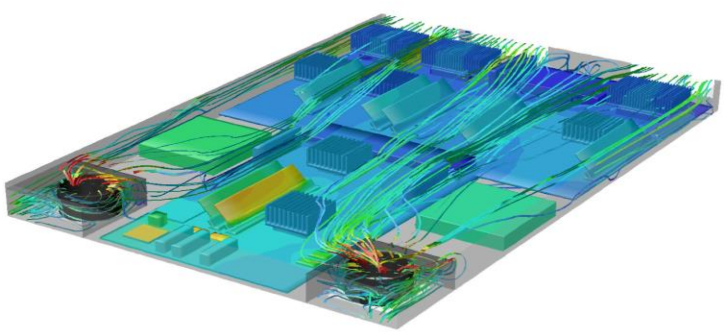
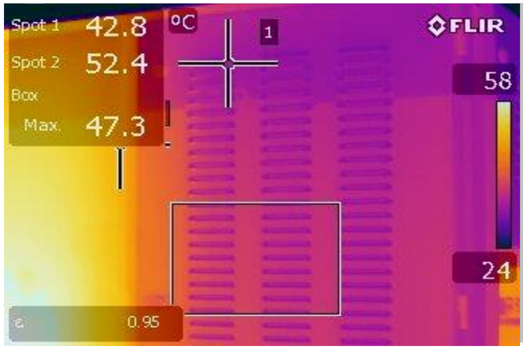
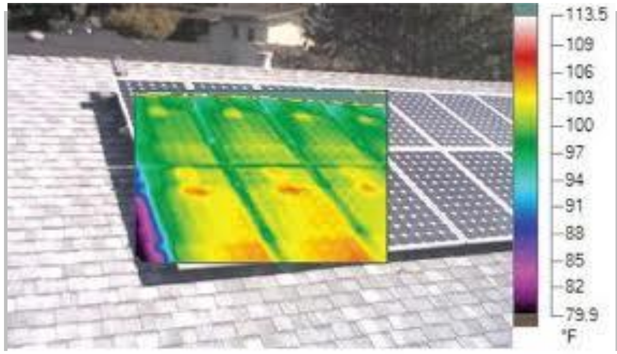
SAND2015-1545PE

Exceptional service in the national interest

Sandia National Laboratories







Inverter Electro-Thermal Modelling

SAND Number: 2015-XXXXC

Kenneth M. Armijo & Olga Lavrova

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Sandia National Labs: PV Systems Reliability Program

Sandia National Laboratories

Statement of Problem

- PV system investment is driven by initial price, system performance over time, and system reliability/availability to adequately assess risk.
- Poorly understood Reliability decreases confidence in PV technology and increases LCOE
- Need to understand WHOLE SYSTEM reliability, not only PV modules

Methodology

- Develop and apply reliability tools for use throughout the PV supply chain, not only PV module
  - Failure Modes and Effects Analyses
  - Accelerated Testing and Diagnostics
  - Real-time testing of systems
  - In-depth reliability and availability models
- Focus is on system reliability, inverter reliability, O&M strategies

Project Objectives

- Reduce LCOE by providing information needed to:
  - Improve BOS lifetime, reliability, safety, availability and performance
- Help investors to quantify bankability, quantify risks and reduce the costs of project financing

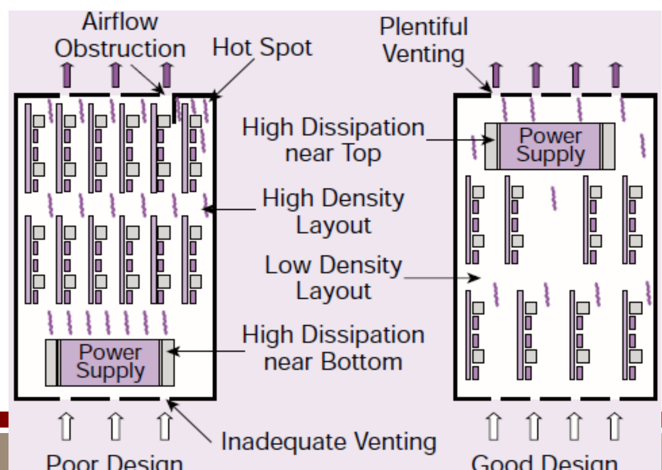
Challenges

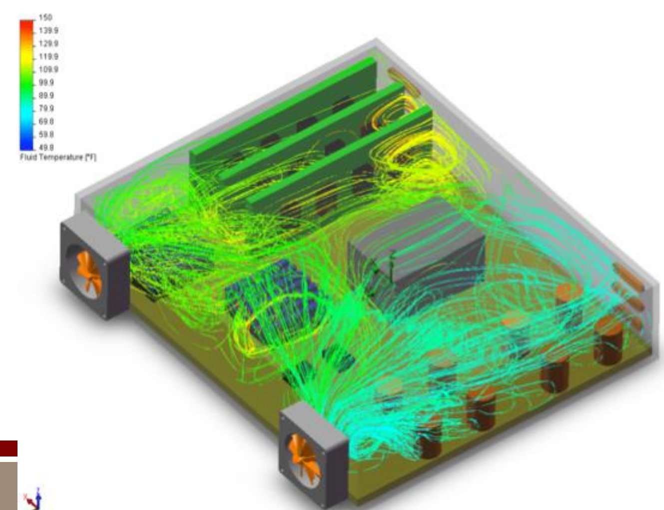
- Constantly evolving technologies, manufacturing processes, and materials
- Increasingly complex systems functions
- Short time-to-market demands
- Risk to owners and underwriters, and associated cost implications

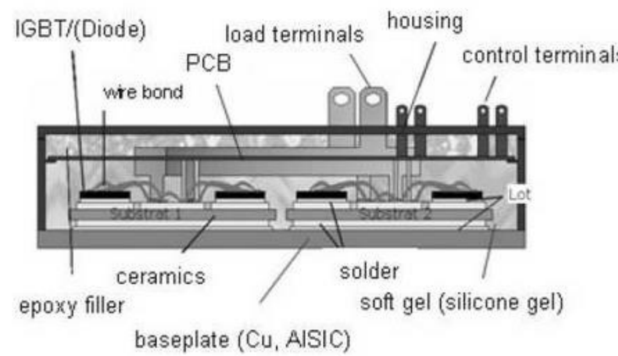
Overview & Need for Electro Thermal Modeling

Sandia National Laboratories

- Decreasing size & growing complexity of power transistors (ie. MOSFETS and IGBTs) and micro-electronic systems, power dissipation of integrated circuits bas become a critical concern.
- Thermal influence upon an electrical system caused by each transistor's self-heating and tightly coupled thermal interaction with neighboring devices cannot be neglected since excessive temperatures can cause deterioration.
  - It is necessary to develop an electro-thermal model which accurately computes the dependence between power dissipation and temperature distribution over the device.







Construction of an IGBT module

Overview & Need for Electro Thermal Modeling

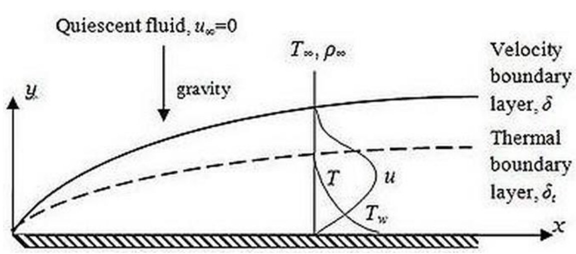
- **Research Goal:** Develop robust, reliable and non-ideal electro-thermal model for an inverter and PV system.
- **Purpose:** Provide an overview of heat transfer challenges and design/operational solutions using fast, comprehensive, transient modelling tools.
- **PV Inverter Reliability:** PV inverters continue to be an area of reliability challenges for achieving levelized LCOE. Electro-thermal issues still contribute to these issues, especially for advanced inverter functionality. Rigorous, non-ideal, and transient electro-thermal models are required for robust development.
- **Sandia Reliability Program:** Sandia's historical and unique capabilities with power electronics, computing resources and PV fundamental science, as well as distinctive experimental platform laboratories and field-sites, provide distinction for electro-thermal modelling.

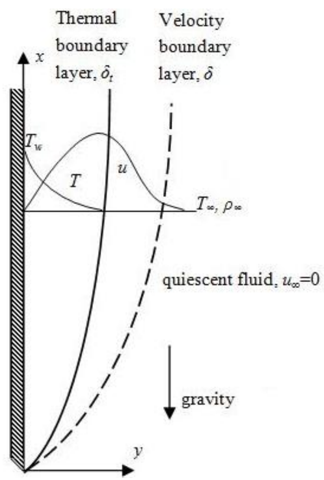
Thermal Heat Transfer

- Heat Transfer & Thermal Management
  - Modes for Electronic Design: Conduction, Convection & Radiation

$\dot{Q}_{Cond} = kA\frac{\Delta T}{\Delta l}$ $\dot{Q}_{Conv} = hA\Delta T$ $\dot{Q}_{Rad} = \varepsilon\sigma A(T_S^4 - T_\infty^4)$

Natural Convection





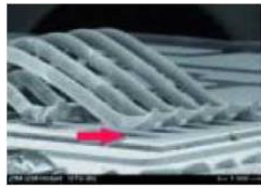
(Incropera and Dewitt, 2002)

- Inverter Thermal Considerations
  - Thermally Sensitive Electronics
    - Passive vs. Active Cooling
  - Temperature Sensing & Controls
    - Derates & Aging/Failure Modes
- Power Electronics Considerations
  - Conduction HT to case & heat sink
  - Radiation HT only ~1-2%

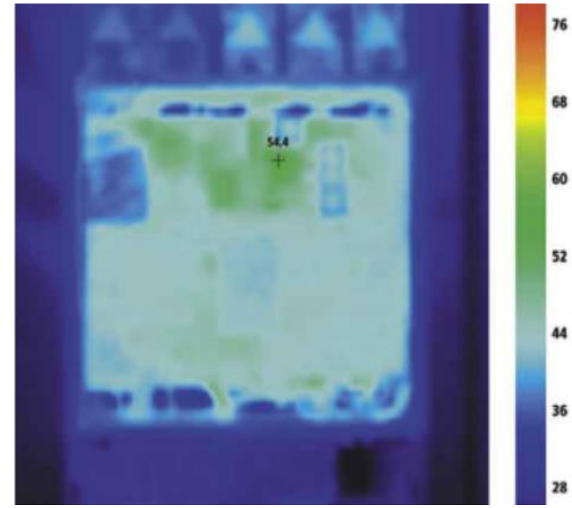
Process	h [W/m^2-K]
Natural Convection	
Gases	2-25
Liquids	50-1000
Forced Convection	
Gases	25-250
Liquids	100-20,000
Convection with Phase Change	
Boiling or Condensation	2,500-100,000

Thermal Design Considerations

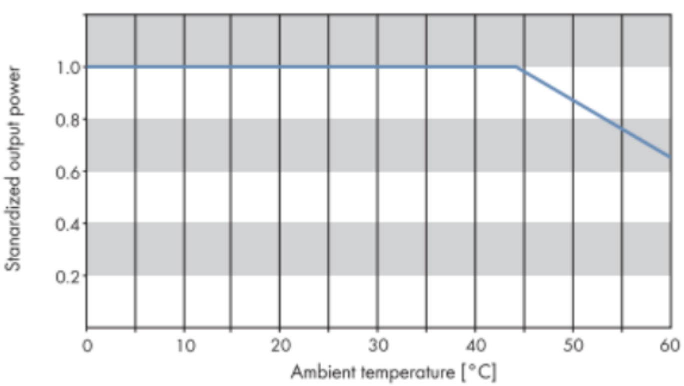
- Critical Thermal Management Components
  - IGBT's/MOSFET's (Flicker et. al, 2012)
    - Latch-Up
    - Bond Lift-Off
  - Capacitors



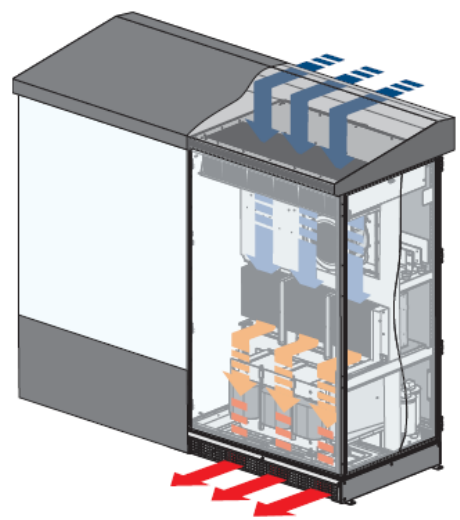
(Saddik, 2013)



- Direct Active Cooling Issues
  - Dust, Salt Build-Up and Fouling
- Conjugate Heat Transfer
- Derate Operation



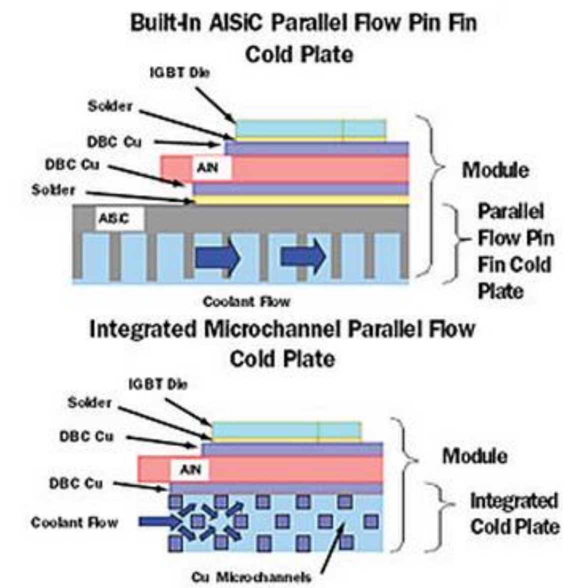
(Saddik, 2013)



(http://www.sma.de)

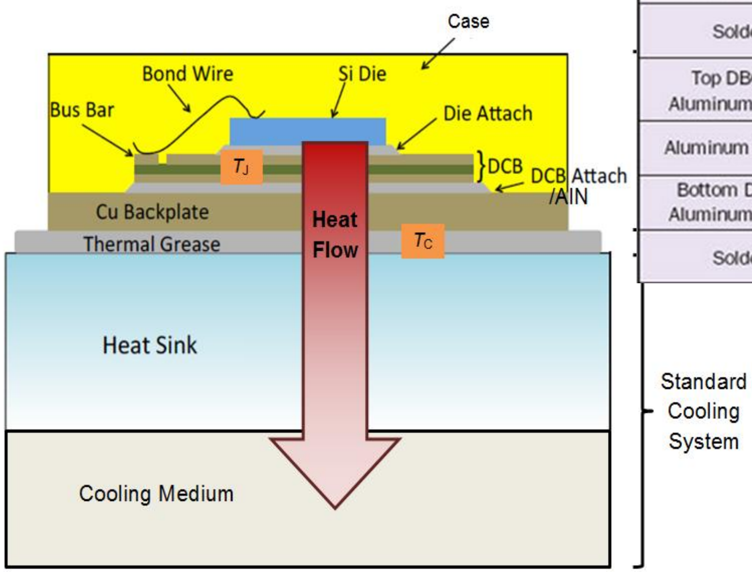
Power Electronics

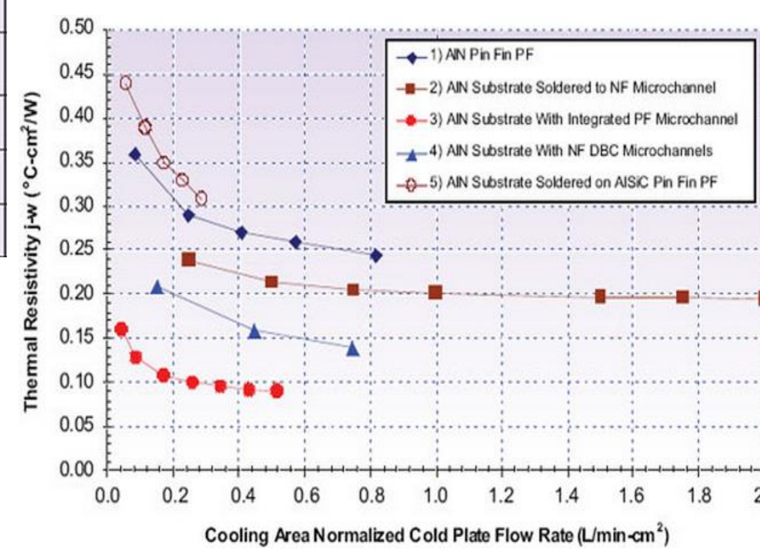
- Greater Number of Layers Increases R_{th} with Standard Configurations Capable of Thermal Dissipation Densities Up to 250-300 W/cm^2
- Power Cycling Degradation Impacts
  - Material Degradation and Micro-Fracturing
- CTE Mismatch Impacts



Layer	Thermal Conductivity (W/mK)	Thermal Resistivity (°C-cm²/W)
Silicon (100°C)	100	0.025
Solder	36	0.036
Top DBC on Aluminum Nitride	393	0.008
Aluminum Nitride	170	0.037
Bottom DBC on Aluminum Nitride	393	0.008
Solder	36	0.035

(Leslie et. al., 2013)





Accelerated Testing

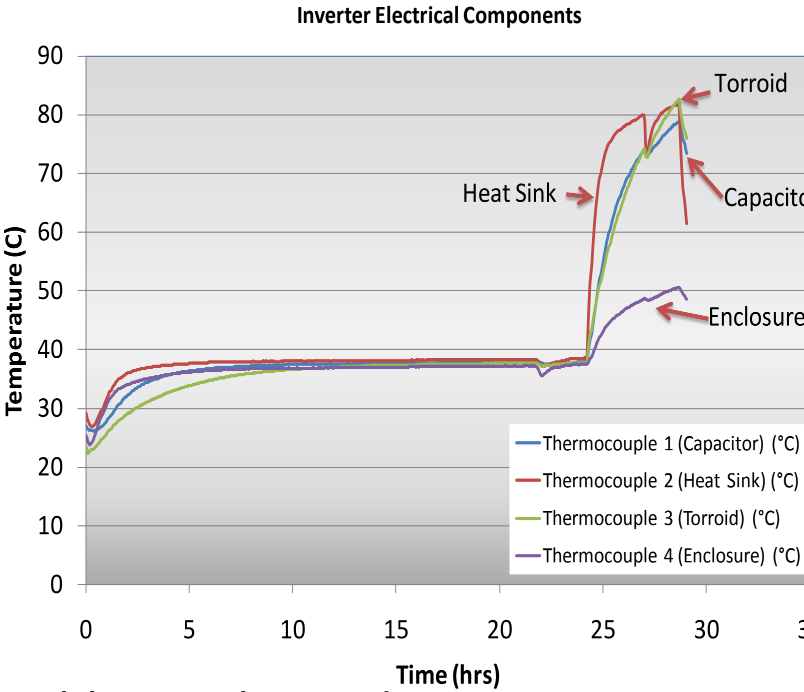
- Thermal cycling
  - Determines the ability of parts to resist extremely low and high temperatures, as well as their ability to withstand cyclical extremes. Stress resulting from cyclical thermomechanical loading accelerates fatigue failures.
- Humidity Freeze
  - This test serves as a mechanical strength test to ensure the reliability of a device/system from failure due to stress and water ingress
- High Temperature Operating Bias (HTOB)
  - It consists of subjecting the parts to a specified bias or electrical stressing, for a specified amount of time, and at a specified high temperature.

System Element	Failure Mechanism	Accelerated Test
Enclosure/Interconnect	Mechanical Deformation, Moisture Ingress, Corrosion, Dielectric Breakdown	Thermal cycling (TC)/Humidity Freeze (HF)/Damp Heat Test/UV Precondition
PCB/Solder system	TCE Mismatch, Electromigration. Corrosion	Thermal Cycling/humidity Freeze/ Damp Heat Test
Passive components	Dielectric/Insulation Breakdown	Humidity Freeze/Thermal Cycling/ UV Degradation
Active Components	Mechanical Wear-Out, etc.	Thermal Cycling/Damp Heat Test/Extreme Temperature Exposure/Integrated Power Cycling
Integrated Circuit Devices	Hot Carrier Injection (HCI), Time-Dependent Dielectric Breakdown (TDDB), etc.	Thermal Cycling/Humidity Freeze/Damp Heat Test

Accelerated Testing (AT)

- Accelerated Stress Testing (ALT)
- Accelerated Stress Testing (AST)
- Highly Accelerated Life Testing (HALT)
- All of the above allow us to correlate to degradation signatures and predictions, as well as to validate novel diagnostic, screening and testing methods.
- Tests include:
  - Thermal Shock (TS), Thermal Cycling (TC), Highly Accelerated Thermal Shock (HATS), Damp Heat (DH) ,Humidity Freeze (HF)

Thermal Profile for Inverter



What is ALT & why?   Issues with ALT:

What?

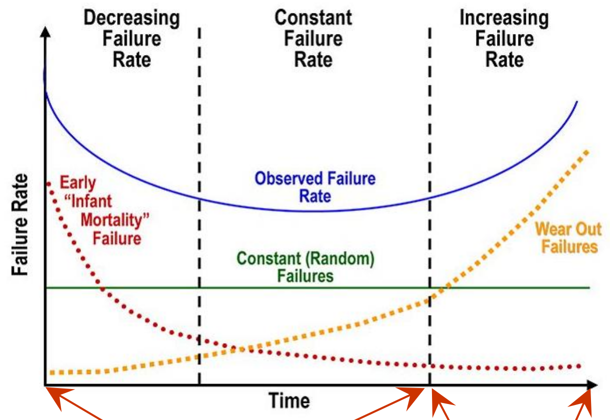
- Component life tests
- High stresses
  - Single or combined
  - Activate “appropriate” failure modes
  - Measureable
- Failure analysis

Why?

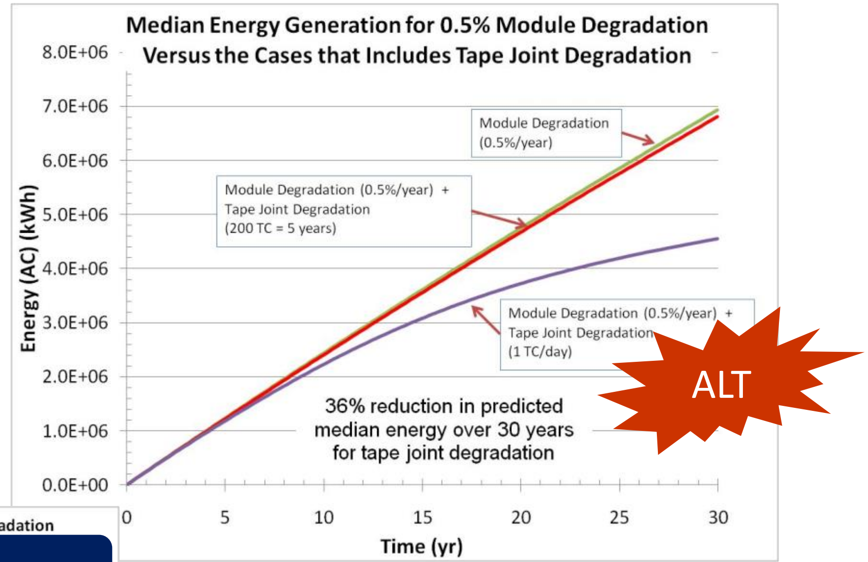
- Time
- Full system is expensive and complicated

- Unknown failure mechanisms
- Unknown / variable use environment
- Changing mechanisms as function
  of environmental stress
- Difficult to control and characterize defects
- Long duration experiments
- Evolving / improving technology

Laboratory testing provides vital information for PV system reliability

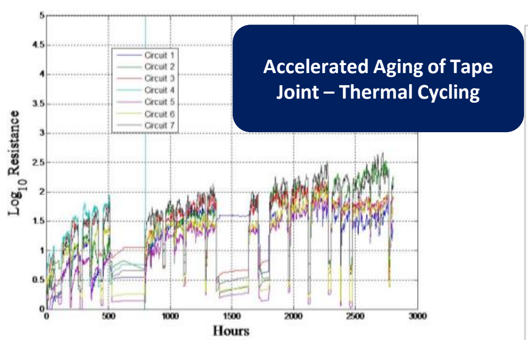


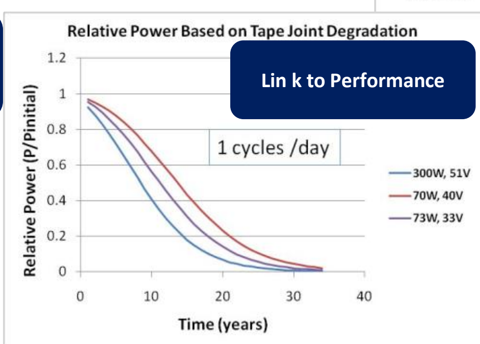
System performance model must include wear out (end of life) information



Field Data (O&M, Failures, …)

Accelerated Testing / Lab Tests

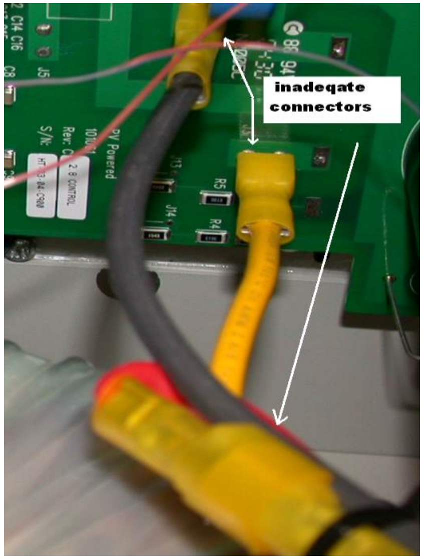


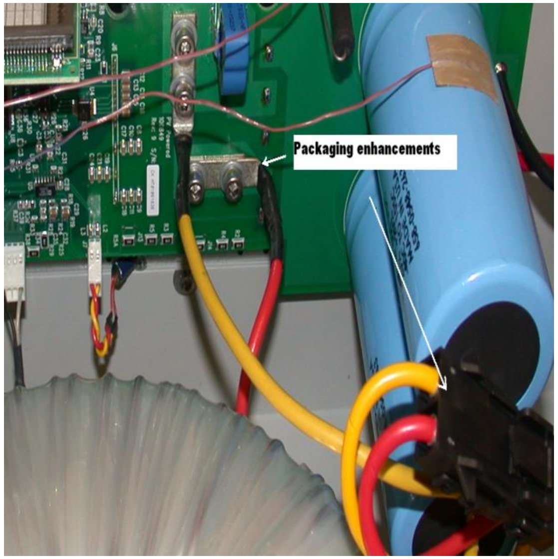


Acceleration Factors

Accelerated Aging for Inverters

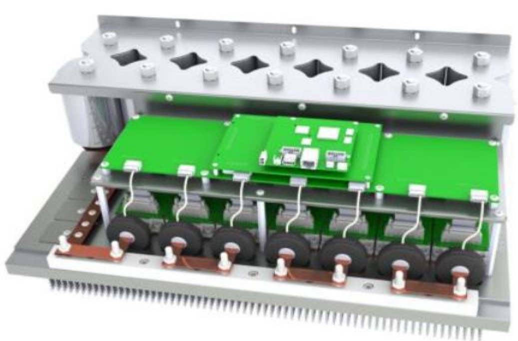
- No specific industry standard exists
  - IEC 61215 is the "de-facto" spec
- HALT testing is spotty; independently applied by inverter manufacturers
  - Data in most cases proprietary
- Separate needs identified for residential and commercial scale inverters
- Failure modes identified but not in a uniform program applicable across the industry
- System predictive models will require inputs for inverters

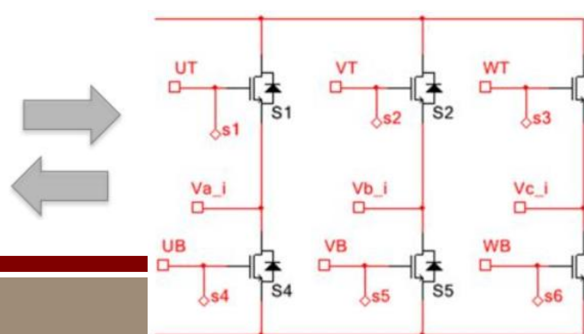


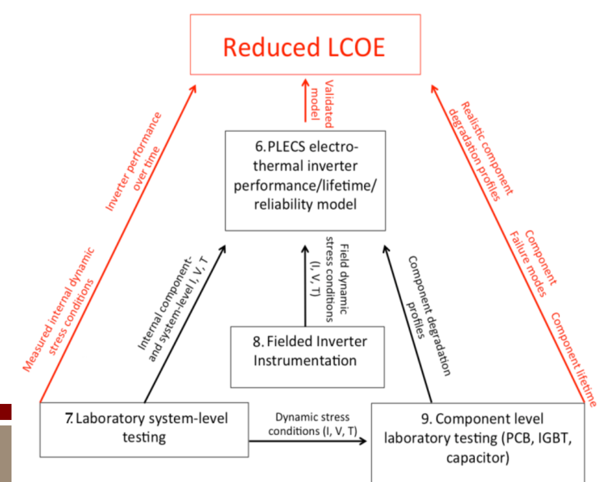


Electro-Thermal Modelling Platforms

- SPICE
  - Good for modelling device-level electrical components though….
- PLECS
  - Idealized Power Electronics & difficult to interface with other platforms
- COMSOL
  - Issues with quick customization and convergence.
- Matlab/Simulink
  - SimPowerSystems
    - Great for general Electro-thermal analysis, though issues with idealities with power electronics.
  - SimElectronics
    - SPICE-Level Modelling with Non-Ideal Characterization

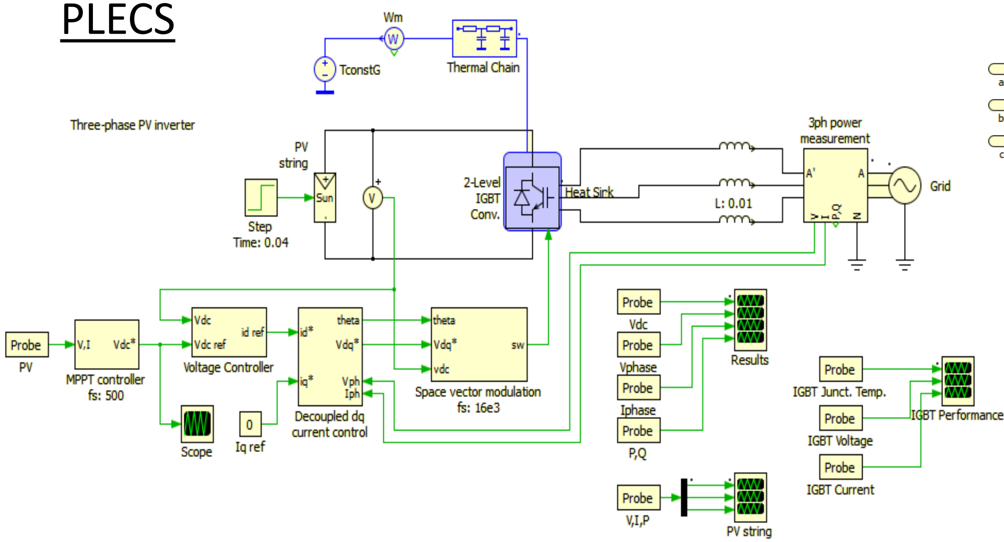


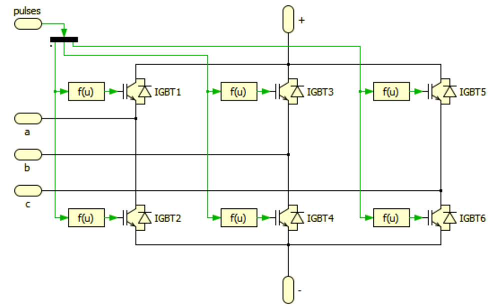


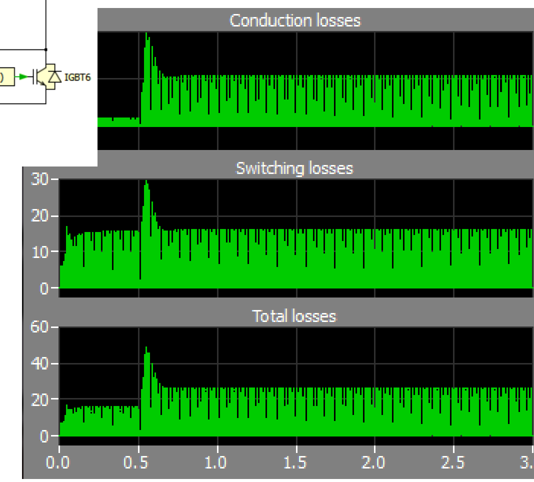


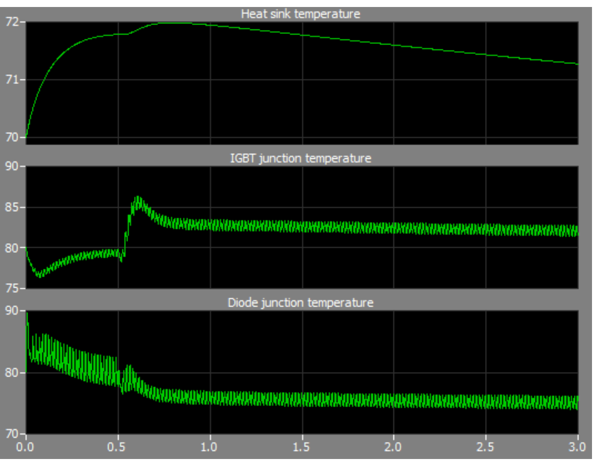
Inverter Modelling Platforms

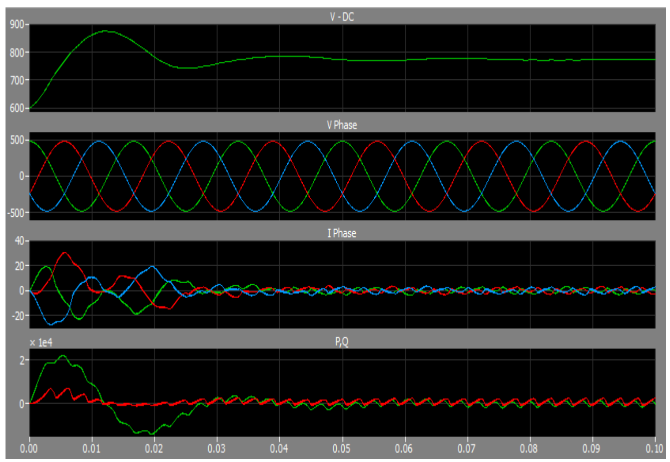
PLECS

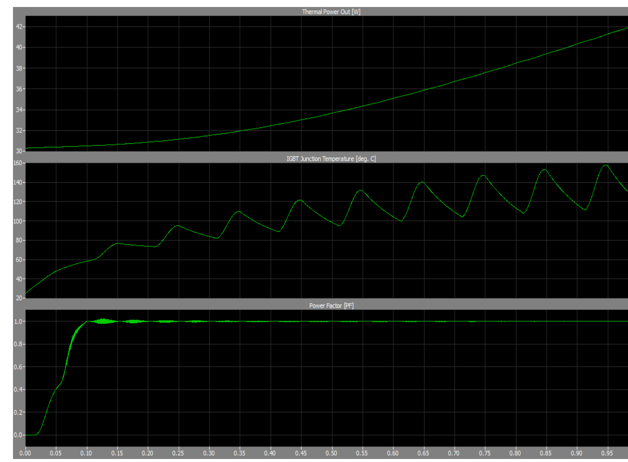






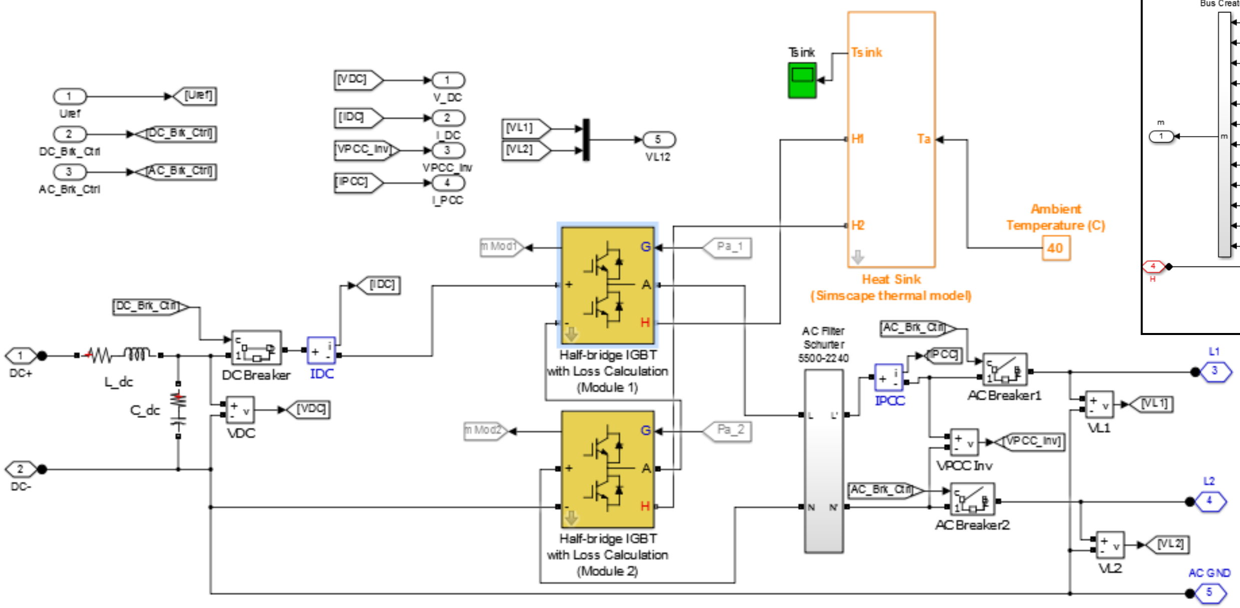


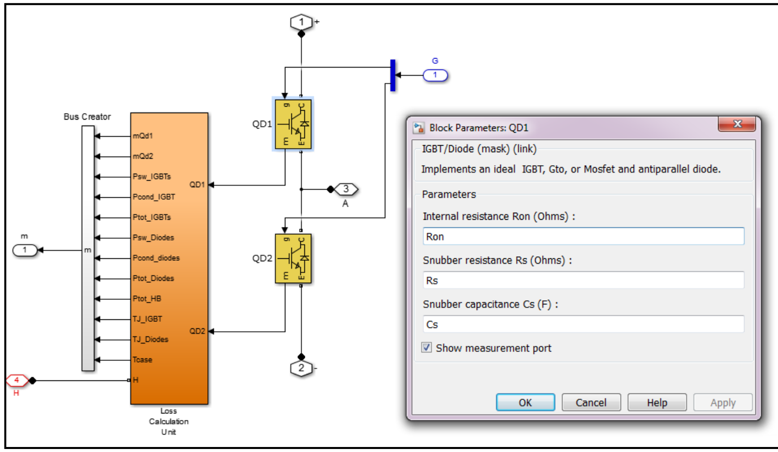




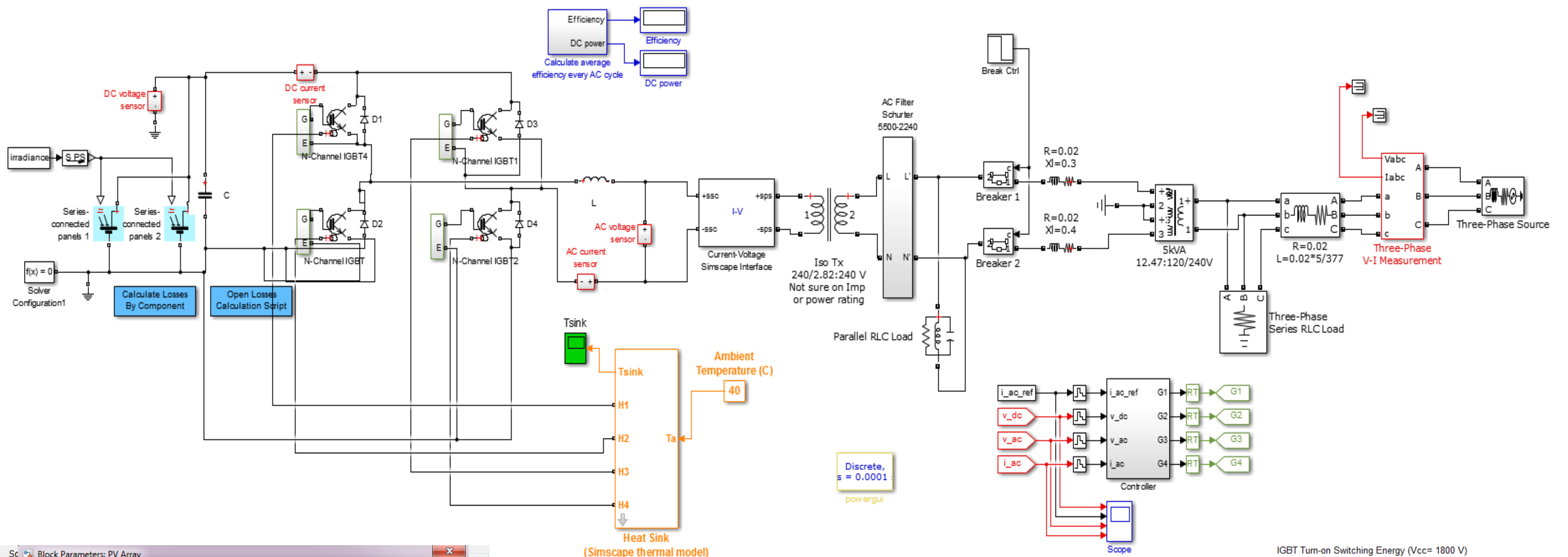
Matlab/Simulink SymPower Systems

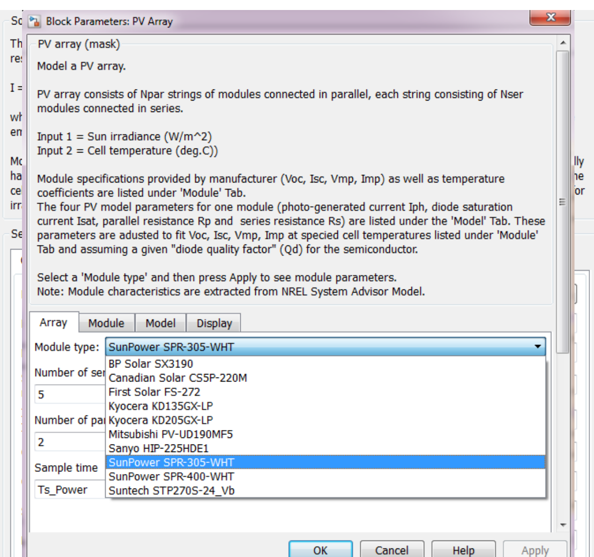
- Simulink
  - Block-Diagram Platform for analyzing systems
- SimPower Systems PV Examples
  - Electrical – Linear Differential Equations
  - Thermal – Modelling based on resistor and capacitor thermal circuits

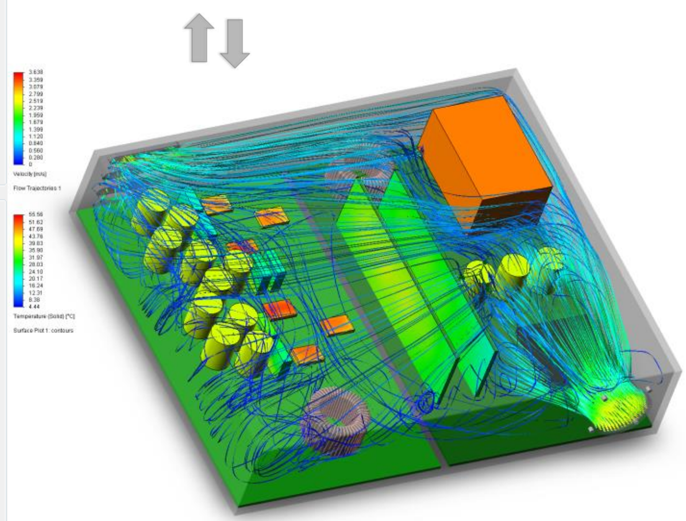


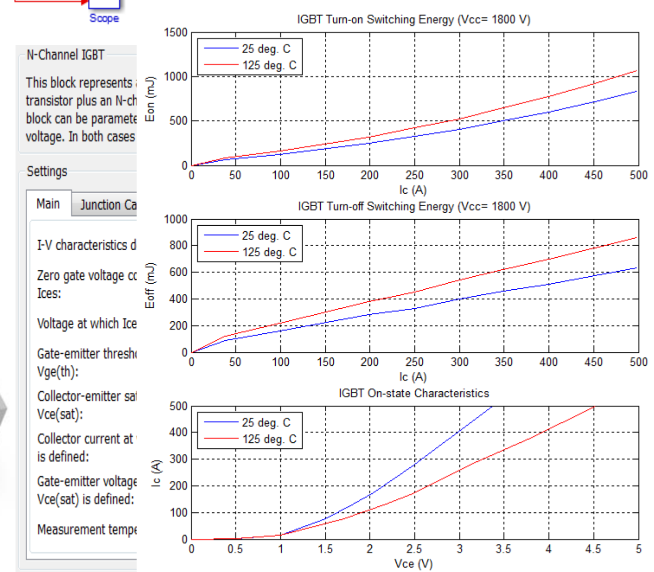


SimElectronics Model



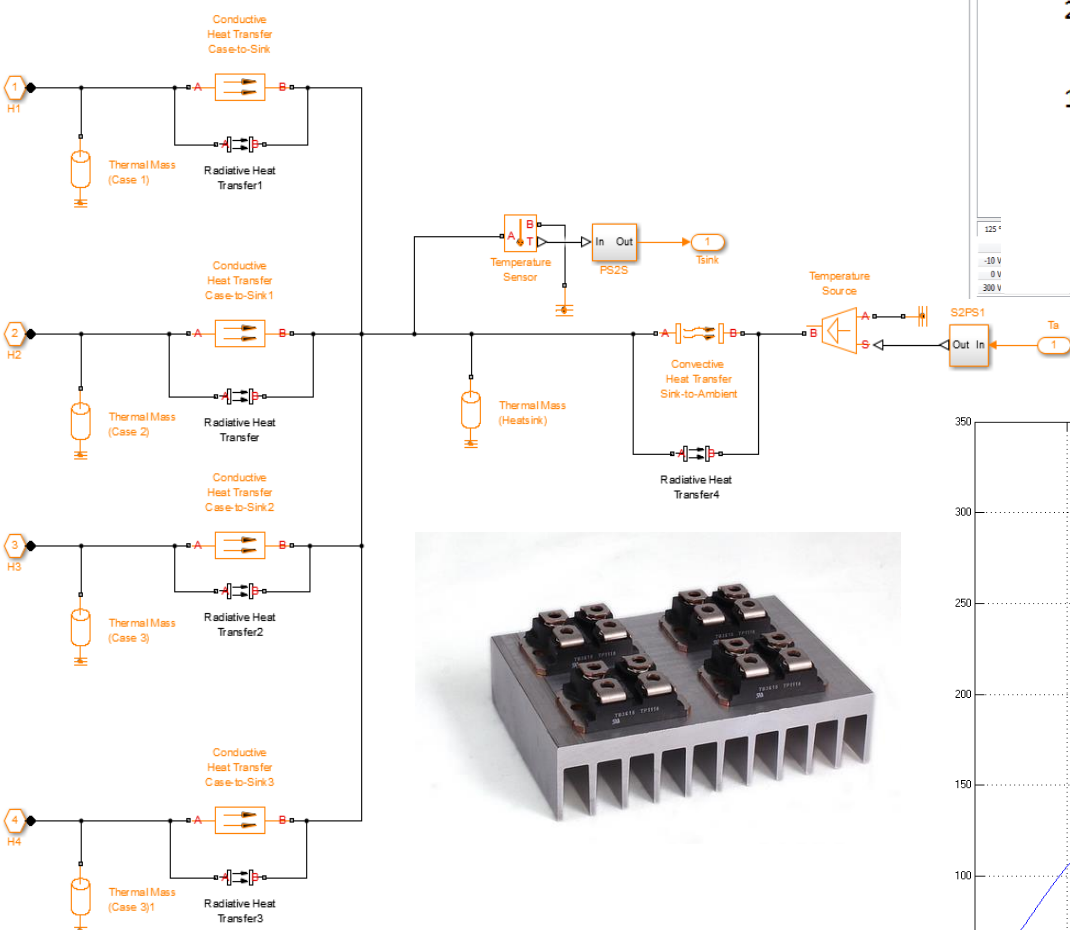


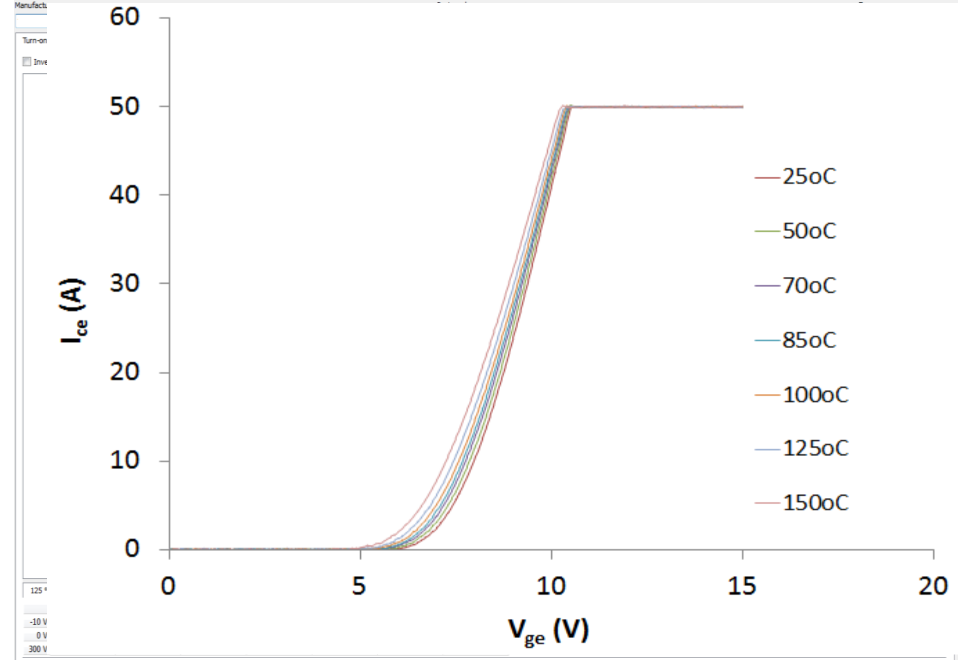




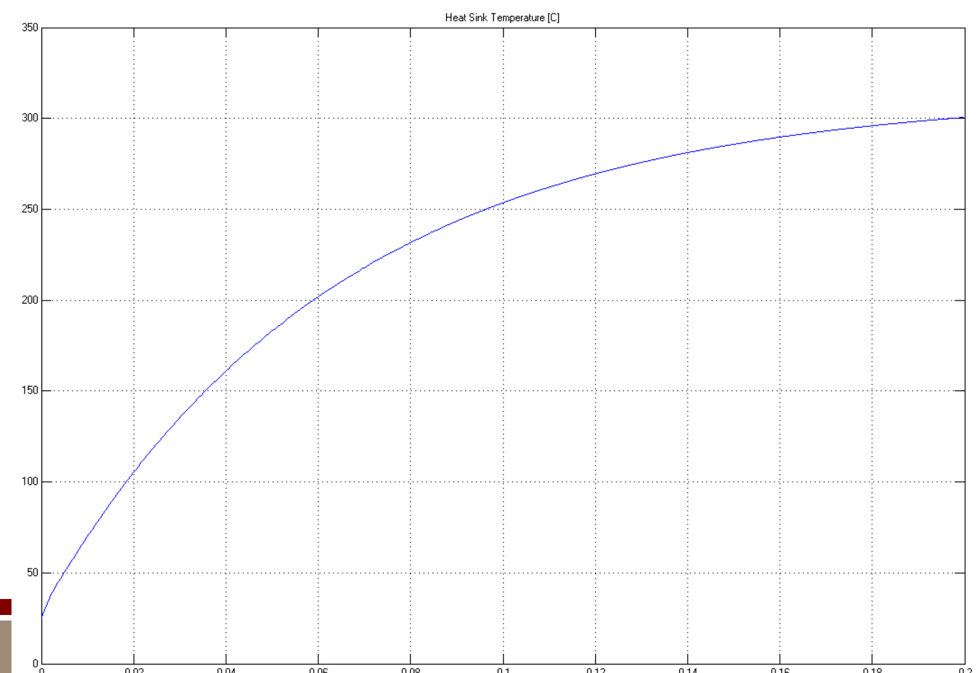
Thermal Sub-Model

Heat Sink Thermal Model

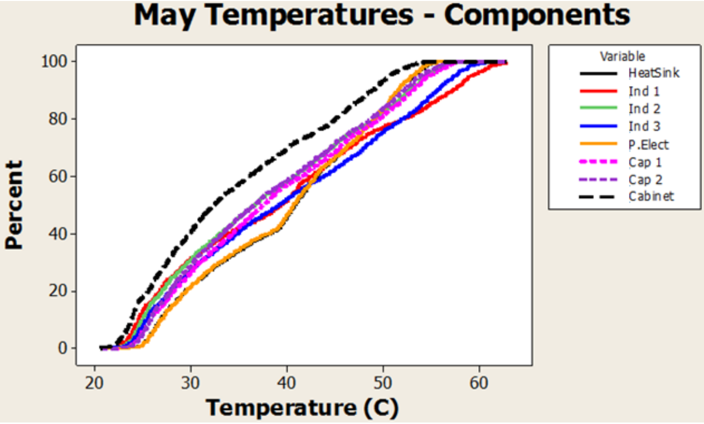


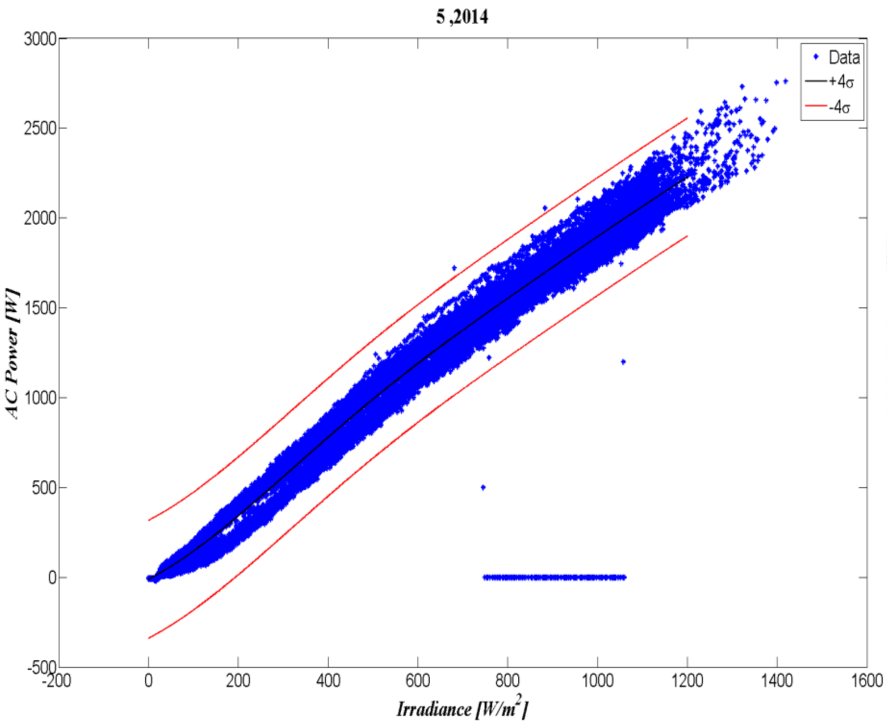


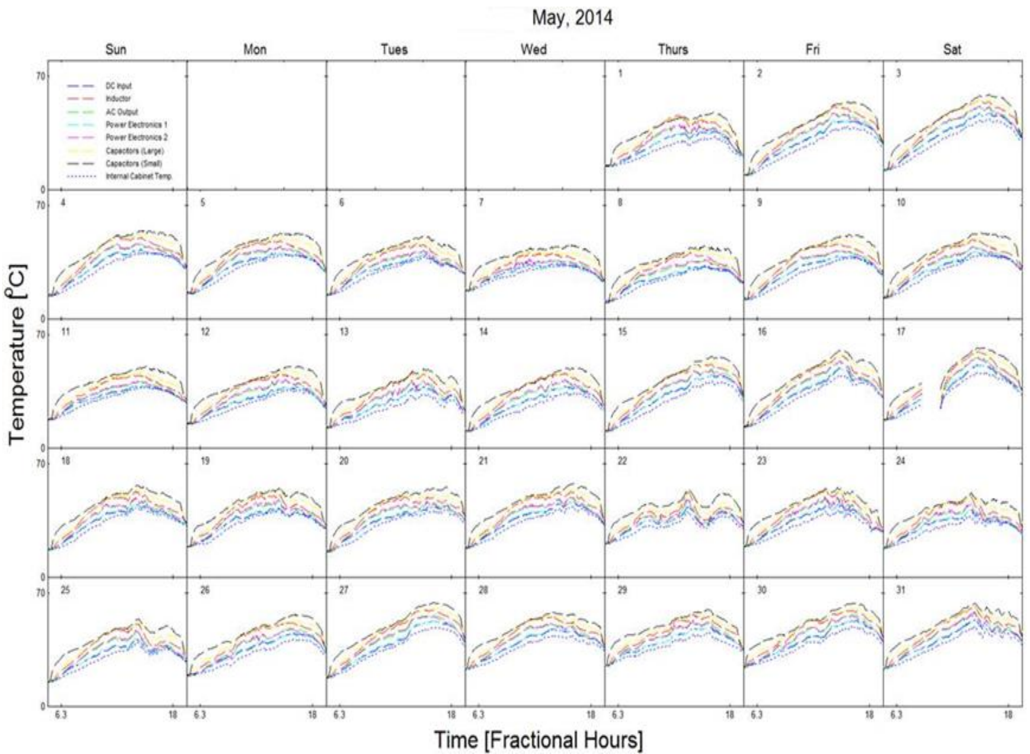
Heat Sink Thermal Profile Results



Fielded Studies Validation



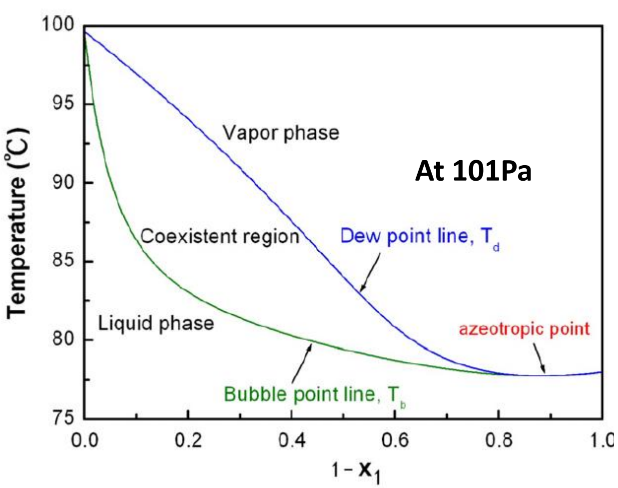


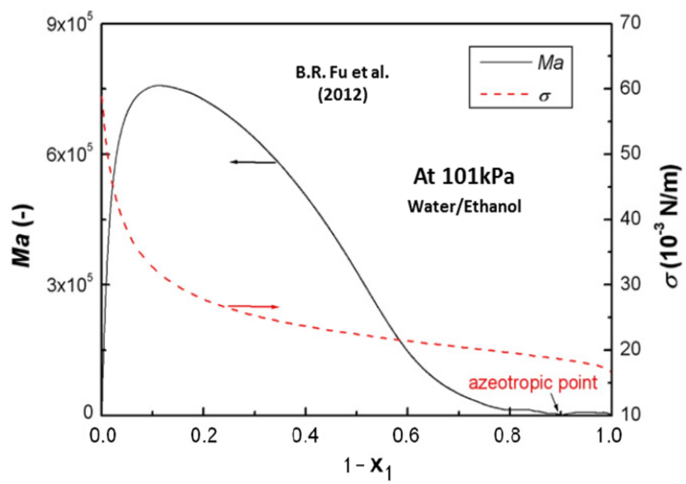


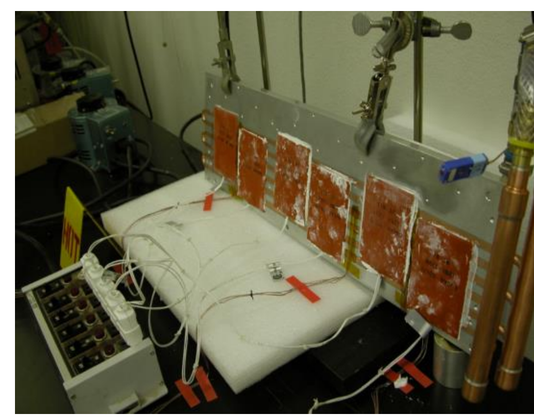
Heat Exchanger Cooling Plate

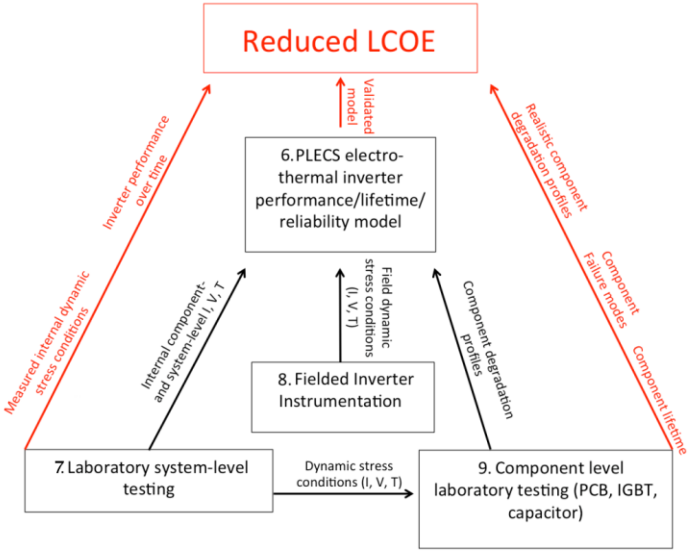
- Current Work Evaluating Heat Transfer Capability of Binary Mixture Working Fluids to Improve Heat Exchanger Performance
  - Propylene-Glycol (PPG)/Water
  - Ethanol/Water
  - Pure Components
- Alternative Adhesives Durability/ Performance Evaluation

[redacted]









U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
SAND No. 2011–XXXXP.

Exceptional service in the national interest

Sandia National Laboratories

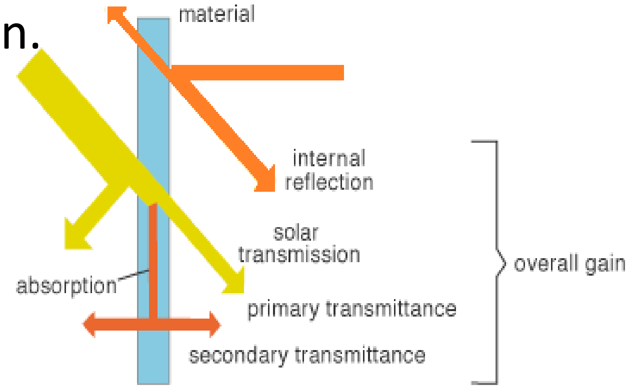
Thank You

Extra Slides

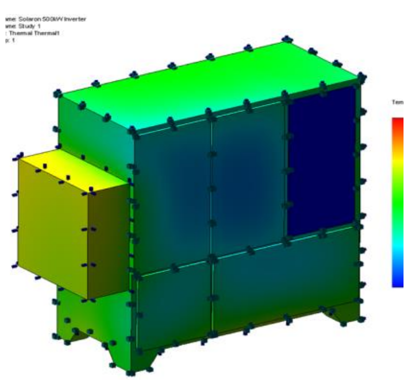
Solar Gain & Thermal Gain

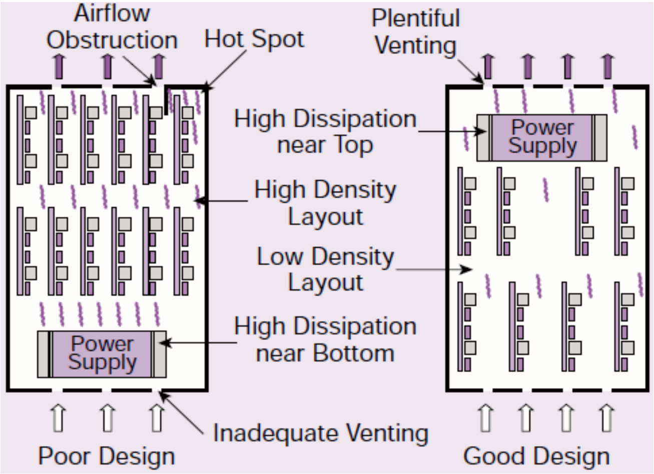
- Thermal gain from solar radiation in an object, space or structure, which increases with the strength of the sun, and with the ability of any intervening material to transmit or resist radiation.

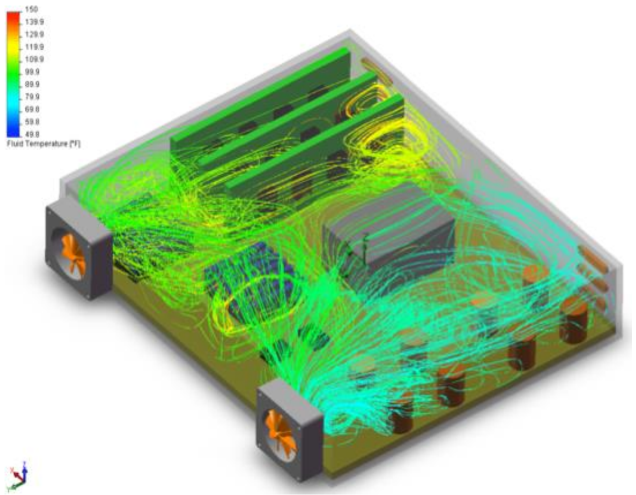
Radiative Energy Balance:



- FEA/CFD Impact Analysis of Internal Comps.

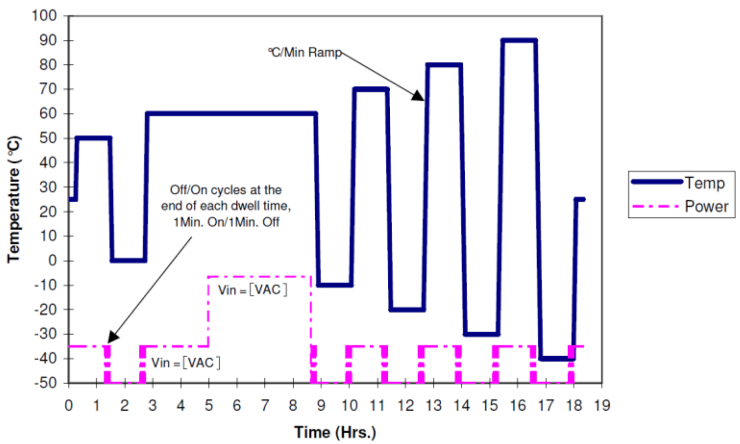






Accelerated Testing

- HALT – Highly Accelerated Life Testing
  - Stress tests not meant to simulate the field env., but find weaknesses in design
  - Stresses are stepped up to well beyond the expected field environment until "fundamental limit of the technology" is reached
  - General Procedures for HALT Testing:
    - 1. Attach thermocouples, & monitor line input Vac, output Vdc, and other signals.
    - 2. Perform temperature cycling
    - 3. Perform functional test
    - 4. Determine root cause of any failures, implement corrective action (if required), and repeat test (if required).



$$A.F. = e^{\left(\frac{E}{K}\right)\cdot\left(\frac{1}{T_1}-\frac{1}{T_0}\right)}$$

T_1 = Normal Ambient Temp. (298 °K)

T_0 = Elevated Ambient Temp (°K)

E = Activation Energy (eV, Typ.)

K = Boltzman's constant