



## ANALYTICAL MODELING AND FEM SIMULATION

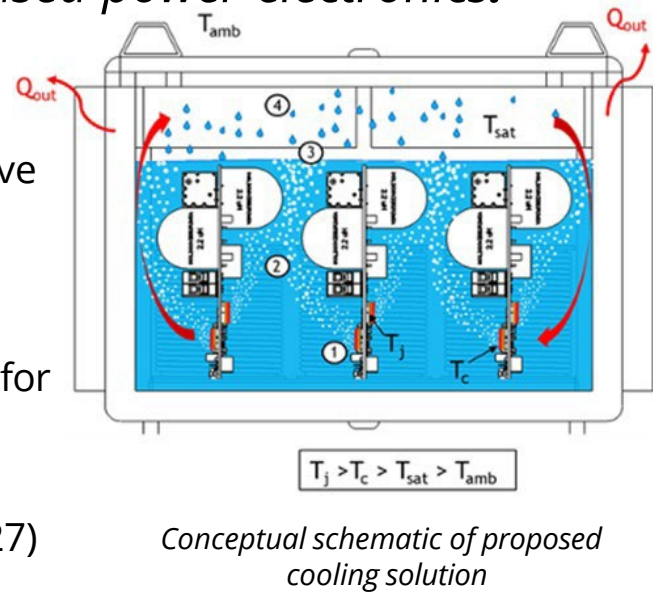
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### OBJECTIVES

Develop an all encompassing, completely passive cooling solution for grid-level energy storage-based power electronics.

#### Primary Objectives

- Model** candidate non-electrically conductive engineered fluids using advanced Finite Element Method boiling models (FY25)
- Develop** a double-side cooled, flip-chip package with integrated finned heatsinks for the power semiconductor switches (FY26)
- Design & fabricate** a 1 kW two-phase immersion cooling solution exemplar (FY27)



### BACKGROUND

- Current immersion cooling used in advanced data centers utilize external heat exchanger and **pumped liquid cooling loop** to enable high power density (2-5 kW/m<sup>3</sup>).
- This method not directly applicable to grid integration since it:
  - Requires **significant maintenance** to ensure maximum performance.
  - Lowers system lifetime** due to actively pumped thermal loop
- Previous Sandia-funded Laboratory Directed Research and Development project (#224288) developed preliminary tools and analysis for "system-as-a-heat pipe" concept
  - Correlations between critical heat flux, system pressure, and MOSFET junction temperature were developed

## HYPOTHESIS, MOTIVATION, & IMPACT

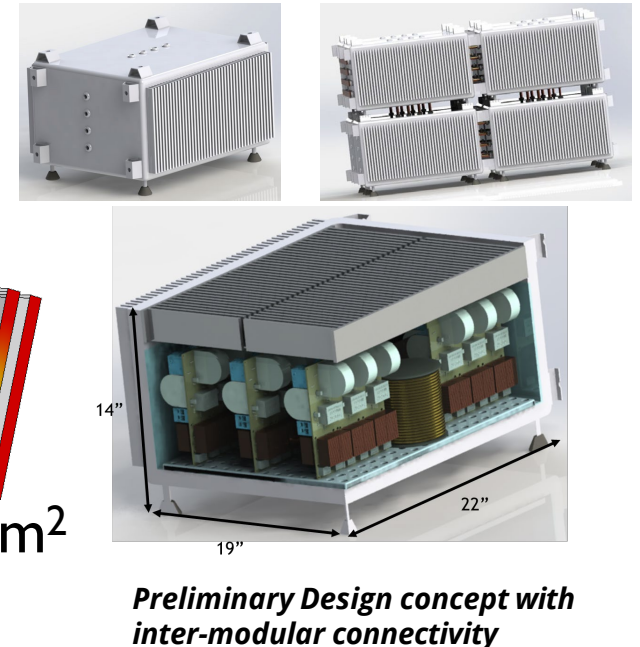
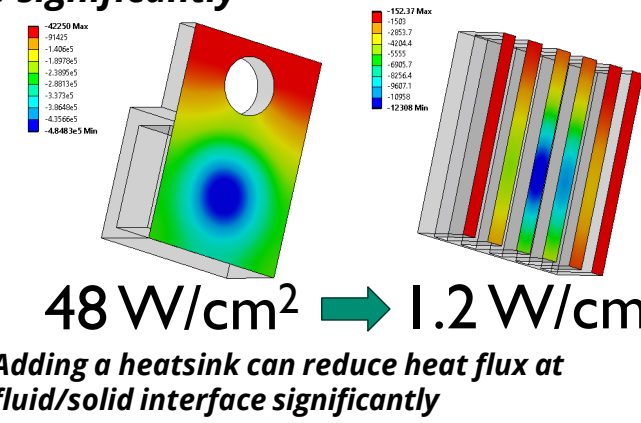
To be implemented in remote areas that have harsh environmental conditions (e.g., New Mexico), Energy Storage Systems require very long (20 year) lifetimes, zero maintenance, and very low operational-costs.

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

- Removal of heat exchanger and cooling loop while maintaining sufficient heat flux would **enable significantly more robust, cost-effective thermal management** for energy storage-based power electronics

#### Informed design through modeling

- Passive immersion cooling system involves **a vast design parameter space**, including:
  - immersion fluid
  - pressure of vessel
  - heatsink fins
  - Condenser area, and more.
- Analytical modeling and FEM simulation used to accelerate design choice and prototyping



## METHODOLOGY & TESTING

#### System requirements:

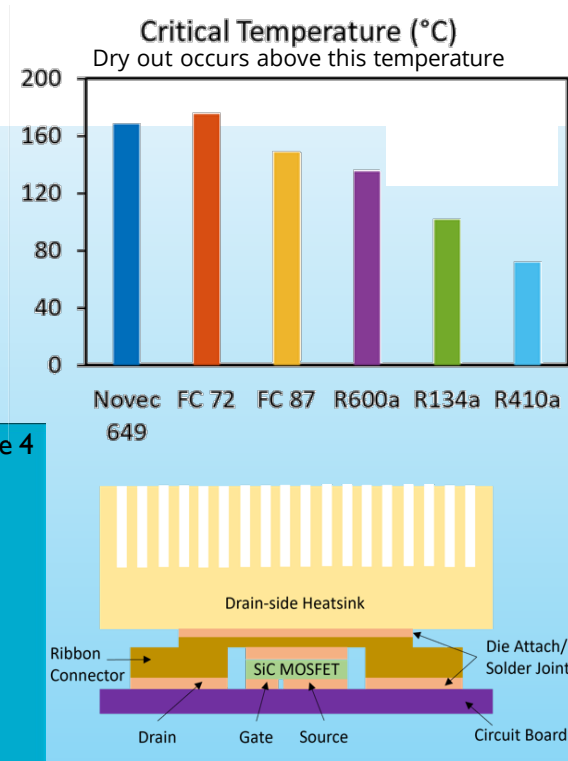
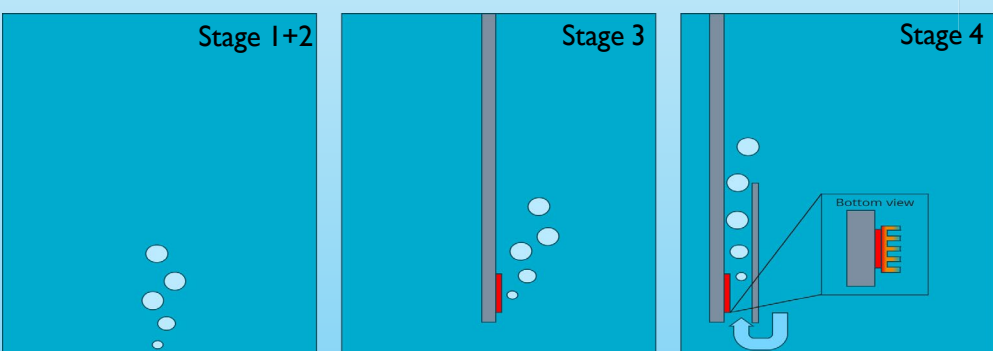
- 50 W dissipation per die
  - Junction temperature rise < 100 °C
  - No active cooling (operates at ambient)
- Down-select engineered fluids by analytical thermodynamic models
    - Critical heat flux (CHF) > 20 W/cm<sup>2</sup>
    - $\Delta T_{junction} < 20^\circ C + \Delta T_{fluid} < 25^\circ C + T_{ambient}$
    - Pressure < 100 PSIG
  - Finite Element Method (FEM) for structural design, validation of analytical models
    - 2D models for rapid feedback
    - 3D models to iterate over design parameters

#### 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

#### Modeling schedule:

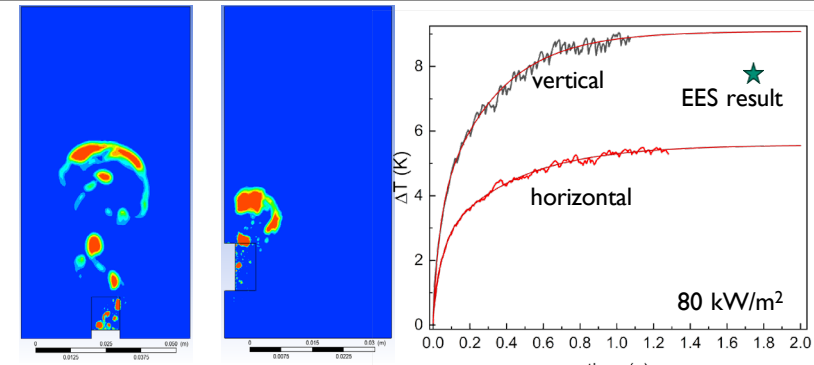
- Replicate analytical model
- Evaluate relevant fluids
- Simulate realistic system orientation
- Implement additional design features to maximize thermal dissipation (heatsink fins, bubble channels to promote convection, etc.)



## RESULTS

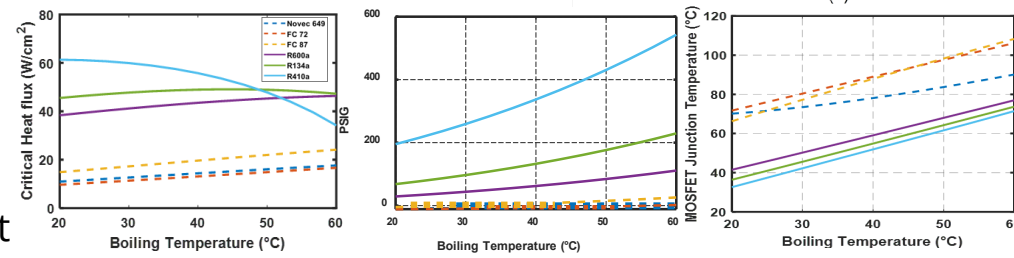
#### Stage 1: Replicate analytical model

- Reasonable agreement between Ansys Fluent and Engineering Equation Solver (EES)
- Simple orientation change → **large difference** in heat exchange



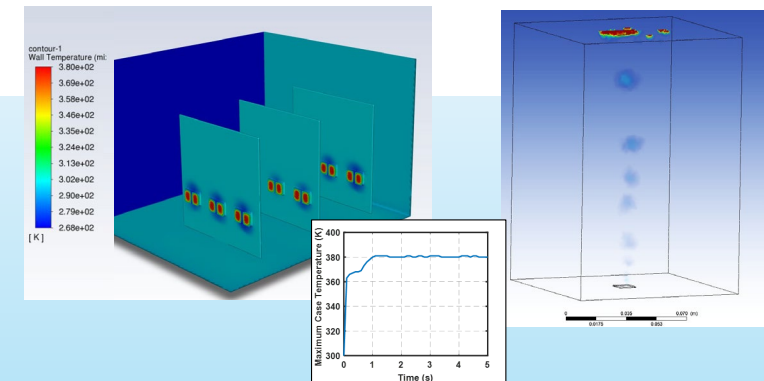
#### Stage 2: Evaluate relevant fluids

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



#### Stage 3: Simulate realistic system orientation

- 3D models demonstrate heat dispersion for entire system
- Rapid feedback before prototyping



#### Stage 4: Implement design features

- Bubble channel promotes convection over heater surface → higher heat conduction
- Reduce ΔT by >30%** with simple channel

