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Thermal Management Solutions for General Illumination Applications with AM

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Study objectives

The study presented here, investigated

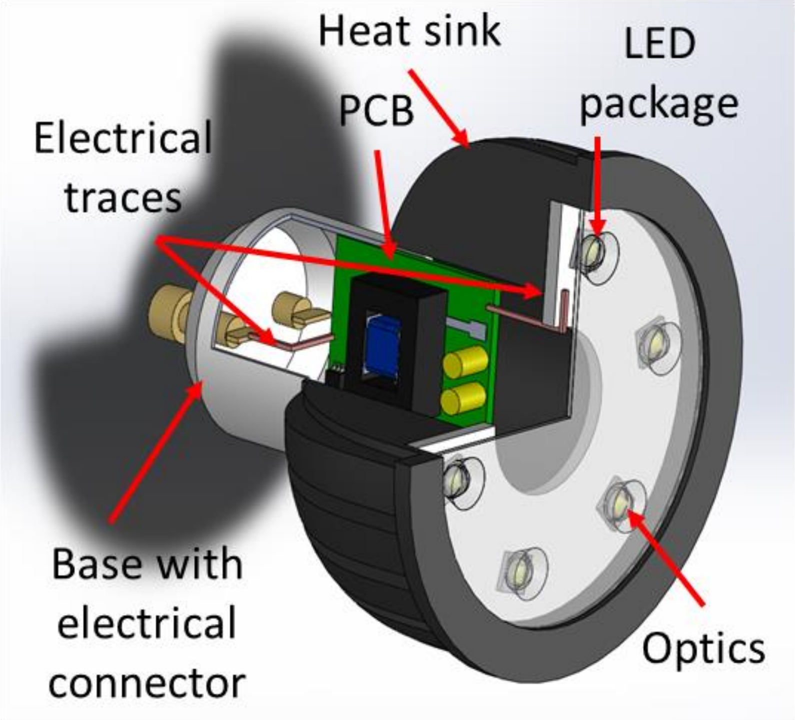
- AM MR-16 heat sinks using different
  - Materials, machines, print parameters, and post-processing methods
- Compared AM heat sinks to commercially available MR-16 heat sinks, traditionally fabricated
  - LED module case temperature and LED light output

Aspects of designing and AM heat sinks for illumination applications and the lessons learned are discussed

Light products for general illumination

Functional lighting product components

- Thermo-mechanical
  - Heat sinks
  - Housing
- Electrical
- Optical

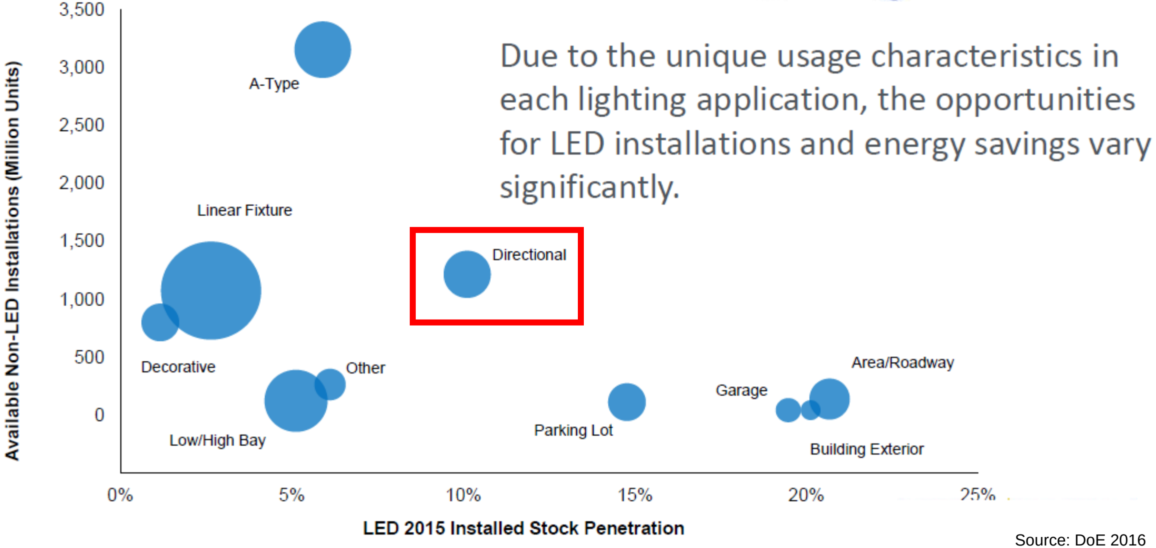


LED lamp and fixture market

- Cost of MR16 lighting fixture
  - $15 to $300
  - MR16 lamp cost $4 to ~$40







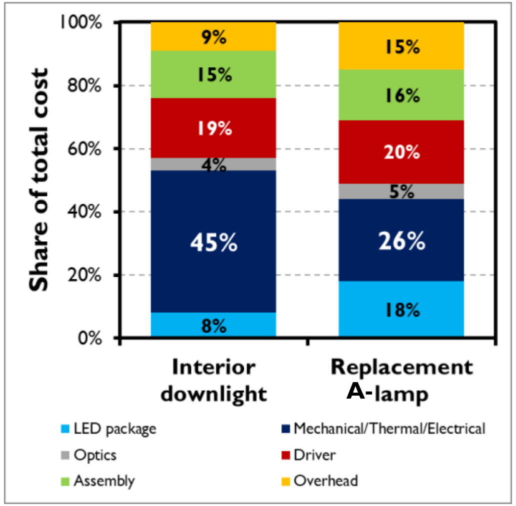
Source: DoE 2016

The cost and weight of heat sinks

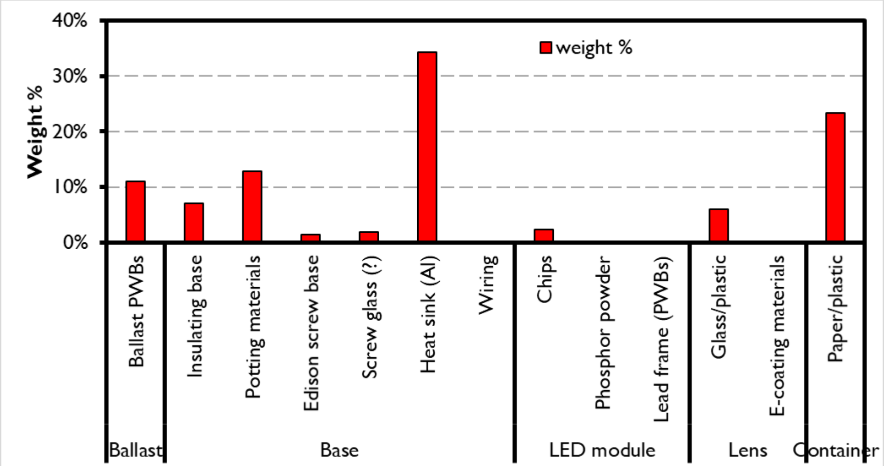
- Heat sinks contribute a significant part of an LED lighting product cost
  - DoE SSL roadmap, R & D plan Sep. 2017.

Stonecipher and Alvarez (Aug. 2014) LEDs magazine webinar, DoE SSL roadmap: R & D plan Sep. 2017

- Heat sinks account for ~30-50% of the weight in a typical LED lighting product
  - Hendrickson et al. 2010: 3 samples up to 60%
  - NEMA 2013 report: 10 samples average 34%
  - Dzombak et al. 2017: 17 samples up to 50%



Comparison of Cost Breakdown for Different Lighting Applications
Source: DOE SSL Roundtable and Workshop attendees and industrial partners
Solid-State Lighting; R&D Plan; Sept. 2017



Exploration of carbon footprint of electrical products: Guidance document, NEMA 2013

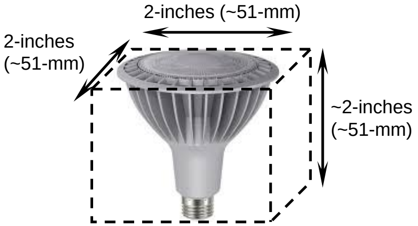
MR16 lamp

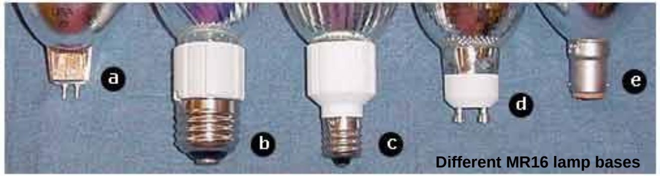
MR16

- “MR” multifaceted reflector
- “16” from 16×1/8-inch or 2-inches (~5-cm) diameter at its largest circumference


MR16 halogen lamp with incandescent A-lamp


LED-based MR16 lamp





Different MR16 lamp bases

MR16 halogen equivalent power [W]	Typical MR16 light output [lm]	LED based MR16 input electrical power [W]	LED based MR16 output thermal power [W]
20	~200	~2.6	~1.7 ($\eta_{optical}$≈35%)
35	**~350**	**~4.5**	**~3.0 ($\eta_{optical}$≈33%)**
50	**~500**	**~6.6**	**~4.8 ($\eta_{optical}$≈27%)**
75	~700	~9.0	~6.7 ($\eta_{optical}$≈25%)

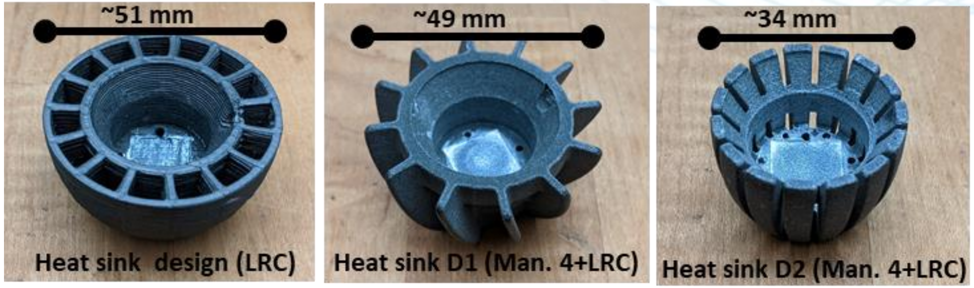
Most common MR16 lamps used in lighting applications

Study tasks

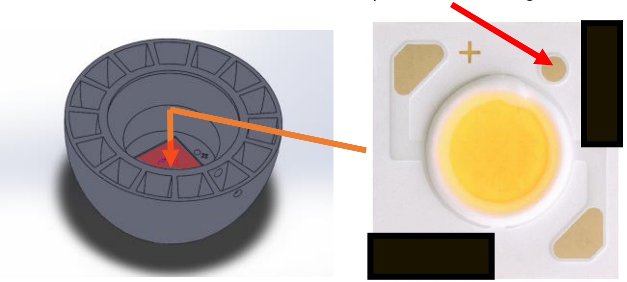
- Design and model the heat sink for an LED-based MR16 lamp
- AM fabrication of the heat sink using the material for heat conduction
- Benchmark testing against commercially available, traditionally manufactured, heat sink
- Performance comparison between AM and traditionally manufactured heat sink
  - Measurement of heat sink performance with surface probes
  - Comparison between testing and simulation results

Study samples

- Tested 14 samples in total
  - AI: 2 benchmark samples
    - commercially available
  - A: Manufacturer 1, 1 sample
  - B: Manufacturer 2, 3 variations
  - C: Manufacturer 3, 2 variations
  - D: Manufacturer 4, 4 variations
  - E: Manufacturer 5, 2 variations
- Measured
  - LED case temperature and light output using injection molded lens as the benchmark



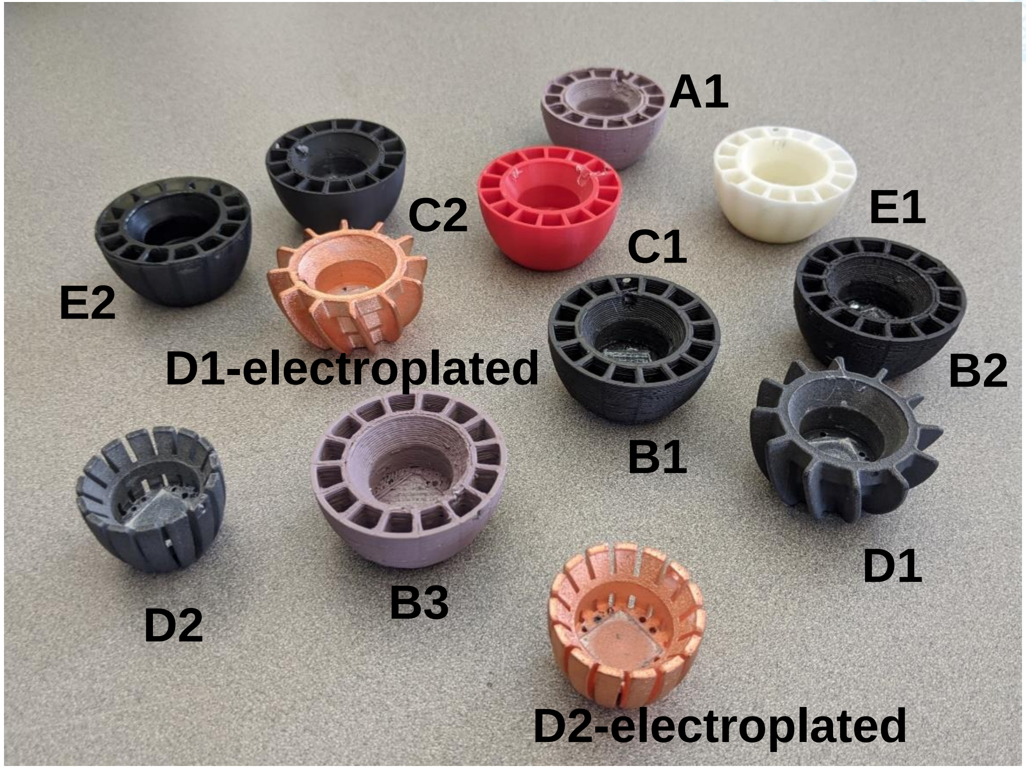
Case temperature monitoring location



Study samples

Tested 14 samples in total

- A: 1 sample (Bound metal deposition)
- B: 3 variations (Material extrusion)
- C: 2 variations (Material extrusion)
- D: 4 variations (Powder bed and inkjet head, 2 variations electroplated)
- E: 2 variations (Digital light processing)



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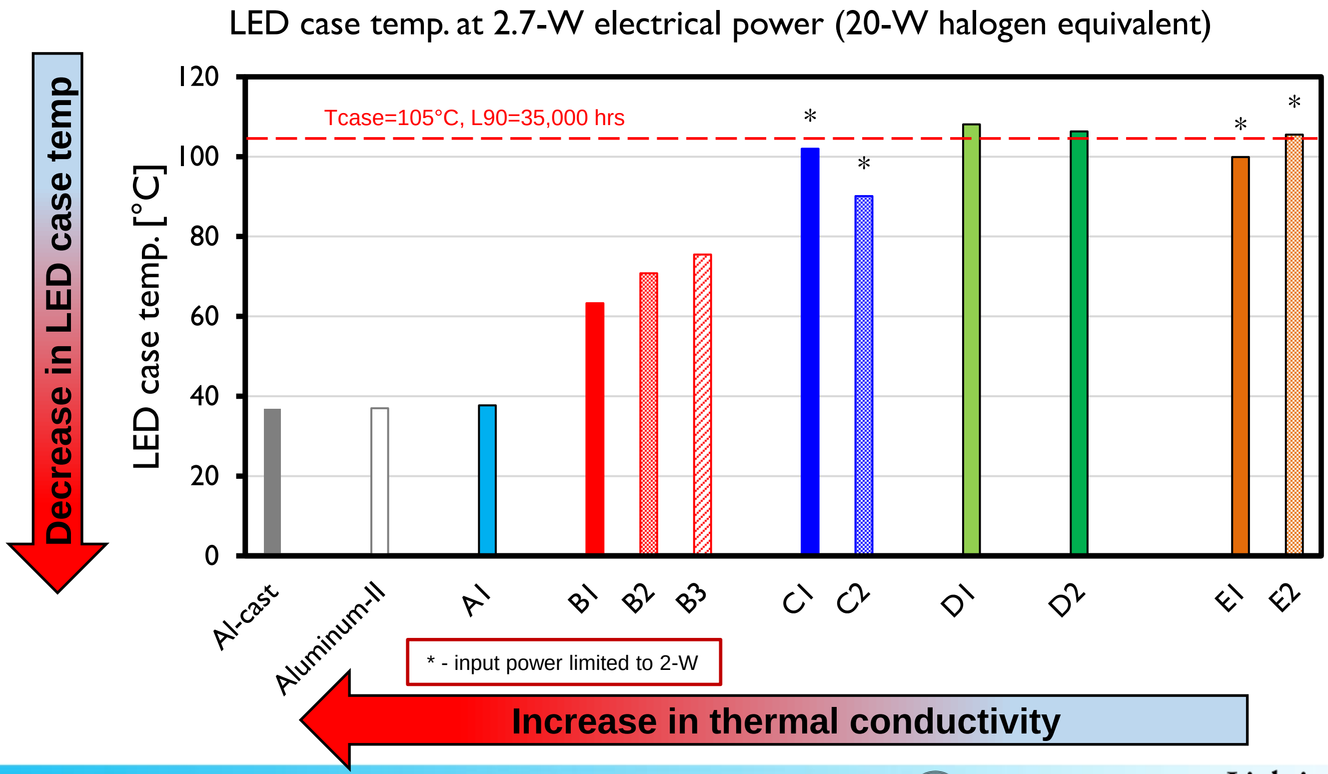
AM material thermal conductivity effects

Heat sink performance – 20 W halogen equivalent



AM material	κ W m⁻¹ K⁻¹
A1	85
B1	4
B2	3
B3	2
C1	~0.4**
C2	~0.5**
D1	0.3
D2	0.3
E1	0.3
E2	0.3

** - in-plane thermal conductivity from material specifications and literature

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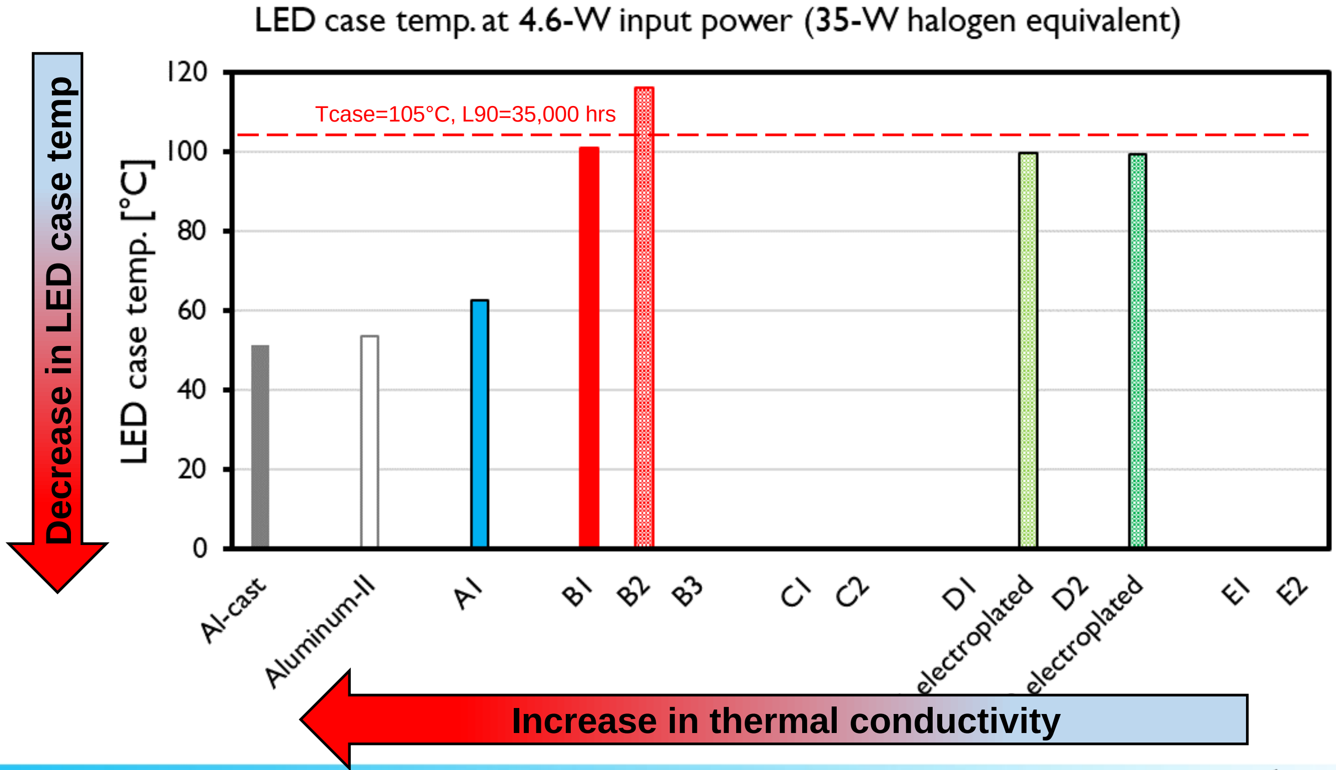

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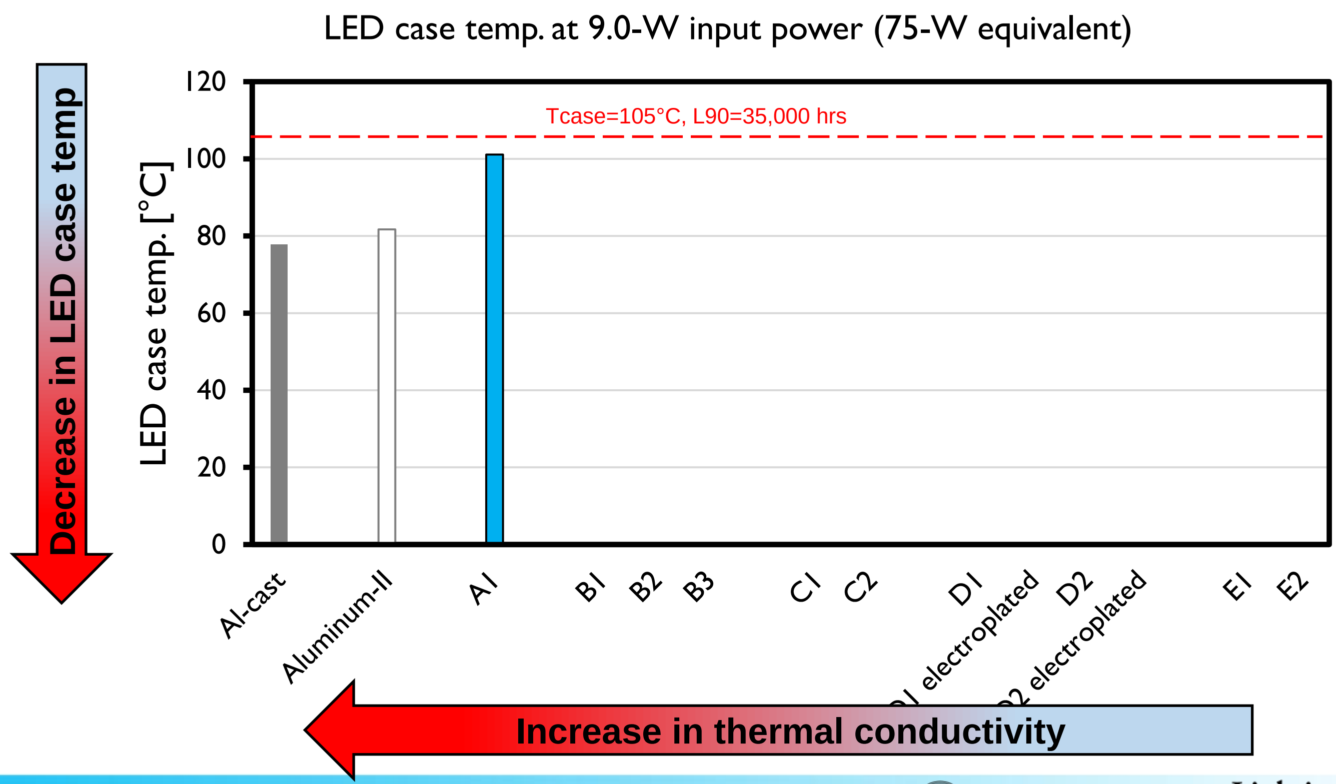

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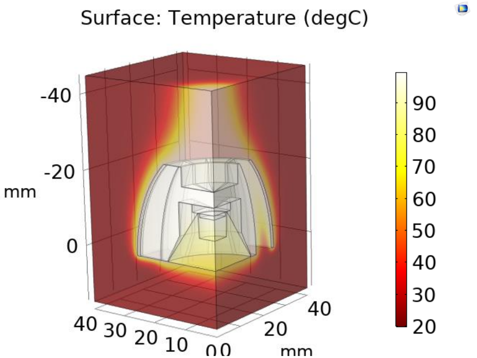
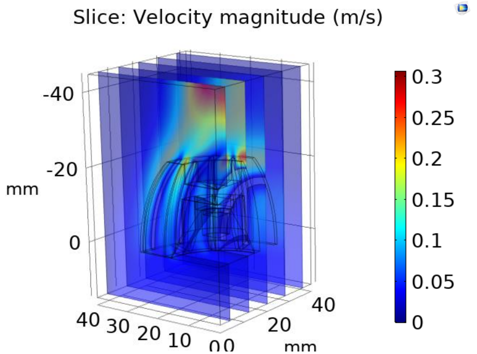
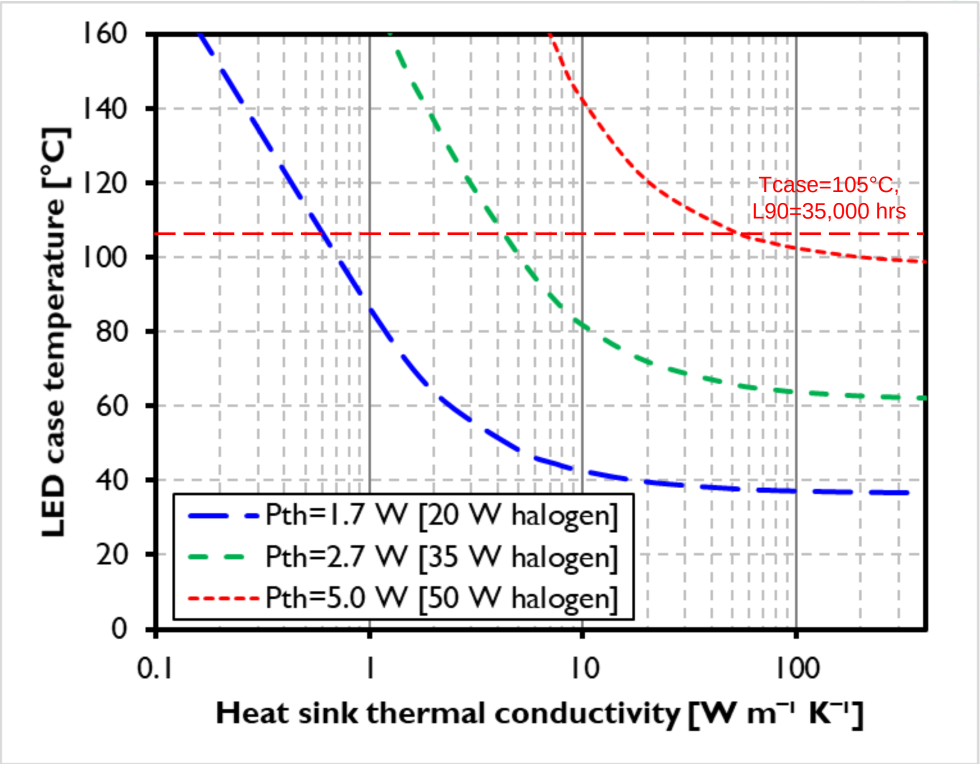
Heat transfer modeling of the MR16 heat sink







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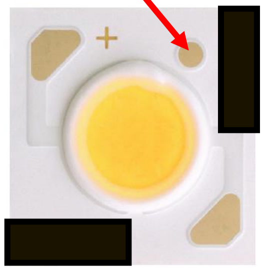
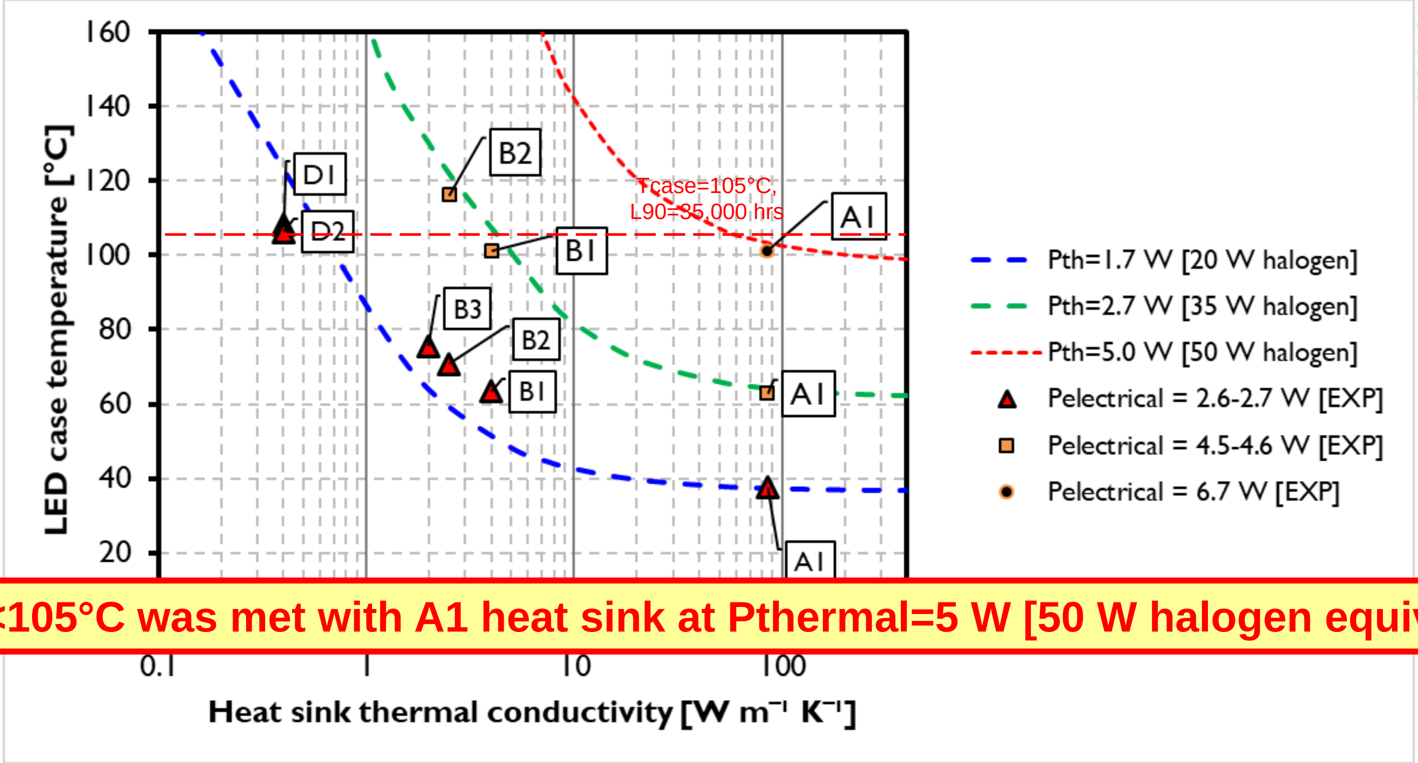


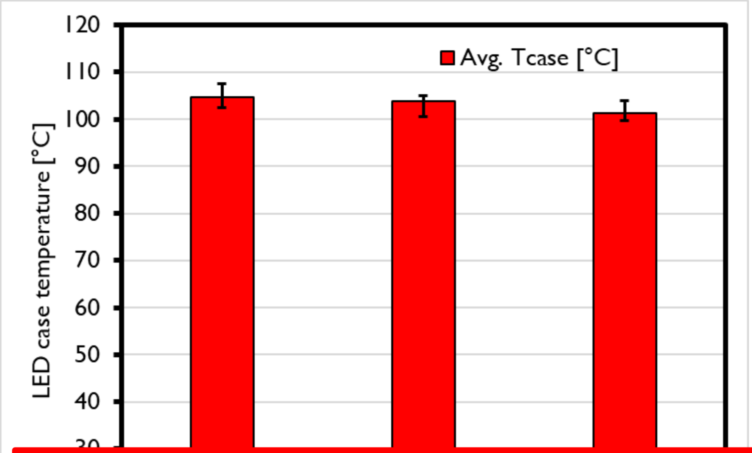
Case temperature measurement vs. model prediction

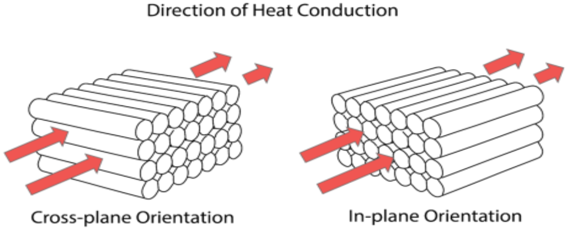


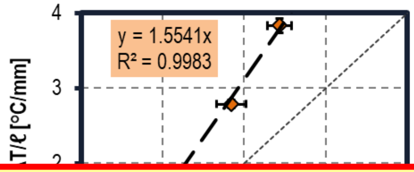
Tcase<105°C was met with A1 heat sink at Pthermal=5 W [50 W halogen equivalent]

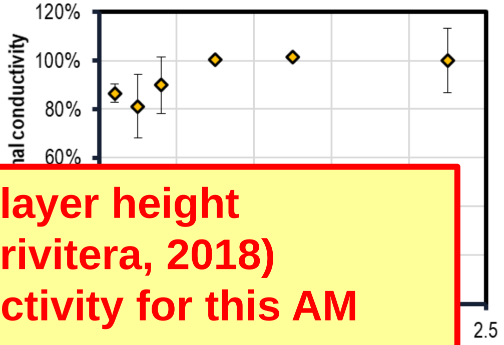
Print layer height effects

Print layer height effect









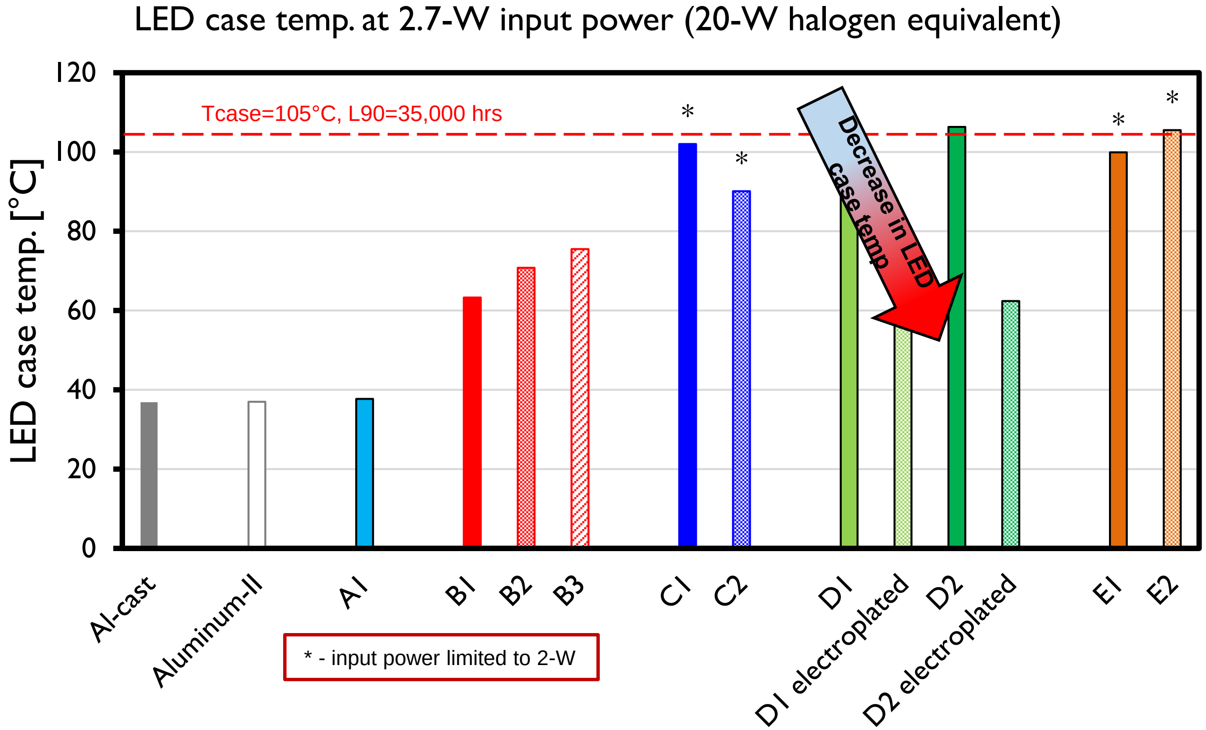
No significant difference in Tcase was observed with layer height

1) **A 15-20% change in relative thermal conductivity (Privitera, 2018)**
2) **The difference in in-plane to cross-plane thermal conductivity for this AM material was 6 to 2.25 W m^{-1} K^{-1}**

Source: Olivia Privitera, Master's project 2018

Copper electroplating effects

Heat sink performance – 20 W halogen equivalent



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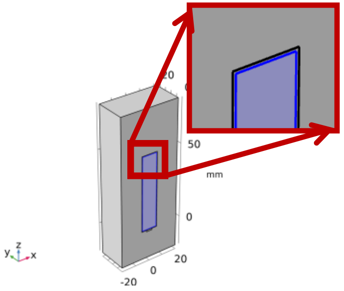
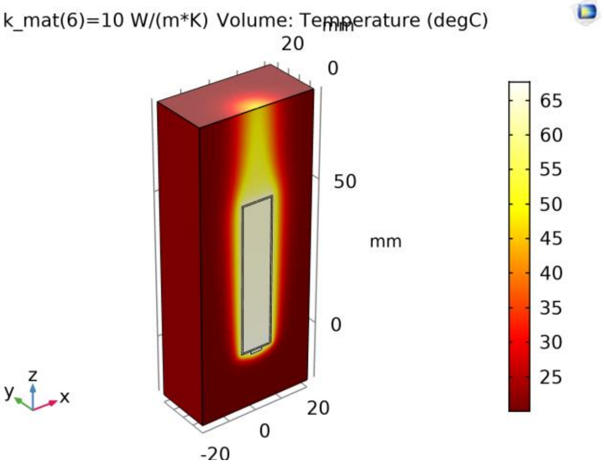
** - in-plane thermal conductivity from material specifications and literature

Investigating Cu plating effects

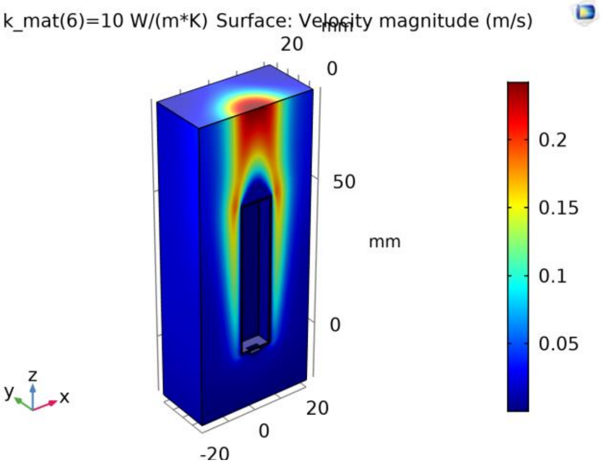
- Conjugate heat transfer thermal modeling
- Thermal power = 1 W
- Skin thickness = 0.5 mm
- Heat sink geometry
  - Diameter=10 mm
  - Height = 50 mm



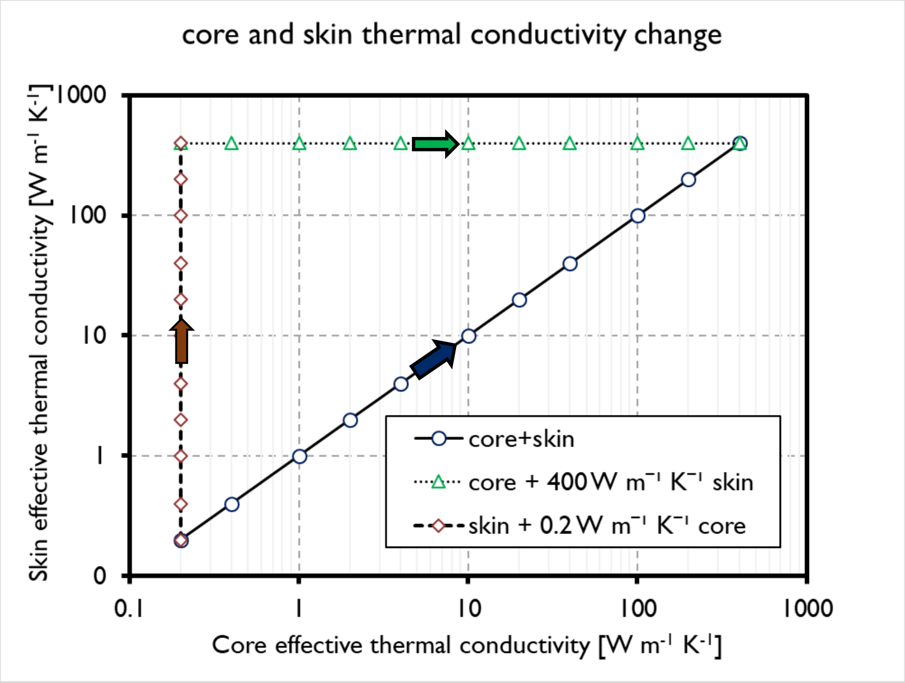
- Temperature distribution profile in the heat sink and fluid flow

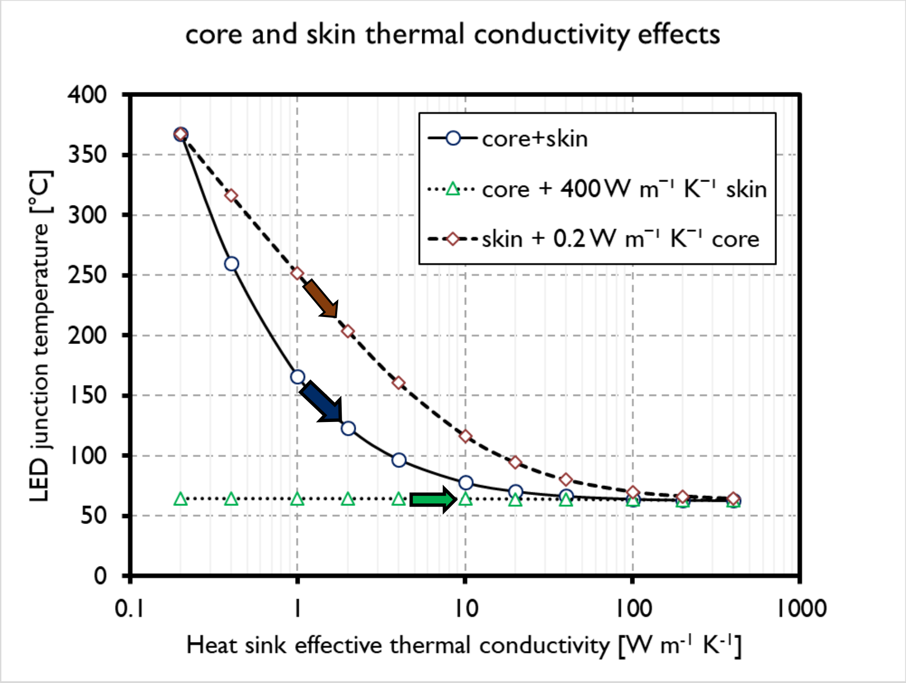


- Fluid flow field around the heat sink



Cu plating effects on thermal performance

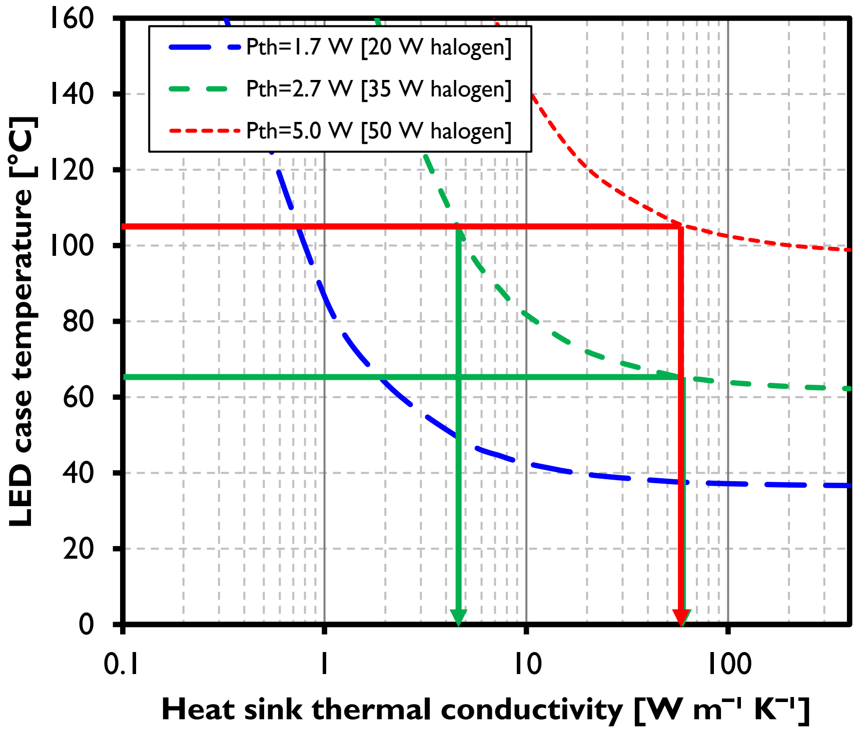




Summary

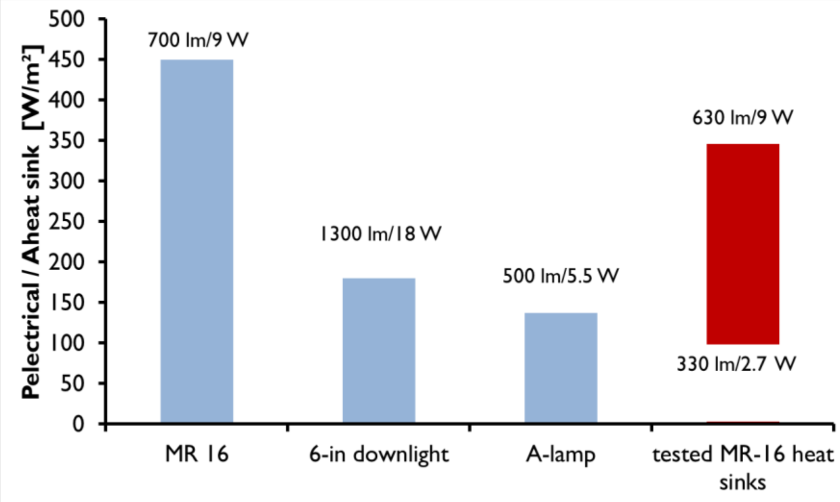
Summary

- AM material with high thermal conductivity and or post-processing was observed to increase thermal performance of AM MR16 heat sink
  - Maintaining Tcase<105°C
- Thermally conductive composite AM material and metal AM material ($\kappa_{effective}$>5 W m⁻¹ K⁻¹) have the potential to maintain a case temperature below 105°C at for 35-W halogen equivalent
  - Post-processing such as copper electroplating also show potential
- Limited material + post-processing combinations capable of handling 50-W halogen equivalent (~5-W thermal power in 5×5×2.5 cm^3 volume)



General illumination application comparison

- The tested conditions represents most common indoor lighting conditions with respect to surface energy density
- For the higher surface energy density application requirements
  - Copper plating or other metallization post-processing the surfaces
    - Most lamp and fixture housings are anodized or powder–coated for aesthetics
  - Material with $\kappa_{effective}$>40 W m^{-1} K^{-1}
  - Part consolidation approach
    - Lamp to lighting fixture with integrated heat sink, since the geometry is not limited by the lamp envelops



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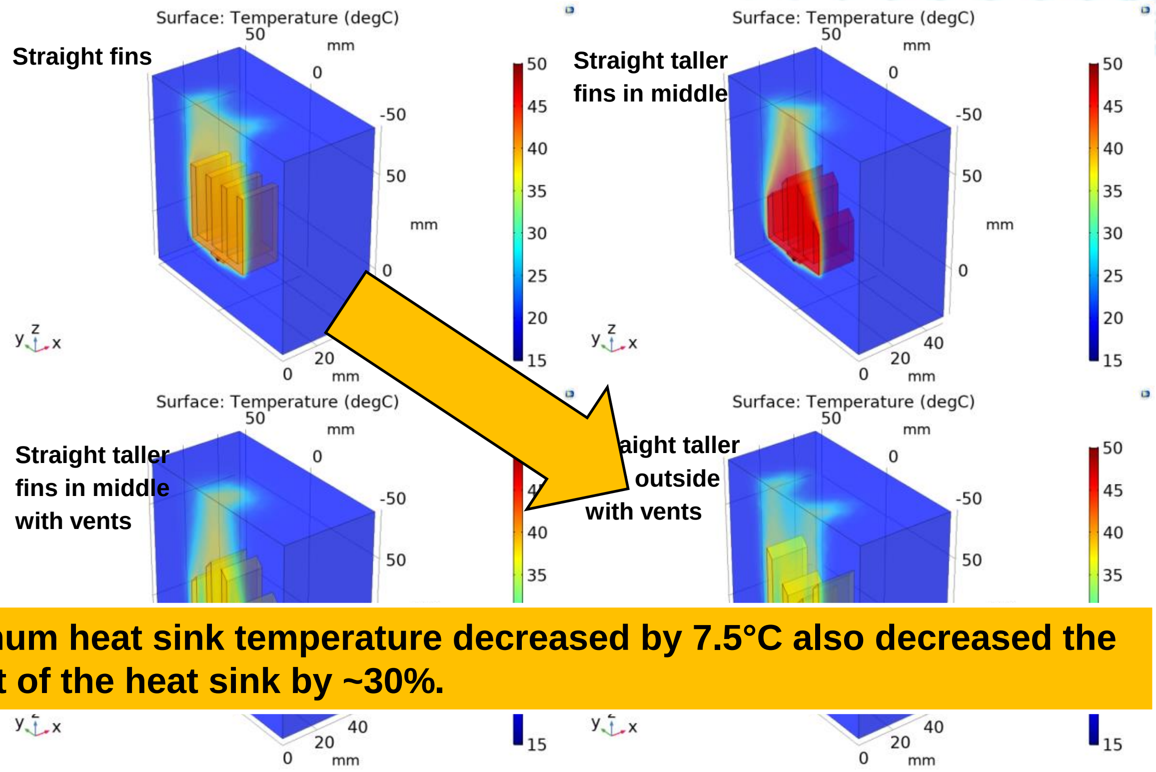
Future work

- Investigate surface post-processing
  - Electroplating material
  - Electroplating thickness
- Investigate geometric designs
  - Increase convective coefficient
  - Increase flow around the heat sink (reduce pressure drop)



Maximum heat sink temperature decreased by 7.5°C also decreased the weight of the heat sink by ~30%.

Acknowledgements

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THANK YOU!

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