Metis M.2 AI Accelerator Card Thermal Design Guidelines

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Document revision history

Revision	Date	Description
1	2025-03-20	First Issue.
2	2025-03-31	Updated *Table 2: Critical component list for heat generation.*

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1 Introduction and scope

This document provides thermal design considerations, specifications, and recommended solutions to optimize heat dissipation for the Axelera AI Metis M.2 Accelerator Card. It outlines key thermal requirements, passive and active cooling approaches, and integration guidelines for different system configurations. The goal is to assist engineers and system integrators in implementing a robust and efficient cooling solution, ensuring sustained and stable high-performance AI inference.

1.1 Recommended reading

The Metis M.2 AI Accelerator Card (referred to as the *Metis M.2 card)* has a single Axelera AI Metis AIPU (AI processing unit) chip and a minimum of 1 GB of LPDDR4X dedicated memory. It is designed to provide AI inference acceleration in any system that has an M.2 card socket, also known as Next Generation Form Factor (NGFF) socket.

In order to integrate the Metis M.2 card, the following steps are recommended:

- **Review** the *Metis M.2 AI Accelerator Card Datasheet* and the provided 3D model to verify that your system is compatible with the Metis M.2 Card.
- **Read and understand this document**: *Metis M.2 AI Accelerator Card Thermal Design Guidelines*.
- **Implement the appropriate thermal solution** based on the information provided in this document to ensure the temperature of the components in the module remain below the specified limits in *Table 2: Critical component list for heat generation*.

1.2 Glossary

Term	Definition
AIPU	AI Processing Unit
AL	Aluminum
CFM	Cubic Feet per Minute
FR4	Flame Retardant. FR4 is a type of glass epoxy used in the Metis M.2 card PCB.
LPDDR	Low Power Double Data Rate. Type of memory used in the Metis AIPU.
NGFF	Next Generation Form Factor. Former name for the M.2 expansion card.
PC	Polycarbonate, when used in the context of Thermal Interface Materials.
PVT	Process, Voltage, Temperature
RP2040	A model of Raspberry Pi microcontroller.
SoC	System-on-Chip
TIM	Thermal Interface Materials

2 About the Metis M.2 card

The Metis M.2 card generates heat during operation, necessitating an effective thermal management solution to maintain performance, reliability, and longevity. Proper thermal design is crucial to preventing thermal throttling, performance degradation, or even hardware shutdown under extreme conditions.

Table 1 provides some key thermal and operational specifications of the Metis M.2 card. For full specification details, refer to the *Metis M.2 AI Accelerator Card Datasheet*.

Table 1: Key thermal and operational specifications of the Metis M.2 card

Specification	Description
Operating Temperature	-20 to 70 °C
Thermal Solution	Options*: - Axelera supplied heatsink with a fan (active cooling) - Custom heat spreader
Typical Power	3.5 – 9.5 W

** Additional options will be proposed in future revisions of this document*

3 Metis AIPU characteristics and protection

The Metis M.2 card features one Axelera AI Metis AIPU system-on-chip (SoC).

3.1 Metis AIPU characteristics

The Metis AIPU has the following characteristics:

Symbol	Definition	Recommended maximum value*	Absolute maximum value
Tj	Junction temperature	95°C	125°C

** To guarantee operating lifetime.*

Symbol	Definition	Value
θjc	Junction-to-case thermal resistance	0.22°C/W

3.2 Thermal throttling and thermal safety

The Metis AIPU has the following features:

- Throttling mechanisms that can be used to reduce power dissipation by controlling peak performance.
- Thermal protection mechanisms to prevent damage to the chip.

These mechanisms include both software and hardware protections and they activate according to temperature thresholds. The mechanisms are triggered based on temperature data read from PVT sensors (process, voltage, temperature sensors), placed across key areas of the chip as well as sensors placed on the board.

Future revisions of this document will document these mechanisms in detail.

4 Thermal characteristics of Metis M.2 card

The Axelera AI Metis M.2 card is designed with a system-level thermal solution to efficiently dissipate heat generated during high-performance AI inference workloads. The primary heat dissipation path is through the top surface of the AIPU, where it can be conducted to a heatsink or other cooling solution. However, additional heat dissipation also occurs through other key components, including the LPDDR, the MPM3695 and MP5416 voltage regulators, and the PCB board.

While these secondary heat paths contribute to overall thermal management, the majority of heat is dissipated from the AIPU to the top surface. For this reason, an optimized thermal solution must focus on effective heat transfer from the AIPU to ambient air through a properly designed cooling system.

4.1 Power distribution and heat dissipation considerations

The power consumption of the Metis M.2 card varies depending on the workload distribution across the AIPU, LPDDR, and voltage regulators. Efficient thermal management depends on ensuring proper heat spreading across these components to avoid localized hotspots.

To achieve optimal thermal performance, the following considerations must be considered:

- **AIPU (Primary heat source)**: Most of the heat is generated by the AIPU and must be dissipated efficiently through a direct heatsink or a passive heat conduction system.
- **LPDDR memory**: Although it generates less heat than the AIPU, the LPDDR memory still contributes to thermal load and should be included in thermal analysis.
- **Voltage regulators (MPM3695 and MP5416)**: These components add to the overall power dissipation and should be considered when designing heat dissipation solutions.
- **PCB board heat transfer**: While a proportion of the heat is transferred through the PCB, this is a secondary dissipation path and should not be solely relied upon for cooling.

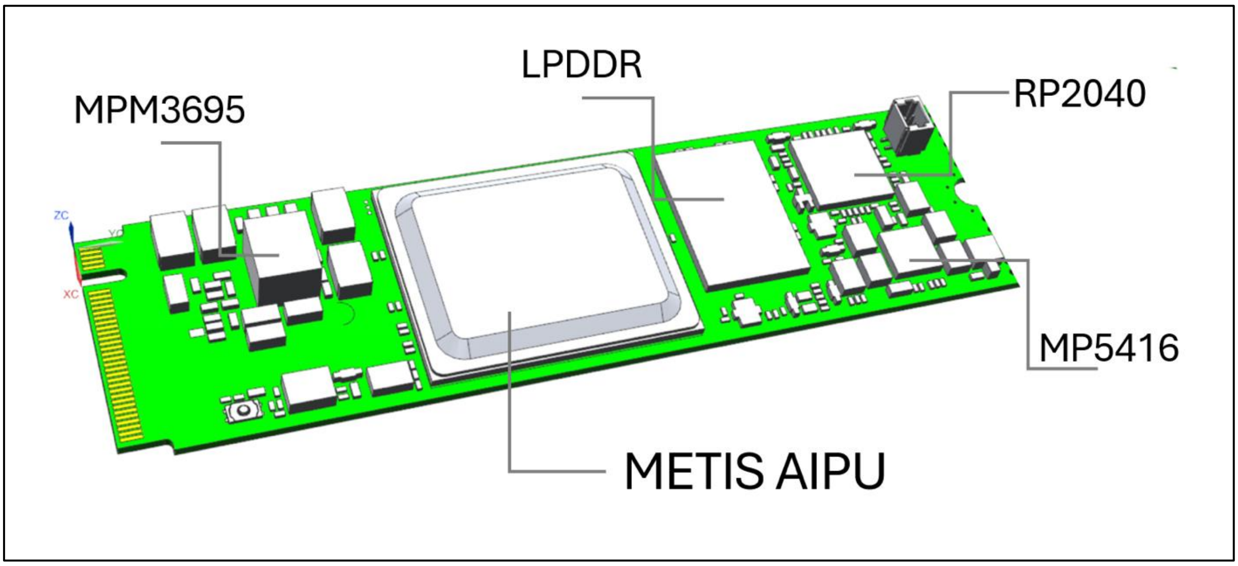


Figure 1: Critical component placement for the heat generation

Table 2: Critical component list for heat generation

Metis M.2 card: Key components	Power consumption (W)	Thermal resistance value (°C/W)	Allowable max. temperature (°C)
Metis AIPU	1.9-7.9 W*	R_{J-C} =0.22 / R_{J-B}=2.86 / R_{J-A}=8.97	**95 (Tj)
LPDDR4X	1.1 W	R_{J-C}= 7.6 / R_{J-B}= 16.9	95 (Tc)
MPM3695	1 W	R_{J-A} =14.1 / R_{C-B}= 4.8	125 (Tj)
MP5416	1 mW	R_{J-A} =44 / R_{C-B}= 9	125 (Tj)

** Power consumption depends on the specific scenario and neural network at different ambient temperatures.*
*** 95°C is recommended by Axelera AI as the "max. working temperature" to guarantee the operating lifetime.*
Note: Tj = junction temperature and Tc = case temperature.

4.2 Thermal resistance model

The thermal behavior of the Metis M.2 card can be represented using a thermal resistance network, similar to other electronic systems. The *junction temperature* (Tj) is related to the *ambient temperature* (Ta) through the following equation:

$$T_j = T_A + (R_{Total} \times P)$$

$$R_{Total} = R_{j-c} + R_{TIM} + R_{Heatsink}$$

Parameters:

- **T**j = Metis AIPU junction temperature
- **T**A = Ambient air temperature
- **P** = Power dissipated by the module
- **R** (j-c) = Thermal resistance from junction to AIPU package top surface
- **R** (TIM) = Thermal resistance of TIM (thermal interface materials). This depends on the thermal selection of the material of TIM. For details, see *Table 5: Suggested thermal interface material*.
- **R** (Heatsink) = Thermal resistance of Heatsink (depends on the thermal selection of the material and the heatsink design and the ambient flow rates. For details, see section 5 *Thermal solution options for the Metis M.2 card*.

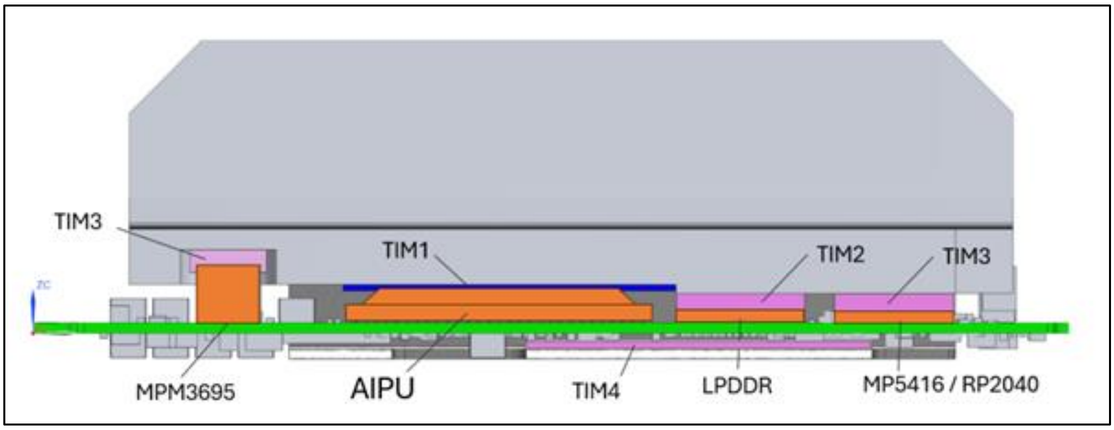


Figure 2: Stack-up of Metis M.2 card (cross-section of Al Heatsink Solution with TIM materials)

The thermal resistance network of the AIPU to ambient is shown in Figure 3. The network diagram is the same as for the other critical heat generated components.

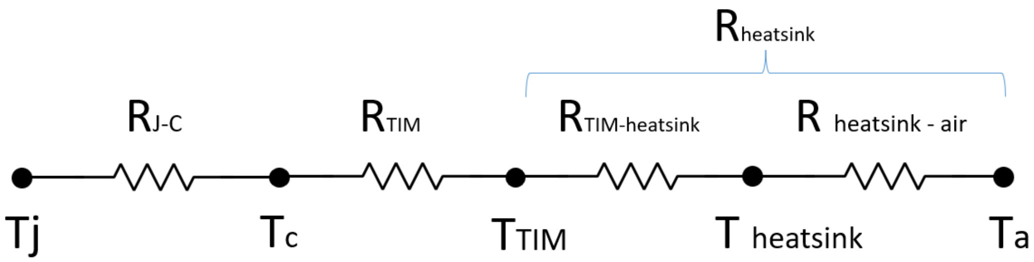


Figure 3: Metis M.2 card thermal resistance network diagram

According to the thermal specifications that are defined in the *Table 2: Critical component list for heat generation*, junction temperatures can be calculated. See the following example.

Example Case: Thermal calculations

This example is for the Metis AIPU chip with the given thermal resistance values.

In this example, using a 0.5 mm-thick thermal pad with a thermal conductivity of 9 W/mK between the chip and an aluminum heatsink, we need to determine the appropriate heatsink selection. Given a power consumption of 6 W and a requirement to keep the junction temperature below 95°C, we must calculate the necessary thermal resistance of the aluminum heatsink to ensure proper cooling. The air flow assumed to be constant as max. 0.5 m/s, such as in a closed system structure.

Parameters:

- $\mathbf{T}_j$ = Junction temperature of the Metis AIPU
- $\mathbf{T}_a$ = Ambient temperature
- **P** = Power dissipation of the AIPU
- $\mathbf{R}_{Heatsink}$ = Thermal resistance from the Heatsink (to be calculated)
- $\mathbf{R}_{j\text{-}c}$ = Thermal resistance of AIPU junction to case
- $\mathbf{k}_{TIM}$ = Thermal Conductivity of TIM
- $\mathbf{R}_{TIM}$ = Thermal Resistance value of the TIM material (to be calculated)
- $\mathbf{t}_{TIM}$ = TIM material thickness
- $\mathbf{A}_{TIM}$ = Area of the Thermal Pad

Example case:

- **T**$_a$ = 70°C
- **T**$_j$ = 95°C (with reference to allowable AIPU junction temperature)
- **P** = 6 W
- **R** $_{j-c}$ = 0.22°C/W
- **k** $_{TIM}$= 9 W/mK
- **t** $_{TIM}$ = 0.5 mm = 0.0005 m
- **A** $_{TIM}$ = 20x24 mm = 0.00048 m^2

Establish Thermal Resistance Path:

Since we are using an aluminum heatsink on top of the chip with a thermal pad, the primary heat flow path is:

Junction → Case → TIM → Heatsink → Air

The total thermal resistance **R**$_{total}$ must satisfy the temperature requirement:

$$R_{total} = \frac{T_j - T_A}{P} \quad (1)$$

To ensure **Tj ≤ 95°C** with **Ta = 70°C**:

$$R_{Total} = \frac{95 - 70}{6} = 4.16\ ℃/W$$

Which means; the total system resistance shouldn't be more than 4.16°C/W to keep the AIPU temperature under 95°C at 70°C ambient.

Thermal Pad Resistance (R$_{TIM}$):

$$R_{TIM} = \frac{t}{K * A} \quad (2)$$

$$R_{TIM} = \frac{0.0005}{9 \times 0.00048} = 0.116\ ℃/W$$

To choose the correct heatsink, we can calculate the required heatsink thermal resistance:

$$R_{total} = R_{j-c} + R_{TIM} + R_{heatsink} \quad (3)$$

$$4.16 = 0.22 + 0.116 + R_{heatsink}$$

$$R_{heatsink} = 4.16 - 0.22 - 0.116$$

$$R_{heatsink} = 3.82\ ℃/W$$

If a similar heatsink is used, a thermal resistance **≤ 3.82°C/W** is required to keep the AIPU temperature within safe limits and the system can safely dissipate up to 6 W without exceeding thermal limits at 70°C ambient temperature.

If the power increased to 10 W, then the equation for total system resistance, (1), becomes:

$$R_{Total} = \frac{95 - 70}{10} = 2.5\ ℃/W$$

To choose the correct heatsink, we can calculate the required heatsink thermal resistance, according to equation (3):

$$R_{heatsnk} = 2.5\ - 0.22 - 0.116$$

$$R_{heatsnk} = 2.16\ ℃/W$$

If a heatsink is used with a thermal resistance **≤ 2.16°C/W**, the system can safely dissipate up to 10 W without exceeding thermal limits. In this kind of case, Axelera AI recommends active cooling solutions or an additional cooling plate that is attached to top of the "Axelera Heat Spreader" in the system. For more information please refer to section 5 *Thermal solution options for the Metis M.2 card*.

NOTE: *Heatsink selection must be considered carefully when configuring system power. This example only considers AIPU heat dissipation as the main heat source in the system. Therefore, please also take into account other heat sources in the system to ensure a proper selection. Refer to Table 2: Critical component list for heat generation* to keep the system within safe limits.

5 Thermal solution options for the Metis M.2 card

To prevent the Metis AIPU from reaching critical operating temperatures, several thermal management solutions are proposed to ensure optimal performance and reliability. The design goal of the different solutions is to keep the chip and the critical component's junction temperature within the specified range.

5.1 M.2 Active Cooling Solution –Aluminum heatsink with fan

In this configuration, the M.2 Active Cooling Solution consists of an aluminum heatsink cooled with forced air from a fan. It is suitable for the following scenario:

- The M.2 slot area has enough height clearance for proper fan air flow : 50 mm from the board surface to upper surface.
- The host systems may or may not have forced airflow.
- With forced airflow (2 m/s), it is suitable for high-power workloads up to 11 W that require to operate at 70°C ambient.
- Low Thermal resistance values from 2°C/W to 3.5°C/W *(for 0.5 and 2m/s of airflow respectively).*
- Can tolerate noise level of fan: ≈ 20 dB *(according to fan flow-0.78 CFM measured from a distance of 1 m).*

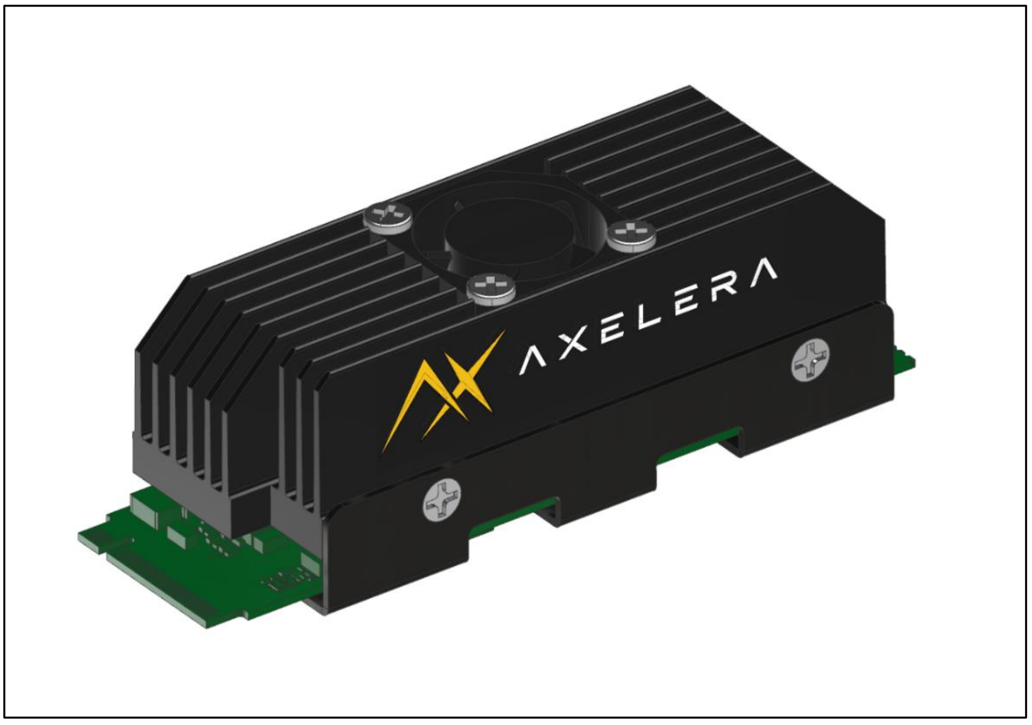


Figure 4: M.2 Active Cooling Solution (heatsink with fan forced air)

Table 3: Product specifications for the M.2 Active Cooling Solution

Part name	Total Length (w-card / Heatsink-only) (mm)	Height to top of the heatsink (mm)	Width (mm)	Weight (g)	Thermal Resistance Values		Total Cooling Capacity (W) *
					(Under constant air flow ≤0.5 m/s)	(With additional fan in the system- air flow of 2.0 m/s)	
Active Cooling	80 / 72.5	12	25	30	~ 3.5 (°C/W)	~ 2.0 (°C/W)	6.5 to 11

* Max. Power defined in accordance with preventing reaching Tj=95℃ at 70℃ ambient temperature.

For more information on dimensions, please refer to the document *Metis M.2 AI Accelerator Card Datasheet.*

Parts list for the M.2 Active Cooling Solution

The M.2 Active Cooling Solution consists of the following parts, as shown in Table 4.

Table 4: Parts list for the M.2 Active Cooling Solution

Part name	Material type	Material Info	Quantity
Metis M.2 card	FR4	0.8 mm	1
AL Heatsink	AL6000 / Anodized aluminum	n/a	1
Fan (Axial) 3.3 V	Polycarbonate (PC) (V0-certified)	0.78 CFM air flow	1
Screw of Fan	M2 x 14 mm	n/a	3
Screw (x4)	M2.5 x 5 mm	n/a	4
Bracket Bottom	Sheetmetal / Powder coating	1 mm	1
Thermal Pad-TIM	Refer to Table 5.	0.5 – 2 mm	4
Isolation Plate-Mylar	A3 PC1870A+3M9448 (adhesive tape)	0.275 mm	1

For the thermal pads (TIM) in the system, thermal values are as shown in Table 5.

Table 5: Suggested thermal interface materials (TIM)

Metis M.2 key thermal components	Material type	Material thickness (mm)	Thermal conductivity coefficient value (K= W/mK)	Allowable max working temperature (°C)
TIM1 / AIPU	VOT- XK9	0.5 mm	9	150
TIM2 /	VOT- A6S2	2.0 mm	1.8	200
TIM3	VOT- A6S2	1.75 mm	1.8	200
TIM4	VOT- A6S2	0.75 mm	1.8	200

Refer also to *Figure 2: Stack-up of Metis M.2 card (cross-section of AI Heatsink Solution with TIM materials).*

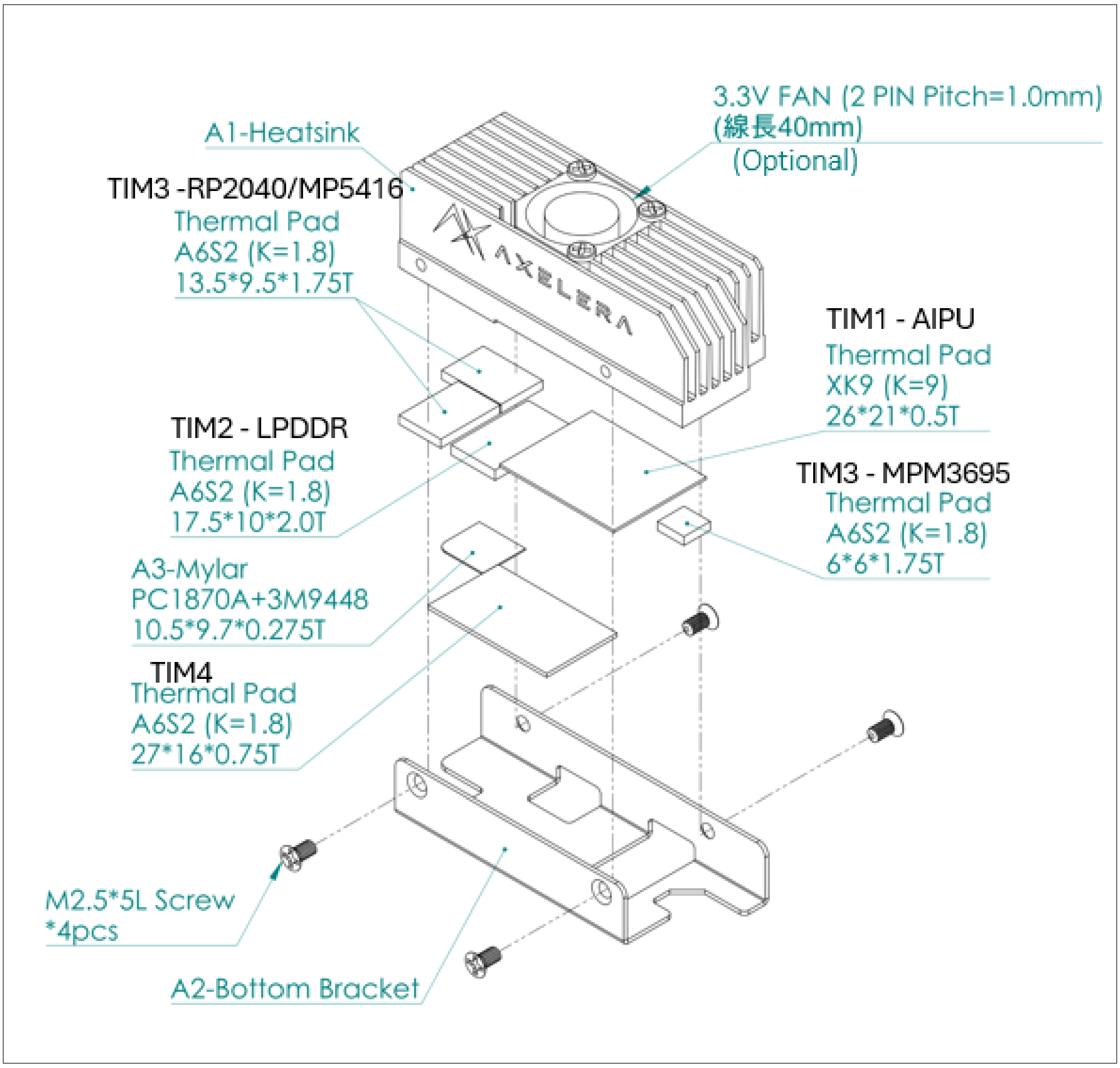
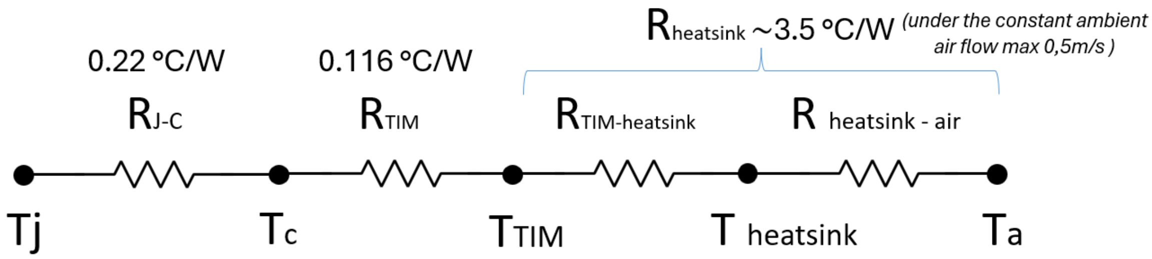


Figure 5: Exploded view of the Active Cooling solution

5.1.1 *M.2 Active Cooling Solution – Cooling capacity*

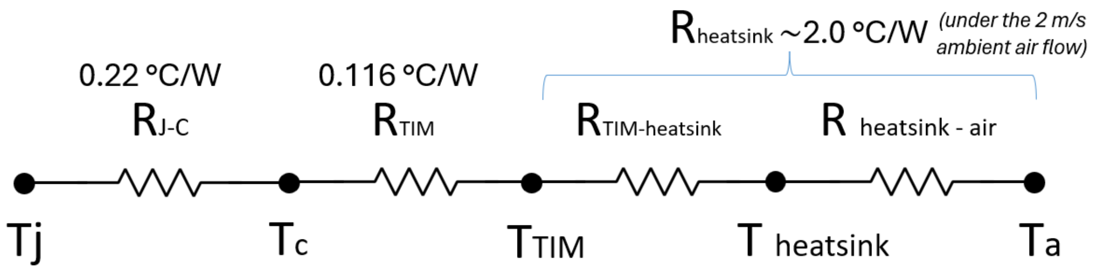
In this configuration, the M.2 Active Cooling Solution is fixed in a closed structure that allows free air ventilation for proper fan working. When the inside air flow is less than 0.5 m/s, the heatsink resistance value is assumed to be around 3.5°C/W (with fan air flow of 0.78 CFM).

Under these conditions, considering the TIM materials (refer to Table 5: Suggested thermal interface materials) and the Metis junction to case resistance (0.22/W) the total resistance to be 3.84°C/W and the thermal path as shown in the following:



External fan conditions:

If the open frame structure has an internal fan and the air flow rate is a minimum if 2 m/s, it is possible to reduce the heatsink resistance values to around 2°C/W. In this case, the total resistance will be 2.34°C/W and the thermal path is given from the following:



According to that configuration, the M.2 Active Cooling Solutions can reach to 6.5 W (at 70°C, at 0.5m/s natural air flow) or up to 11 W (at 70°C at 2 m/s forced air flow) cooling capacity. See Figure 6.

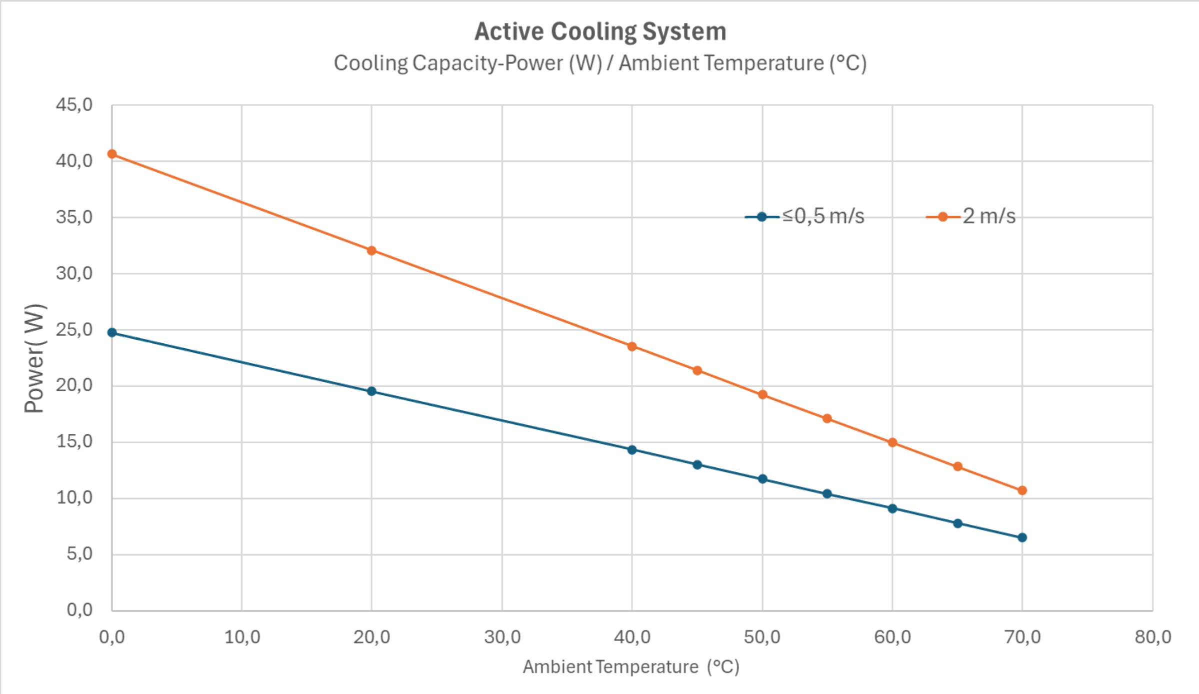


Figure 6: Cooling capacity of Active Cooling solution in different ambient temperatures and different air flows at ambient air-flow rate (max 0.5 m/s) and 2 m/s air-flow rate

5.2 M.2 Passive Cooling solution - Fan-less system with embedded aluminum heat spreader

The M.2 Passive Cooling Solution with an embedded aluminum heat spreader is the preferred solution for fan-less embedded systems with space constrains. It has the following characteristics:

- In embedded systems, if there is a space between main heatsink and the M.2 board, the aluminum heat spreader solution can be used as a heat transfer component from the M.2 board to the external enclosure.
- Provides efficient heat dissipation for compact and fan-less designs.
- Suitable for lower power applications and critical small spaces as 12 mm height (total module height of 6 mm from top of the Metis AIPU).

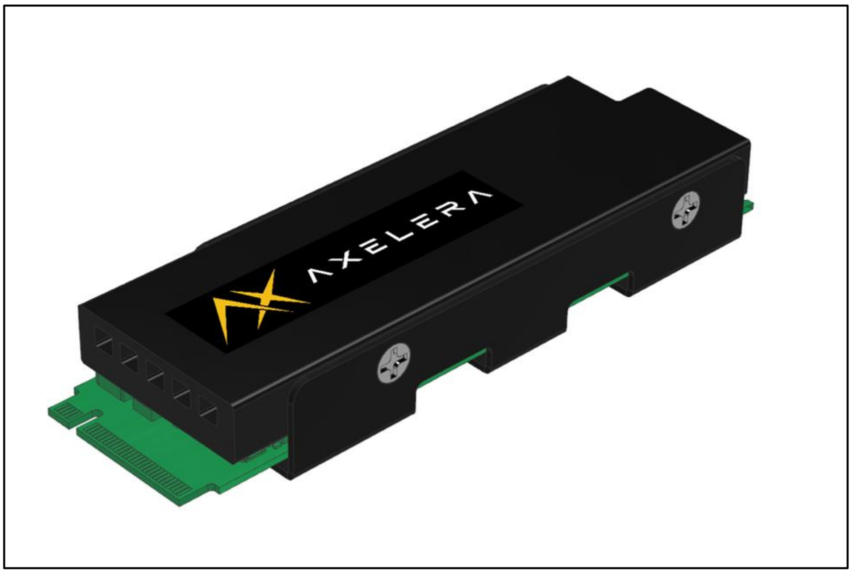


Figure 7: Rendering of the Metis M.2 card with an example heat spreader. Heat spreader not supplied by Axelera.

Figure 8: Example of a fan-less embedded system

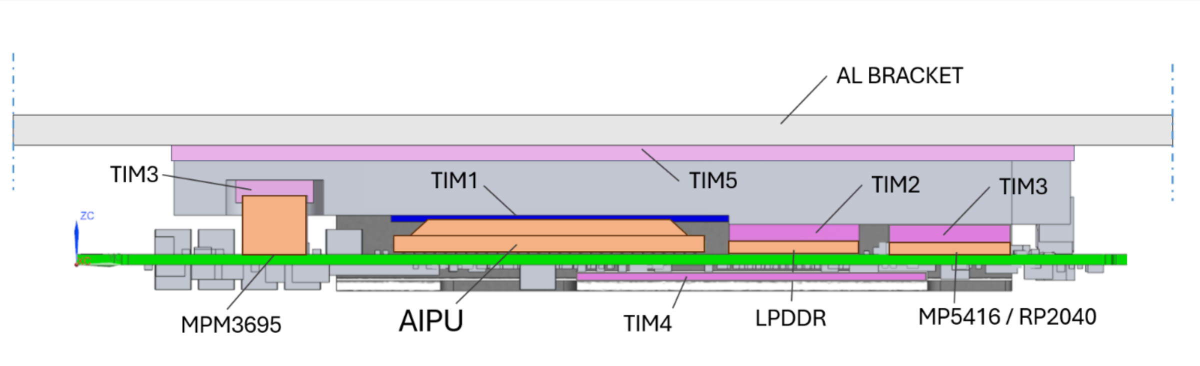


Figure 9: Stack-up of the M.2 Passive Cooling solution showing the heat spreader in an embedded fan-less system

The thermal values are as following according to standalone and with an additional cooling plates.

Table 6: Product specifications of M.2 Passive Cooling Solution with embedded heat spreader

Part name	Total Length (w-card/ Heatsink-only) (mm)	Height to top of the heatsink (mm)	Width (mm)	Weight (g)	Thermal Resistance Values		Total Cooling Capacity (W)
					Standalone	In case of attached to 200x250 mm, 2 mm thick Al Cooling Plate *	
Heat Spreader / Passive Cooling	80 / 72.5	12	25	25	~ 8.3(°C/W) (under forced air flow of 3 m/s)	~ 3.3(°C/W) (constant Air flow of max 0.5 m/s)	3 to 7.4

** For the attached cooling plate, a TIM material (1 mm thick, 1.8 W/mK thermal conductivity) between Aluminum Heat spreader and Cooling Plate is considered.*

Parts List for the M.2 Passive Cooling Solution

The M.2 Passive Cooling Solution consists of the following parts as shown in Table 7.

Table 7: Parts list for the M.2 Passive Cooling Solution with embedded aluminum heat spreader

Part name	Material type	Material thickness (mm)	Qty
M.2 2280 Metis PCB	FR4	0.8 mm	1
AL Heat Spreader	AL6000 / Anodized aluminum	n/a	1
Screw (x4)	M2.5 x 5mm	n/a	4
Bracket Bottom	Sheetmetal / Powder coating	1 mm	1
Thermal Pad-TIM1/2/3/4	Refer to Table 5.	0.5 - 2 mm	4
Thermal Pad-TIM 5	VOT- A6S2	1 mm	1
Isolation Plate-Mylar	A3 PC1870A+3M9448	0.275 mm	1

5.2.1 M.2 Passive Cooling Solution - Cooling Capacity

If the embedded structure has an internal fan and the air flow rates is a minimum of 3 m/s, the Heat Spreader Solution can be usable under the following ambient temperature. Under these conditions, the total system thermal resistance value will be 8.3°C/W.

To improve power, Axelera AI recommends using the heat spreader with an additional aluminum plate (For example an aluminum plate 200x250 mm 2 mm-thick) and fixed with a 1.8 W/mK thermal pad. In this assembly configuration, the total resistance will be 3.3°C/W under the natural convection conditions (natural convection - max air flow 0.5 m/s).

According to test results, the M.2 Embedded Aluminum Heat Spreader Solution can reach 7.4 W (at 70°C) cooling capacity with an additional cooling plate in the embedded system.

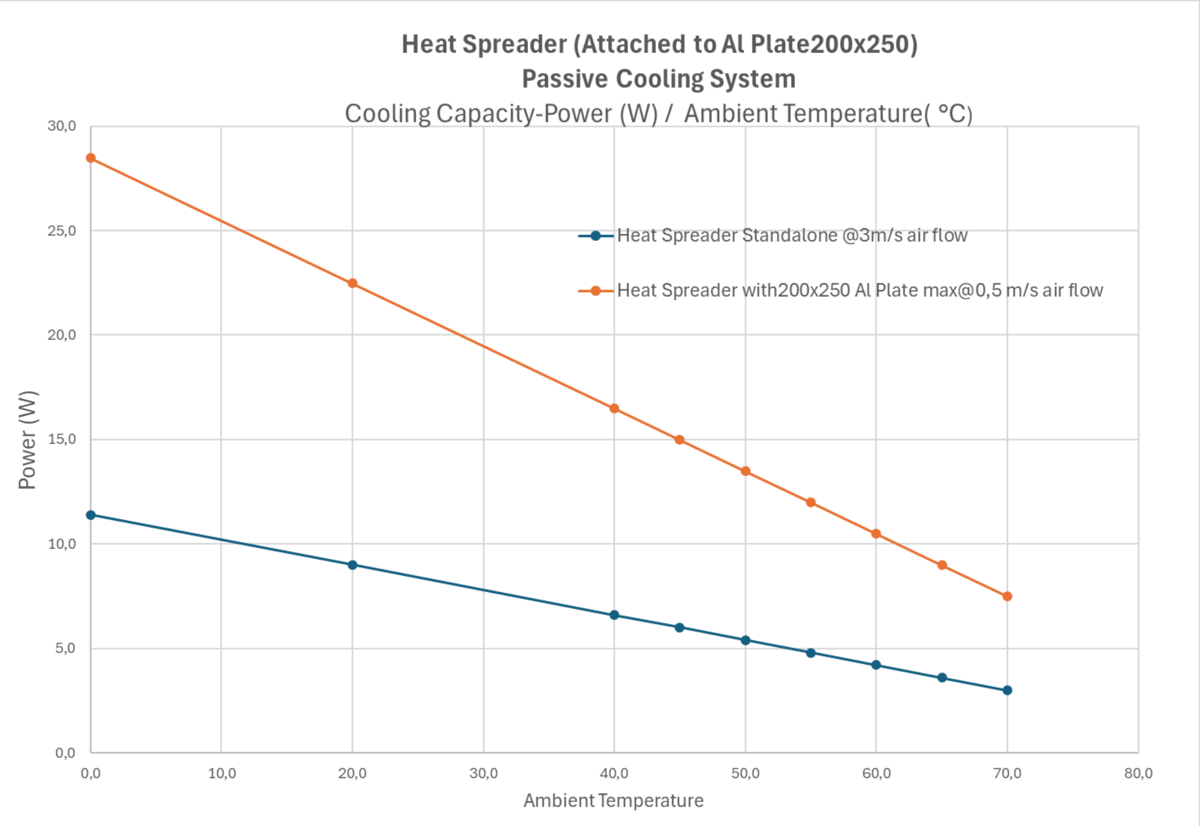


Figure 10: Cooling Capacity of Heat Spreader Solution-Embedded System Solutions in different Ambient Temperatures

5.3 Passive cooling solution with forced airflow

Future revisions of this document will also include the characterization of a system that uses a passive heatsink on the M.2 card with forced airflow at the system level.

6 Appendix

6.1 3D model documents

Information is provided in the following IGS documents:

- **M.2 Board Standalone (No Cooling)**
    - Metis M.2 AI Accelerator Card – No Cooling Solution
- **M.2 Active Cooling Solution**
    - Metis M.2 AI Accelerator Card - Active Cooling Solution

6.2 2D drawings

Please refer to the *Metis M.2 AI Accelerator Card Datasheet* for 2D drawings of the Metis M.2 card.

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