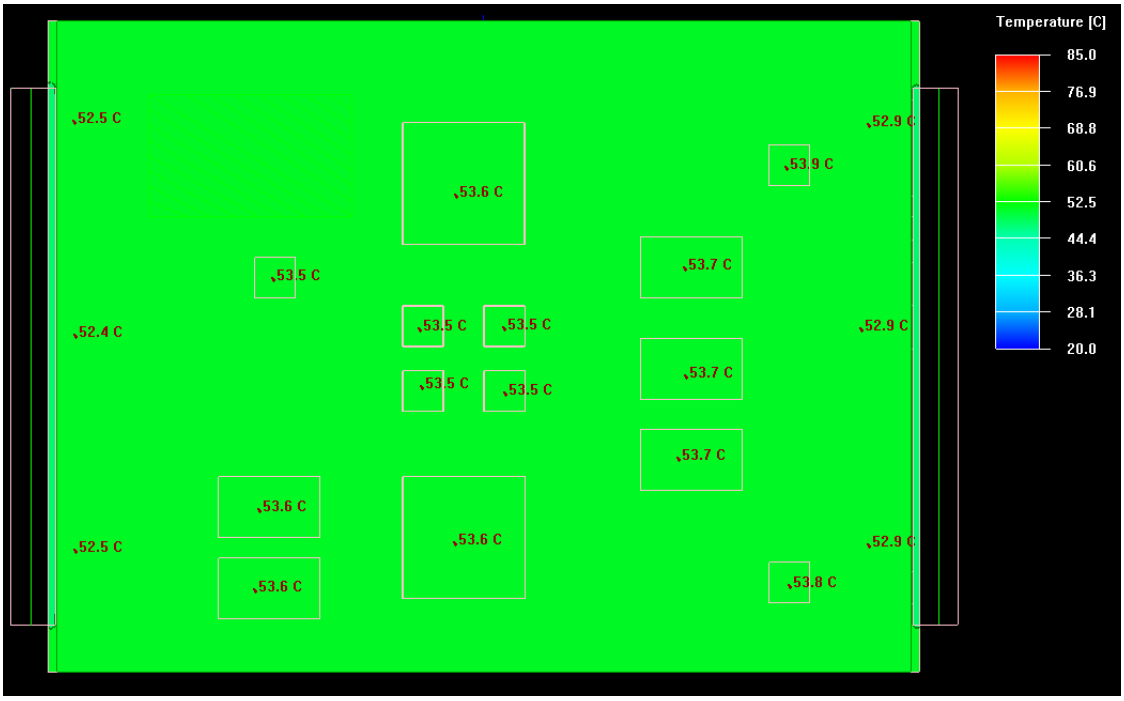


Figure 28 Temperature over the VC for the TC card

6.6 Temperature graphs

After the simulations were done the temperatures gathered were compiled and displayed in the following graphs. Two graphs have been created for each circuit board showing the temperature variation made by the technologies. Three lines can be seen which visualize the temperature change in three chosen components, where these components are placed can be found in appendix C figure 21, figure 22 and figure 23. Like in the simulations two different positions have been evaluated, the first one shows the temperature in the solder joint of the component, the second one the temperature on the back plate. The graphs are based on temperatures from the simulations which can be found in table 1, table 2 and table 3 in appendix D. The loop heat pipe and the cold plate system have not been included in these graphs.

6.6.1 Graphs for the solder joint

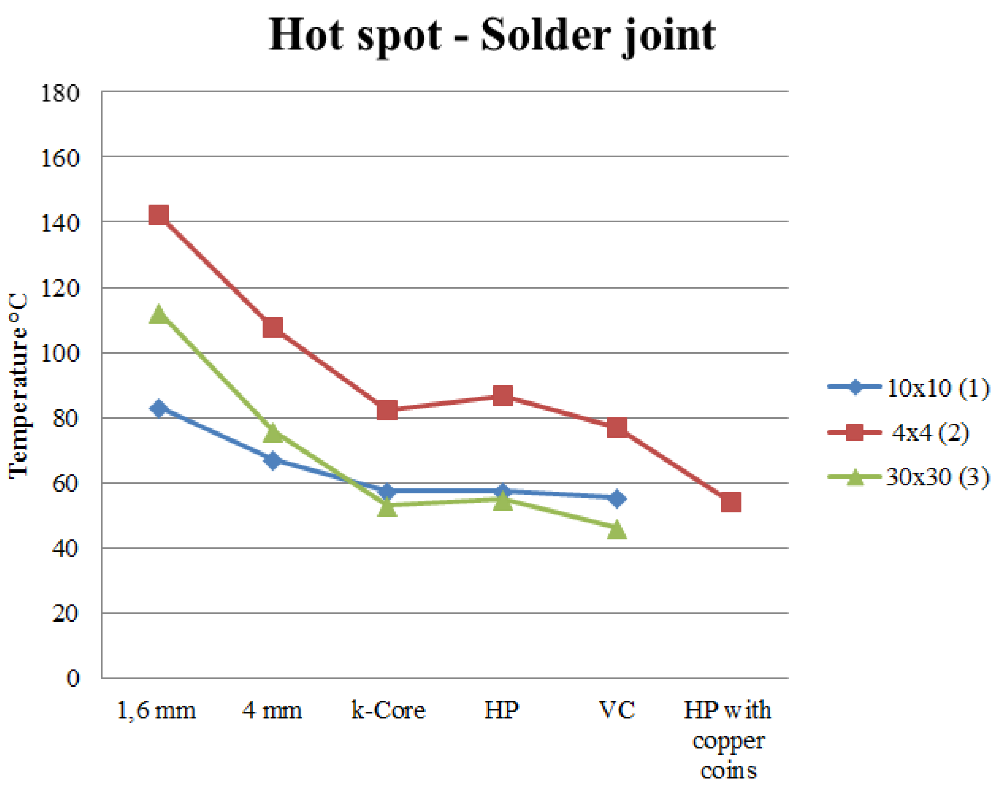


Figure 29 Graph over temperature in solder joint for components on the TSO circuit board

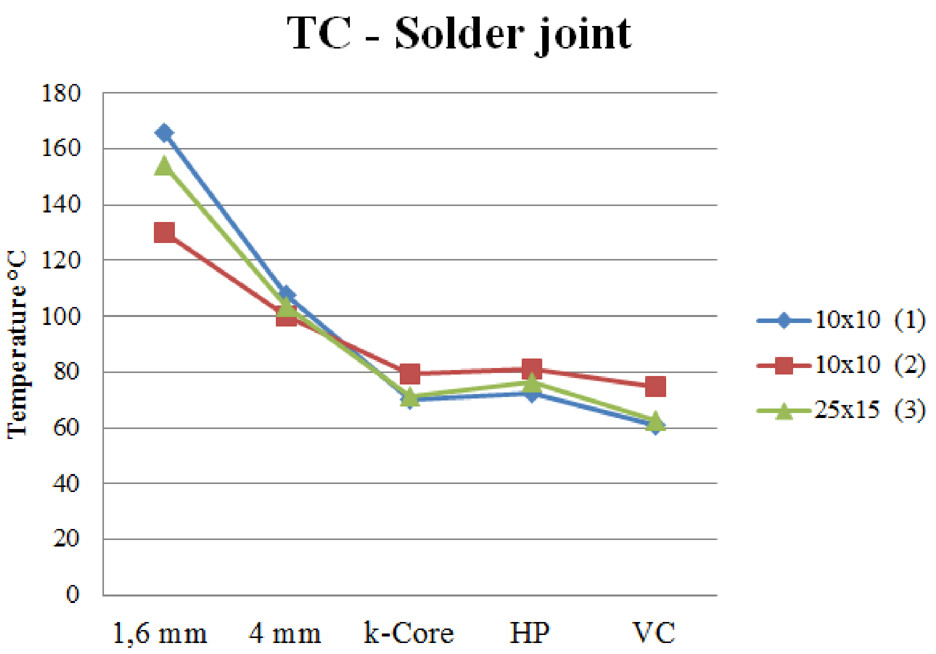


Figure 30 Graph over temperature in solder joint for components on the TC circuit board

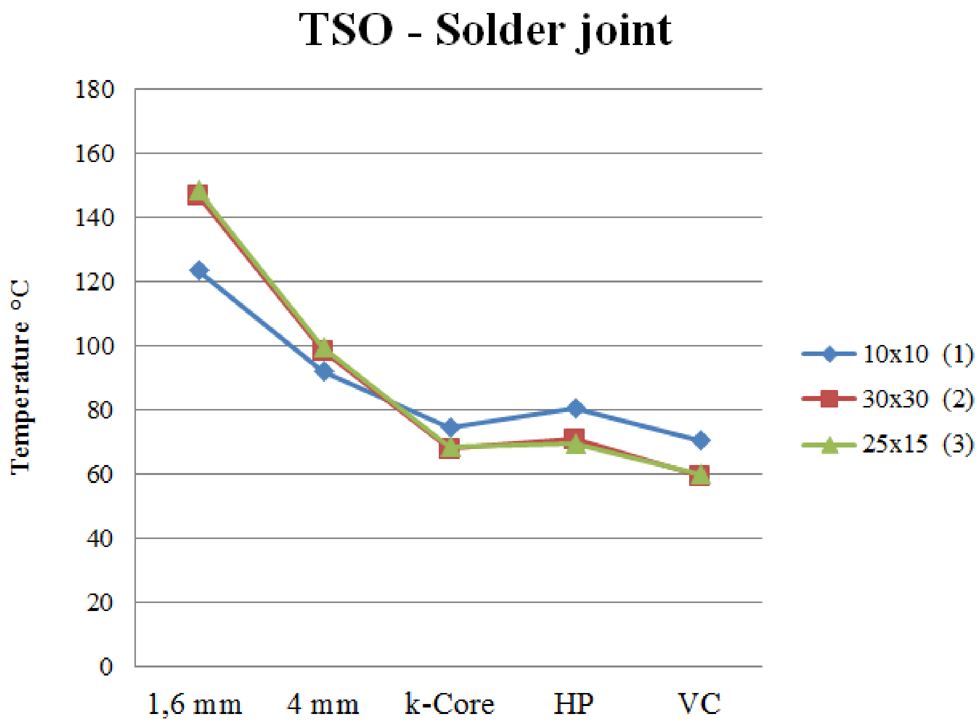


Figure 31 Graph over temperature in solder joint for components on the TSO circuit board

What can be seen in the figures above is the temperature in the solder joint for the hot spot, the combined and the temperature spread out circuit board. Throughout the three graphs the highest temperature can be found in the smallest components which are mainly because of the high power density generated and the PCB´s poor thermal conductivity. Larger components are therefore easier to manage. Another thing to take in account is that the components that had the lowest starting temperature are cooled the least and generally end up having a higher temperature after that the technology have been implemented. The reason why this happened is because that the cooling systems work more efficient when having a higher temperature input.

Interesting with these graphs is to see if the generated heat from the components exceeds the set requirement of 85°C. As can be seen in figure 29 the temperature for component (2) when cooled by a HP is over 85°C. This problem has been discussed in the simulation part and a copper coin solution was tested. The result of implementing copper coins can be seen in figure 29 which shows that the temperature in the risk components now are fairly similar to the ones of the larger components.

6.6.2 Graphs for the aluminum back plate

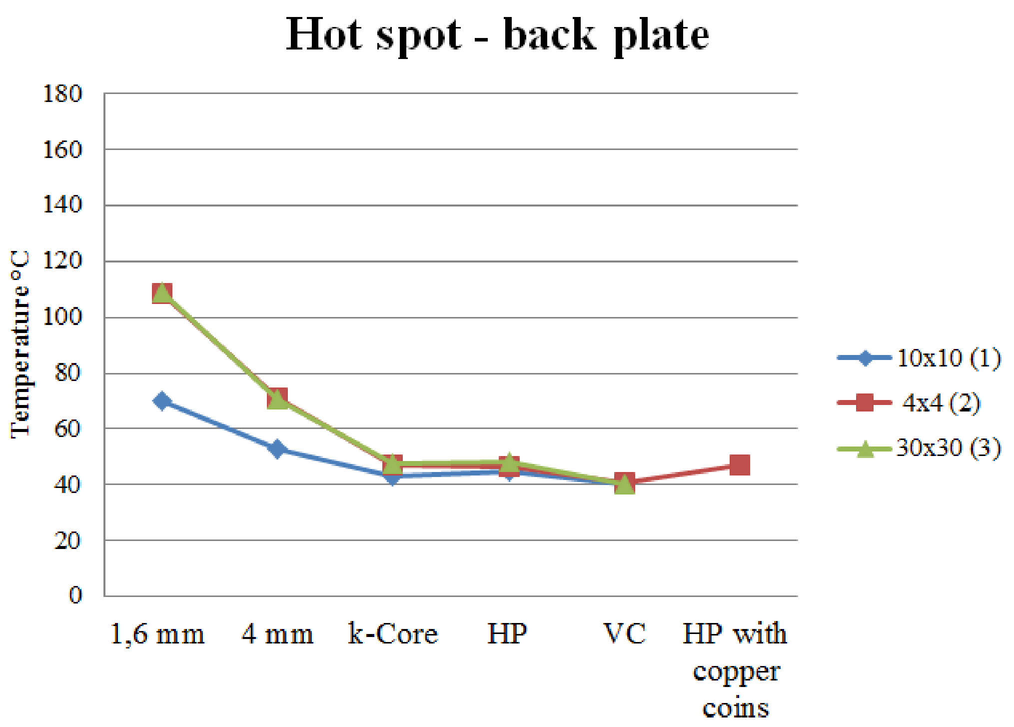


Figure 32 Graph over temperature in aluminum back plate for components on the HS circuit board

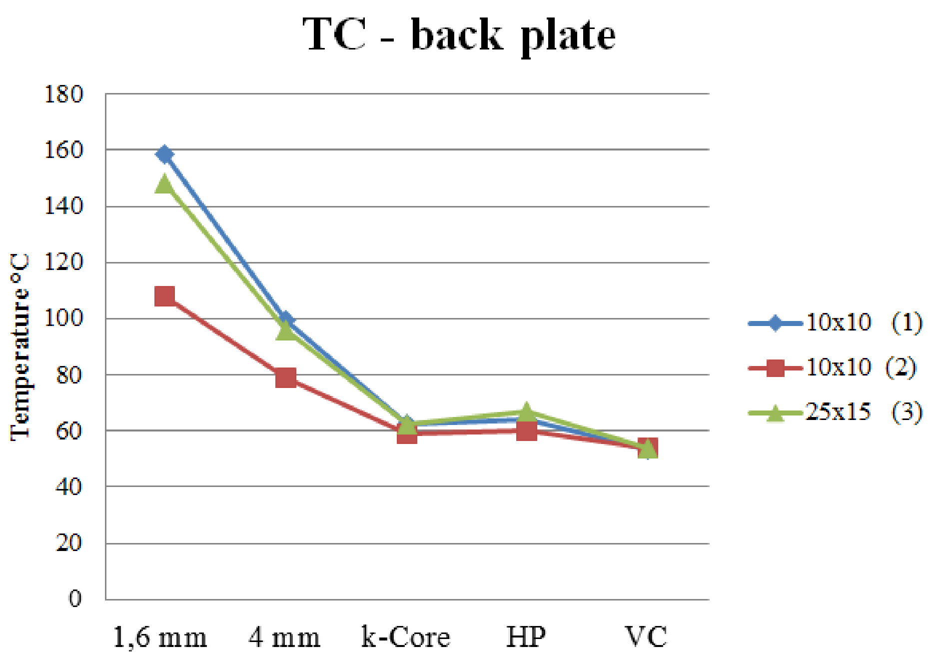


Figure 33 Graph over temperature in aluminum back plate for components on the TC circuit board

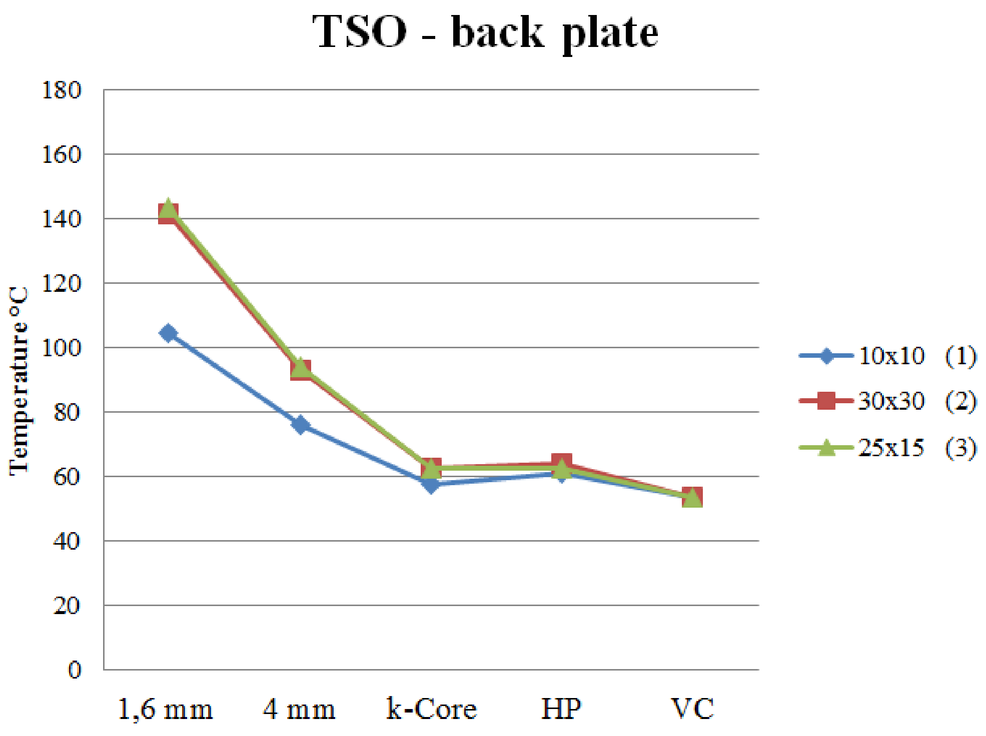


Figure 34 Graph over temperature in aluminum back plate for components on the TSO circuit board

For the temperature in the aluminum back plate a wanted temperature difference between the components should be as low as possible. What can be seen in the three graphs above is that when any of the technologies are implemented the temperature difference becomes lower. For example in the TSO graph the green and the red line seems to align for the technologies k-Core, HP and VC.

6.7 Economic estimation

After the simulations were completed the dimensions for the technologies had been decided and an economic estimation could be done. Due to the complexity of the LHP and the liquid cooling system, the dimensions could not be determined.

The prize for the reference 1,6 mm thick aluminum back plate was received by Mikael Schmid[7] engineer at Saab. The estimation was that it would cost around 75€ per plate, this can be compared to the later cost estimations for the technologies.

During the visit at Thermacore a power point of the price range for every technology was received. Figure 35 visualizes a number of specific technologies' thermal conductivity and price range. Due to the wide price range a specific price was impossible to point out. For example VC has a price range from 10 $ to almost 10000 $, therefore a detailed list of dimensions and the purchase volume was sent to Geoff Thompson Vice president at Thermacore.

The purchase volume that was sent out specified 500 generic houses, 6 plug-in units in every generic house, which is a total of 3000 plug-in units. The payment was over a period of 10 years.

6.7.1 Prices for the technologies

The cost estimation was received by an email from Mr. Thompson[8] where he explained his way of thinking and a price for the k-Core, vapour chamber and the heat pipe assembly was delivered.

Today the supply chain for the APG is limited, there is not many suppliers of APG in the world. Because of that the price for APG is high which is directly correlating to the price of the k-Core. Mr. Thompson estimated that with the given design one k-Core would cost around 1200€, though they anticipate that in the future the price will drop to below 1000€ due to a more competitive supplier market of APG.

For the Heat pipe design including the aluminum heat sink the anticipated price would be around 450€. The price for one heat pipe is much lower but because there are several flattened HP embedded in an aluminum plate the cost for the assembly becomes higher.

Currently Thermacore is manufacturing a vapour chamber with similar dimension to the one given to Mr. Thompson. The estimation therefore is more accurate and the suggested price is around 500€, this is an all copper vapour chamber. Due to a smaller volume the price therefore becomes higher.

Because of the complexity of the LHP and the liquid cooling system a cost estimation could not be done. The price range for a LHP system ranges from 5000 $ to 10000 $ depending on the size and design of the system (figure 35).

[7] Mikael Schmid Engineer	Saab	May 23 2016
[8] Geoff Thompson Vice President, Sales & Marketing Europe	Thermacore Euope	May 4 2016

For the liquid cooling system the price range is 4000 $ to 8000 $ and is also affected by the size and design of the system (see appendix E figure 24).

6.7.2 Index calculations

Due to the earlier weight estimations and simulations, indexes regarding price, weight and temperature decrease could be made. These values will be part of the later comparison work.

	Heat Pipe	Heat Pipe with copper coins	k-Core	Vapour Chamber
Type of card	temp decrease/prize	temp decrease/prize	temp decrease/prize	temp decrease/prize
HS	0,046	0,120	0,021	0,062
TC	0,078	-	0,031	0,093
TSO	0,067	-	0,026	0,079
Type of card	temp decrease/weight	temp decrease/weight	temp decrease/weight	temp decrease/weight
HS	0,040	0,105	0,077	0,052
TC	0,068	-	0,115	0,078
TSO	0,059	-	0,096	0,066

Table 8 index values for each technology working on the different circuit boards

Two different types of indexes have been made as can be seen in the table above. The first column shows the relation between the temperature decrease and the price while the second one displays the relation between the temperature decrease and the weight.

The temperature decrease was determined by looking at the highest temperature on a specific component for the 4,0 mm back plate solution and then subtract that value with the temperature of the same component generated by the technologies. The chosen component of each specific circuit board was located in the center of the PCB which can be found in appendix C, more specific is component (1) used in figure 21, component (2) in figure 22 and lastly component (3) in figure 23. The temperature decrease can be seen in appendix D, table 4 and table 5.

The price and weight for the HP, VC and KC can be found in 6.7.1 price for the technologies and 6.4 Weight estimation.

The temperature decrease/price was then calculated by dividing the temperature decrease with the price of the technology. Calculations can be found in appendix F.

An ideal value for this index would be as high as possible, because the optimal solution will have a high temperature decrease and low price.

The next index temp decrease/weight is calculated by dividing the temperature decrease with the weight of the technology. It is the same temperatures used in the first index, and like the earlier mentioned index an ideal value would be as high as possible.

What can be seen in the table 8 is that the VC gets the highest index value when price is the factor but k-Core gets a higher value when weight is the priority. Though, the HP assembly gets an overall high result throughout all the calculations.

What can also be seen is that index for the HP with copper coins on the HS card has been done. These index values are much higher than for the other technologies, which point out that by improving the thermal conductivity through the PCB the cooling solutions will achieve better results.

Because of the LHP and CP complexity no weight estimation or thermal simulations could be done and therefore no accurate indexes have been made.

This cost estimations and indexes will later be a part of the evaluation and comparison of the technologies.

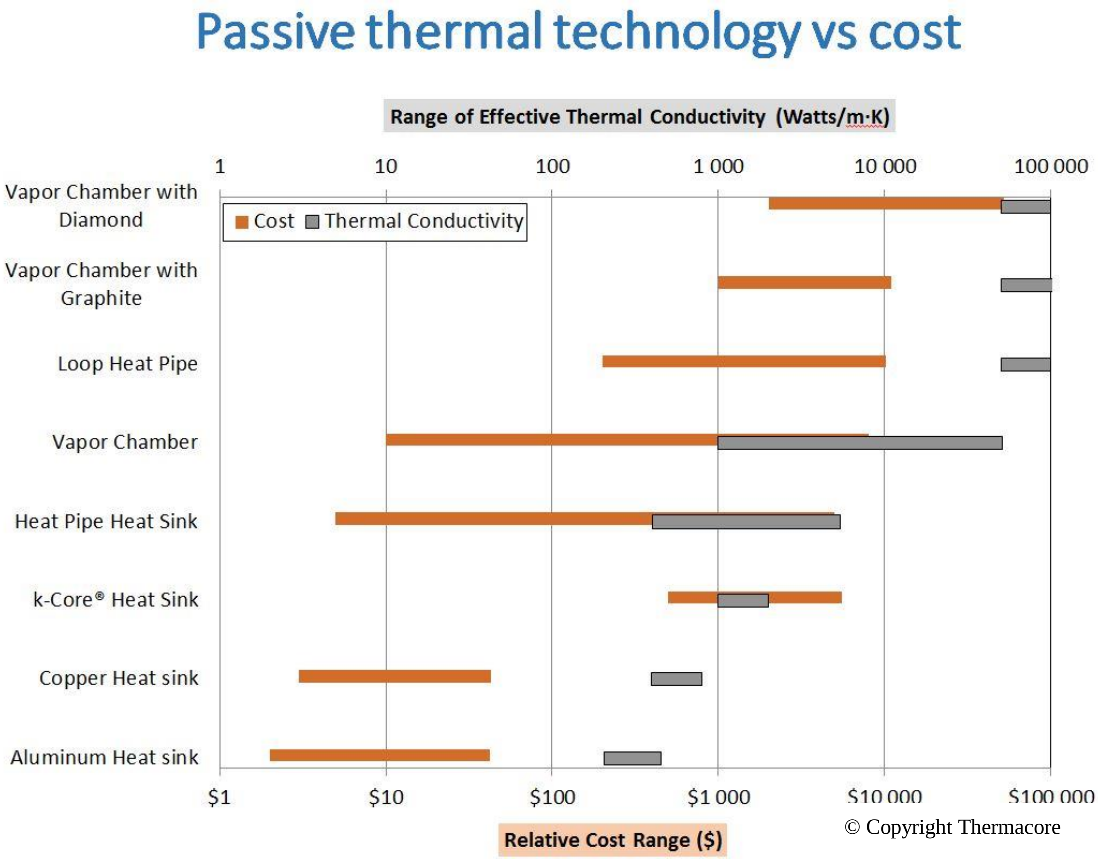


Figure 35 cost indication for passive thermal technologies

6.8 Cooling for the generic house

Most of the earlier analysis has been about how to cool the plug-in units but this chapter will focus on discussions about what options one might have regarding cooling improvements for the generic house. This information was gained and worked out mostly by discussions held at Thermacore together with their engineers.

6.8.1 Three ways of improvement

When the dialogue came to a close, the conclusion was that three possible steps of cooling improvements could be done.

First of them were minor adjustments on the already existing generic houses. These changes could be broken down even further to the following three. The first two steps focus on increasing the mass of cold air that goes through the housing. The first of them is being to increase the volume of air that is blown through the side walls of the generic house see the purple areas in figure 1. This is an external factor which demands more power for the system in whole but no changes on the housing are needed. The second adjustment that could be done was increasing the volume of which the air is blown through, enabling the possibility of forcing more air through the side plates. This gives a similar effect as the first one but instead of increased power needed, it requires some dimension changes on the housing itself. The final improvement change was to optimize the fins located on the inside of the side walls. By improving the fins a more turbulent flow of air will occur in the generic house, which enables higher capacity for heat transfer.

The second step to improve the cooling capability of the generic house was to implement one of the discussed technologies from Thermacore. The two main arguments for doing this are to create an isothermal environment and transferring more heat away from the generic house. Isothermal environment means that the temperature of the outlet air is the same as the temperature of the inlet air. This can be made by implementing a HP, k-Core or a VC. The LHP and the HP can transfer away heat from generic house and easing the cooling demand, still the heat has to be cooled by air but the limitation of only cooling to house by air in the side walls will go away.

The final step of improving the cooling performance of a generic house, when air or other passive technologies are not enough is to convert to liquid cooling. Liquid has a much better heat transfer capability than air which enables it to cool very high powered systems. Though, this requires a lot of adjustments to not only the generic house but the system in whole and the risk of leakage will always be a factor.

These three steps will all try to help the generic house to handle the heat generated in the plug-in units. Later on a discussion of the possibility to implement any of the technologies on the generic house will be done.

7. Evaluation of the cooling technologies

When the product analysis had been completed and all the necessary information gathered the next step was to evaluate the technologies. Firstly a pros and cons comparison was made to easily showcase some of the features each product has. This was followed up by an evaluation consisting of three steps. The first one was to see how well the cooling tech fulfilled the factors found in the requirement and request matrix. The second part evaluated the compatibility each technology has with the different application areas. Finally the third part, which bases from the two earlier steps by combining the application areas and factors and points on which product the technologies are most suited for.

7.1 Pros and cons

To easier understand the upcoming evaluation part a simplified summary have been listed below displaying some elements that stands out for each specific technology.

7.1.1 Heat Pipe

+ Totally passive
+ High thermal conductivity in one direction
+ Cheap
+ Lightweight
+ Flexible
+ A reliably and long lasting solution
+ Maintenance free due to no moving parts
+ Can operate in any orientation
− Affected by gravity
− Risk of freezing and dry out

7.1.2 k-Core

+ High thermal conductivity in the plane
+ Unaffected by gravity and surrounding temperature
+ Lesser weight compared to a pure Al-plate
+ Maintenance free due to no moving parts
+ Flight approval
+ Neglects all the negative aspects of containing a working fluid due to totally solid
− High cost
− Poor thermal conductivity through the plane

7.1.3 Vapour Chamber

+ High total power capacity
+ Thermal conductivity in all three directions (x-,y-,z-orientation)
+ A reliably and long lasting solution
− Affected by gravity
− Risk of freezing and dry out

7.1.3 Loop Heat Pipe

- \+ Very high heat load capacity
- \+ A flexible, long heat transport up to 25 m
- \+ Vibration and shock resistance up to 34 g
- \+ Unaffected by orientation and gravity up to 9 g
- – Difficult to make
- – High cost solution

7.1.4 Cold Plate

- \+ Highest total power capacity
- \+ Robust construction
- \+ Vibration and shock resistance up to 40 g
- – In need of external parts, e.g. a pump
- – Leakage

7.2 Evaluation matrix

First off, an evaluation matrix was created where each technology were given a value from one to five where five is the highest possible depending on how well it answered towards the factors from the requirement and request matrix. Worth noticing is that not all of the cells have got a value and some are more proven than others and this is due to not having the opportunity for further testing on a prototype. Though, they are good indications based on the research done. This chapter will not bring up every factor specified in the matrix but instead take out some a little more special.

Evaluation matrix					
Factors	Technologies				
	HP	k-Core	VC	CP	LHP
Term	V	V	V	V	V
Temperature decrease	3	4	5	N/A	N/A
max Heat load for tech	2	3	4	5	5
Cooling capacity	4	3	4	5	5
Weight	3	4	2	1	4
Reliability	5	5	5	3	5
Life span	5	5	5	3	5
Flexibility	4	3	3	1	4
allowed maximum volume	Yes	Yes	Yes	N/A	N/A
allowed maximum area	Yes	Yes	Yes	N/A	N/A
max Temperature in the soldering joints	4	5	5	N/A	N/A
Vibration resistance	4	5	4	4	5
Shock resistance	4	4	4	4	5
ΔTsurrounding	4	5	4	4	4
Pressure alternation	5	5	4	3	4
Corrosion resistance	5	5	5	5	5
Humidity	5	5	5	5	5
Frost resistance	3	5	3	4	5
Dryout	3	5	3	5	4
Effect by gravitation (G-force)	1	5	1	4	5
Attitude	5	5	5	5	5
Maintenance	4	4	4	2	4
Generically	2	4	4	1	1
Total cost	5	3	5	2	1
Index: temperature decrease/prize	4	3	5	N/A	N/A
Index: temperature decrease/weight	4	5	4	N/A	N/A

Table 9 Evaluation matrix factors/ technologies grading from 1 to 5

7.2.1 Temperature decrease

When comparing the temperature decrease the VC was the best option while the heat pipe was the weakest of them all. The temperature decrease can be seen in the simulation chapter 6.5.

7.2.2 Weight

The technologies with the lowest weight are the HP assembly, the k-Core and the LHP. The heat pipes alone make a very light application though, due to the need of an embedding Al-plate the whole assembly gets a bit heavier. The k-Core is by nature a lighter solution compared to a pure Al-plate and this because the lesser density of the APG. The LHP however is much harder to evaluate because its diversity. It can be made in many different shapes and sizes and the weight can thereby change.

As earlier mentioned indexes for the temperature decrease divided by weight was made. The indexes showed that when weight is the main factor the k-Core is the best solution as can be seen in the matrix were it was given a value of five. The HP and VC received the same value in the matrix, these index numbers are quite similar mainly because the HP is the lightest but the VC is better at decreasing the temperature the factors are canceling out each other.

7.2.3 Vibration and Shock resistance

When comparing the vibration and shock resistance of each technology the matrix shows an overall high result. But factors like these are typical ones that needs to be tested on prototypes to get accurate values. However the high results are based on following, the embeddedness of the HPs which covers them and therefore makes a resistant assembly. The same can be said about the k-Core with its strong aluminum casing protecting the somewhat weaker APG and because it is a complete solid. The k-Core is also proven by Thermacore to be so called “flight approval” taking air applications into account. The VC is tightly screwed together with the back plate and contains inside columns which strengthen the construction. The Cold plate is tested for up to 40 g but because it is in need of an external pump, testing on the complete system must be done. Lastly the LHP which is vibration and shock tested to withstand values up to 34 g.

7.2.4 Temperature

All the technologies can properly operate in a temperature interval ranging from -40°C to 85°C and due to that the k-Core is unaffected by the ambient temperature it was given a score of five. When at the same time the HP, VC, CP and LHP are all in need of a suitable working fluid and therefore got a lower value.

7.2.5 Freezing and dry out

Talking about the frost and dry out resistance the k-core is once again on the top and this is due to its complete solidness. The HP, VC and LHP can all manage to withstand both freeze and thaw which directly correlates to the chosen WF and the wick structure. However if they freezes the technologies will stop working and will stay disabled until heat reenters the system.

Regarding dry out it is important that the HP and VC have been given a correct amount of WF for a specific application so it does not happened because, the increased heat if a dry out was to occur could possibly damage the wick structure inside. The CP system includes an active pump that will circulate the fluid and the LHP system includes reservoirs of working fluid to constantly saturate the wick structure and therefore both products neglects the risk of dry outs.

7.2.6 Effect by gravitation

Once again the k-Core gets the highest value together with the LHP. The k-core is unaffected by gravity because its solidness and the LHP is tested to operate under conditions of 9 g. The CP will probably be somewhat effected but with the power from the pump still able to work. The VC and the HP will both fail when affected by negative g-force. A simple calculation was made at Thermacore to show the impact of g-force on heat pipe performance with similar structures.

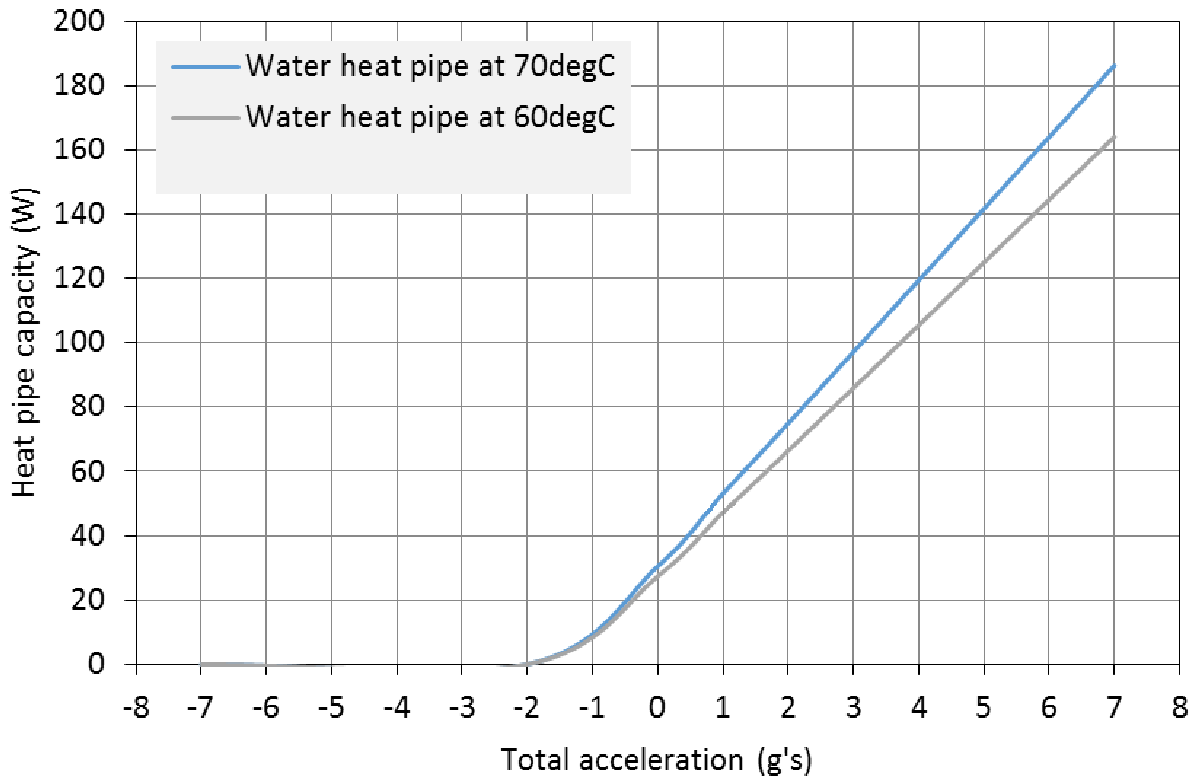


Figure 36 Impact of g-force on heat pipe performance

The result shows that a heat pipe rapidly loses its efficiency operating against the g-force but at the same time increases the capacity when working with it. However, the dramatic changes make the HP and VC not suitable for products affected by high negative g-forces.

7.2.6 Cost

The cheapest one is the HP assembly closely followed up by the VC and then the k-core. Hence all three believes to be more suitable on a plug-in unit level compared to the remaining two which instead seems better applicable on a whole system like combining several generic houses.

For the price index the VC gets the highest value in the matrix. Mainly due to that the VC has the highest temperature decrease but also because of that the cost difference between the HP and VC is small. The k-Core received the lowest value because it is a much more expensive technology compared to the other two.

7.3 Application area

The next step was to evaluate how suitable the technologies were for the different applications areas. This table below visualizes with help of a colour scheme how applicable the technologies are on different areas. Green colour indicates that the technology is suitable for that area. Red colour indicates that the technology is not suitable. Yellow indicates a potential solution, there are both possibilities but also limitations for that area. Important to understand that in this particular evaluation it has not taken into consideration if the technology is placed on the plug-in unit or the generic house.

This table is based on the earlier mentioned evaluation matrix and information about the different application areas found in chapter 6.1. As mentioned before some requirements and requests are more important for a specific application area. If the technology then cannot meet that requirement then it is not suitable. How well the technology accomplish the listed requirement and request can be seen earlier in the evaluation matrix table 9. The technologies will all fulfill the cooling need and therefore the suitability will only be affected by how well they accomplish the listed requirement and requests.

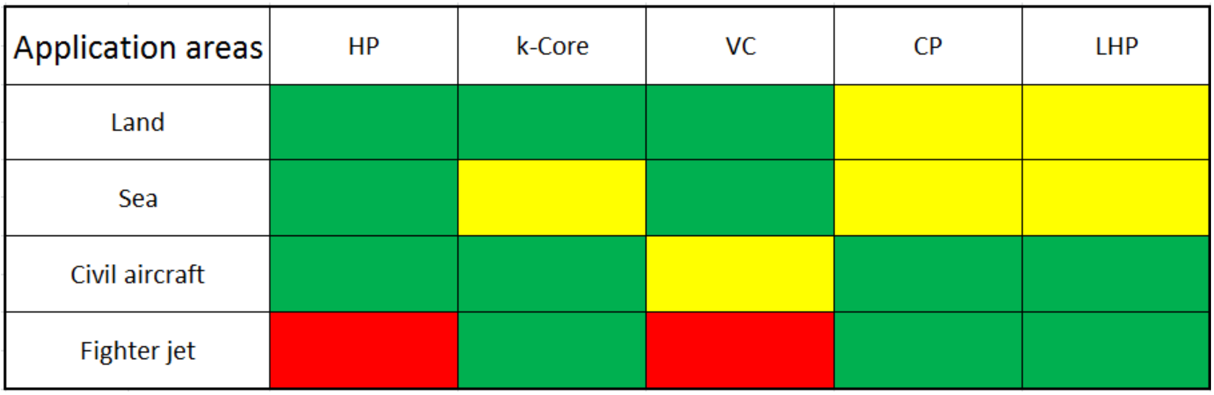


Figure 37 is displaying the suitability for the technologies to be used in the specific application areas

7.3.1 Heat pipe

As can be seen above the heat pipe is not applicable for a fighter jet, this is mainly because of how it is affected by g-force. For the other areas the heat pipe is a good option, even for the civil aircraft where it already being used today. The same can be said for land and sea where the heat pipe will fulfill and meet the requirement and requests set for those products. For example a heat pipe assembly is a low cost solution which is desirable for sea applications and can today be found for cooling radar electronics. (Thermacore, 2016)

7.3.2 K-Core

The k-Core is a suitable solution for most of the application areas but with a potential setback for naval units. This is because the KC is a high cost product and therefore not designed for the low cost driven sea market. On the other hand, for the two flight applications the k-Core has many favorable features, for example it is a flight approved technology and can today be found in different flight applications such as the F-35, F-22 and F-16 (Thermacore, 2016).

7.3.3 Vapour chamber

As earlier mentioned the vapour chamber is similar to a heat pipe, this can also be seen above that the HP and VC are almost applicable for the same areas. The VC is affected by g-forces in the same way as a HP and therefore not applicable for the fighter jets. The only difference is for the civil aircraft application. Were weight is the main factor in concern. The flight applications are sensitive of weight increase and therefore the VC got a “yellow” colour for that area.

7.3.4 Cold plate

The cold plate liquid system is a more suitable solution for the two flight applications. Its complexity will be negligible for these applications, due to that they are more of cost insensitive markets where the cost and the need for a redesign are more accepted. For both these areas weight is an important factor. A liquid system can be made in different sizes and that will affect the weight of the system. For land and sea the CP is not a very suitable solution mainly because of its price, complexity and needed system redesign. As can be seen in the evaluation matrix the CP receives low values for these factors. But if the other technologies cannot manage the thermal demand the CP is perhaps the only remaining solution.

7.3.5 Loop heat pipe

The suitability for the loop heat pipe is similar to the cold plate solution. The loop heat pipe is an expensive, lightweight and complex technology which therefore is more suitable for the flight applications. Today it is mostly used for space projects and fighter jets, for example in the F-16 (Thermacore, 2016), therefore it gets a “green” colour in the table above for the fighter jet. It is unaffected by g-forces and resistant to high vibrations and shocks. Due to its flexibility it can be integrated in limited areas which are a desirable capacity for the fighter jet application. For the land and sea products the LHP might not seem too optimal due to the similar reasons for those regarding the CP including price and the need of redesign. Neither is the LHP commercially used in these areas today. Though, if the total generated power is high enough, the LHP might be the best choice.

7.4 Product implementation

This last step is a compilation of the two earlier ones and show how well the technologies would fit on to the plug-in units and the generic house. The result can be seen in the matrix below. First, let us take a deeper look at the possibilities of implement them on a plug-in unit.

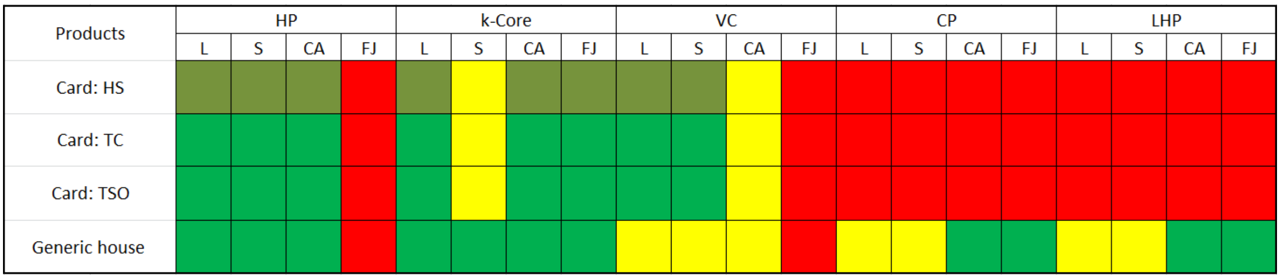


Figure 38. Result matrix that shows the suitibility for the technologies to be implemented on the different products with regards to the application areas land, sea, civil aircrafts and fighter jets.

7.4.1 Plug-in unit

For clarification, it is the upper three rows that are in focus. There are primarily two larger areas to be seen, a green one to the left and a red one to the right. The decision is made mainly based on four factors including weight, price, total power and the generically aspect.

The reddish area is the result of costly and complex cooling solutions that are not suited for the small amount of total power each circuit board dissipates. Both the CP and the LHP have the possibility of transporting many thousands of watts and would therefore over compensate the needed work done many times over and when these solutions are the most expansive ones, other technologies would have a better fit. Regarding the generic factor and especially the LHP with both its high cost and complexity makes it less applicable for products made in small sizes and high numbers and instead are better suited for fewer but rather larger systems.

The greenish area includes the HP, k-Core and the VC. These technologies are on a smaller scale making them easier to be implemented on the PCB but also to be generically made which means that a single solution can be used on several circuit boards. Compared to the earlier mentioned CP and LHP these three have lower price tags which likewise suits products made in large numbers.

A darker green colour can be seen for the HS card which indicates a somewhat deviated result. The simulations showed the bottleneck created by the PCB which made the technologies to not fully work at their maximum potential and a worse result was given.

7.4.2 Generic house

For the generic house all of the evaluated technologies can be implemented and will improve the cooling capacity for the house. But as stated earlier, the HP and VC cannot work in the fighter jet environment. Every technology will enhance the cooling performance in different ways.

The k-Core and the VC are heat spreaders and when integrated on the generic house they will spread the heat and improve to a more isothermal environment, they will enhance the ΔT. They cannot transfer away the heat from the house but they will improve the possibility for cooling. The suitability for the VC became “yellow” that is mostly because of the uncertainties of how to implement it on a generic house.

When integrated on the generic house the HP have the ability to both transfer heat and enhance to a more isothermal environment. If designed and placed it will have the possibility to transfer heat from the generic house to another cooling option, easing the cooling demand on the generic house. Because it is a more lightweight and cheaper solution it is perfectly appropriate cooling option.

The CP and the LHP are suitable cooling solutions for the generic house, most due to their ability to dissipate high heat loads. Preferably should they be integrated in such a way that they are cooling several generic houses in the same cooling system. Both of the cooling technologies transfer heat away from the generic house like the HP easing the cooling demand. Both of the technologies are complex and expensive but when integrated to cool several houses the cost and the effect of redesigning the construction will be less affected. Because of the price and complexity the both technologies receives yellow for the land and sea applications areas, but if the cooling demand is high enough they are perfectly suitable cooling options.

8. Conclusion

This work has clearly shown that solving the thermal problems early in a product´s development process is essential, not only making sure it achieves today's demands but also focusing on the future to come. It is therefore important to understand that heat is a constraint that cannot be left unsolved which otherwise could break the whole system.

By improving the cooling capabilities of the design standardization, making it possible to add more advanced technologies to it, enhancing its properties and increasing its overall performance.

First up recommendations will be given for which cooling technology that is most suited on the plug-in units in regards to the application areas, following up by similar advice for the generic house.

8.1 Technologies on plug-in unit level

For both land and sea units we think that heat pipes in an effective way will do the job. They are price worthy, have a long life span, maintenance free, flexible and do not demand any large adjustments to the systems. The HP´s main drawbacks are its effect of g-forces, risk for dry out and freezing. The first one is negligible due to operating on land or sea while the last two spoken will be avoided due to adding the right amount of chosen working fluid.

The HP is a long lasting solution but looking even further in the future the expected heat load might finally overcome the heat pipe capabilities. In this case, the vapour chamber will be its replacer. The VC has the best thermal properties out of the simulated technologies (HP, KC and VC) but comes with a somewhat higher cost and increased weight.

Looking at the air units and foremost the fighter jets the k-Core is the obvious answer. It offers a lower weight construction compared to the Al- back plate and achieves the stated environmental aspects seen in the requirement and request matrix, primarily the g-force factor. A HP solution for the civil aircraft would also be possible due to its lower request of the amount of g-force the assembly needs to manage. Heat pipes operating in civil aircraft can already be found today.

8.2 Technologies on generic house level

For the generic house we see two main solutions involving either an HP assembly or a constellation of a LHP. The HP assembly primarily focusing on cooling one single house by transporting out the heat followed up by a heat sink. This design would out of the pros and cons named above be better suited on ground, sea or civil aircraft rather than on a fighter jet.

The LHP in other hand can also do the job and cool a single generic house, but the opportunity of implementing a LHP system with its high total heat load capacity would enable it to possible cool several amounts of houses at the same time. Doing that would even out its expenses and if needed justify a redesign of today's system, making it a high contender for the work.

It is a lightweight, long heat transporting system that can operate under the toughest of circumstances including high g-forces, vibrations and shocks. It would therefore be able to operate in any application area given but maybe foremost in the fighter jets where it already can be found today.

8.3 Power density

During our work we found out that one of the bigger problems to solve was the high power densities some of components generated, which together with the interaction of the PCB´s and the TIM´s poor thermal conductivity and thicknesses created major hot spots. Because of this, the cooling technologies could not receive the heat needed to operate at their fully potentials. Interesting to notice is that though the thickness of the PCB and TIM was only 2,15 mm it still had such a large impact.

One solution to this problem was the implementation of copper coins as could be seen in chapter 6.5.4.2. A negative aspect though is the increased weight to the circuit board which in our case was small, but if larger and more components would need them, the total weight gained could be too high.

Improvements of the PCB and TIM need to be done and further development of its conductivities. Referring to the introduction of this chapter telling about early solving thermal problems, it is once again clear that finding the heat sources and follow its path, removing all the potential bottlenecks. When doing so an optimized thermal solution can be established.

With further simulations and testing, finding the most optimized construction for these cooling technologies and then implements them on either a plug-in unit or the generic house, we are most certain that they will manage the thermal demands waiting in the future, (Nilsson, 2012).

9. Further work

Below we give suggestions of future studies. These ideas have been generated during this thesis work but due to different factors they have not been able to be done, but we think that theses aspects should be taken into account so that the implementation can be realized.

Prototype testing: Many of the answers in the requirement and request matrix are indication, but for more accurate answers testing on real prototypes have to be made. For example this could include vibration and shock testing. It would also be interesting to do thermal prototype testing to verify if the result given in the simulations would be the same in reality.

Simulations on the liquid cold plate system and the loop heat pipes: To evaluate the two systems further, simulations should be made to receive numbers about the heat transferring properties.

Evaluating thermal improvements on the PCB: The PCB´s poor thermal conductivity through the plane prevents the heat from effectively being transferred. Therefor further evaluation on the possibility to improve the thermal conductivity for the PCB, investigate what possibilities exist on the market today and if they would work on Saab products. For example as stated in the simulations part the possibility of implementing copper coins.

Optimization of the cooling technologies: By creating and testing more concepts for each cooling technology we think that one can find the most optimized solution. For example how many HP should one use in the heat sink and what thickness should the back plate have for an improved cooling solution?

Apply cooling technologies on real Saab products: The simulations have been done on our own made boards, but to be able to apply technologies on real Saab products simulations and testing on actual used circuit board must be made. We can then find the most suitable solutions and evaluate if there are any differences depending which technology being used.

Evaluate an optimized cooling solution for the generic house: More focus have been put on cooling the plug-in units rather than the generic house and therefore further studies on how the cooling can be improved for the generic house should be done. This could for example involve generating new concepts for the generic house using the evaluated technologies, simulations and prototype testing.

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Appendix

Appendix A- Own made circuit board

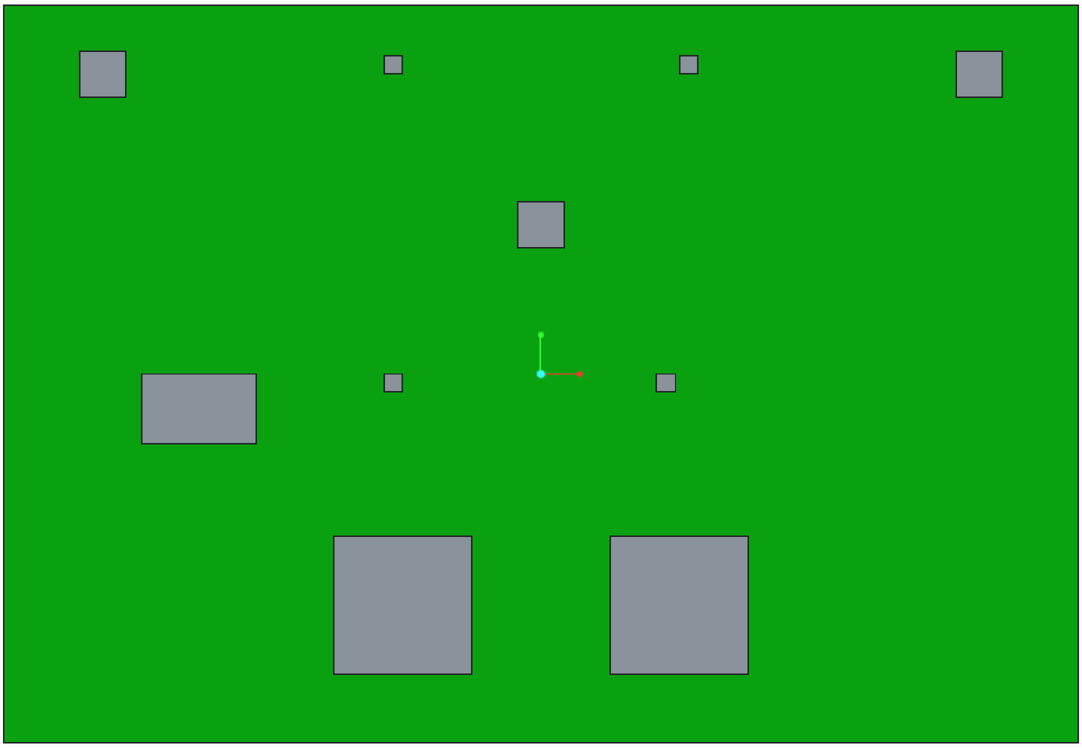

Figure 1 Placement of components for the HS circuit board.

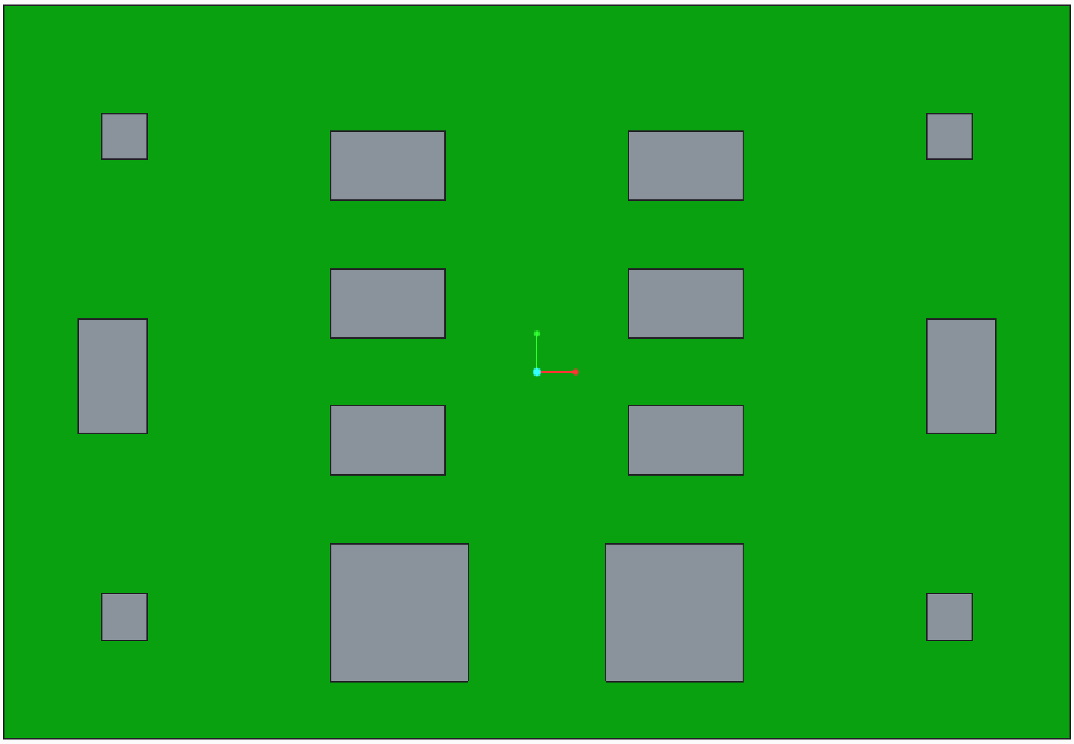

Figure 2 Placement of components for the TSO circuit board.

Appendix B- Simulations

Figures from the simulation for 1.6 mm thick Al-back plate

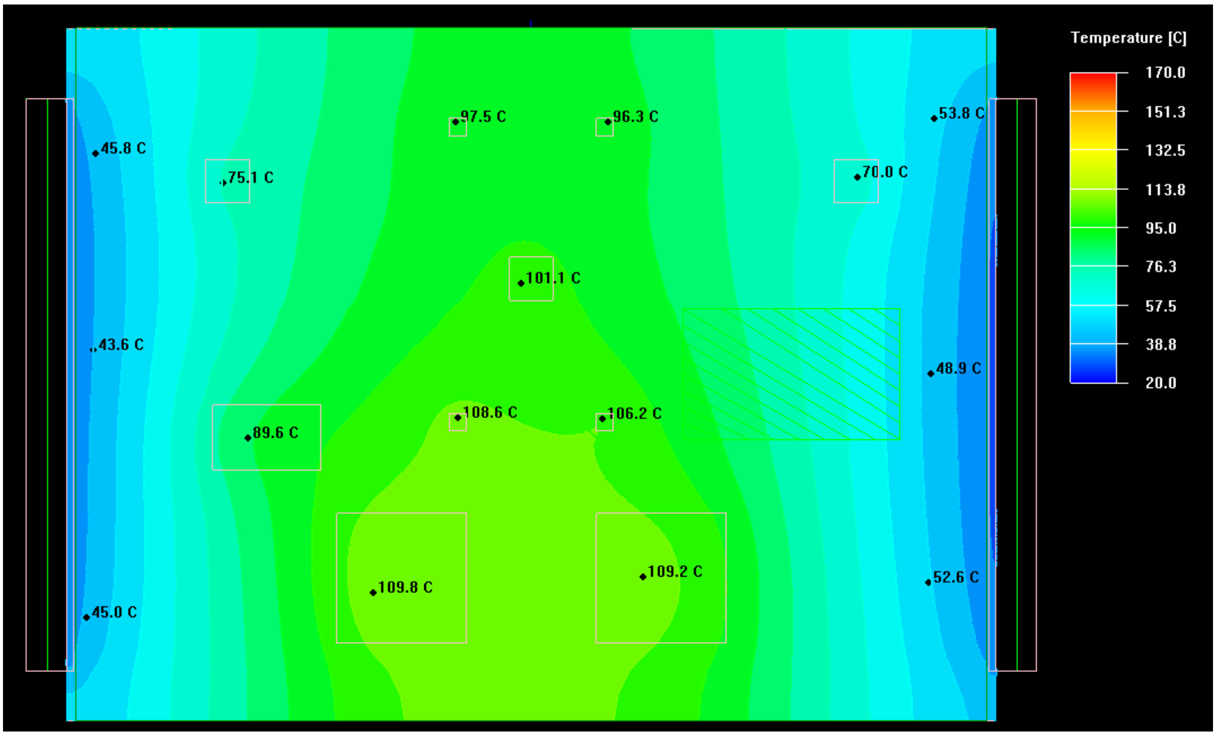

Figure 3 Displays the temperature on the AL-back plate for the HS circuit board, the temperature interval for this picture is between 170-20 [°C].

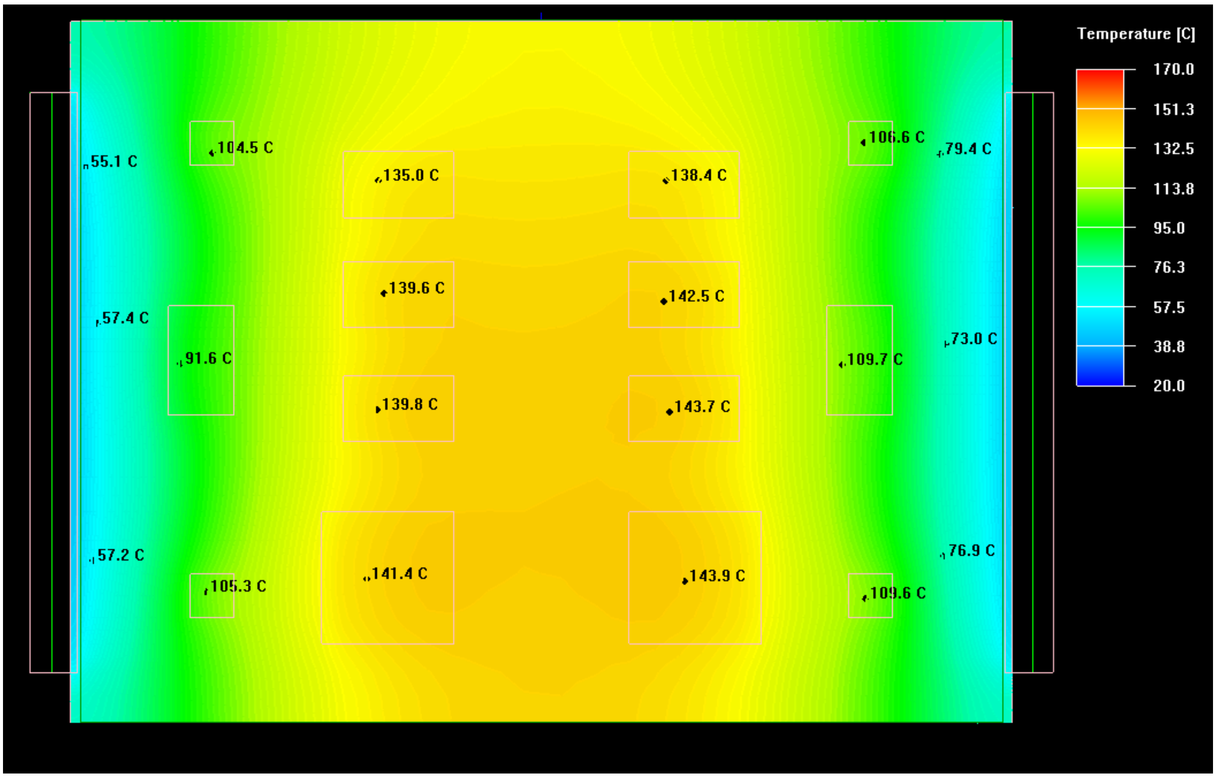

Figure 4 Visualize the temperature on the Al- back plate for the TSO card, the temperature interval for this picture is between 170-20 [°C].

Figures from the simulation for the 4.0 mm Al-back plate

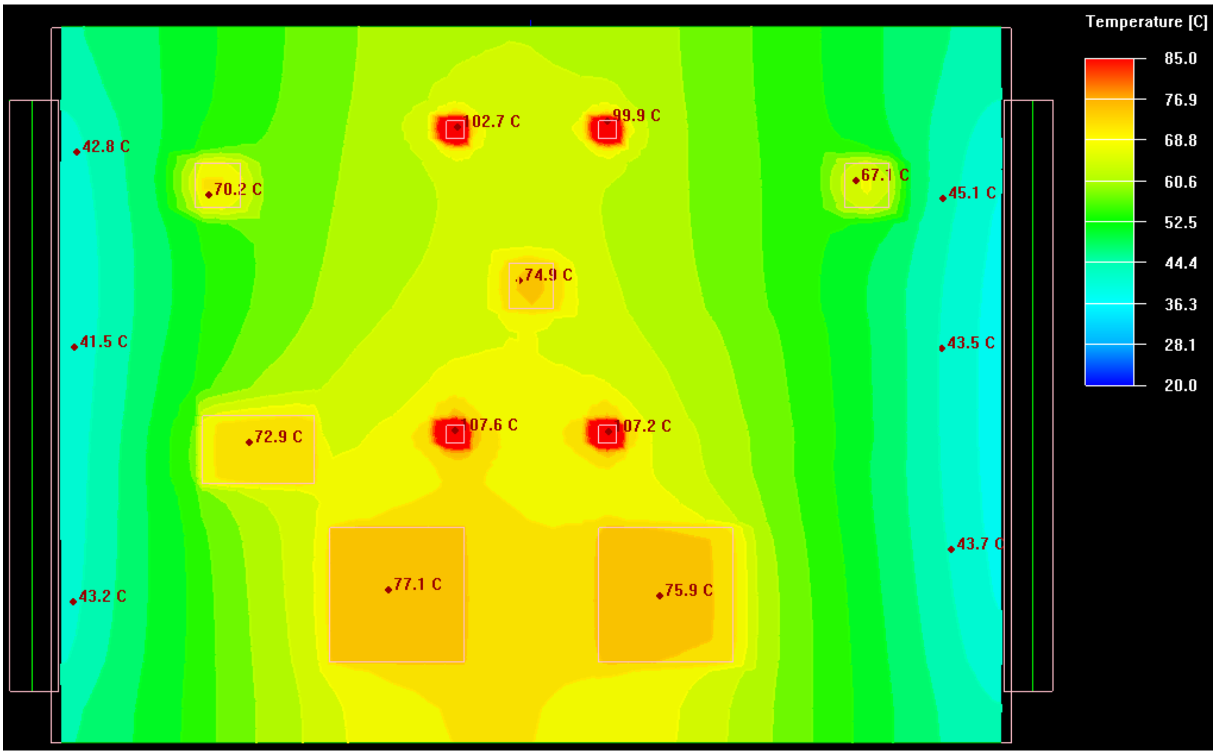

Figure 5 Visualize the temperature in the solder joint for the HS circuit board, the temperature interval that will be used further on for all of the figures are 85-20 [°C]. Red colour indicates non approved temperatures.

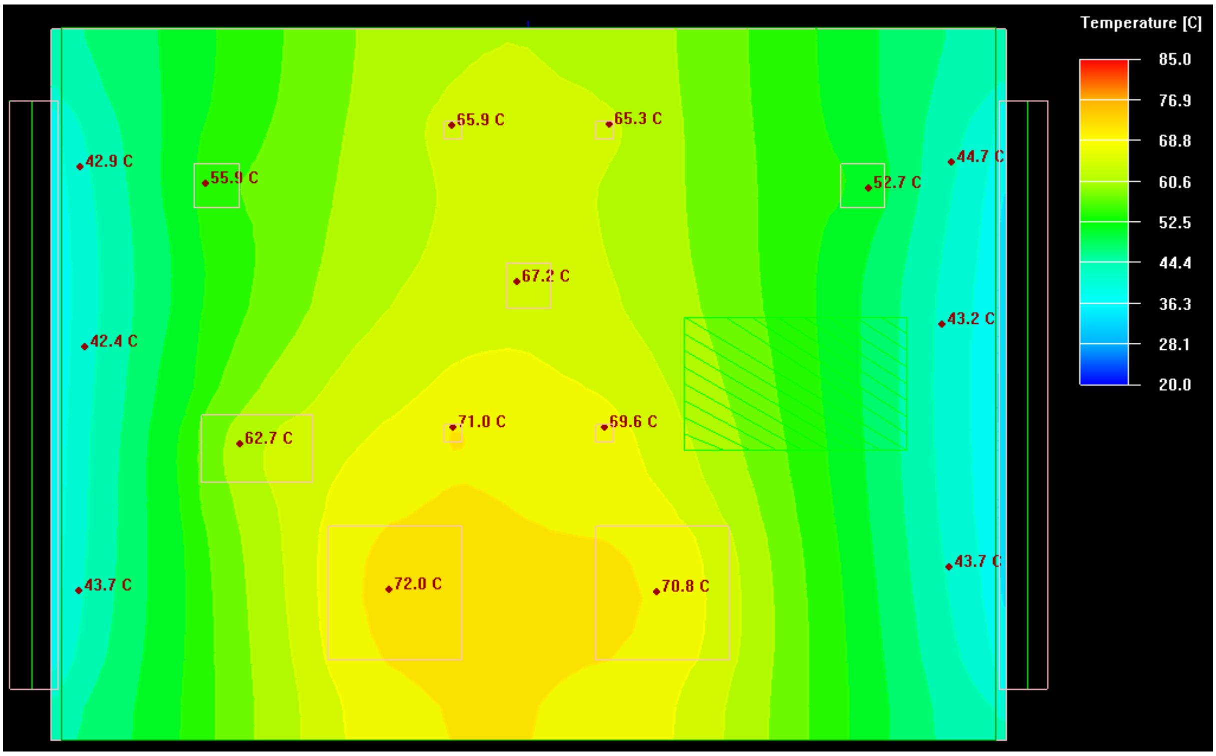

Figure 6 Temperature on the Al-back plate for the HS circuit board.

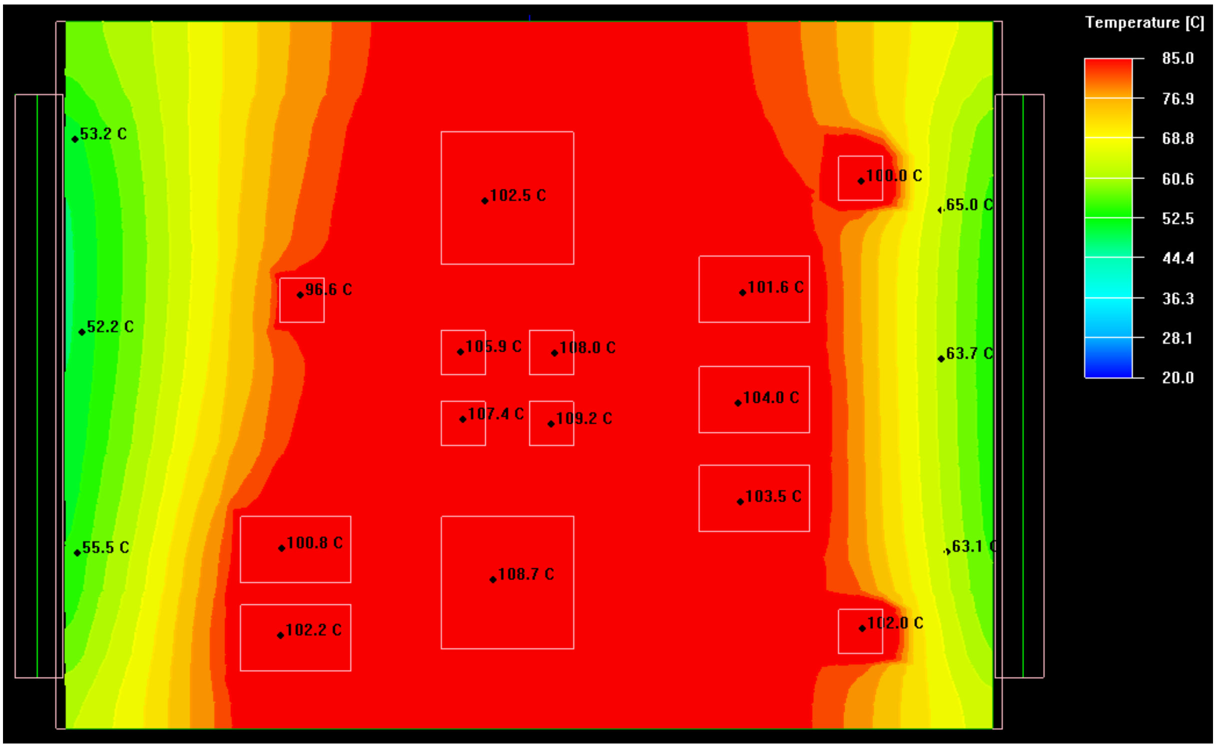

Figure 7 Display the temperature in the solder joint for the TC card, Red colour visualize non approved temperature.

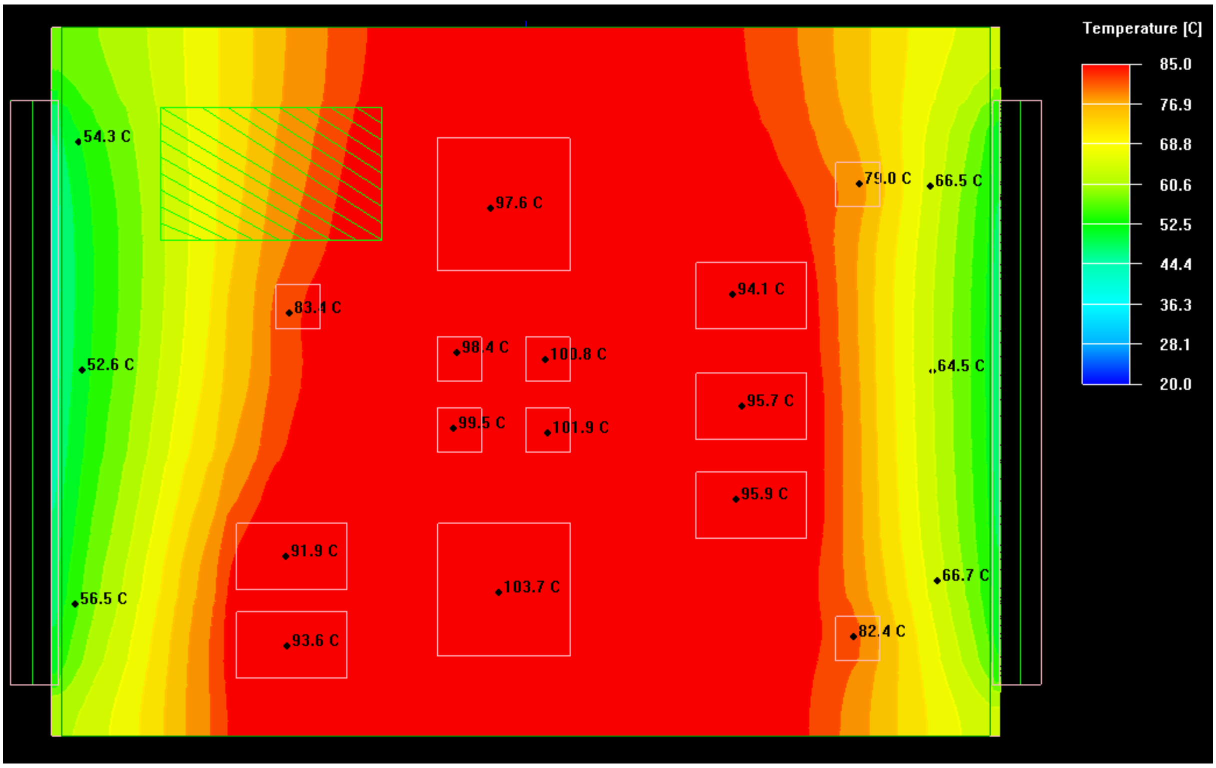

Figure 8 Temperature on the Al- back plate for the TC circuit board.

Pictures from the simulation implementing heat pipes

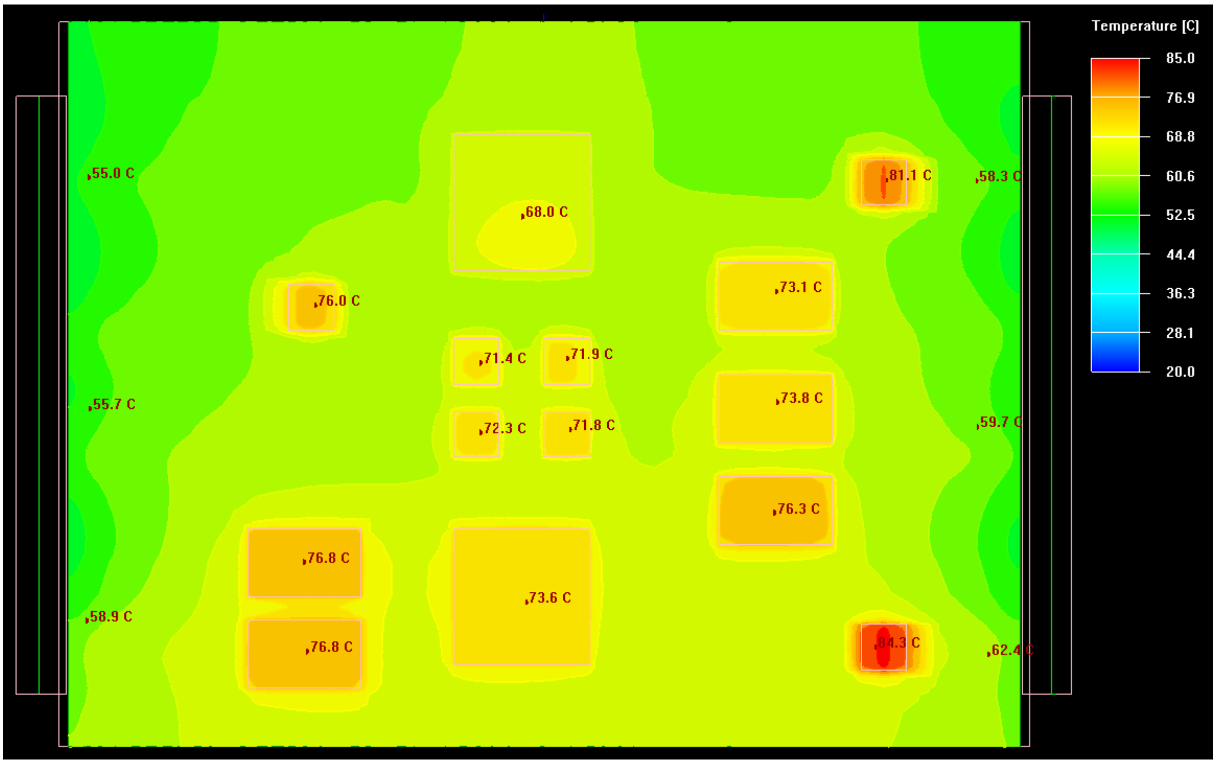

Figure 9 Temperature in the solder joint for the TC circuit board when heat pipes are implemented.

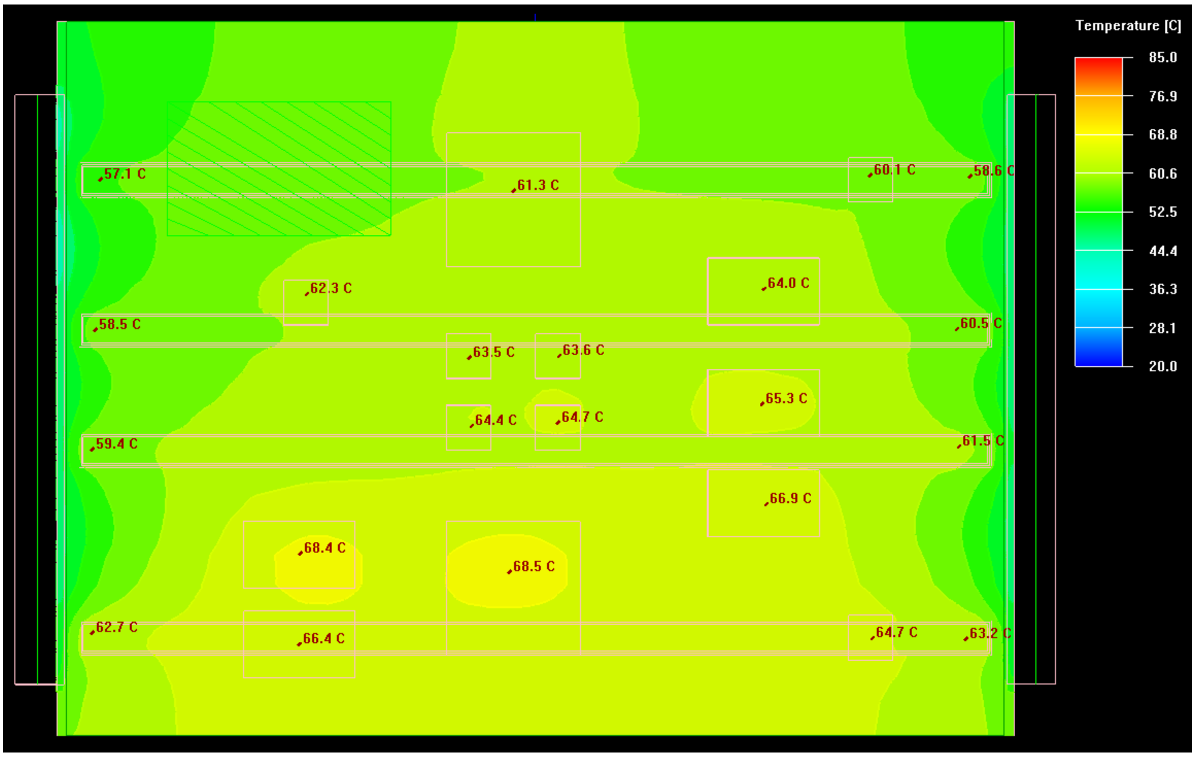

Figure 10 Temperature on the Al-back plate for the TC card, placement of the heat pipes can be seen in the figure.

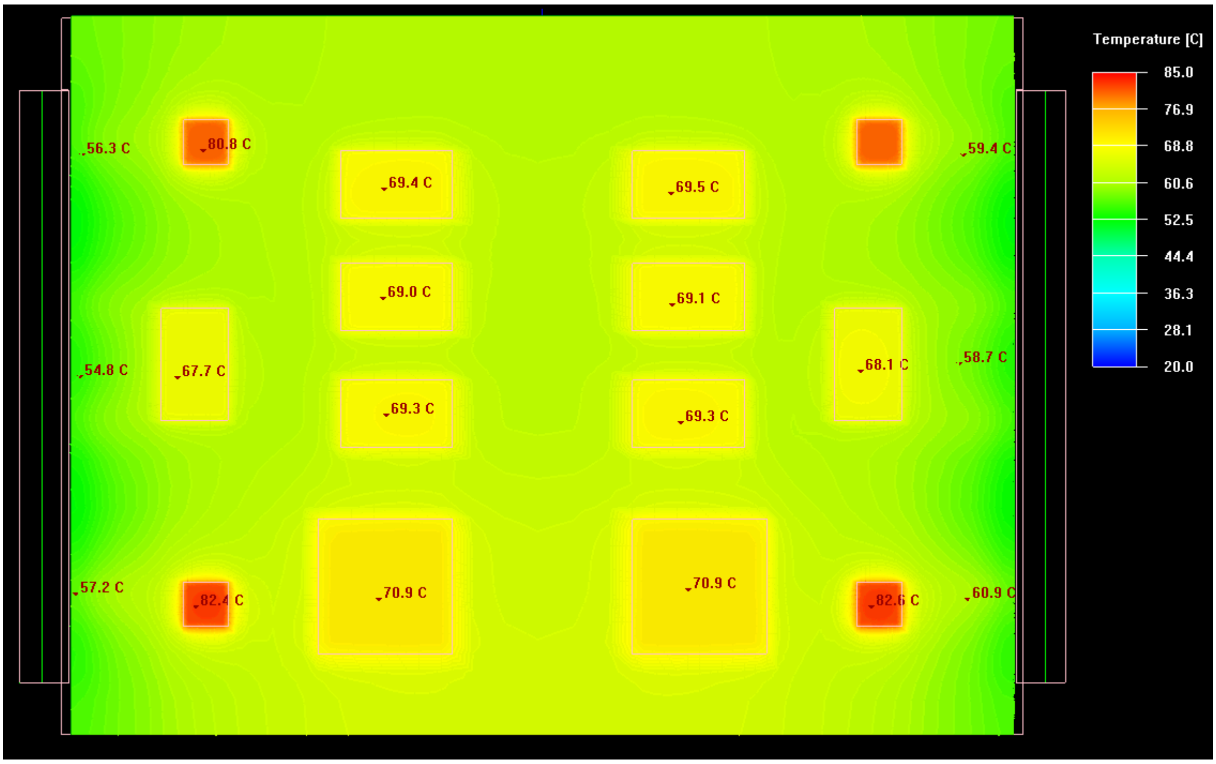

Figure 11 Visualize the temperature in the solder joint for the TSO card, once again red colour indicates non approved temperatures.

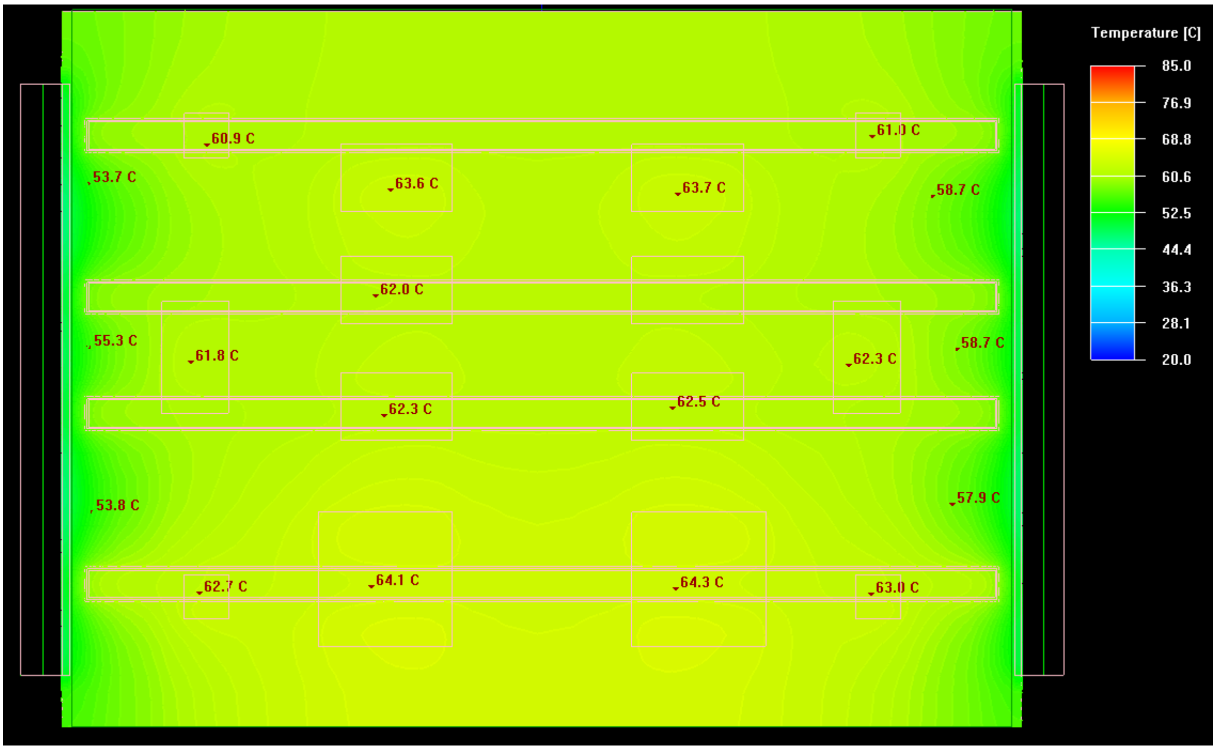

Figure 12 Temperature on the Al-back plate for the TSO card, the position for the heat pipes can be seen in the figure.

Figures from the simulations for the k-Core

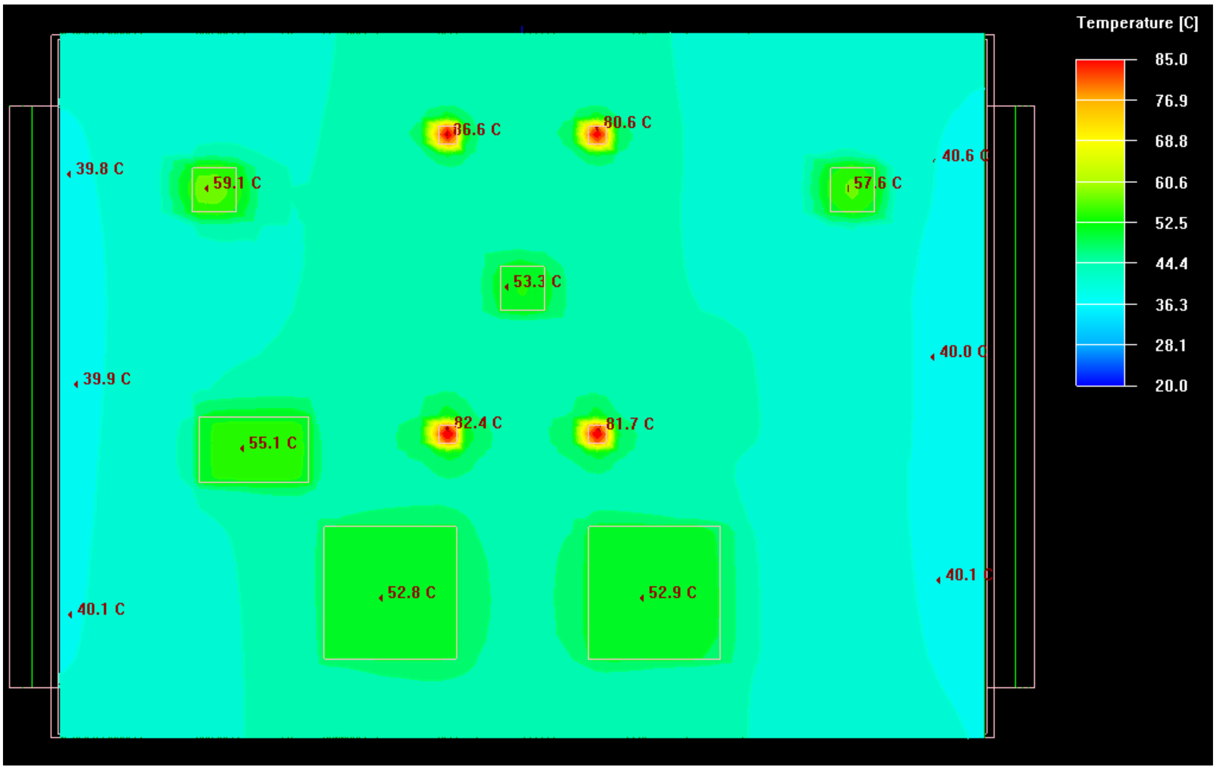

Figure 13 Temperature in the solder joint for the HS circuit board, when the k-Core is implemented.

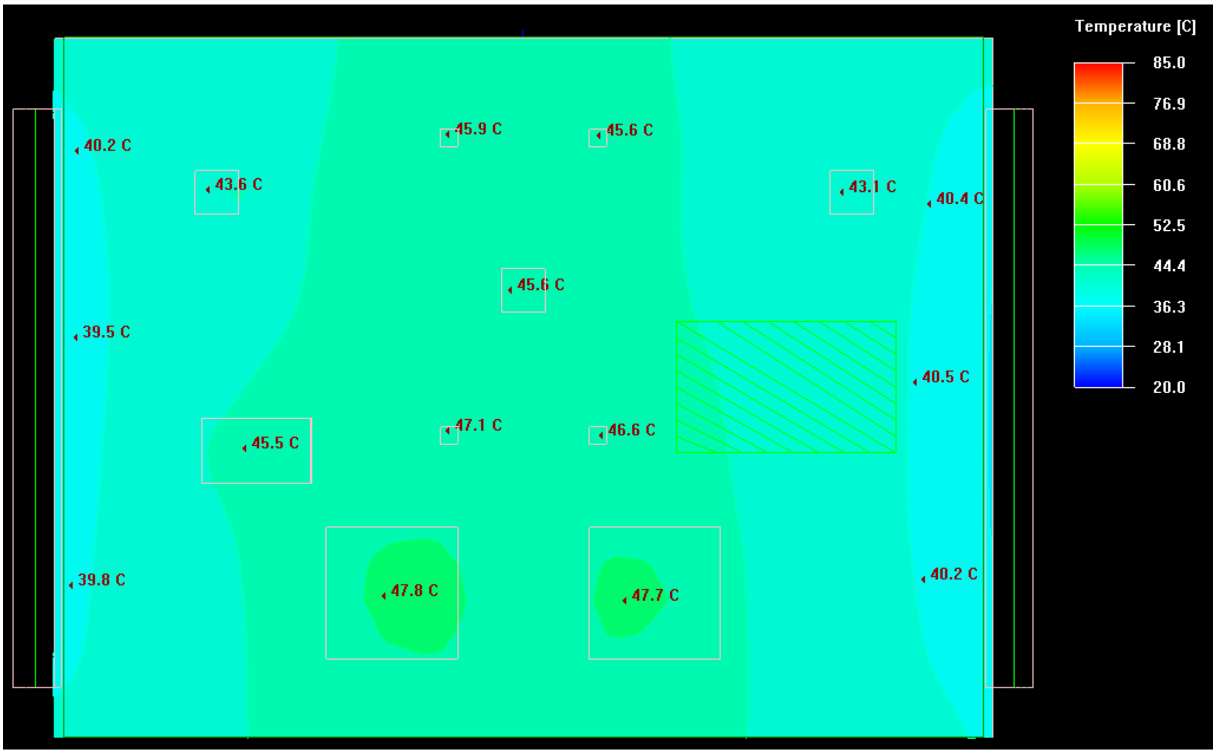

Figure 14 illustrating the temperature on the Al-back plate for the k-Core.

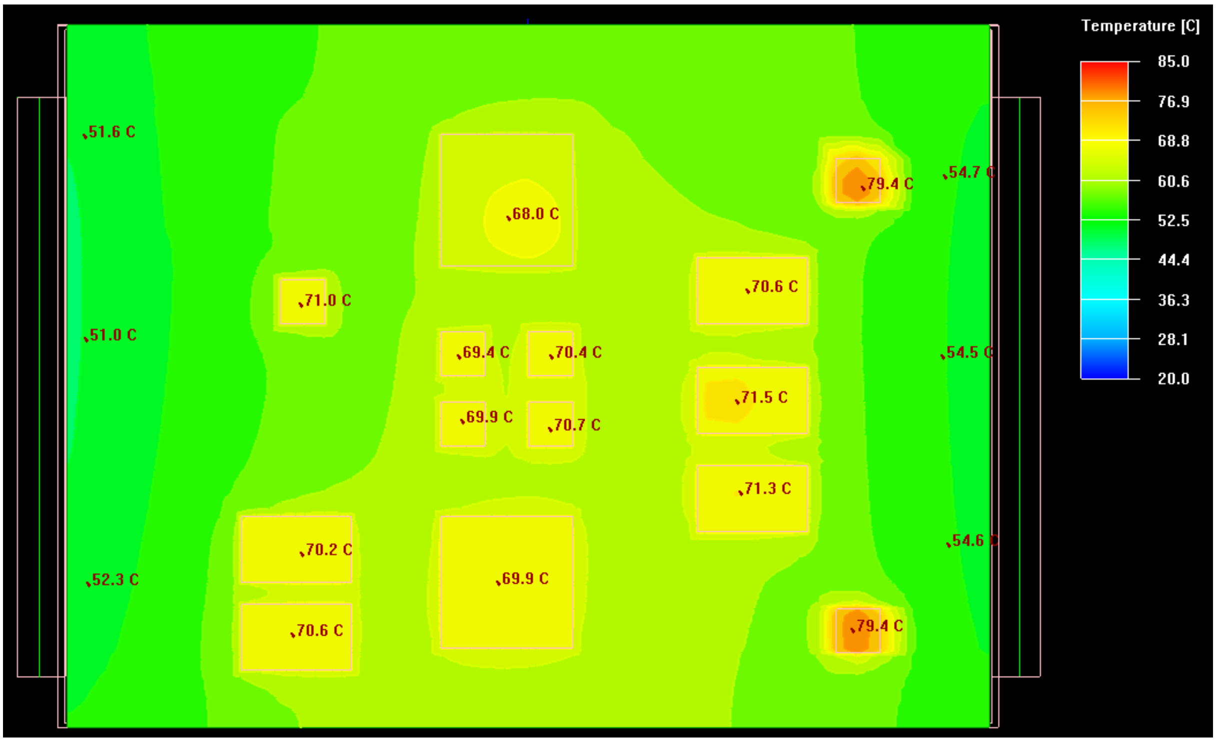

Figure 15 visualizing the temperature in the solder joint for TC card.

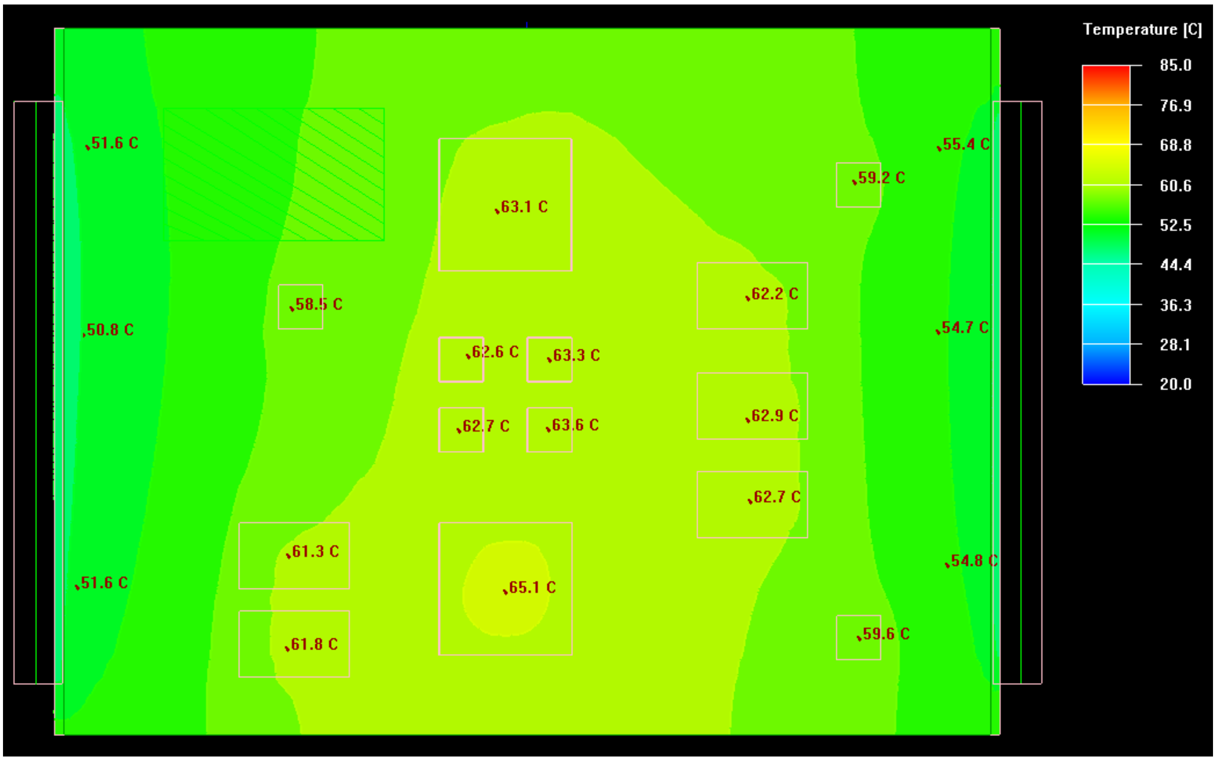

Figure 16 The temperature on the Al-back plate for the k-Core.

Figures from the simulation when the vapour chamber is implemented

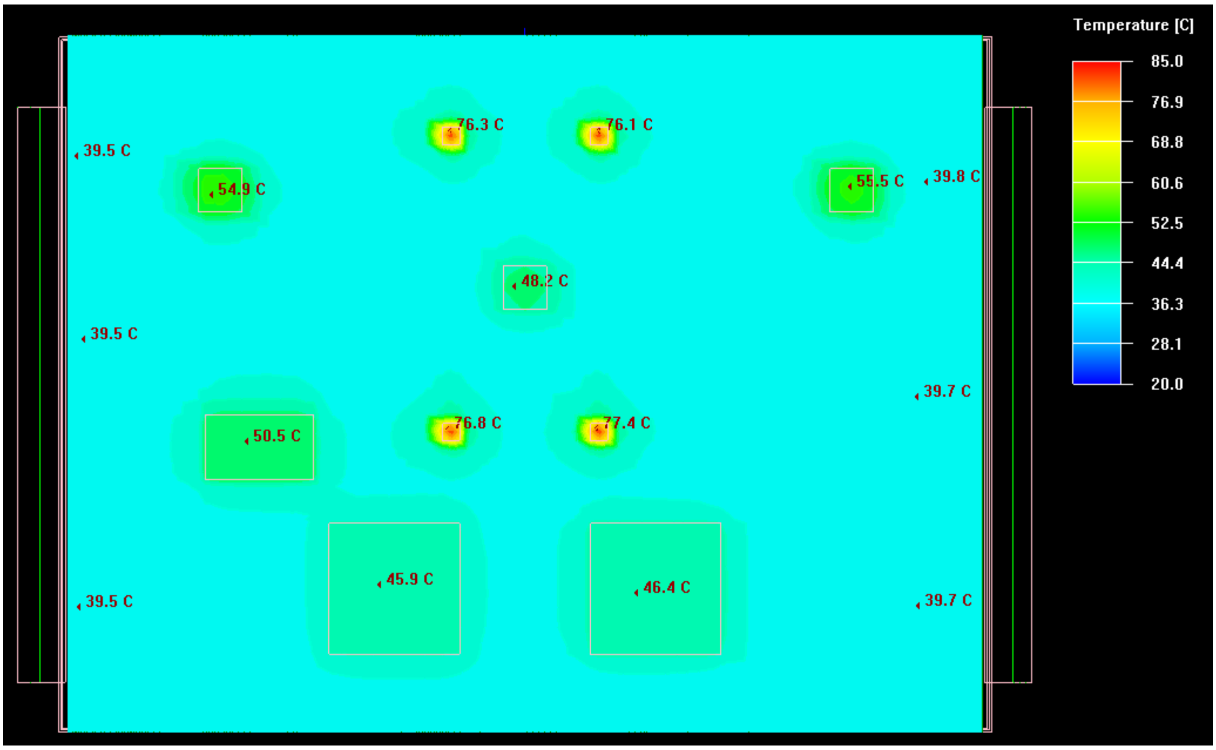

Figure 17 illustrating the temperature in the solder joint for the HS circuit board when the vapour chamber is implemented.

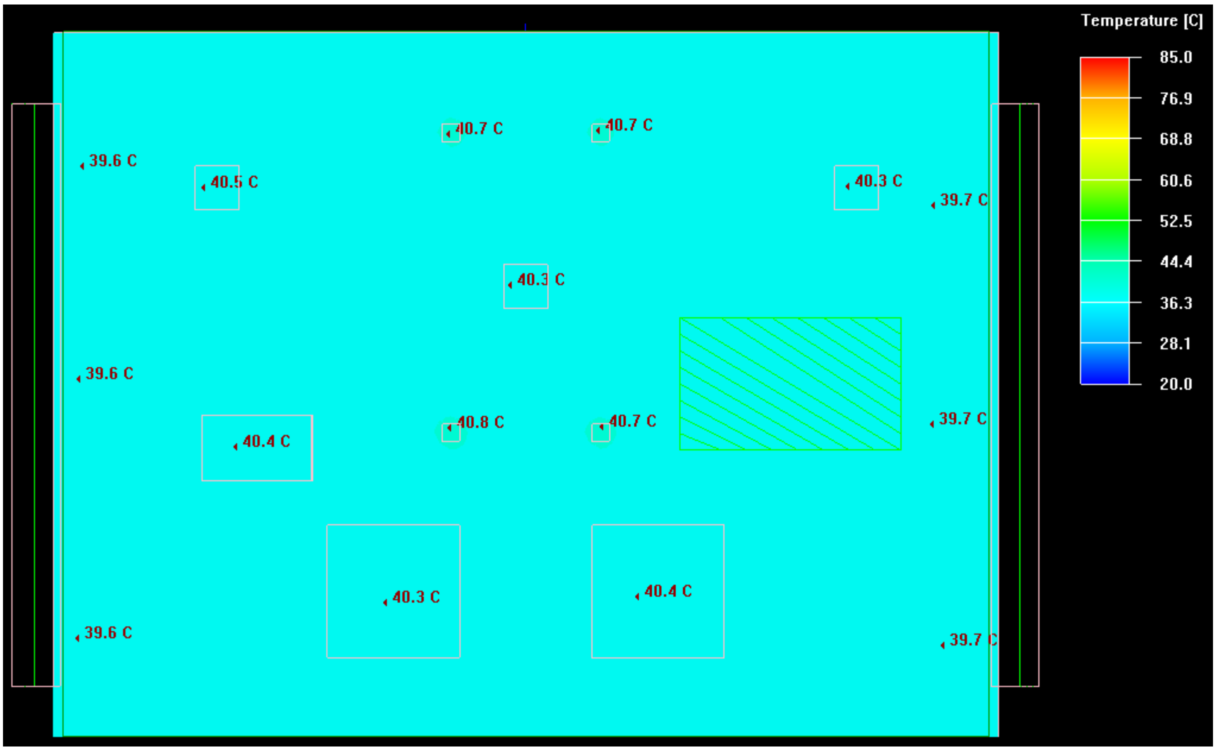

Figure 18 the temperature in the Al-back plate for the vapour chamber.

Figure 19 Visualize the temperature in the solder joint on the TSO circuit board for the vapour chamber.

Figure 20 the temperature on the Al-back plate for the TSO card when the vapour chamber is implemented.

Appendix C- Components for the graphs and index calculations

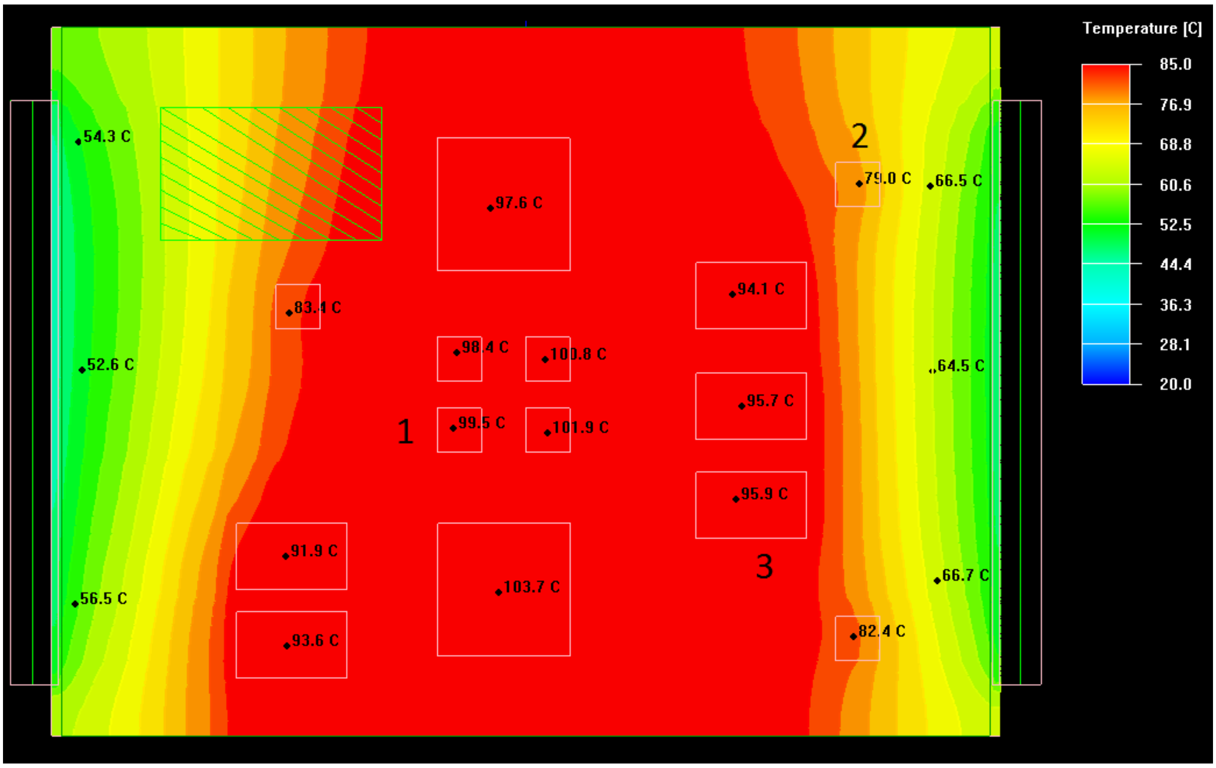

Figure 21 components used for the graphs for the TC circuit board

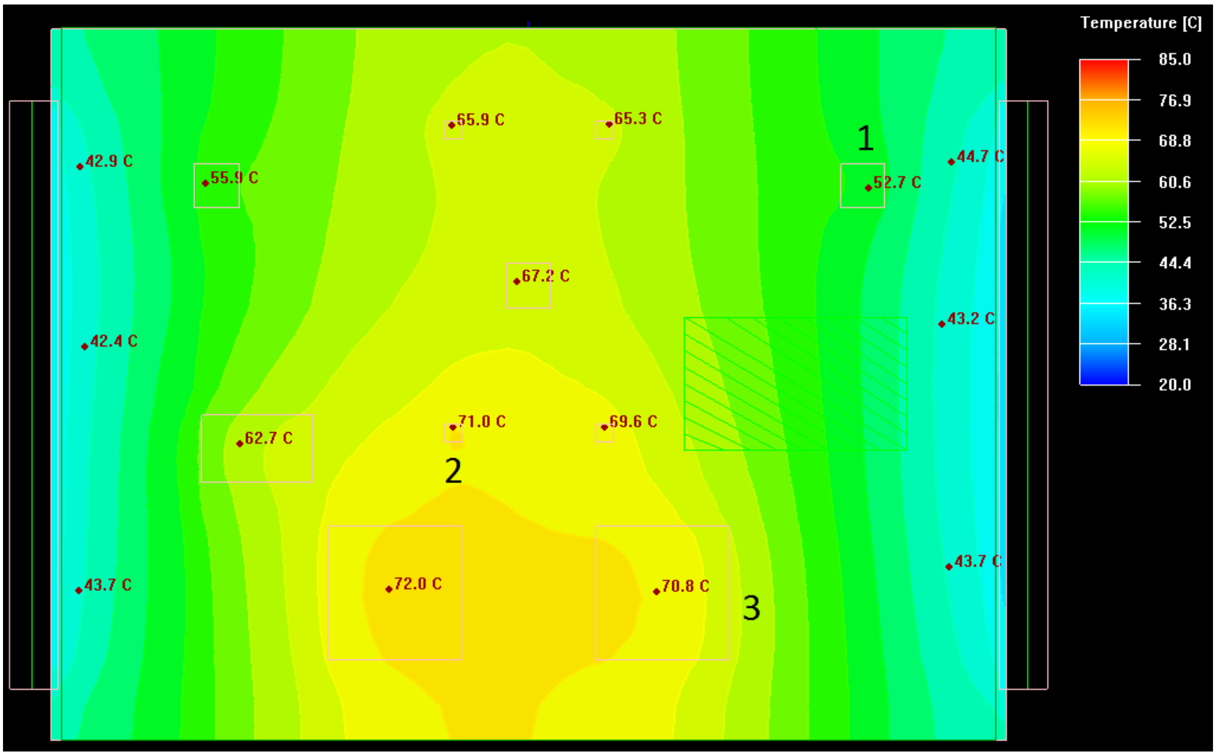

Figure 22 components used for the graphs for the HS circuit board

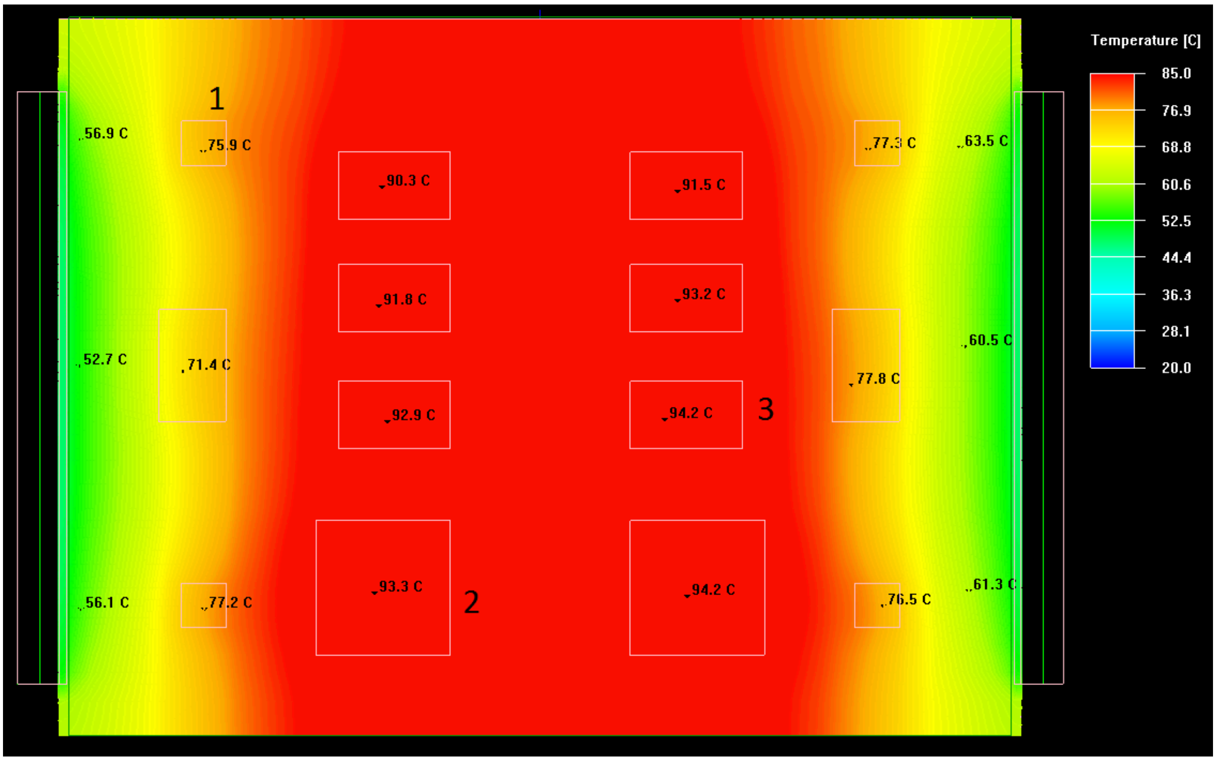

Figure 23 components used for the graphs for the TSO circuit board

Appendix D- Temperatures for the graphs and index calculations

Circuit board: Hot spot							
	Technology	1,6 mm back plate [°C]	4 mm back plate [°C]	k-Core [°C]	HP [°C]	VC [°C]	HP with copper coins
Solder joint							
10x10 (1)		83,2	67,1	57,6	57,6	55,5	-
4x4 (2)		142,2	107,6	82,4	86,8	76,8	53,8
30x30 (3)		112,4	75,9	52,9	55,1	46,4	-
AL back plate							
10x10 (1)		70	52,7	43,1	44,9	40,3	-
4x4 (2)		108,6	71	47,1	46,8	40,8	46,9
30x30 (3)		109,2	70,8	47,7	48,4	40,4	-

Table 1 Temperatures on the hot spot board

Circuit board: The Combined						
	Technology	1,6 mm back plate [°C]	4 mm back plate [°C]	k-Core [°C]	HP [°C]	VC [°C]
Solder joint						
10x10 (1)		165,7	107,4	69,9	72,3	60,8
10x10 (2)		129,8	100	79,4	81,1	74,7
25x15 (3)		154	103,5	71,3	76,3	62,8
AL back plate						
10x10 (1)		158,5	99,5	62,7	64,4	53,5
10x10 (2)		108	79	59,2	60,1	53,9
25x15 (3)		148,5	95,9	62,7	66,9	53,7

Table 2 Temperatures on the combined circuit board

Circuit board: Temperature Spread Out						
	Technology	1,6 mm back plate [°C]	4 mm back plate [°C]	k-Core [°C]	HP [°C]	VC [°C]
Solder joint						
10x10 (1)		123,8	92,1	74,5	80,8	70,3
30x30 (2)		146,9	98,5	67,9	70,9	59,5
25x15 (3)		148,5	99,6	68,3	69,3	60
AL back plate						
10x10 (1)		104,5	75,9	57,8	60,9	53,6
30x30 (2)		141,4	93,3	62,5	64,1	53,5
25x15 (3)		143,7	94,2	62,4	62,5	53,5

Table 3 Temperatures on the temperature spread out

Circuit board	Hot Spot	The Combined	Temperature Spread Out
Technology	Temperature in soldering joints [°C]		
4 mm back plate	107,6	107,4	99,6
Heat Pipe	86,8	72,3	69,3
k-Core	82,4	69,9	68,3
Vapor Chamber	76,8	60,8	60
Heat pipe with copper coins	53,8	-	-

Table 4 reference temperatures used in the index calculations

Circuit board	Hot Spot	The Combined	Temperature Spread Out
Technology	Temperature decrease for each technology [°C]		
Heat Pipe	20,8	35,1	30,3
k-Core	25,2	37,5	31,3
Vapor Chamber	30,8	46,6	39,6
Heat pipe with copper coins	53,8	-	-

Table 5 Temperature decrease compared to values of the 4,0 mm back plate

Appendix E- Cost range for the active cooling technologies

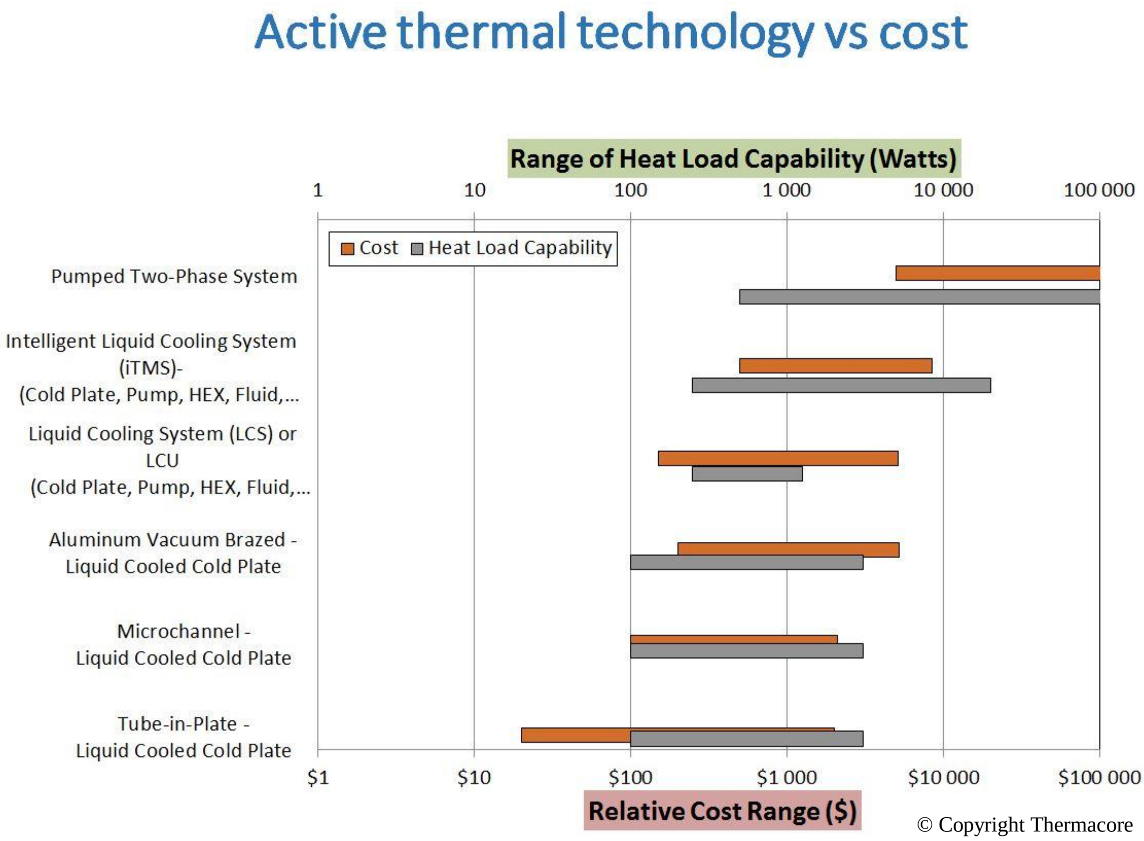

Figure 24 Cost range and heat load capability for active cooling technologies

Appendix F- Index calculations

Calculations for the indexes

Prize for the HP: 450 €

Prize for the VC: 500 €

Prize for the KC: 1200 €

Weight for the HP: 514,3 g

Weight for the VC: 597,7 g

Weight for the KC: 326,3 g

Temperature decrease can be found in table 5 in appendix D

Temperature decrease/prize

Type of card, which technology

HS, Heat pipe: $\frac{20,8}{450} = 0,046$

HS, Heat pipe with copper coins: $\frac{53,8}{450} = 0,120$

HS, k-Core: $\frac{25,2}{1200} = 0,021$

HS, Vapour Chamber: $\frac{30,8}{500} = 0,062$

TC, Heat pipe: $\frac{35,1}{450} = 0,078$

TC, k-Core: $\frac{37,5}{1200} = 0,031$

TC, Vapour Chamber: $\frac{46,6}{500} = 0,093$

TSO, Heat pipe: $\frac{30,3}{450} = 0,067$

TSO, k-Core: $\frac{31,3}{1200} = 0,026$

TSO, Vapour Chamber: $\frac{39,6}{500} = 0,079$

Temperature decrease/weight

Type of card, which technology

HS, Heat pipe: $\frac{20,8}{514,3} = 0,040$

HS, Heat pipe with copper coin: $\frac{53,8}{514,3} = 0,105$

HS, k-Core: $\frac{25,2}{326,2} = 0,077$

HS, Vapour Chamber: $\frac{30,8}{597,7} = 0,052$

TC, Heat pipe: $\frac{35,1}{514,3} = 0,068$

TC, k-Core: $\frac{37,5}{326,2} = 0,115$

TC, Vapour Chamber: $\frac{46,6}{597,7} = 0,078$

TSO, Heat pipe: $\frac{30,3}{514,3} = 0,059$

TSO, k-Core: $\frac{31,3}{326,2} = 0,096$

TSO, Vapour chamber: $\frac{39,6}{597,7} = 0,066$

Appendix G- Calculations for the weight

Density of Aluminium: 2,8 gram/cm^3

Density of APG: 2,0 gram/cm^3

Dimension for the calculation can be found in table 6, chapter 6.4 Weight estimation

Weight for the aluminum back plate without any heat pipes

$$((21{,}43 * 16 * 0{,}4) - (21{,}4 * 0{,}786 * 0{,}3 * 4)) * 2{,}8 = 327{,}43\ g$$

Weight for aluminum back plate with four heat pipes integrated

$$327{,}43 + (46{,}714 * 4) = 514{,}286\ g$$

Weight for the aluminum casing for the k-Core

$$21{,}43 * 16 * 0{,}2 * 2{,}8 = 192{,}0128\ g$$

Weight for the APG layer in the k-Core

$$21{,}23 * 15{,}8 * 0{,}2 * 2 = 134{,}1736\ g$$

Total weight for the k-Core

$$192{,}0128 + 134{,}1736 = 326{,}1864\ g$$

Information about an already existing vapour chamber at Thermacore:

Dimensions: 286,65 cm^3

Weight: 1398 gram

Density of a Vapour chamber

$$\frac{1398}{286{,}65} = 4{,}87\ g/\text{cm}^3$$

Total weight for the vapour chamber

$$(4{,}87 * 102{,}864) + (21{,}43 * 16 * 0{,}1 * 2{,}8) = 597{,}67\ g$$