Confined Direct Two-phase Jet Impingement Cooling with Topology Optimized Surface Engineering and Phase Separation Using Additive Manufacturing

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COOLERCHIPS™

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PURDUE UNIVERSITY

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Prof. Justin Weibel

BINGHAMTON UNIVERSITY
State University of New York

Prof. Bahgat G. Sammakia
Prof. Srikanth Rangarajan
Prof. Scott Schiffres

SEGUENTE

Dr. Ryan Enright
Dr. Raffaele Luca Amalfi

Project Vision

- *To address the instability, boiling crisis and reliability of confined two-phase jet impingement cooling, our solution includes new algorithms for topology optimization of the cooling structure, novel on-chip direct printing methods for laser powder bed fusion of multi-porosity wicks, and an additively manufactured multi-input\multi-output fluid distribution manifold.*

Total Project Cost:	$1.8M
Length	36 mo.

COOLERCHIPS Kickoff Meeting
October 18 & 19, 2023

Team and Program Organization

Fed. funding:	$1.8 M
Length	36 mo.

Principal Investigator
Tiwei Wei
Purdue University

Multi-level Modeling, & Design

Justin Weibel
Purdue University (ME)
- Topology optimization
- Microscale, multi-phase transport modeling

Tiwei Wei
Purdue University (ME)
- Semiconductor packaging
- Electronic cooling

Bahgat G. Sammakia
Binghamton University (ME)
- System level modeling
- System/rack level reliability modeling

Fabrication, Packaging, & Integration

Scott Schiffres
Binghamton University (ME)
- Additive manufacturing of metal wicking and vapor membrane manifold structure

Tiwei Wei
Purdue University (ME)
- Thermal test chip design
- Cooler integration and packaging assembly

Sever Level Two-phase Cooling Loop Test and Reliability Investigation

Tiwei Wei
Purdue University (ME)
- Two-phase liquid loop pumps and systems
- Thermal/fluidic characterization

Justin Weibel
Purdue University (ME)
- Characterization of Two-Phase Jet Impingement enhancement
- Cooling test facilities

Rack Level Two-phase Cooling Loop Test and Reliability Investigation

Srikanth Rangarajan
Binghamton University (ME)
- System/rack level predictive modeling and reliability testing

Ryan Enright
Seguente
- Enhanced phase change heat transfer
- Integrated thermal management for ICT

Raffaele Luca Amalfi
Seguente
- Active and passive thermal technologies for datacenter cooling

Brief COOLERCHIPS Project Overview

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Tiwei Wei
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Ryan Enright
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Dr. Gopinath Sahu


Dr. Ketan Yogi


Shuhang Lyu

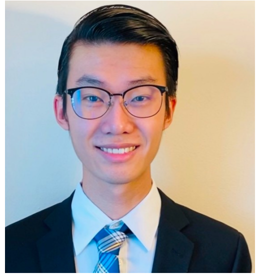

Sidharth Rajeev


Dr. Emily Stallbaumer-Cyr

Raffaele Luca Amalfi
Seguente


Keyu Wang


Akshat Patel

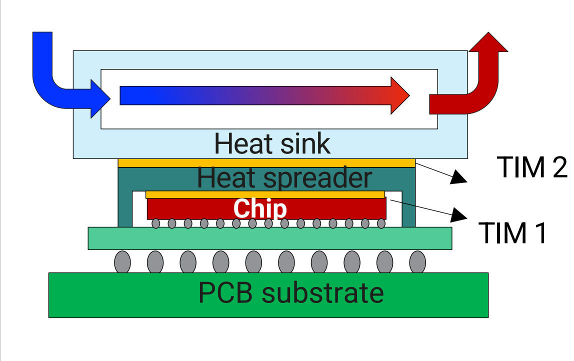

Yubo Song


Md Asif Iqbal

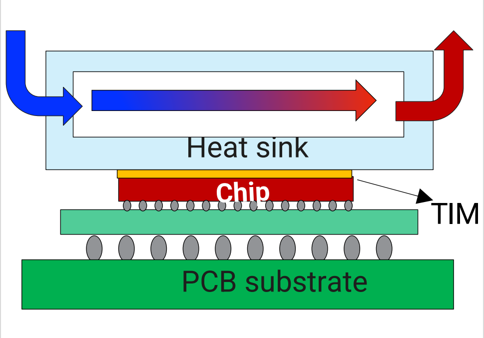

Harish Kumar Lattupalli

Rationale : State of the art liquid cooling for high performance system

Liquid cooling with Thermal interface material: TIM

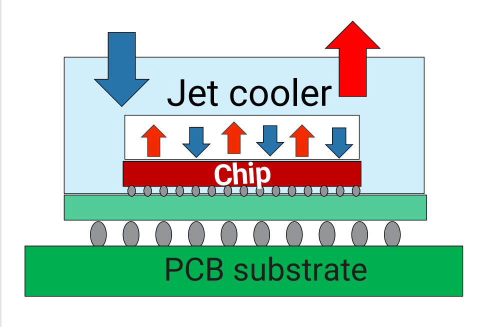


A: Liquid cooling + heat spreader (metal lid) with TIM 1 and TIM 2

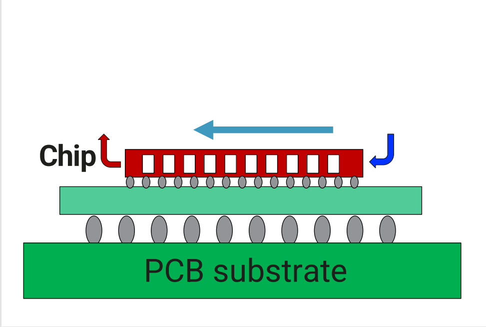


B: Directly attached liquid cold plate with TIM 1

Direct Liquid cooling on top of the chip backside



C: Bare die backside jet cooling



D: Embedded microchannel cooling inside the die

<u>Direct liquid jet cooling on the chip</u> can eliminate the thermal resistance of thermal interface material!

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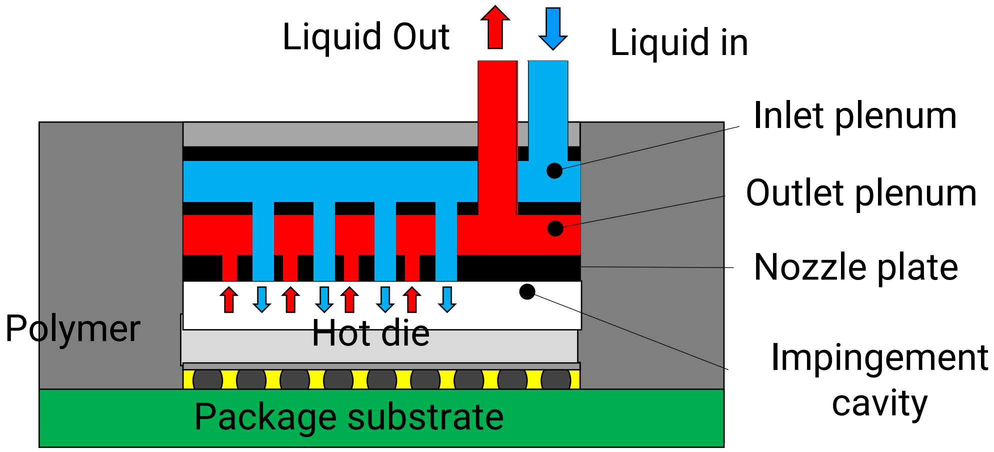
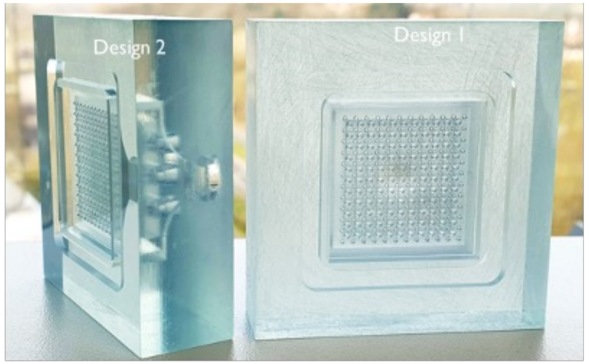
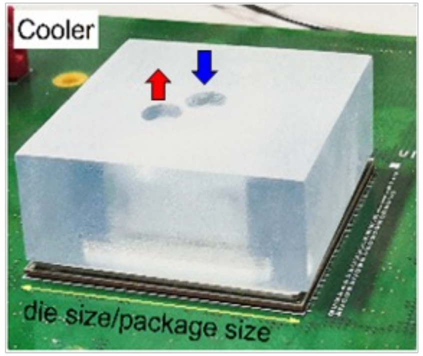
Previous efforts in our team: Single/two-phase impingement jet cooling

Single-phase jet cooling





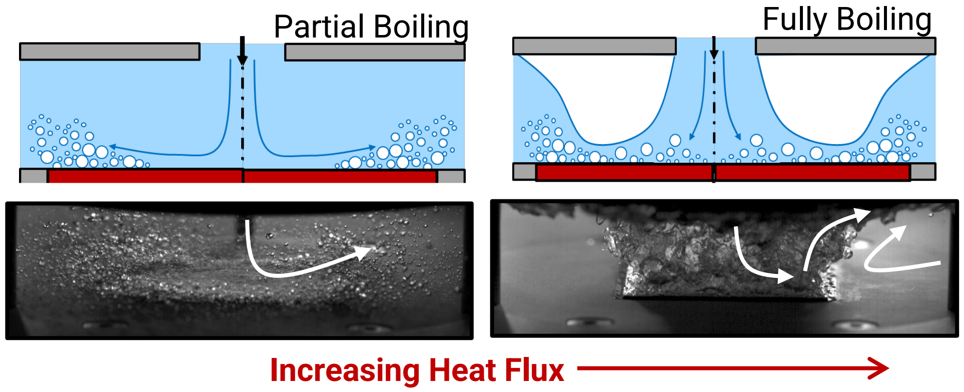


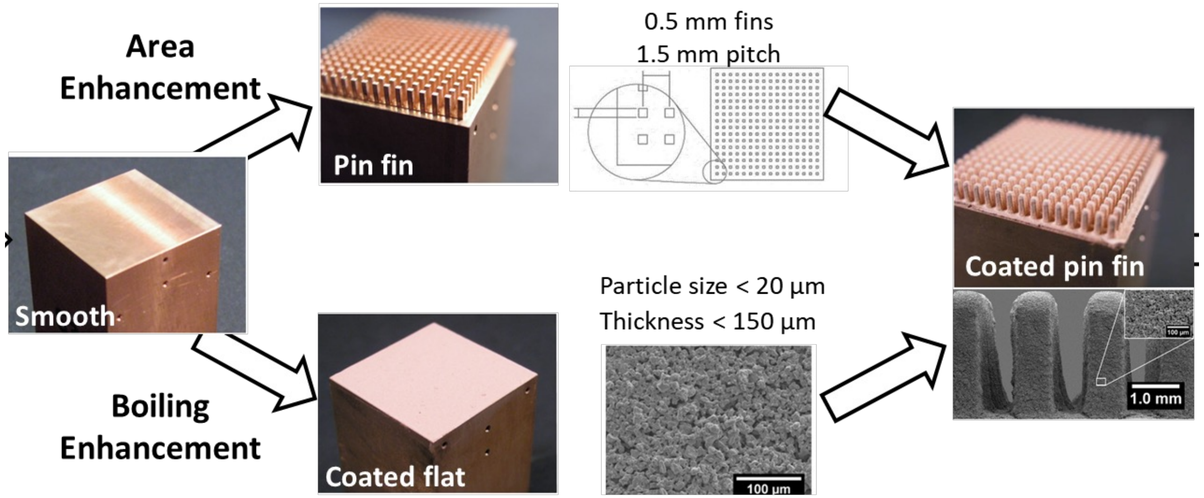
Wei *et al., IEEE IEDM*, 2017

Wei *et al., IEEE ECTC*, 2018

Wei *et al., IEEE Trans. Compon. Packag. Manuf. Technol*, 2021: 415-425.

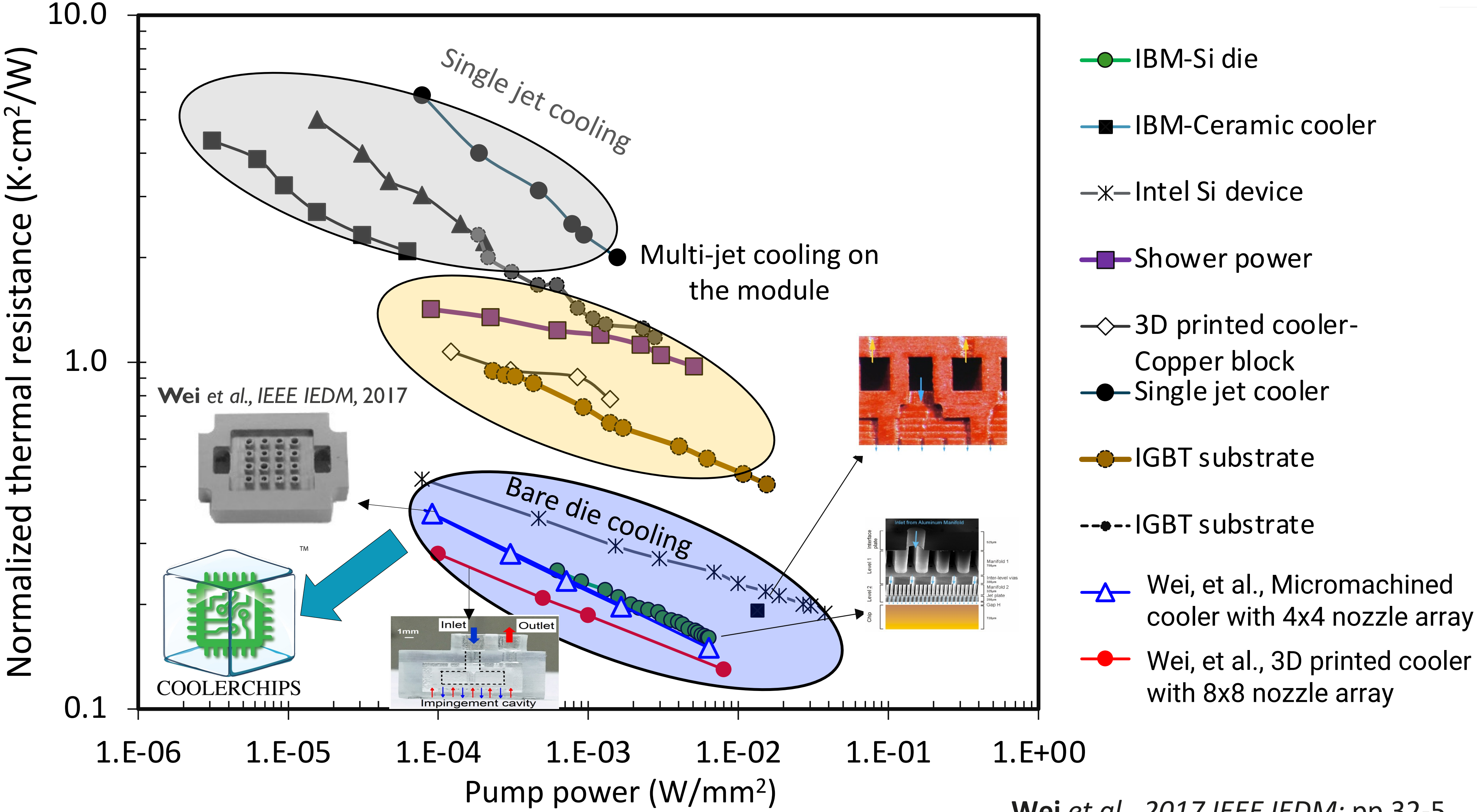
Two-phase jet cooling





[1] Clark, M. D., Weibel, J. A., & Garimella, S. V. IEEE ITherm 2018, pp. 424-428.
[2] Clark, M. D., Weibel, J. A., & Garimella, S. V. *International Journal of Heat and Mass Transfer*, 2019, *128*, 1095-1101.

Rationale : Polymer-based bare die microjet cooling benchmarking



Wei *et al., 2017 IEEE IEDM:* pp.32-5.

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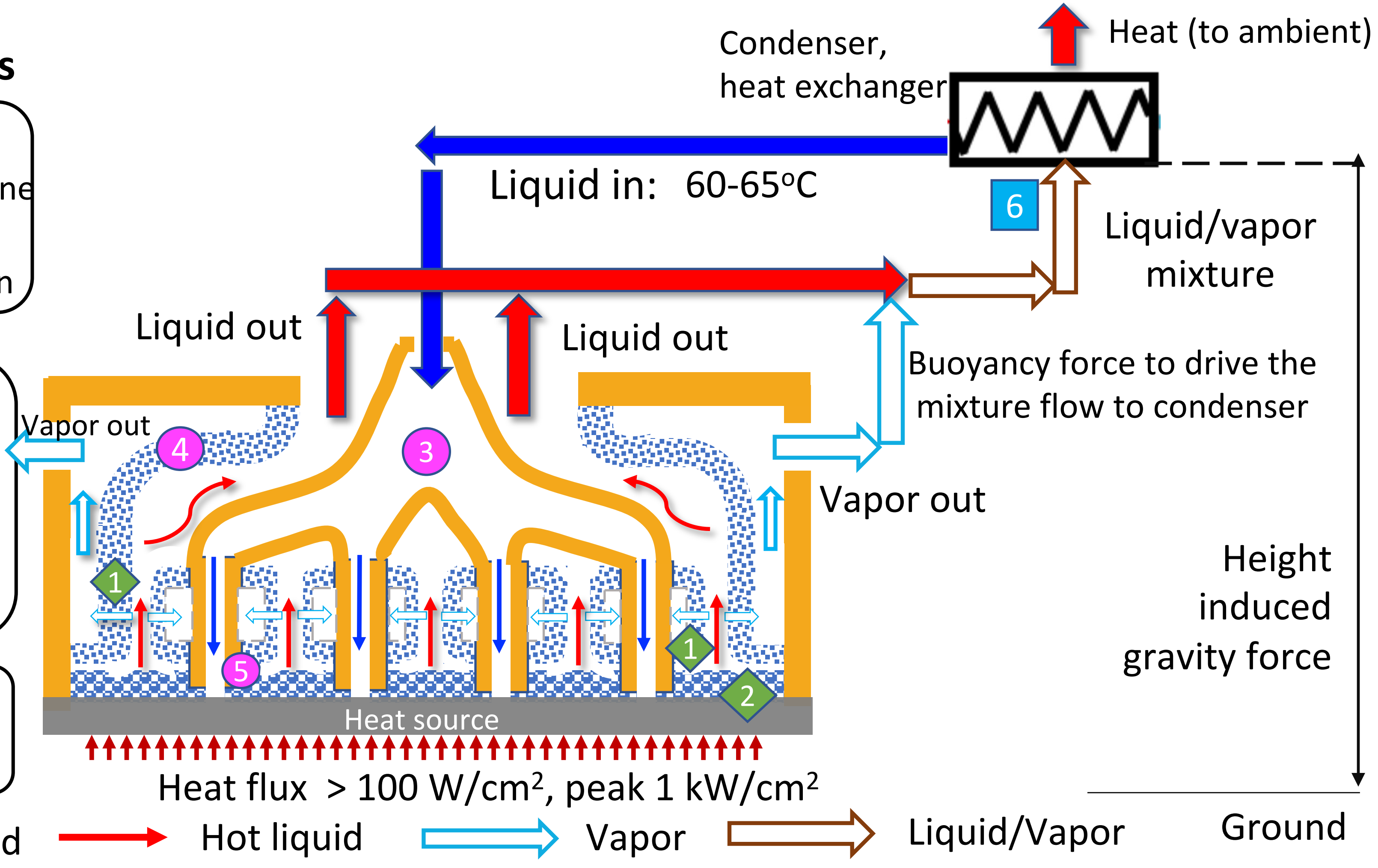
Moving from single-phase jet cooling to two-phase jet cooling

Key innovative features

- 1 Printing vapor venting multi-porosity membrane
- 2 Direct printing porous wick structure on Silicon

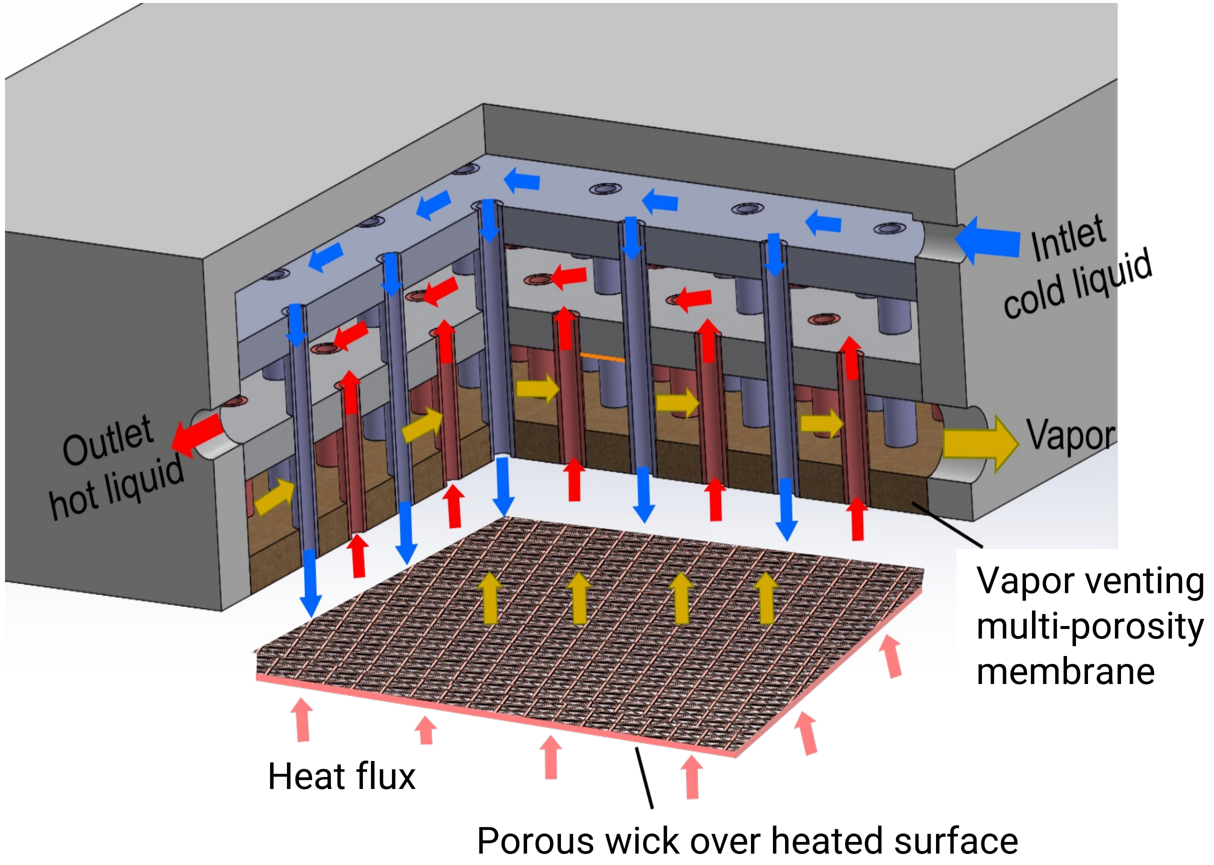
- 3 Topology optimized inlet manifold
- 4 Topology optimized membrane structure
- 5 Topology optimized inlet/outlet nozzle

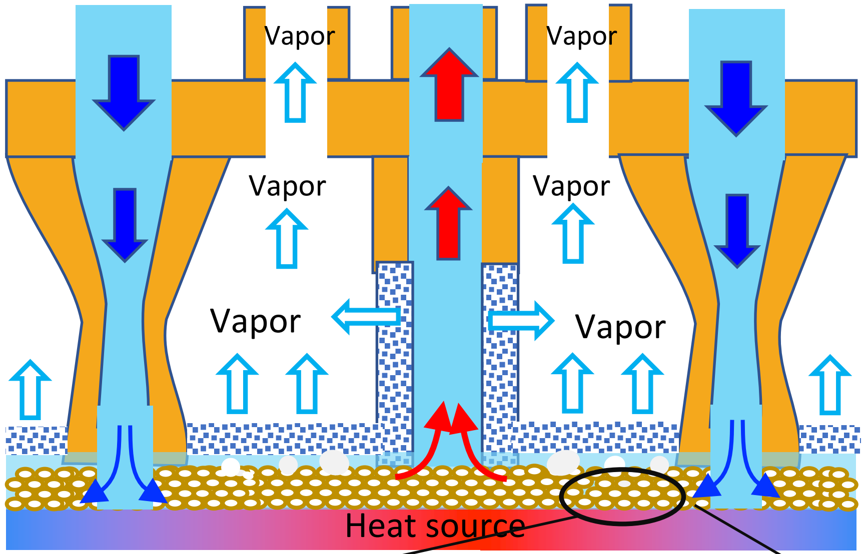
- 6 Passive thermosyphon loop system

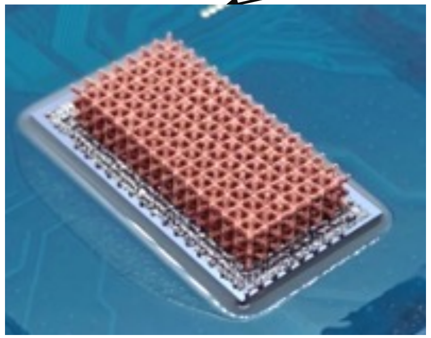


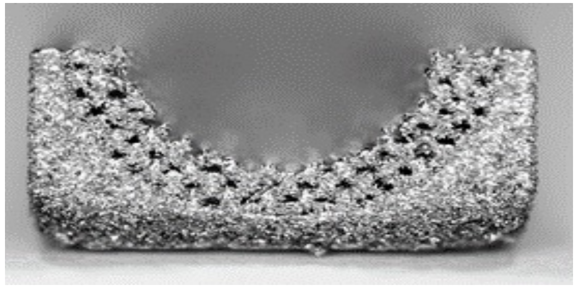
Our concept: Confined two-phase jet cooling in bare die packaging

Confined Direct Two-phase Jet Impingement Cooling with Topology Optimized Surface Engineering and Phase Separation Using Additive Manufacturing









Direct printing porous wick structure on silicon

Overview of the proposed project

Thrust 1: Multi-scale modeling

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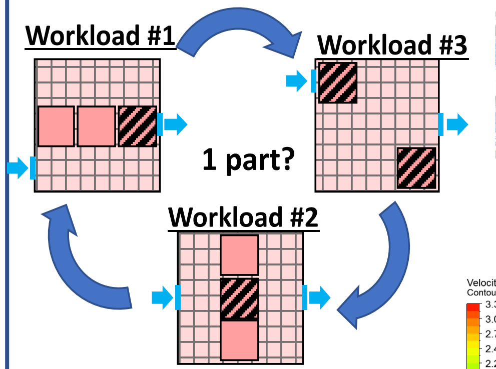
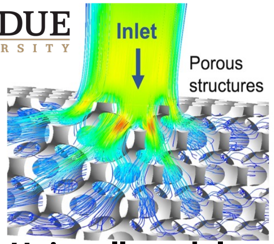
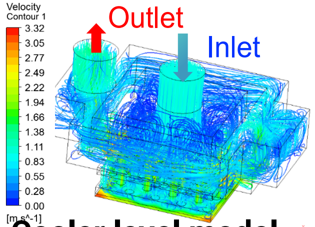


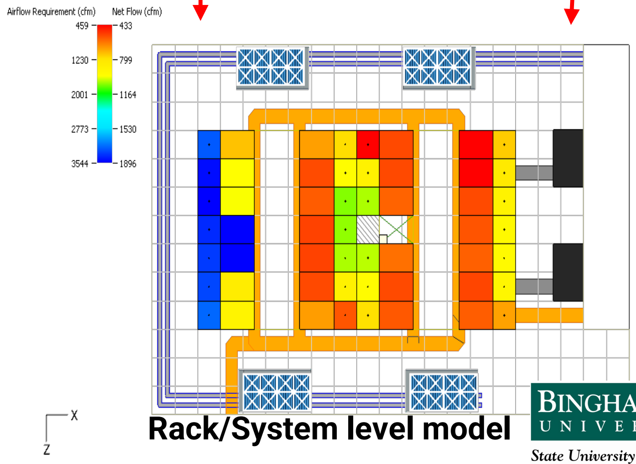
Topology optimization



Unit cell model



Cooler level model



Rack/System level model

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Thrust 2: Additive Manufacturing of the Cooling structure

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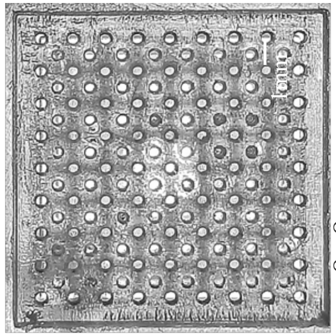
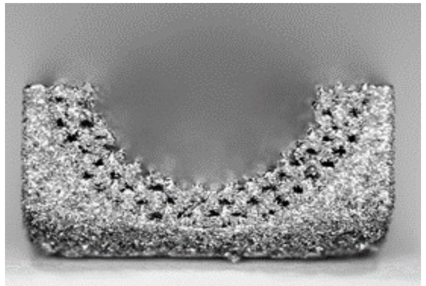


3D printed jet array



Direct on silicon porous structure

Thrust 3: Chip/Package-level cooler integration & test, reliability

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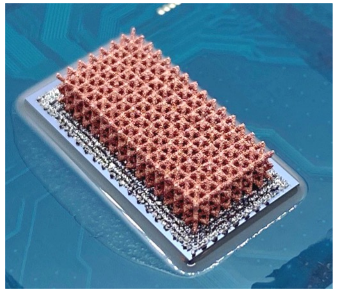

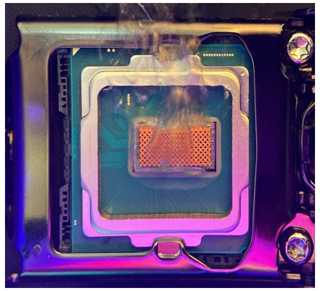

Boiling test on 3D printed porous structure on commercial server chip

Thrust 4: System/rack level test & reliability tests

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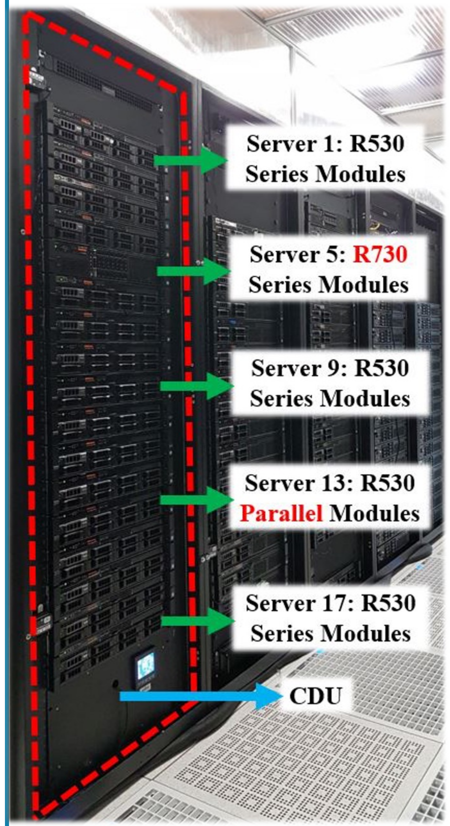


Rack level testing facility at Binghamton University

Seguente multi-evaporator thermosyphon CPU

Concept Summary

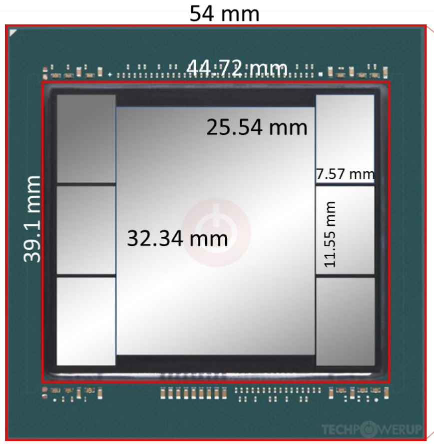
Project Goals

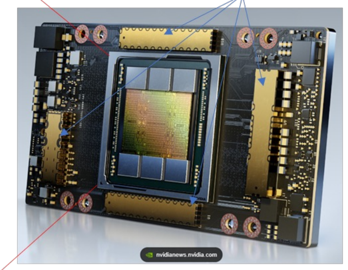
➢Achieve scalable fabrication of metal wick structures on Silicon; reliable integration with vapor venting membrane manifold structure;

➢Evaluate performance of evaporative two-phase jet cooler to meet target metrics;

➢ Develop a validated regime based empirical/theoretical predictive models;

➢Advancement of fundamental flow boiling models that account for complex vapor-liquid interfacial phenomena in two-phase confined jet impingement cooling;





nVidia A100 GPU chipset with central logic die (high power) surrounded by six high bandwidth memory HBM (low power, but more temperature sensitive).

Project Metrics

FOA Metrics	Units
Resistance Target	0.0035 K/W
Cooling Power % of IT_power	≤ 5%
System availability	99.9821 %
Chipset	high power mezzanine card GPUs (e.g. nVidia A100 GPU chipset)
Chip Power	3.5 kW/U (passive pumping loop) 8.77 kW/U (active pumping loop)
Power per server	17.5 kW (passive pumping loop), 5U 26.31 kW (active pumping loop) , 3U
Demonstration power mid project	7 kW (passive pumping loop), 2U 17.54 kW (active pumping loop) , 2U

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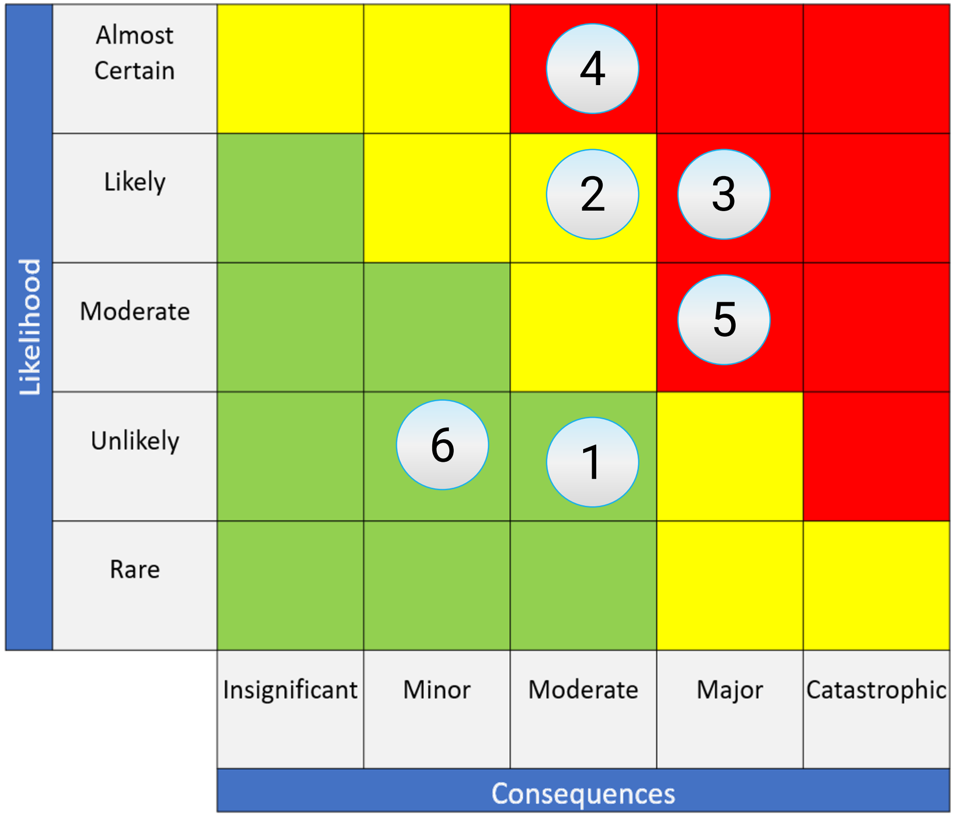
Challenges and Risks

Prof. Srikanth Rangarajan and his team from Binghamton University is developing a Markov Chain model for reliability system modeling to ensure our system can achieve 99.982% uptime.



Risk Status

Risk	#
The topology optimized structure could not be fabricated using additive manufacturing due to the manufacturability constraints	1
Cost/accuracy for topology optimization: The models for TO have to be sometimes simplified (either model physics or 2D vs. 3D) for computational cost reasons. We may not be able to extend to 3D or may have to make modeling assumptions due to cost.	2
Accuracy of sub-component modeling, system level modeling, compact modeling, and prediction control of system level model	3
Due to issues such as fouling, oxidation, clogging, surface contamination, and leaks, technology fails to meet the FOA target for thermal resistance. These problems can result in changes in contact angle, capillary performance, and other forms of degradation.	4
Technology does not meet the chip reliability target due to failure of the electronic package. This can be an initial failure due to a defect that is (b.1) created during printing, or (b.2) worsens or develops during thermal cycling/lifetime.	5
Technology does not meet the FOA target for cooling power as a percentage of IT load	6

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Technology-to-Market Approach

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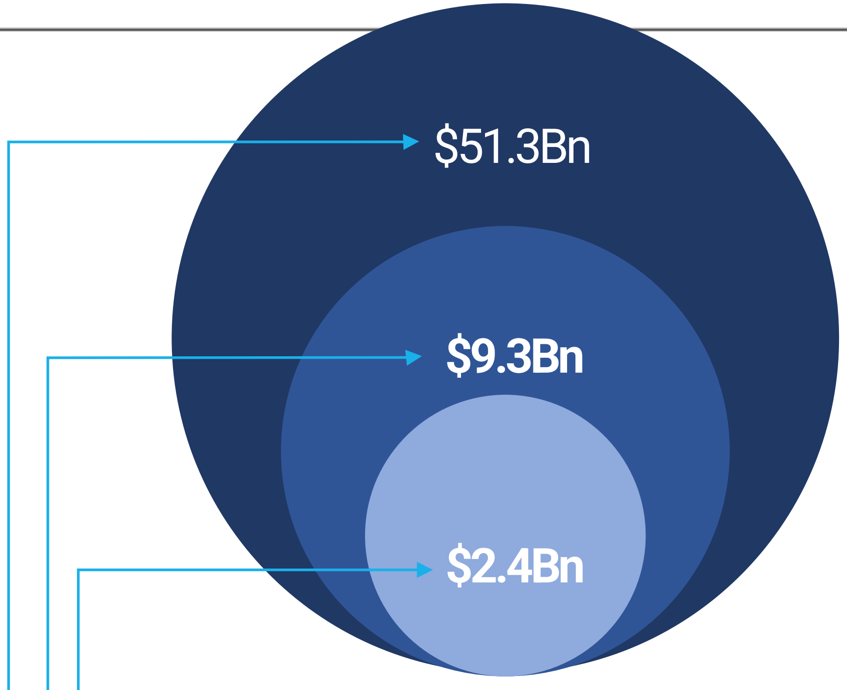
- *Commercialization* will be managed through *SEGUENTE* in its role as commercialization partner in the project
- *Follow-on investment* will be made by *SEGUENTE*. A successful technology development will then be incorporated into *SEGUENTE*'s portfolio of two-phase component technologies for implementation in *SEGUENTE* systems.
- *Anticipated first market* is the high value add server-class CPU and GPU segment in the DC market which are positioned to be able to absorb higher cost associated with new thermal technology deployment
- *Long-term* we expect to deploy the technology more broadly within the ICT market as supply-chain costs decrease with increasing volumes



2027 Forecast

TAM for liquid cooling
Recent figures show that liquid cooling is forecast to grow from 5% of the data center thermal management market to as much as 26% by 2027 as more high-performance infrastructure is deployed (The Register)

Total cooling market
Total spend on data center cooling solutions based on CAPEX benchmarks per geography and customer segment (includes primary and secondary cooling systems)

Total data center market
Global data center capacity is set to grow by **9% CAGR** 2022-2027
Growth driven largely by **hyperscale and colocation**, with enterprise set to decommission facilities

Power Density Trends
- Current air-cooling techniques cannot keep up with increasing power densities forcing the industry to adapt

Regional Trends
- The United States has a revenue **CAGR of 4.56%** over the period 2016-2027

Market Trends
- Hyperscalers and colocation players will account for **81% of the incremental capacity builds by 2027**

Sustainability & ESG
1. **Carbon-neutrality**
2. **Zero waste**
3. **ESG Compliance**
4. **Climate-proofing**

- There is an increase focus on maintaining **low PUE scores.**

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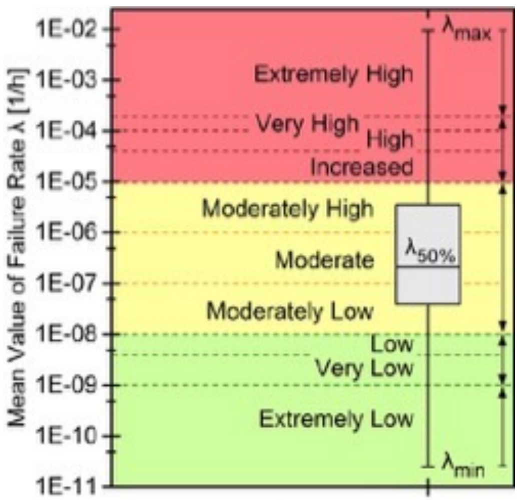
Source: McKinsey, The Register, online research, Market Insights

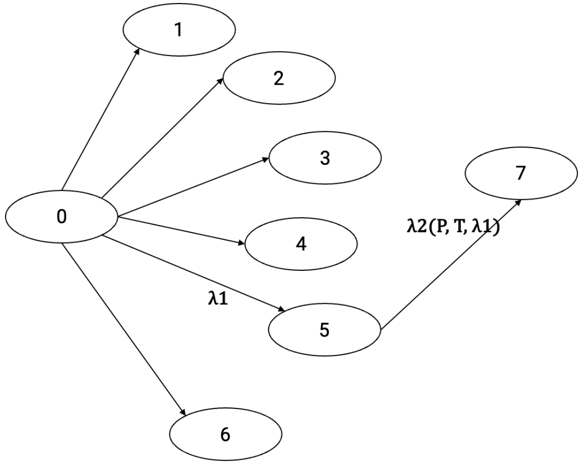
Needs and Potential Partnerships

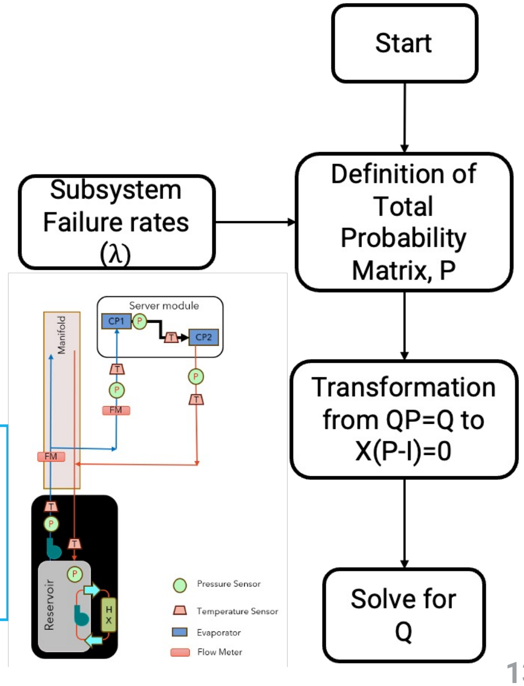
- *Resources: Liquid coolant refrigerant vendors for two-phase cooling*
- *Resources: chip vendors with high power mezzanine card GPUs*
- *Expertise: Need Industry on-site test failure rate values inputs or suggestions for System availability risk matrix*
- *Resources: materials supplies vendor for the additive manufacturing*

Risk matrix

Sl.No	Description	Shut down	Failure rate (λ):
1	O-ring worn out	Shut down	0.02628
2	Quick coupling for manifold	Shut down	0.01
3	Lower evaporator effectiveness	Shut down	
4	Coolant contamination	Shut down	
5	Leakage on Manifold	Shut down	
6	Reservoir leakage	Shut down	0.005
7	Primary Pump Fail	Shut down	0.000255
8	Membrane clogging	Shut down	







"Need to add failure rates values", based on the values, will find high risk states. Those states will be given priority.

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Q & A

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