Liquid Immersion for Next Generation Utility Scale Power Electronics

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Introduction

Wolfpeed
3.3kV, 50A, 50mΩ
(125W)

Integrate control, sensing, communication, and power circuit for kW's of power throughput using PCBs and other packages

Wide band gap semiconductors → high frequency, high power, fast switching

Main Obstacles

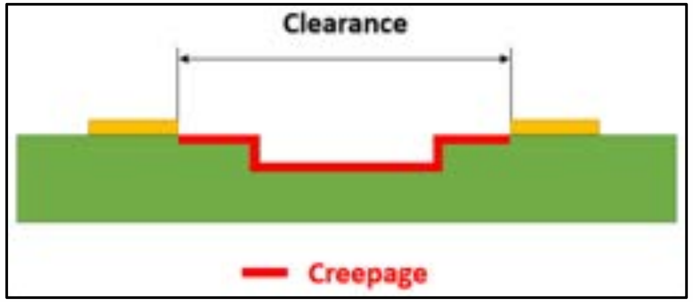
Thermal Stress

Electric Field Intensity

Proposed Solution

Submerge electronic system in an electrically insulating and thermally conductive liquid

Introduction



https://resources.altium.com/p/high-voltage-pcb-design-creepage-and-clearance-distance

- Design of power devices and PCBs dictated by clearance and creepage considerations to prevent flashover and breakdown

https://www.cargill.com/doc/1432076501275/fr3-fluid-brochure.pdf

https://grcmain.wpenginepowered.com/wp-content/uploads/2018/06/GRC_Fact_Sheet_ElectroSafe.pdf

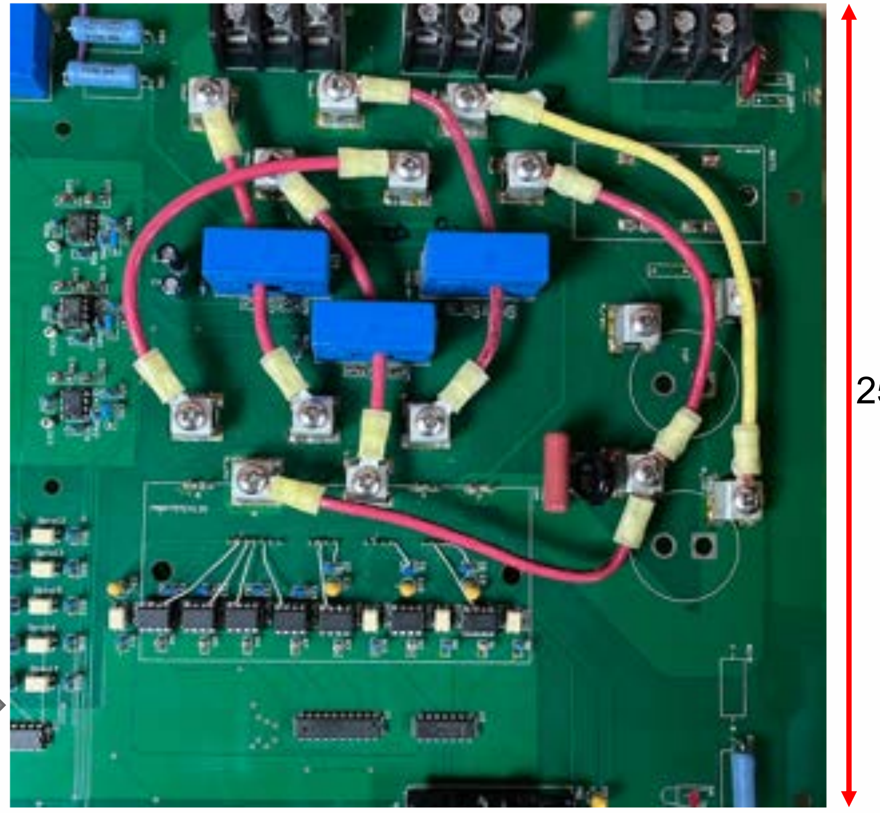
- Liquid immersion cooling
  - Transformers and high voltage rectifiers >100 year history
  - Data centers >20 year history
- Typically some type of mineral oil
- FR3 fluid is renewable alternative to mineral oil
  - Soy-based, non-toxic, and biodegradable

Introduction

<u>Focus of work</u>

Empirical study to evaluate the thermal performance and high voltage properties of prototypes immersed in Cargill FR3

<u>Example</u>: can we design this more compact for a liquid immersed PCB application?

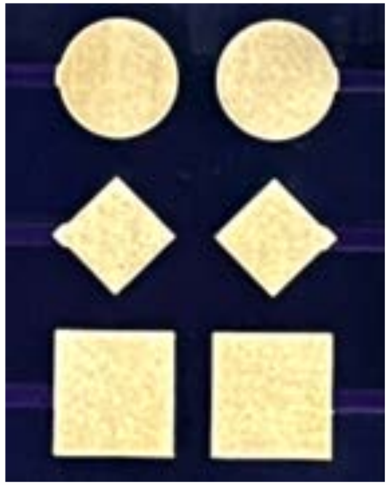


Preliminary Model – Electric Field Distribution in Circuit Layout

Investigate the impact conductor shape and spacing have on the intensity of the electric field

- 2D Electrostatic FEA Models Created using Ansys Maxwell

PCB pad shapes



3kV excitation. Maximum electric field magnitude as a function of conductor clearance x:

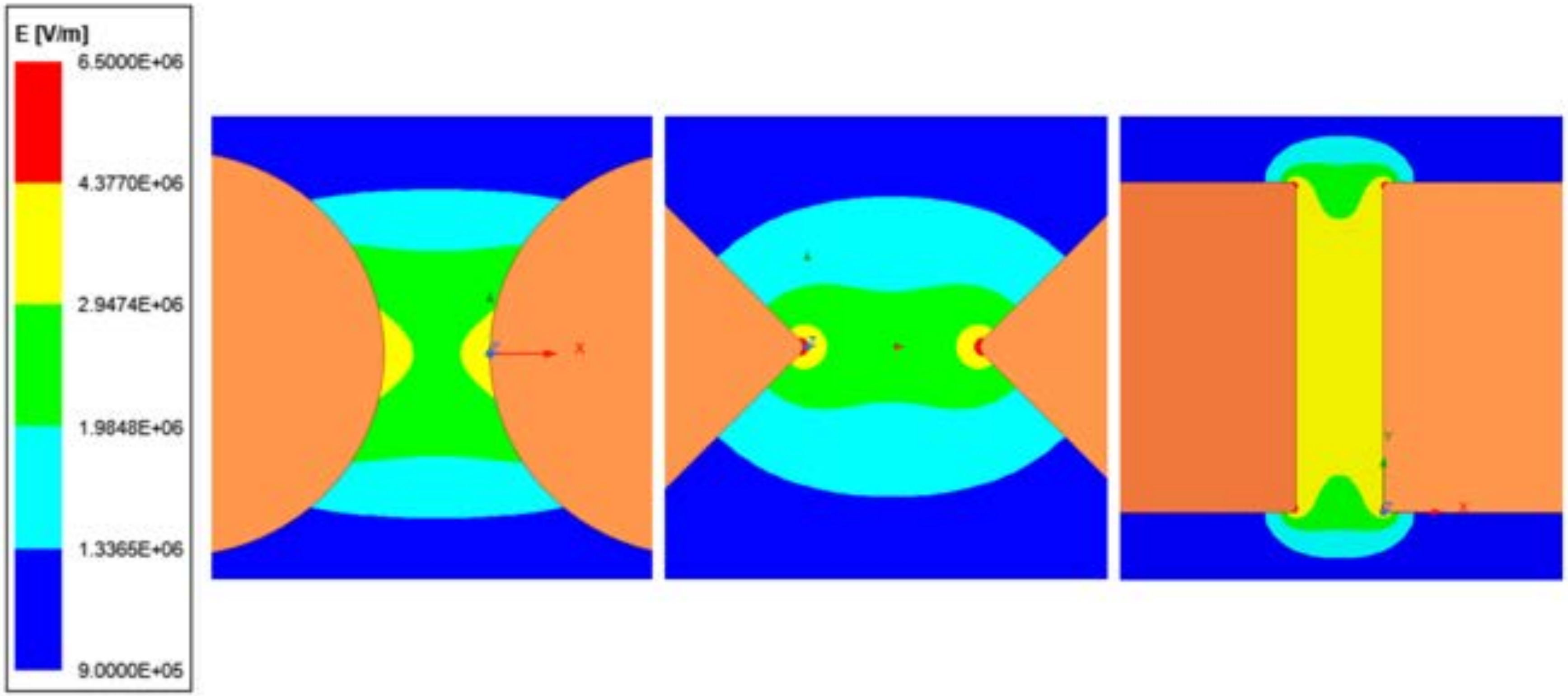
$$E_{max}[kV/mm] = \frac{a}{x^b}$$

coefficients →

Shape	a	b
Circle-Circle	3.23	0.85
Square-Square	6.22	0.72
Diamond-Diamond	6.30	0.66

Preliminary Model – Electric Field Distribution in Circuit Layout

FEA results for 3kV Excitation Voltage and 1mm Clearance



Max E-Field [kV/mm]	3.25	6.3	6.2

Preliminary Model – Thermal Analysis of Immersion Cooling

- Represent hot surface (ex: semiconductor) as a horizontal flat plate cooled upwards experiencing natural convection cooling

$$L_{char} = \frac{A_s}{per}$$

$$Ra_{Lchar} = \frac{gL_{char}^3\beta\left(T_{surface} - T_{fluid}\right)}{\nu\alpha}$$

$$Pr = \frac{\nu}{\alpha}$$

$$\bar{h} = \frac{k\overline{Nu}_{Lchar}}{L_{char}}$$

Preliminary Model – Thermal Analysis of Immersion Cooling

Thermal and Physical Properties of Air at T = 26.85℃ and Cargill FR3

- Highly simplified model solved for 1cm x 1cm flat plate

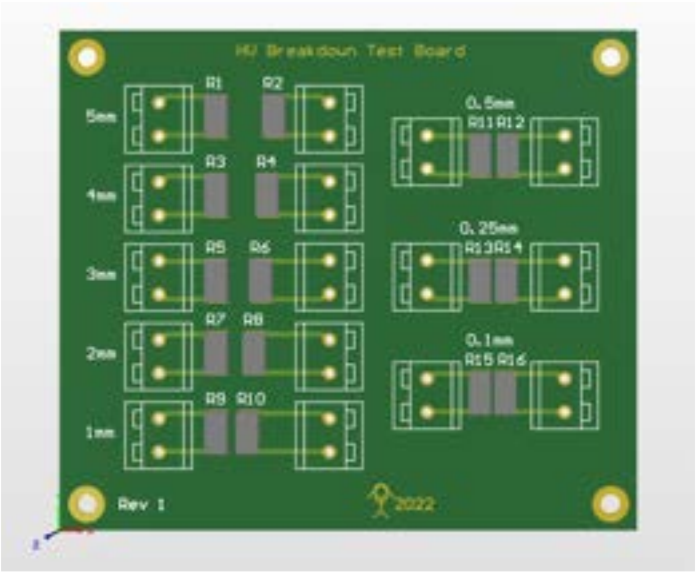
Property	Air	FR3
Kinematic Viscosity °C: ν $[mm^2/s]$	15.75	32.54
Viscosity °C: μ $[mPa \cdot s]$	.019	30
Density °C: ρ $[kg/m^3]$	1.177	920
Expansion coefficient: β $[m/C]$	3.33	0.75
Specific heat at °C: c_p $[kJ/kg \cdot C]$	1.01	1.88
Thermal Conductivity °C: k $[mW/m \cdot K]$	26.4	167
Thermal Diffusivity: α $[mm^2/s]$	22.27	.097

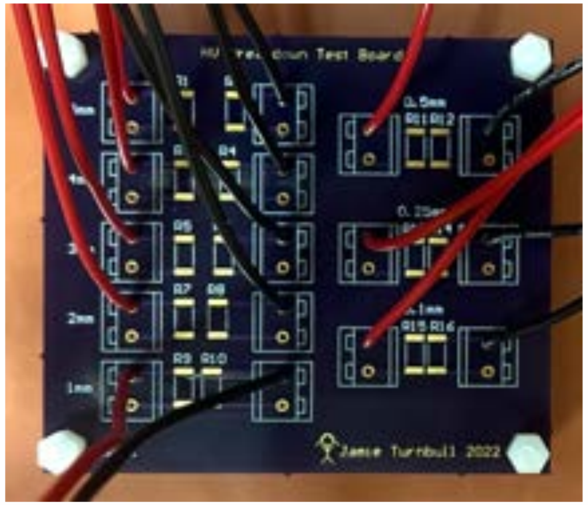
FR3 expected to improve heat transfer of electronics

Parameters	Air	FR3
$Power[W]$	3	3
T_{inf}°C	20	20
Plate dimensions [cm]	1x1	1x1
$\bar{h}$ $[W/m^2 \cdot K]$	33.45	325.5

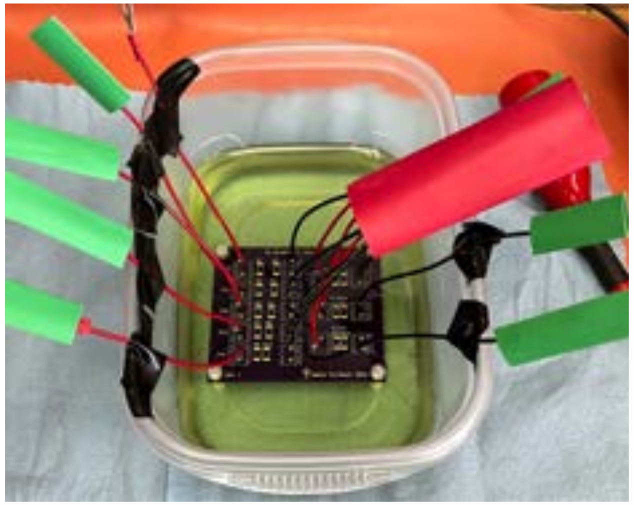
Experimental Evaluation – Liquid Immersed PCBs
Initial Evaluation of Insulating Properties of FR3

- Custom PCB designed to test dielectric properties of air vs. Cargill FR3
- Test clearances from 5mm down to to 0.1mm
- Size 2512 surface mount pads



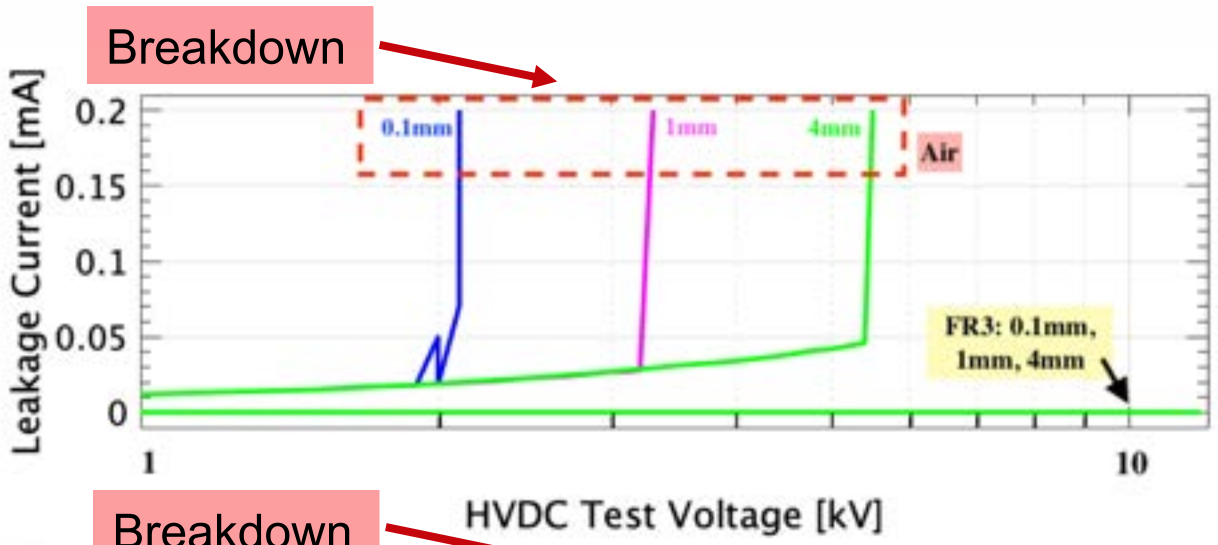


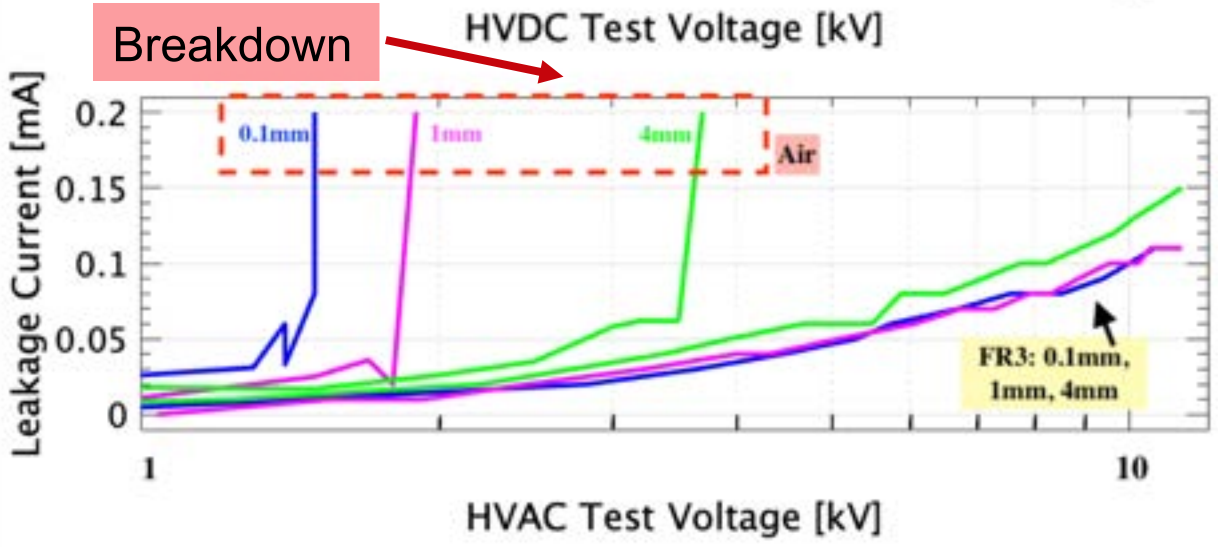
Air



FR3

Experimental Evaluation – Liquid Immersed PCBs
Initial Evaluation of Insulating Properties of FR3

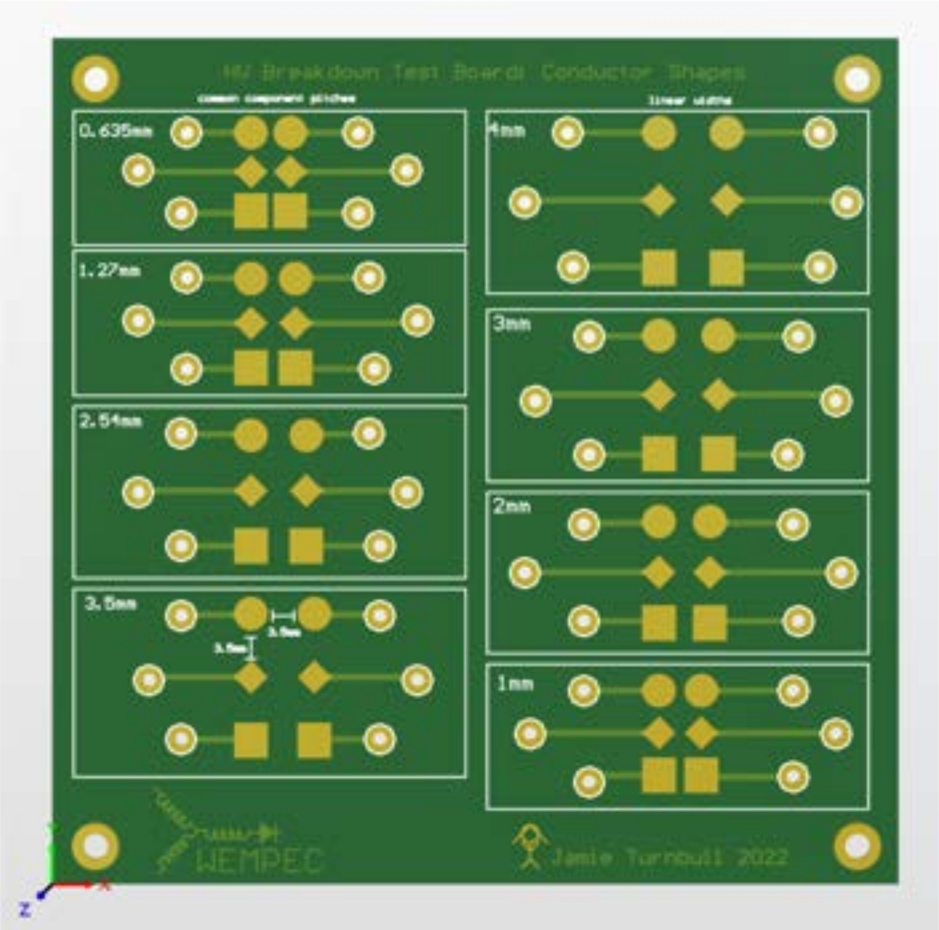




- **HVDC breakdown in air**
  - 0.1mm : 2.1kV
  - 1mm : 3.3kV
  - 4mm : 5.5kV
- **No breakdown in FR3**

- **HVAC breakdown in air**
  - 0.1mm : 1.5kV
  - 1mm : 1.9kV
  - 4mm : 3.7kV
- **No breakdown in FR3**

Experimental Evaluation – Liquid Immersed PCBs
Conductor Shape and Voltage Breakdown



- Second PCB to test conductor shape and high voltage breakdown
- Common component pitches used: 25mil, 50mil etc.

- Can test:
  - Circle-circle
  - Diamond-diamond
  - Square-square
  - Circle-diamond
  - Diamond-square

Experimental Evaluation – Liquid Immersed PCBs
Conductor Shape and Voltage Breakdown

Breakdown

Breakdown

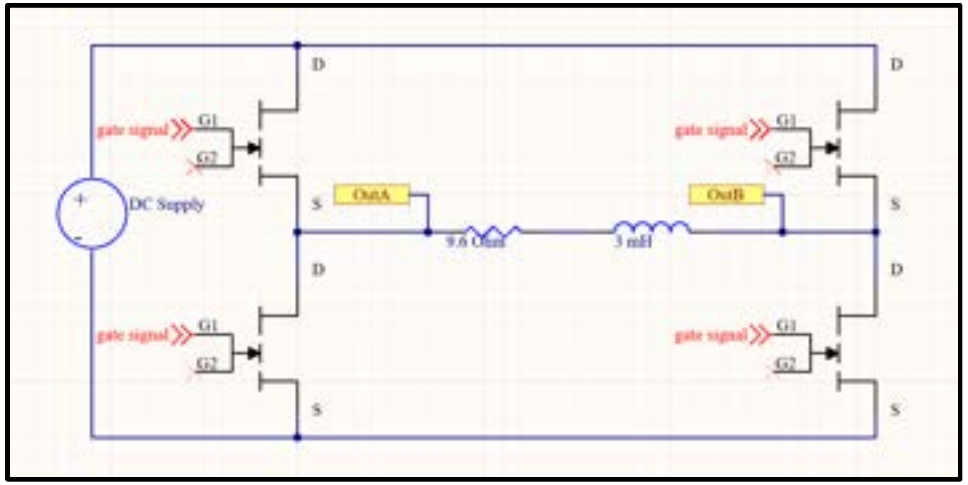
Air

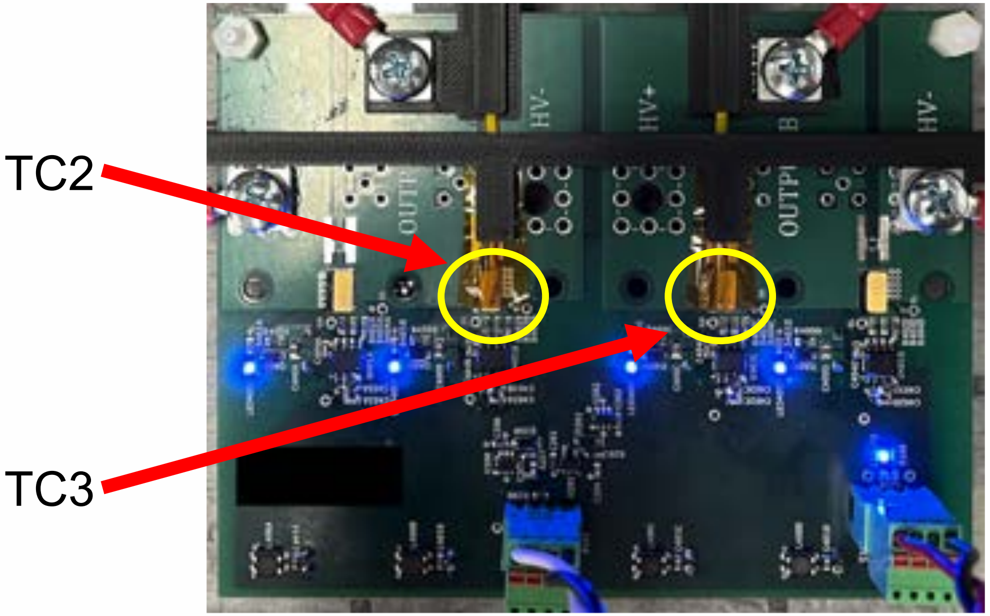
FR3

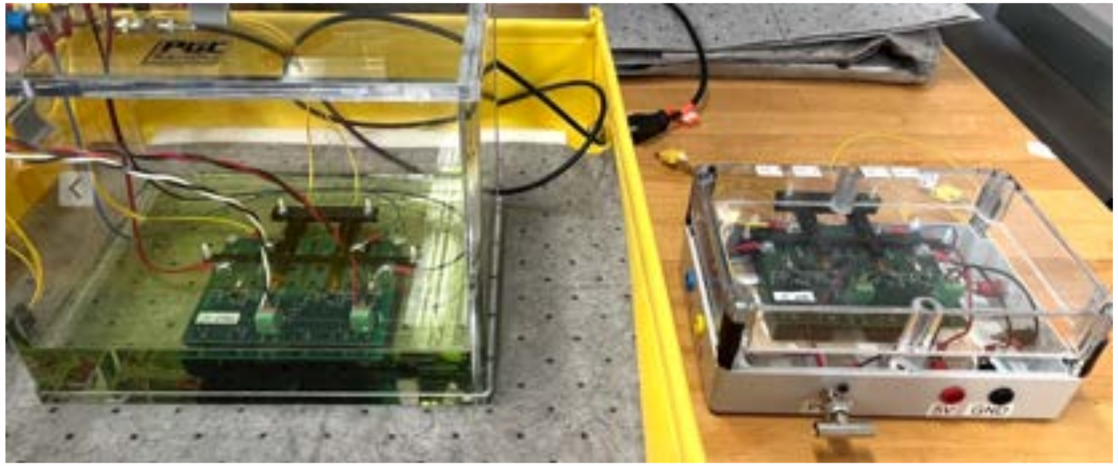
All conductors immersed in FR3 withstood maximum DC & AC HiPot voltage

Experimental Evaluation – Liquid Immersed PCBs
Thermal Performance

- GaN Transistor based H-Bridge
- Performance evaluated with PCB in ambient air and immersed in FR3 fluid

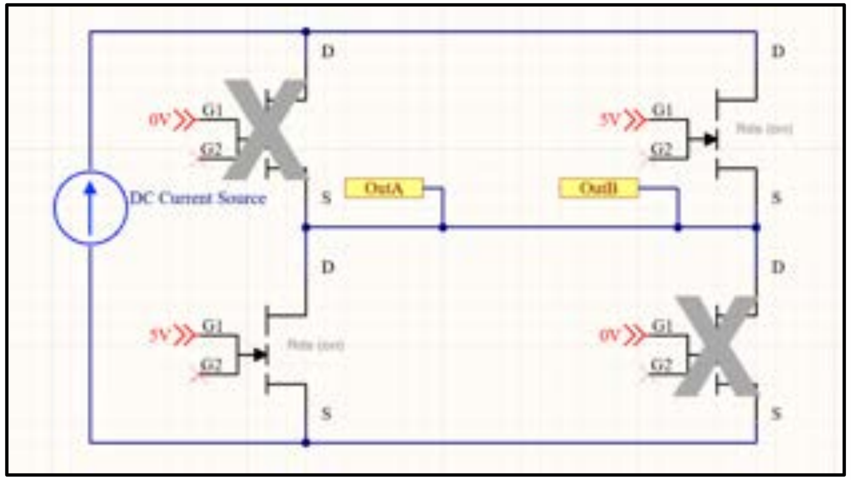


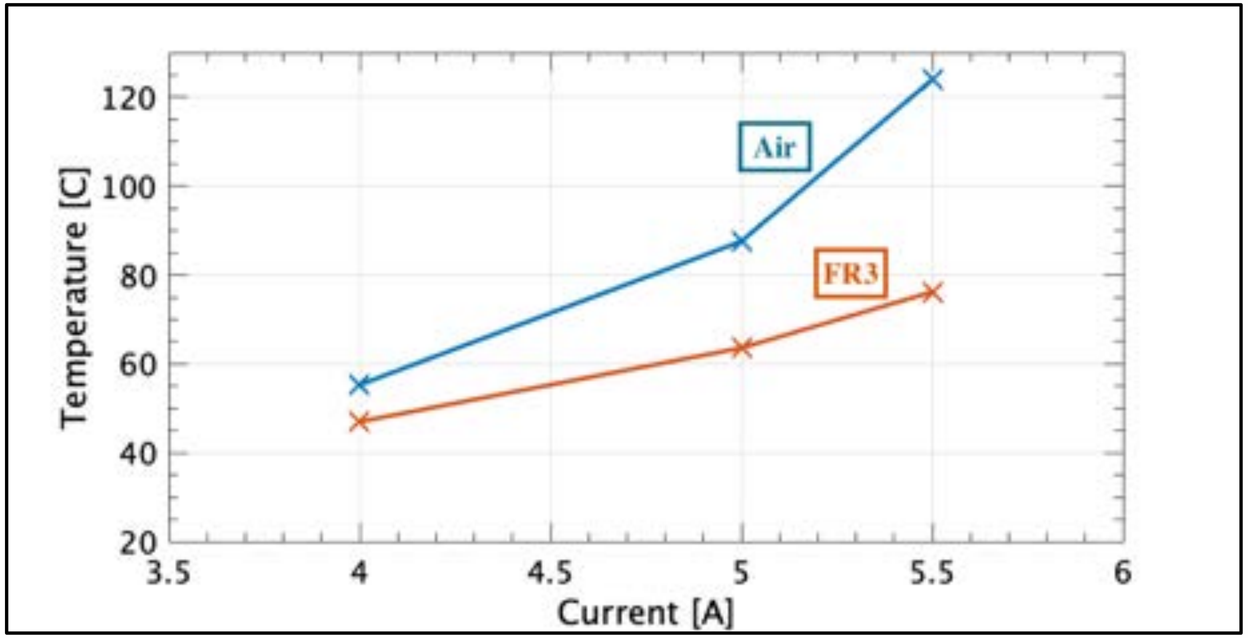




Experimental Evaluation – Liquid Immersed PCBs
Thermal Performance – Continuous Current Test

- Steady state case temperature measured with thermocouples
- Current measured with power analyzer





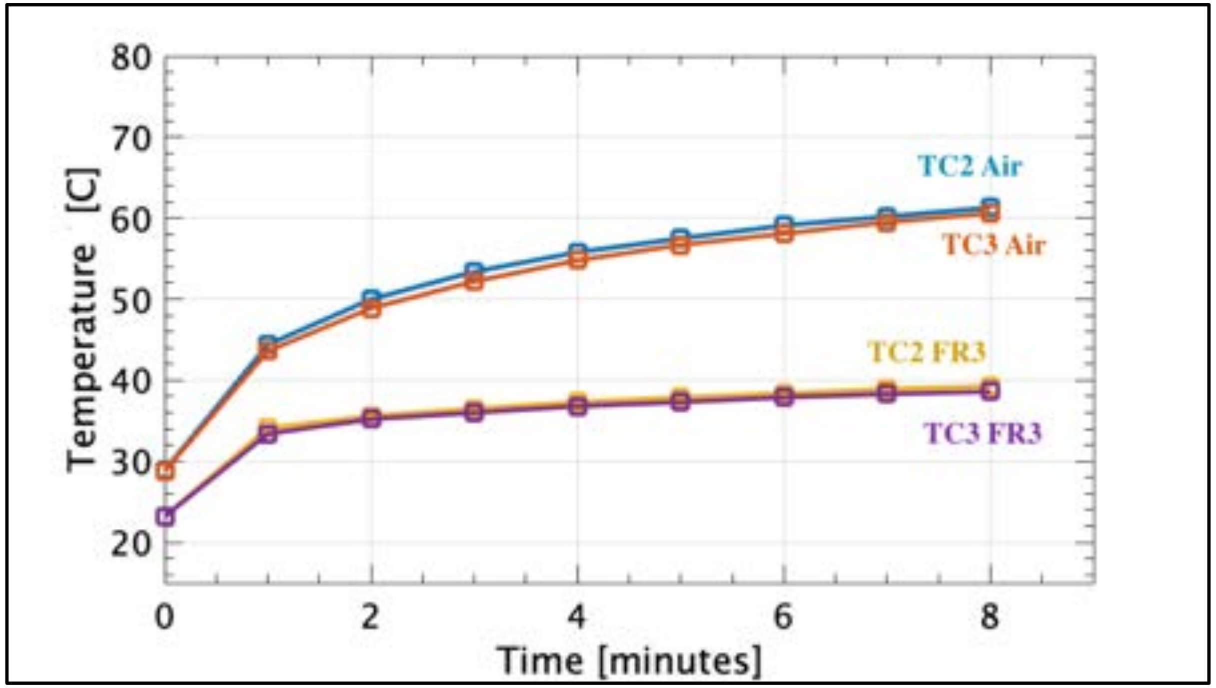
50℃ lower steady state temperature in FR3

Experimental Evaluation – Liquid Immersed PCBs
Thermal Performance – Continuous Current Test

- GaN H-Bridge switching at 10kHz with 75% duty cycle
- Output connected to RL load

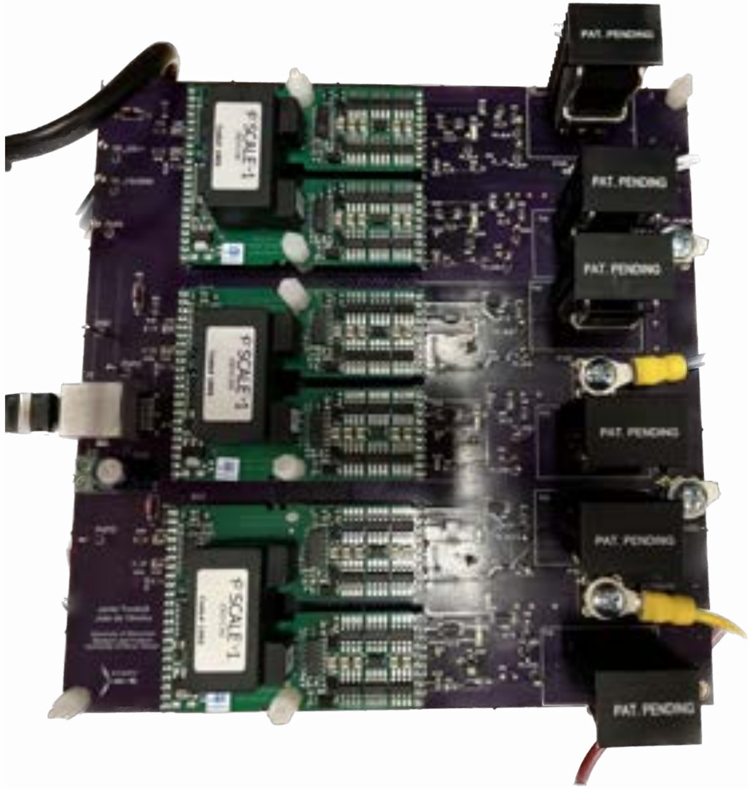
250W throughput power test.
GaN case temperature.

20℃ lower steady state temperature in FR3



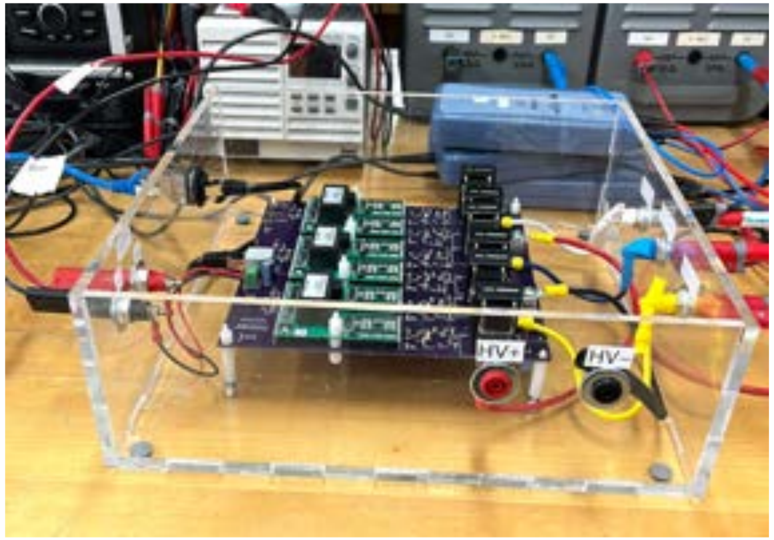
Compare TC temp to IR image

Inverter Evaluation



3 phase inverter using 3000V, 20A IXYS BiMOSFETs

Plan to demonstrate the thermal performance of inverter in air and custom enclosure (LiquidCool Solutions) which will pump FR3 fluid over fully immersed inverter.

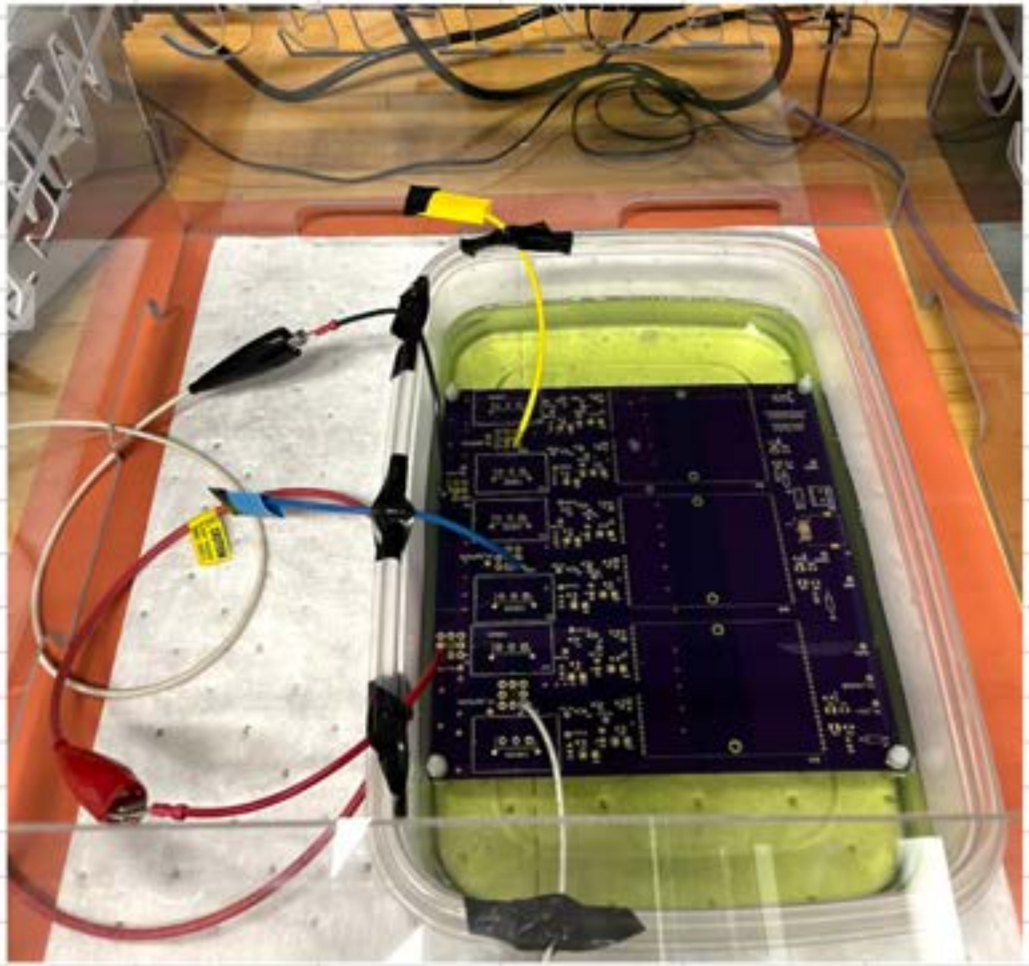


www.liquidcoolsolutions.com

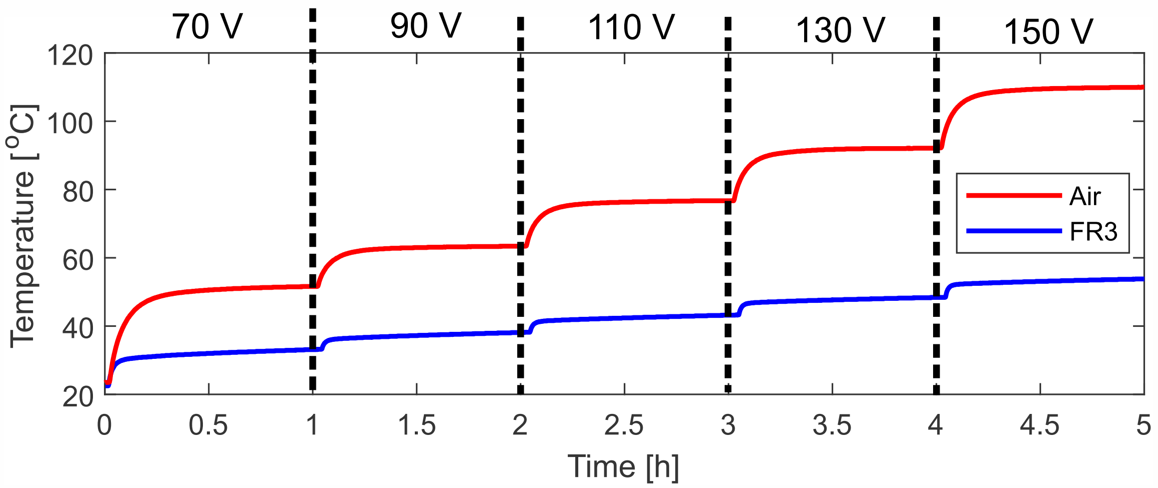
Inverter evaluation high pot testing

HVDC HiPOT	Test Voltage (kV)	
Terminals	Air	FR3
HVDC+ to HVDC-	4kV - FAIL w/spark	11.8 - PASS
HVDC+ to 3 phase Output	4.5kV - FAIL w/spark	11.8 - PASS
HVDC- to 3 phase Output	3.5kV - FAIL w/spark	11.8 - PASS

HVAC HiPOT	Test Voltage (kV)	
Terminals	Air	FR3
HVDC+ to HVDC-	3.2kV - FAIL w/spark	11.3 - Pass
HVDC+ to 3 phase Output	3.3kV - FAIL w/spark	11.3 - Pass
HVDC- to 3 phase Output	3.3kV - FAIL w/spark	11.3 - Pass



Inverter evaluation thermal performance



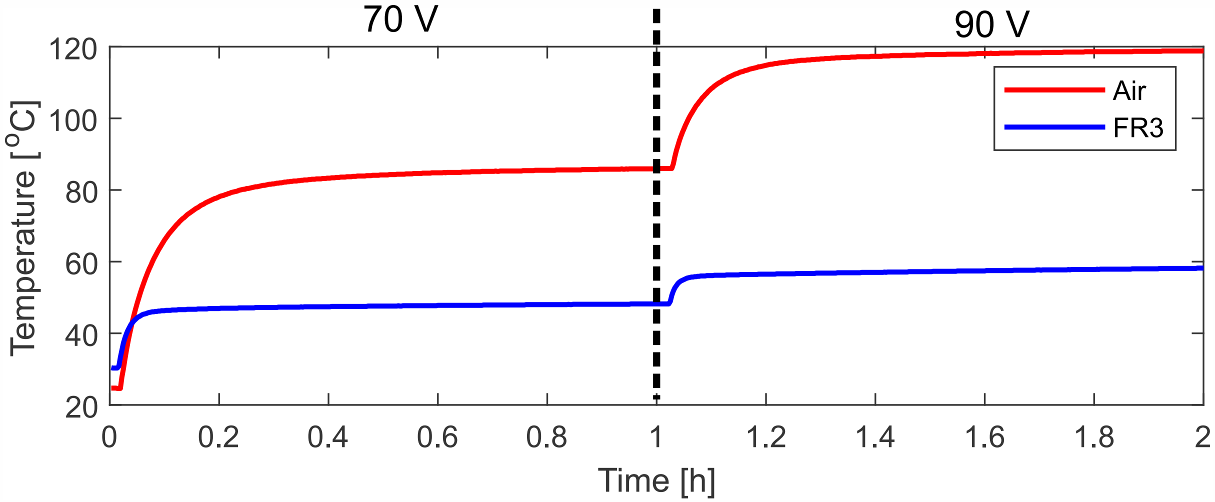
2.5 kHz and 20 kHz

temperature rise tests

Performance results at

~1000V dc bus

3 phase ac output



Conclusions

- Utility scale power electronics
  - High electric field intensity
  - High thermal loading
  - Mismatch in reliability experiences
- Liquid immersed power electronics
  - Decades of experience
  - High altitude: overcome Paschen discharge challenges
  - Under water pressure vessel challenges
- Ripe for definitive studies in research, engineering
  - Bridge the expectations gap

Thank You!