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IMMERSION COOLING OF POWER ELECTRONICS

Presentation ID: 803

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Power Electronics for Next Generation Storage

Sandia National Laboratories

DOE OE Energy Storage Peer Review & Annual Meeting, 2026
July 30, 2026

Dallas, TX

U.S. DEPARTMENT of ENERGY

NNSA National Nuclear Security Administration

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SAND2026-23966C

PROJECT OVERVIEW

- **Goal:** Develop a ***totally passive, fully enclosed*** immersion cooling solution known as system-as-a-heat-pipe that fully immerses electrical components (converter, cells, etc.) in non-conductive engineered fluid as a high reliability, zero maintenance thermal management solution

- **Current Practice:** Active cooling methods (*i.e.*, fans or pumps) are effective in dissipating heat, but limit overall lifetime and require regular maintenance

- **Why Sandia:** As part of an internally funded research effort, Sandia previously developed a preliminary analytical framework for system-as-a-heat-pipe. The work also simultaneously leverages expertise in thermal management, packaging, power electronics, and materials. These areas are all strong capabilities within Sandia

- **Innovation:** Current thermal management approaches in energy storage systems are not appropriate for long-term reliability at zero-maintenance. Dielectric fluids and immersion cooling have been utilized in data centers, but this still requires a ***recirculating fluid loop*** driven by pumps to work and thus isn't appropriate for remote locations

PROJECT OVERVIEW

- **Duration:** 3 years (FY25-FY27)
    - Develop 3D FEM fluid boiling model
    - Demonstrate flip-chip semiconductor packaging suitable for immersion cooling
    - Evaluate different working fluids in simulation for cost, impact, performance, etc.
    - Validate model results with ***physical 100 W*** demonstration prototype
    - Develop double-side cooling semiconductor package with optimized heat sinks for immersion cooling
    - Build ***full 1 kW*** prototype

- **Impact:** Immersion cooling has the potential to meet the stringent maintenance and lifetime goals for energy storage systems in remote environments. These environments are very challenging for systems utilizing active cooling methods because they require significant and regular maintenance

- **Vertical/Investment Area:**
    - Materials and Systems Innovation

- **Alignment/Supports strategic pathway:** This project **grows** the grid by delivering affordability and modernizing for reliability
    - Eliminates operations and maintenance
    - Removes pumps and fans, which are a common failure point
    - Encloses electronics in a sealed environment for long-term reliability

PROBLEM

Growing the grid requires Energy Storage ***everywhere***

- Remote locations and harsh environments
    - Difficult or impossible to repair/replace on site

Optimizing the grid requires high reliability at zero cost

- 30 year lifetime
- Zero maintenance

Typical Active Cooling methods (forced air/liquid) ***cannot*** *achieve these goals*

How can we have a high thermal dissipation in a ***totally passive system?***

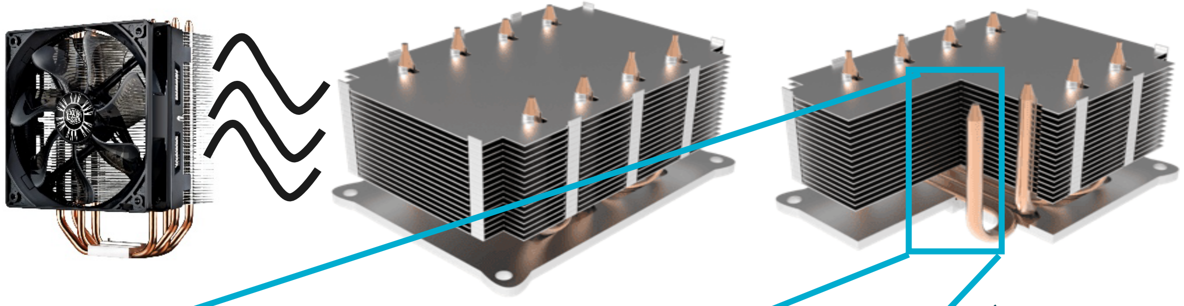
- Active cooling (HVAC, fan, liquid cooling)
- Regular Operations and Maintenance (O&M)

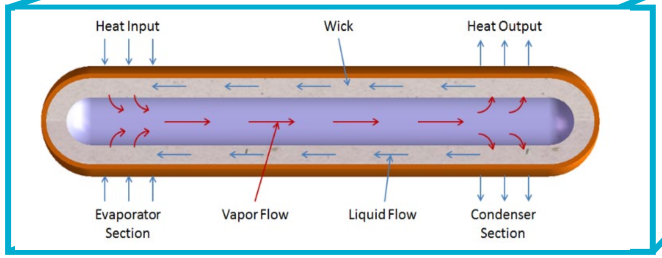
- Passive Cooling
- Hermetically sealed
- No pumps, no fans, no O&M

HOW IS THERMAL MANAGEMENT DONE TODAY?

Heat pipes

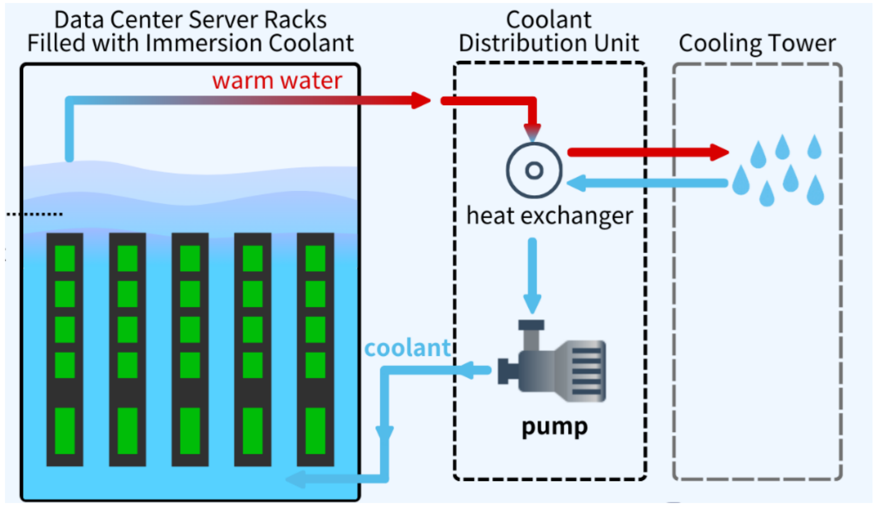
- Closed system of pipes with liquid
- Use forced convection with a fan
- Used in high performance power converters

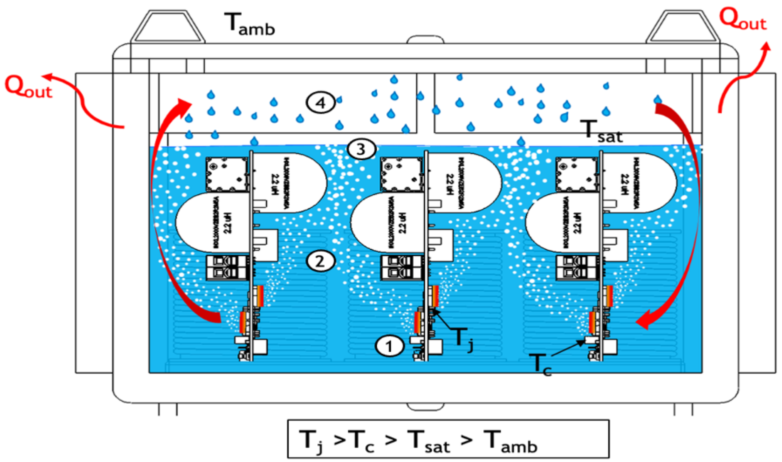




Immersion Cooling

- Power Electronics submerged in non-conductive liquid
- Slowly pumped liquid loop to external heat exchanger
- Used in high performance data centers

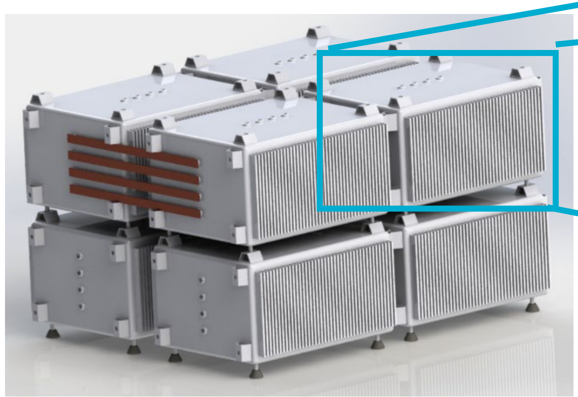


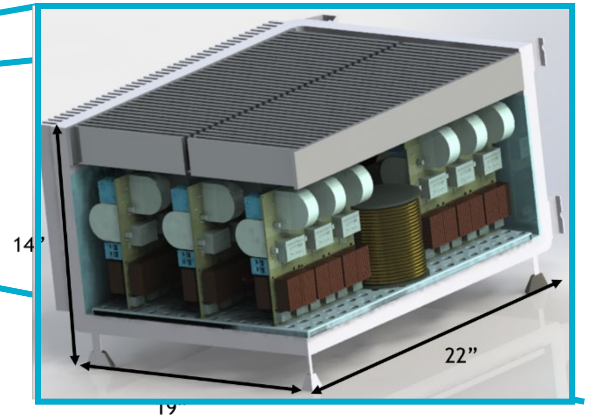


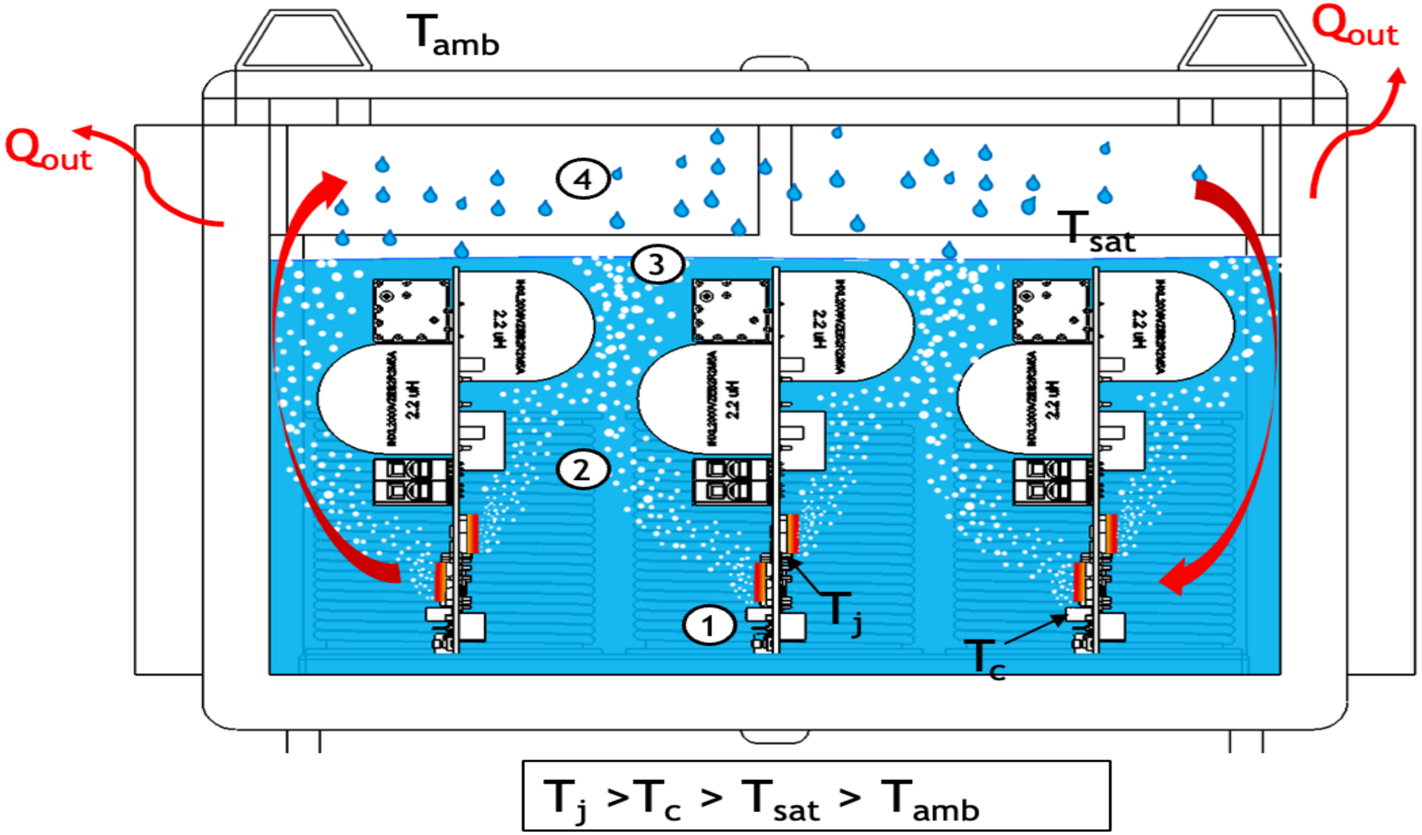
We propose a ***totally passive immersion cooling*** solution known as system-as-a-heat-pipe

HOW IS IT DONE TODAY?

- Places thermal solution extraordinarily close to heat generation
- Can be totally hermetically sealed







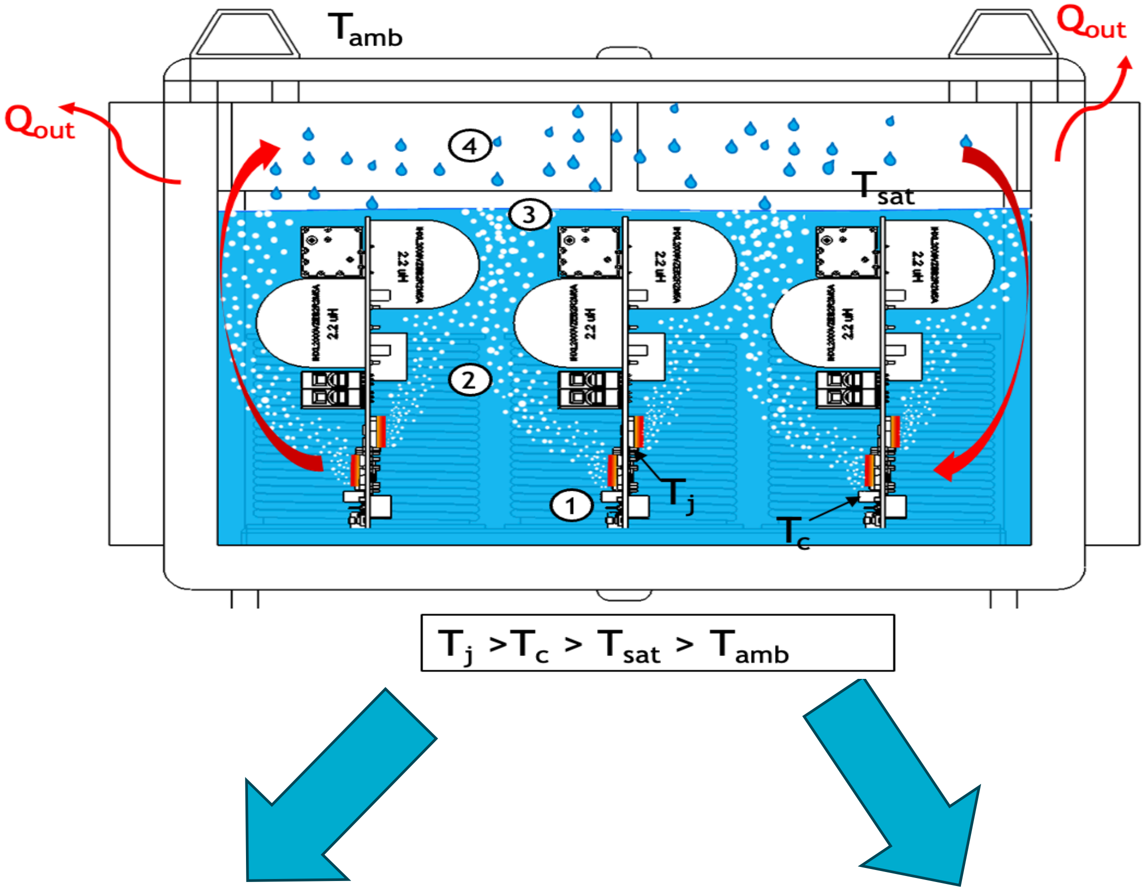
1. Heat generation at MOSFETs
2. Nucleate boiling at package surface
3. Saturated vapor
4. Heat removal through condensation and conduction

APPROACH

FY25
- Develop 3D Finite Element Method (FEM) fluid boiling model
- Demonstrate flip-chip packaging
- Evaluate working fluids in simulation

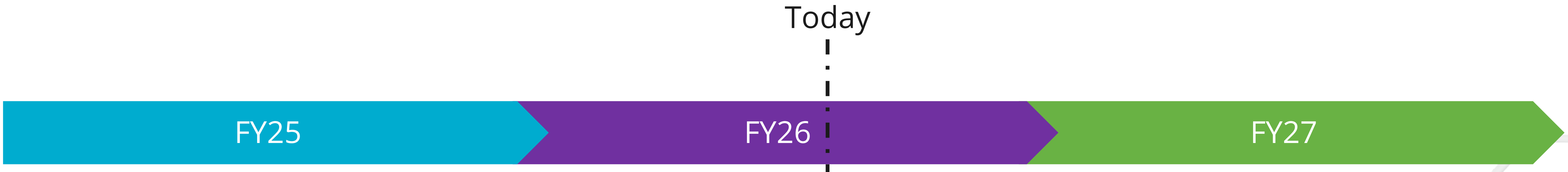
FY26
- Validate Model with 100 W prototype
- Demonstrate Double-side cooling package

FY27
- 1 kW prototype with custom, optimized double-side package



Finite Element Modeling of System

Custom Packaging and Heat Sinks

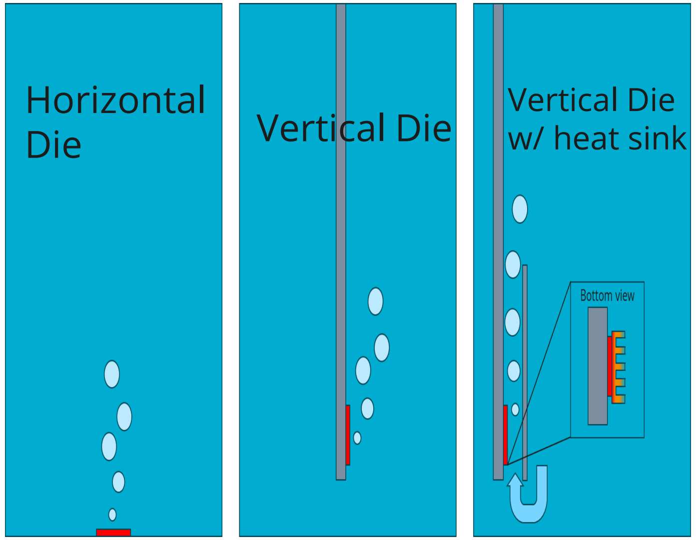


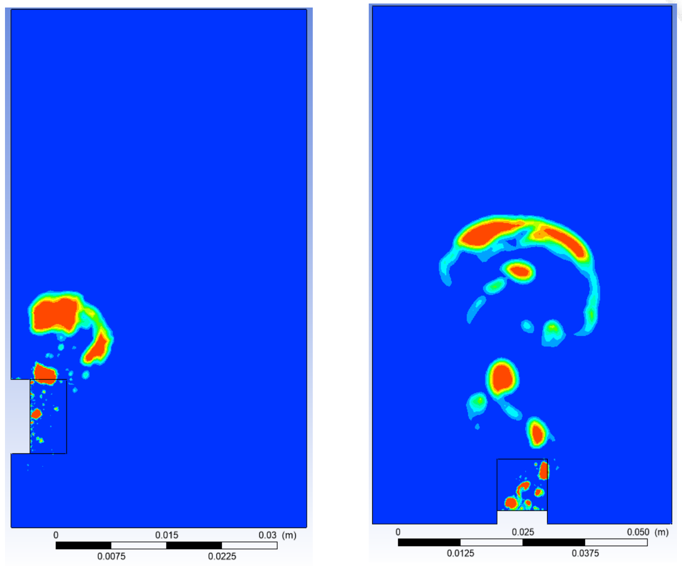
RESULTS FLUID MODELING

Informed design through modeling

Vast design parameter space

- Immersion fluid
- Pressure of vessel
- Heatsink fins
- Condenser area, and more





Can we model preferential boiling?

<u>Modeling schedule:</u>

Stage 1: Replicate analytical model

Stage 2: Evaluate relevant fluids

Stage 3: Simulate realistic system orientation

Stage 4: Implement additional design features to maximize thermal dissipation (heatsink fins, bubble channels to promote convection, etc.)

on

RESULTS

FLUID MODELING

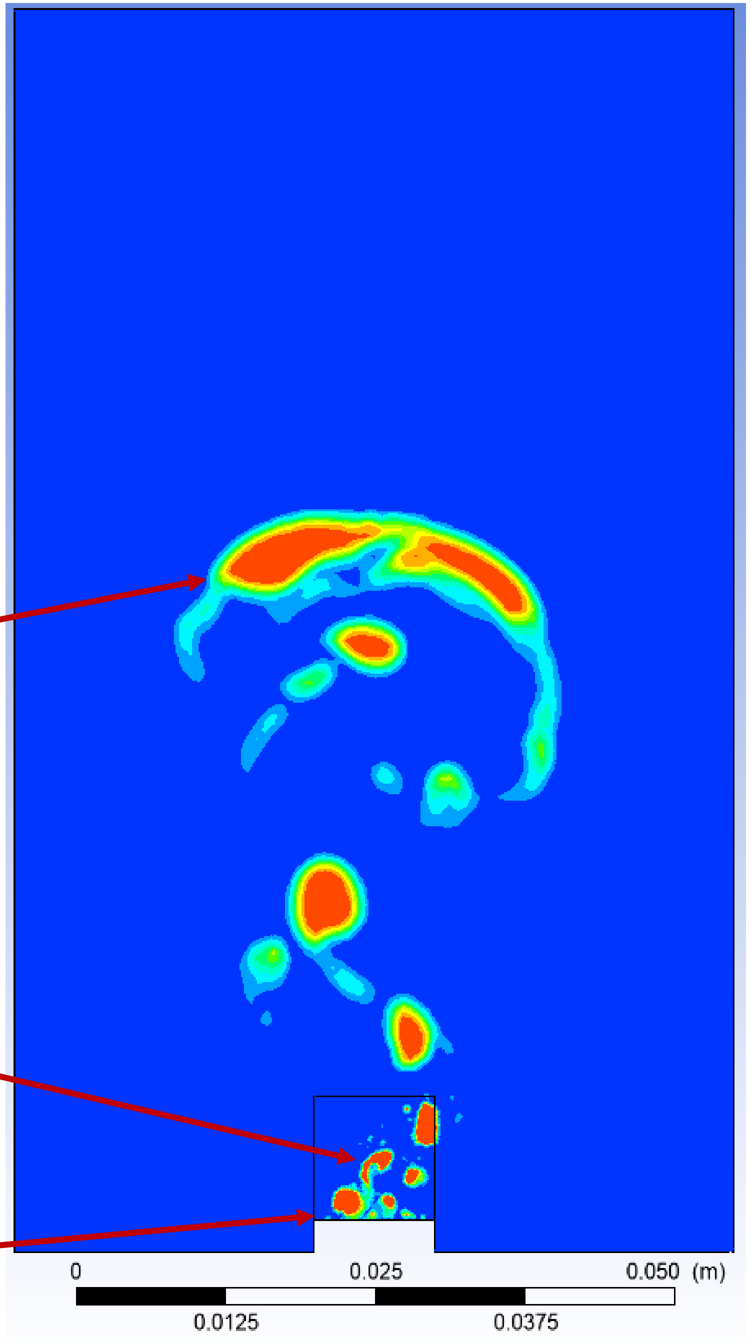
Working Fluid

System requirements:

- 50 W dissipation per die
- Junction temperature rise < 100 ˚C
- No active cooling (operates at ambient)

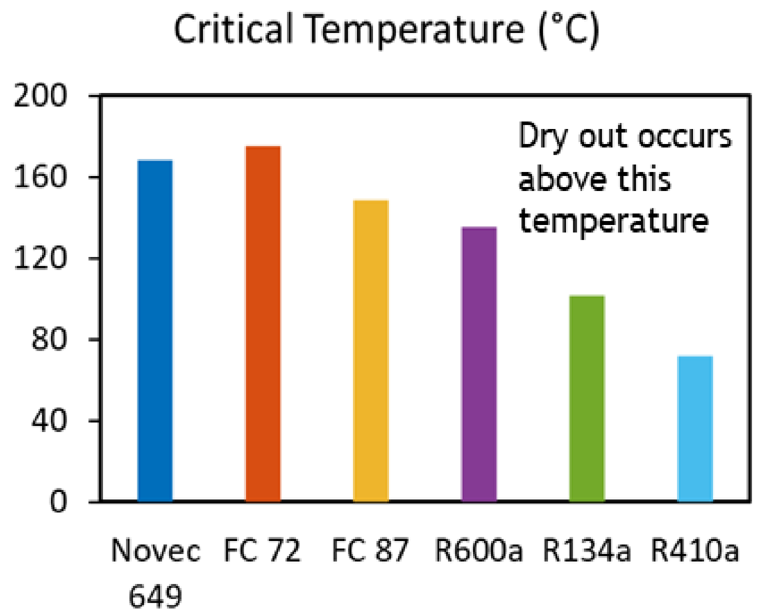
Down-select engineered fluids by analytical thermodynamic models:

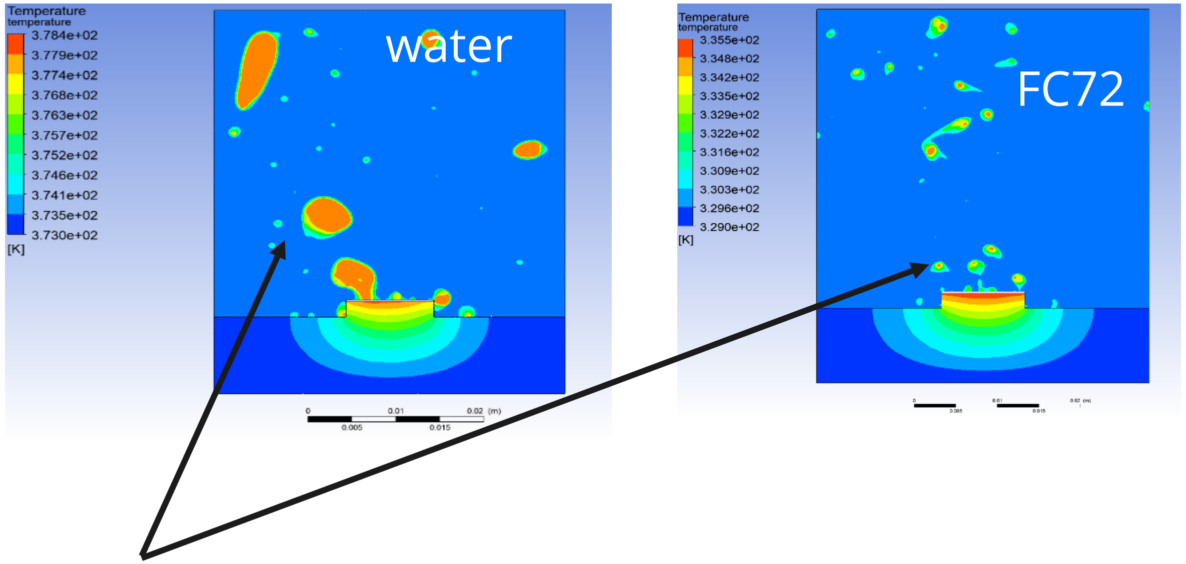
- Pressure < 100 PSIG
  - Pressure builds in headspace
  - Higher pressure increases heat transfer to bubbles
  - Very high pressure
    - Suppresses boiling
    - May lead to containment issues
- Critical heat flux (CHF) > 20 W/cm^2
  - Maximum thermal limit for boiling heat transfer
  - At heat flux > CHF
    - Bubbles generate rapidly
    - Merge and form insulating vapor “film”
- Boiling point
  - Initiate boiling 90-150^{o}C



RESULTS FLUID MODELING

Working Fluid





d_{bubble} smaller with FC 72
surface tension 5x less

ΔT = 5.5 (Water), 6.5 (FC 72)

Possible Fluids:

- **Novec 649** – lowest fluorocarbon junction temp
- **FC 87** – highest fluorocarbon CHF
- **R134a** – reasonable pressure, high CHF, low $T_{junction}$
- **Water-based** – Best thermal performance, cheapest, but special design necessary
- **Ether based** – "PFAS free", good thermal properties, but limited long-term field data

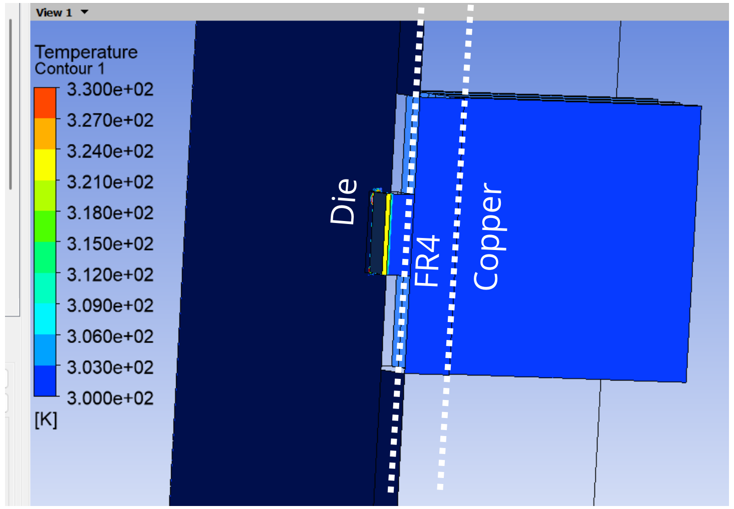
- Refrigerants (R) meet thermal requirements, but ***fail pressure requirement*** (<100 PSIG)
- Fluorocarbons (FC) work well at low pressure, ***but require heat spreading***

RESULTS FLUID MODELING

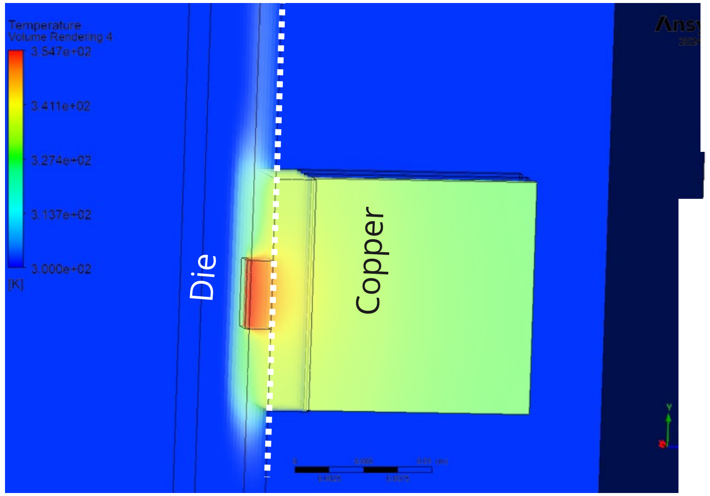
Heat Sink/Heat Spreader

Heat transfer from die to heatsink is limiting mechanism

- Fr4 material blocks all heat
- At 25 W, T_{die} >420 K

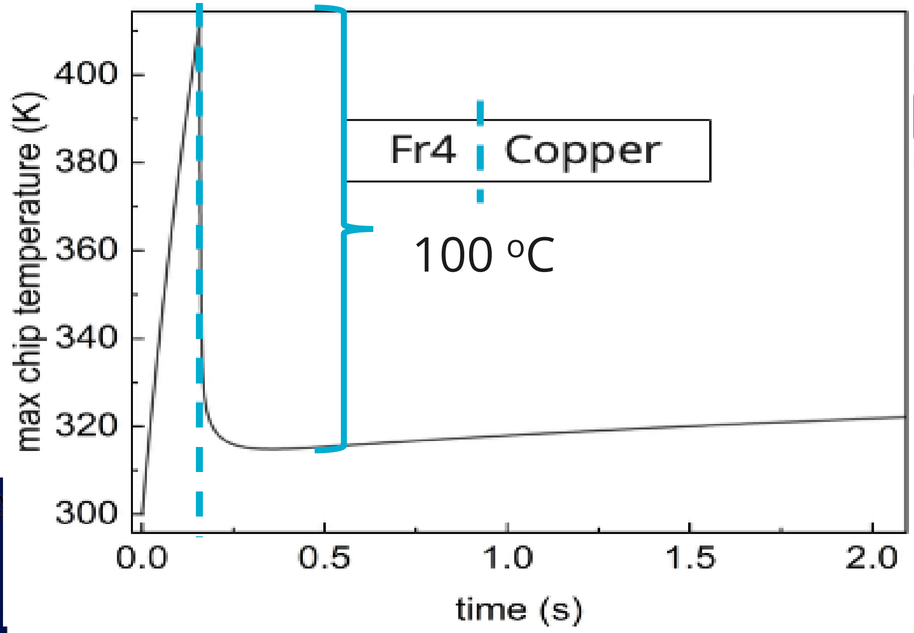


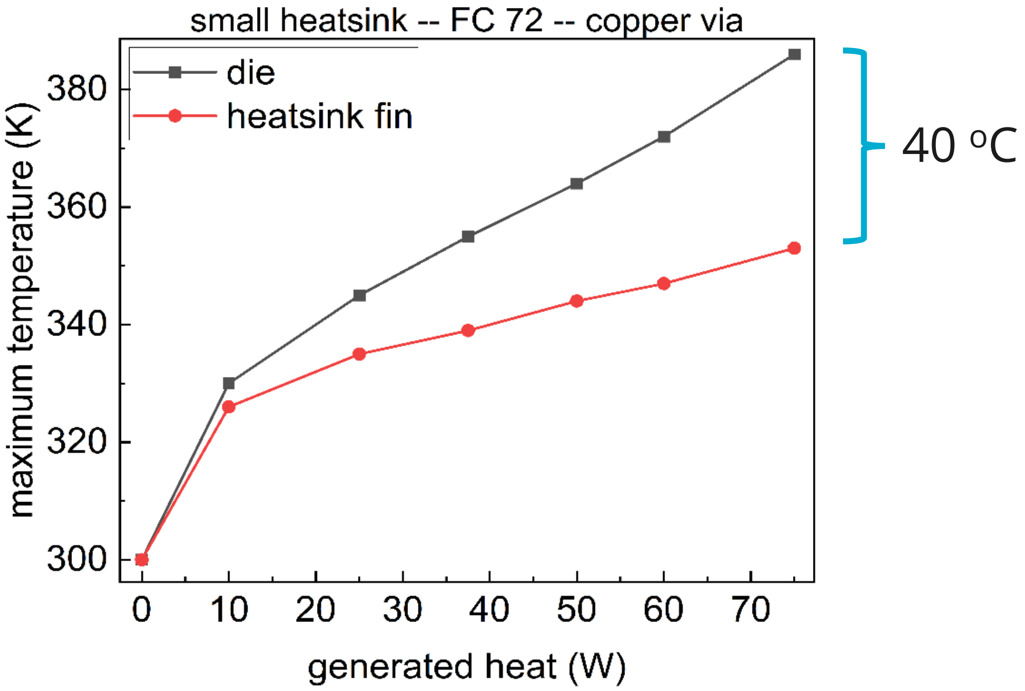
Die > FR4 > Copper



Die > Copper

- When via material changes to copper, ~ half of heat into heatsink
- ΔT manageable even for >50 W per die
  - ~80A at 50% duty cycle ($R_{ds\text{-}on}$ = 15 mΩ)

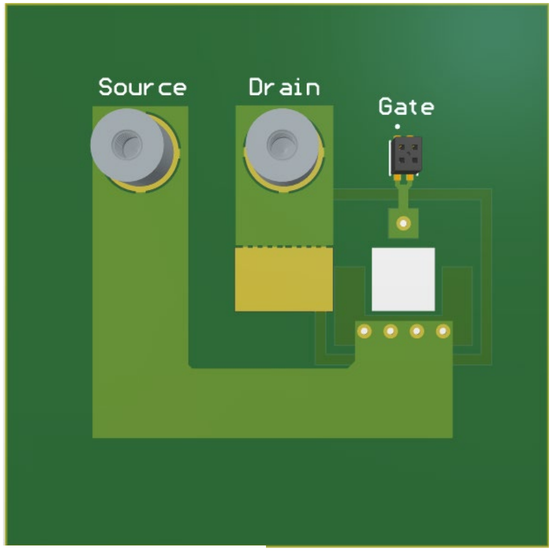




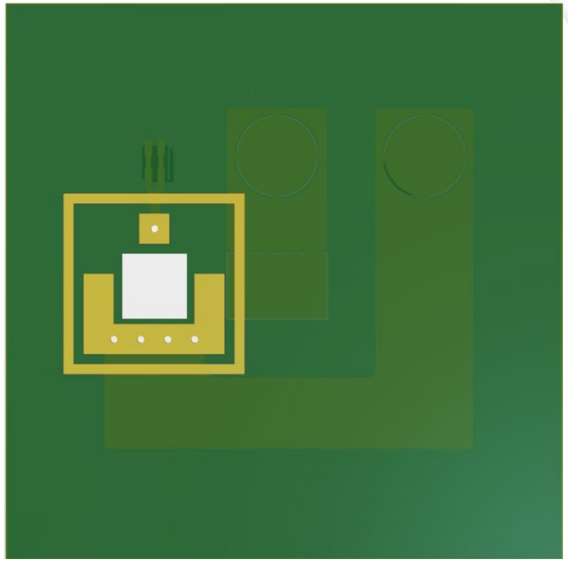
RESULTS PACKAGING

- Passive immersion cooling system requires ***double-side cooled, flip-chip*** package with integrated heatsinks for the power semiconductor switches
- Package will maximize thermal dissipation with optimized size/layout of heatsink fins as determined by FEM models
- ***Direct bond copper (DBC) substrate*** required to transfer heat from die to heatsink

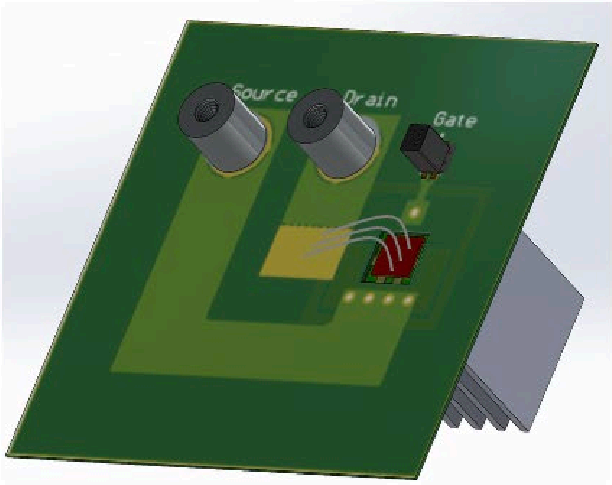
Board Topside 3D



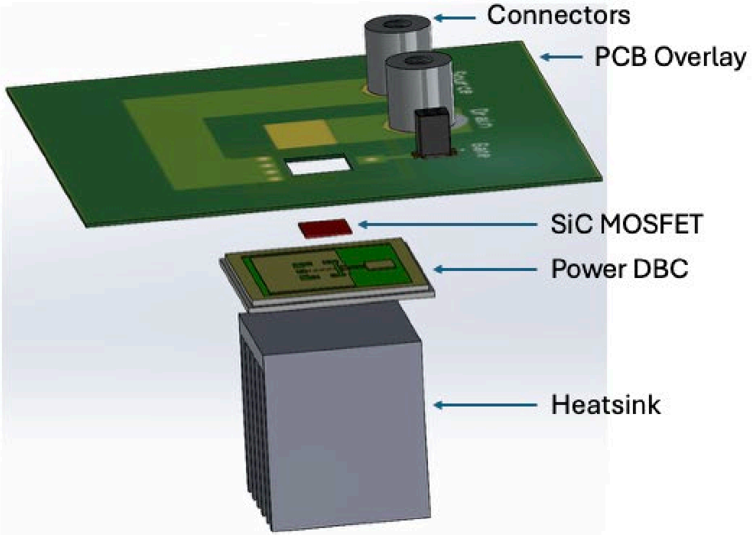
Board Backside 3D

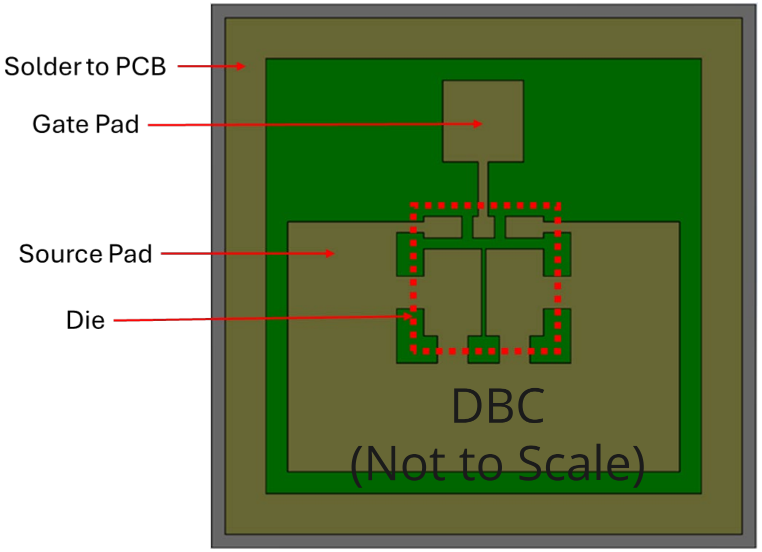


Prototype Assembled



Exploded View

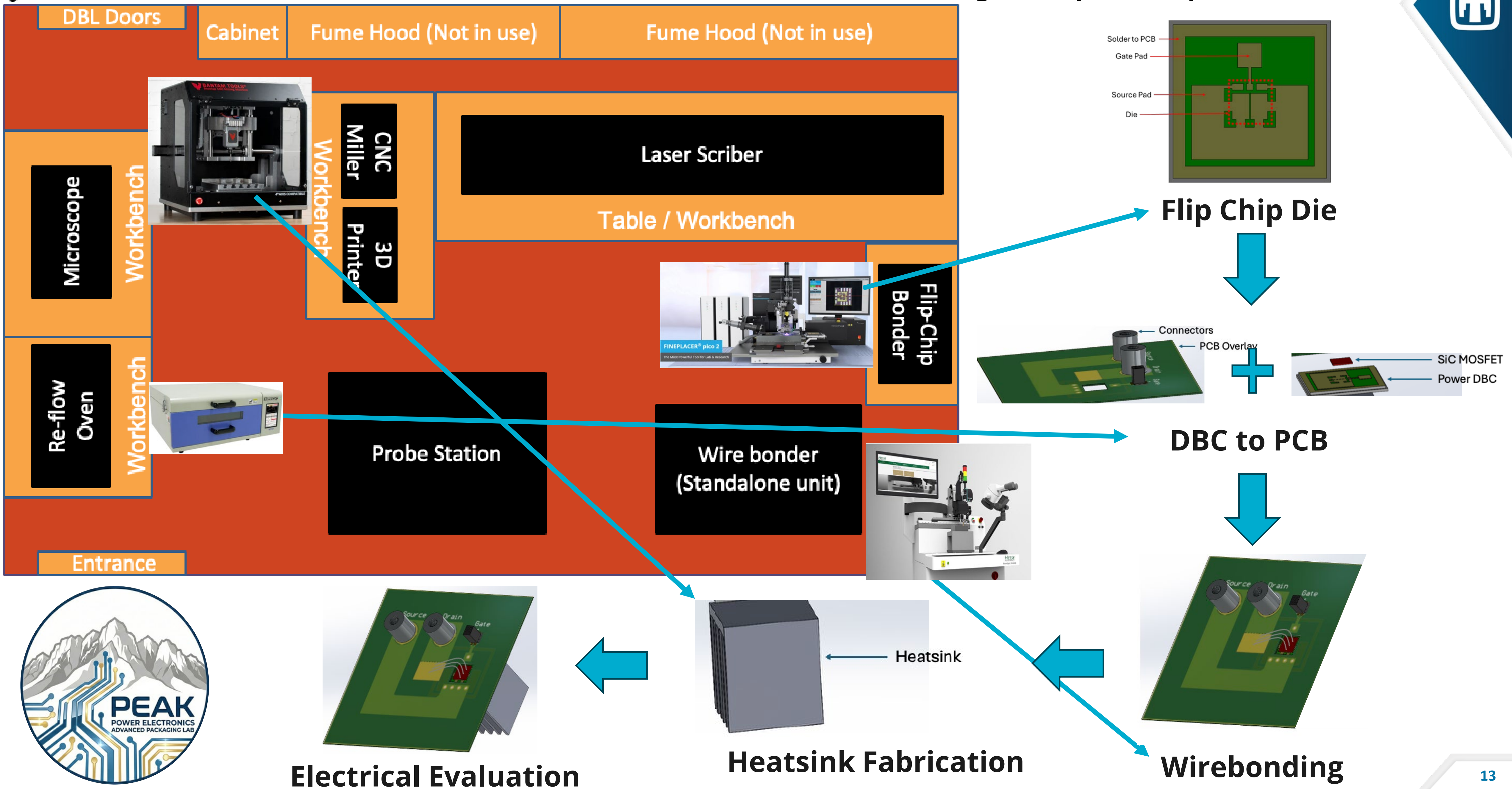




RESULTS

Power Electronics Advanced pacKaging lab (PEAK)

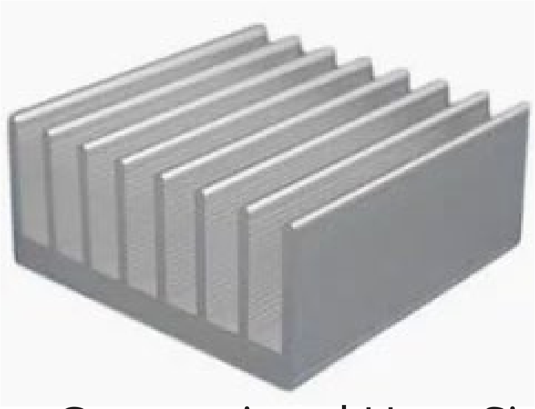
Commissioned FY25



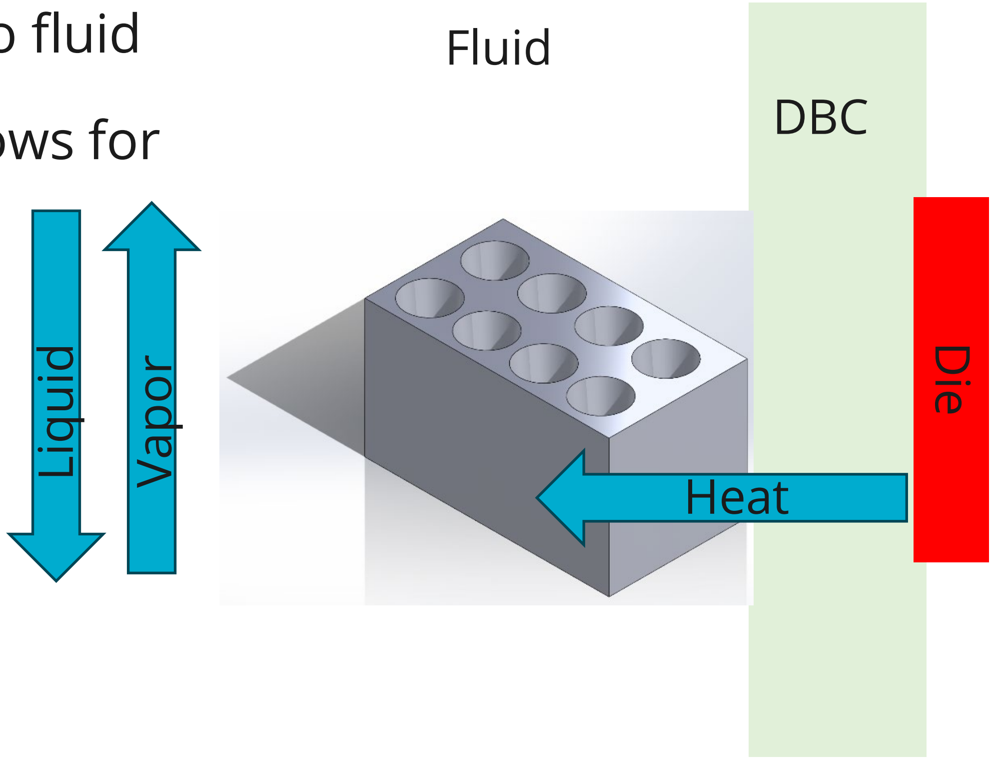
RESULTS

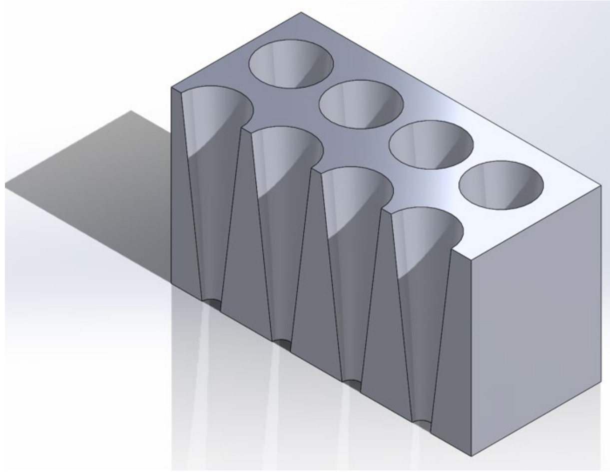
INVERTED HEAT SINK DESIGN

- Designed immersion-specific heat sink
  - Inverted heat sink design
  - Honeycomb chambers with conical sidewalls
- Small diameter allows for efficient transfer for heat from heatsink to fluid
- Increase in diameter of holes allows for vapor expansion
  - Reduces pressure, increases vertical force
  - Allows for more effective liquid/vapor loop



Conventional Heat Sink



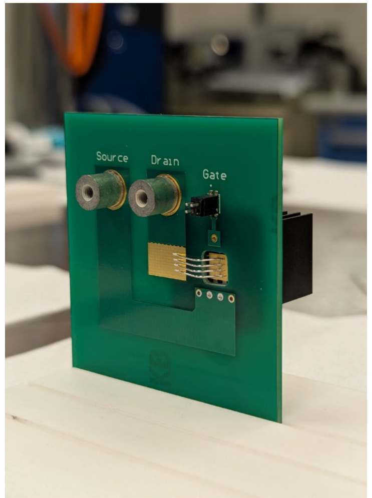


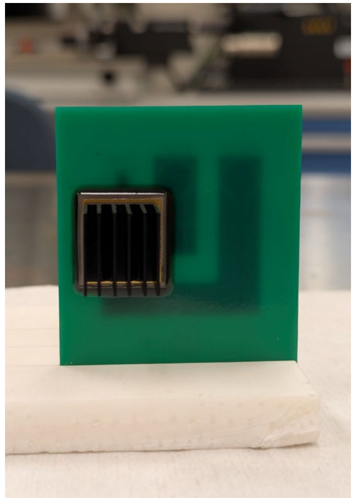
Boiling Optimized Heat Sink

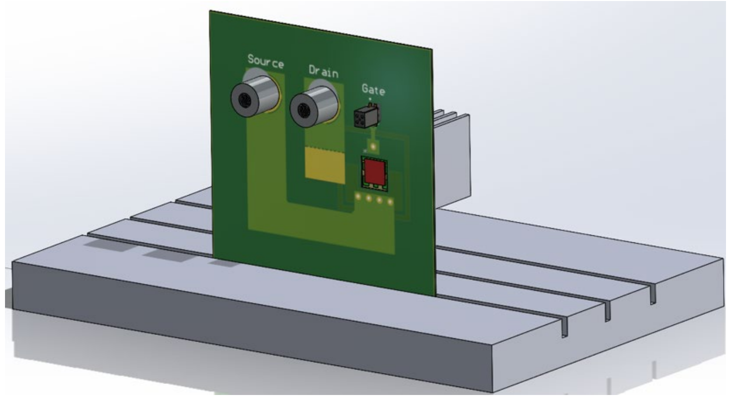
RESULTS

INITIAL 100W PROTOTYPE

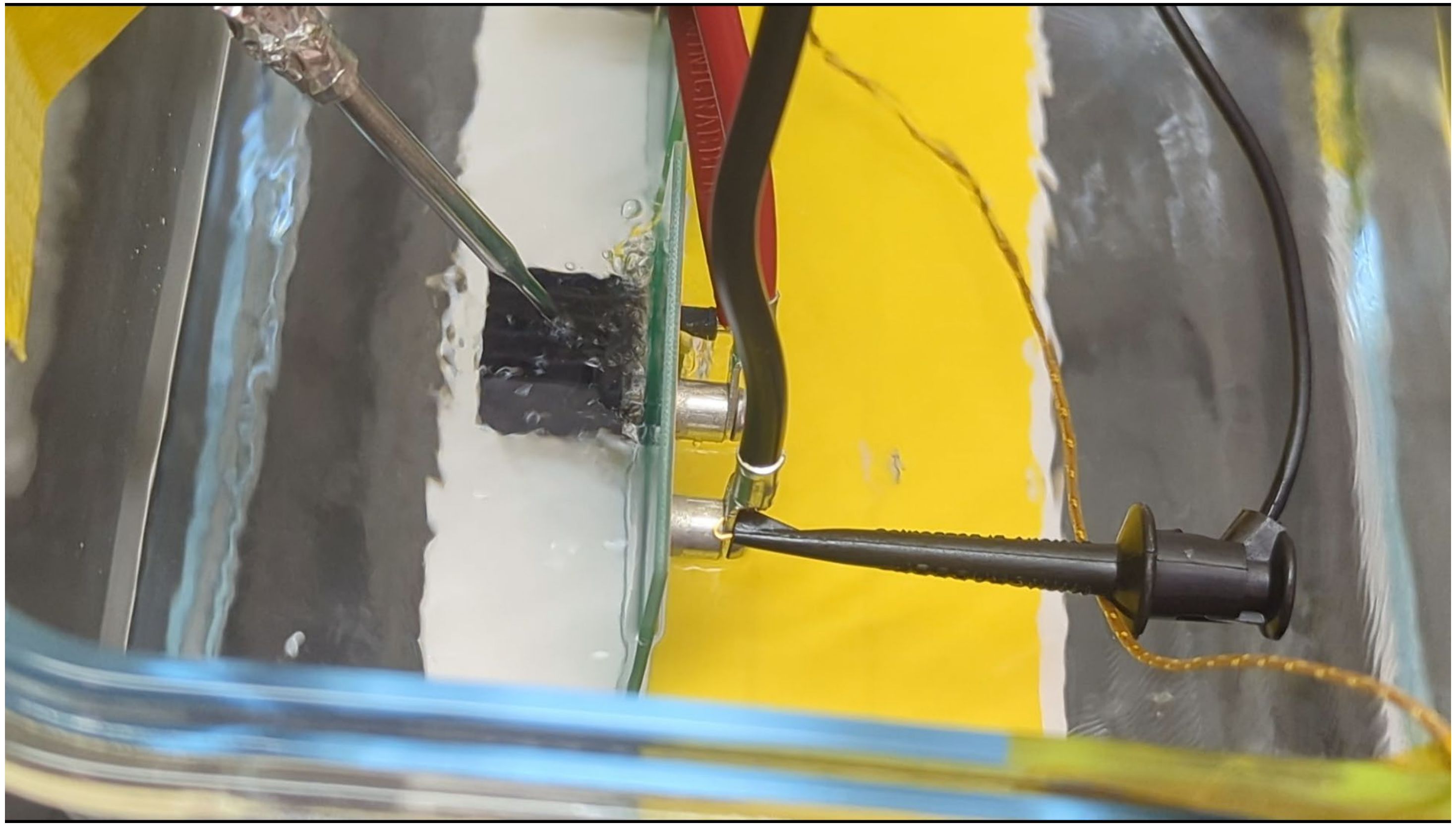
- Preparing initial 100W prototype
  - Multiple SiC die
  - **Objective:** Show initiation of fluid boiling
- PCB and Enclosure **are ready**
- DBC has been ordered **expected imminently**
- FC72 dielectric liquid **is ready**







Testing expected late summer



CONCLUSION AND IMPACT

"System-as-a-Heat-Pipe" immersion cooling

- Totally passive, fully enclosed approach
- Nucleate boiling/condensation for heat transport

Modeling-driven design framework established (3D FEM) to explore design space

- Different working-fluids evaluated tradeoffs of FCs, refrigerants, water-based, and ether-based options
- Identified primary thermal bottleneck as die-to-heatsink conduction path

Specialized packaging for immersion environments

- Double-side-cooled, flip-chip with DBC substrate and integrated heatsinks
- Innovative heatsink architecture with conical vapor expansion

Currently working on prototype validation and scale-up

- October 2026: 100 W hardware to validate model predictions
- October 2027: scaled-up 1 kW prototype

Impact

- Enables ***zero-maintenance*** thermal management for remote energy storage
- Eliminates pumps, fans, and external fluid loops
- Enables long-lifetime energy storage system in harsh remote environments

FUTURE DIRECTION/NEXT STEPS

FY26
- Validate Model with 100 W prototype
  - Demonstrate nucleation and boiling
  - Full, closed system modeling

FY27
- 1 kW prototype with custom, optimized double-side package

Beyond FY27
- Long-term reliability evaluation
  - Interactions between fluids and submerged electronics
  - Effects of fluid/system aging (*e.g.*, loss of fluid)
- Dynamic ambient operating conditions
  - Irradiance heat rise
  - High/low $T_{ambient}$
- Multi-dimensional analysis of working fluids
  - Voltage/thermal behavior
  - Cost
  - Environmental impact
  - Supply Chain

ACKNOWLEDGEMENTS

- *This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE), Energy Storage Division.*

THANK YOU!

QUESTIONS?

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