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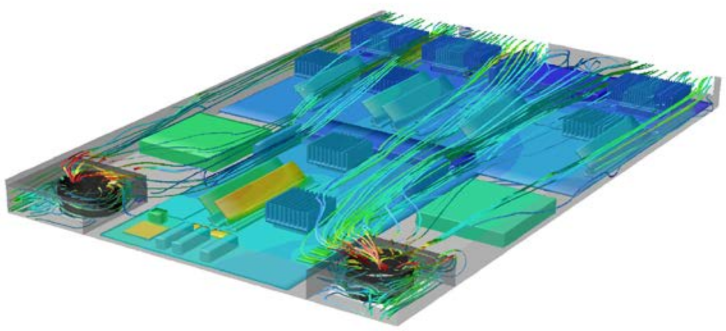

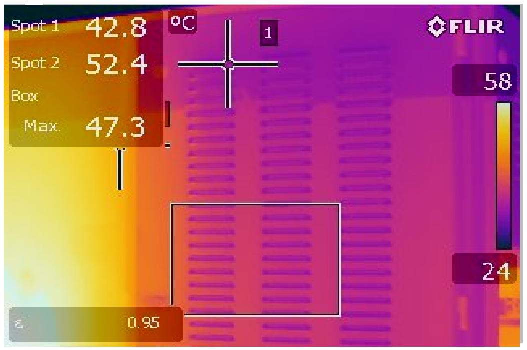

Inverter Electro-Thermal Modelling

Kenneth M. Armijo & Olga Lavrova

Sandia National Laboratories – Photovoltaic and Distributed Energy Dept.

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Sandia National Labs: PV Systems Reliability Program

Sandia National Laboratories

Overview

- 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

Program Objectives

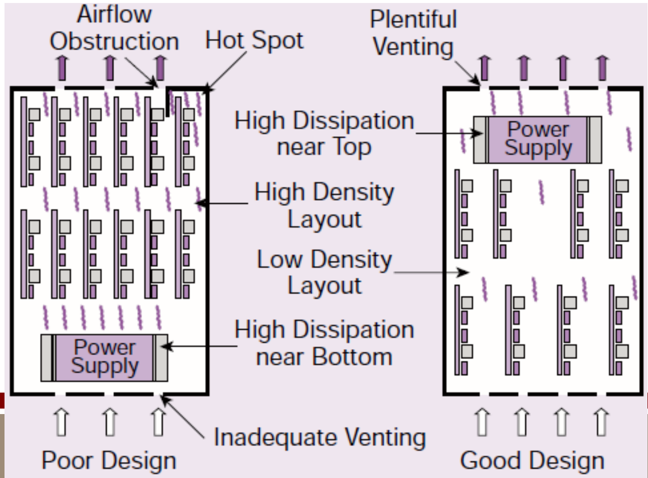
- Reduce LCOE by providing information needed to:
  - Improve BOS lifetime, reliability, safety, availability and performance
- Help investors to quantify bankability, quantify risks and reduce the costs of project financing

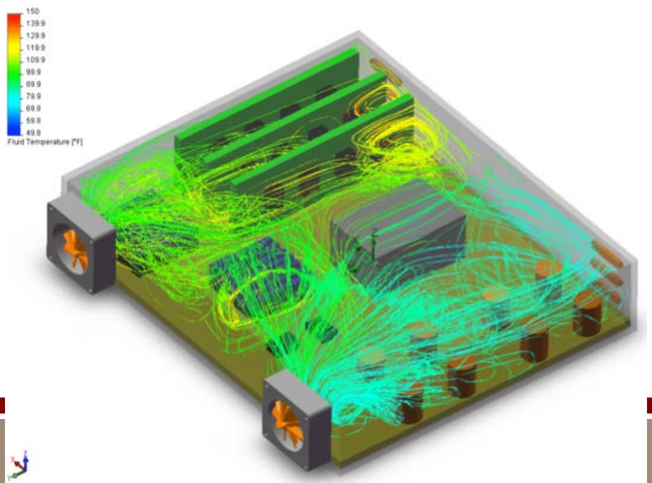
Challenges

- 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

- Decreasing size & growing complexity of power transistors (i.e. MOSFETS and IGBTs) & IC systems, power dissipation is 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.
- PV inverters continue to have reliability challenges for achieving LCOE. Coupled electro-thermal issues contribute to these issues, especially for advanced inverter functionality.
- Rigorous, non-ideal, and transient electro-thermal models are required for robust development.



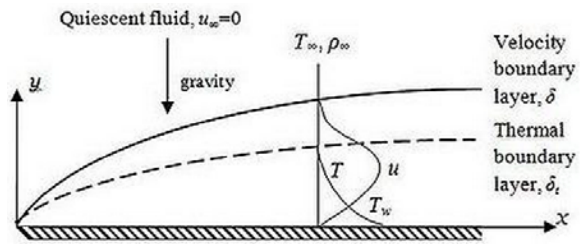


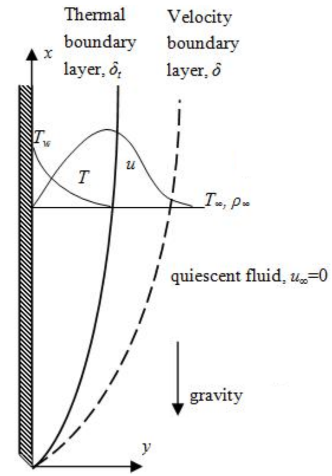
Thermal Heat Transfer

- 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

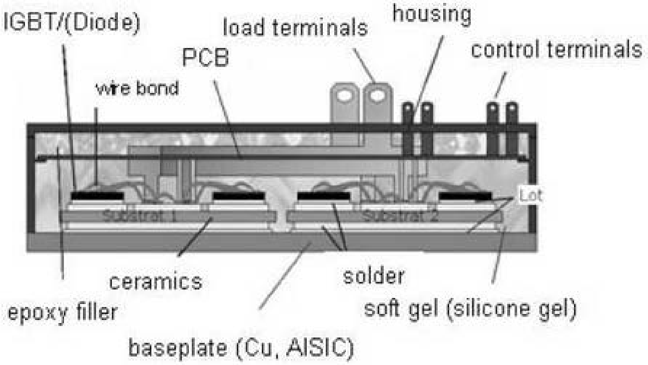




(Incropera and Dewitt, 2002)

- 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%

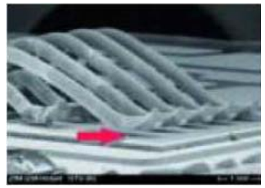
Process	h [W/m^2-K]
Natural Convection	
Gases	2-25
Liquids	50-1000
Forced Convection	
Gases	25-250
Liquids	100-20,000
Convection with Phase Change	
Boiling or Condensation	2,500-100,000



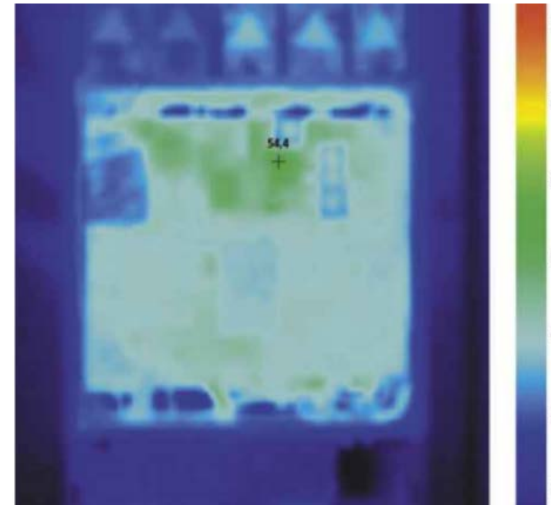
Construction of an IGBT module

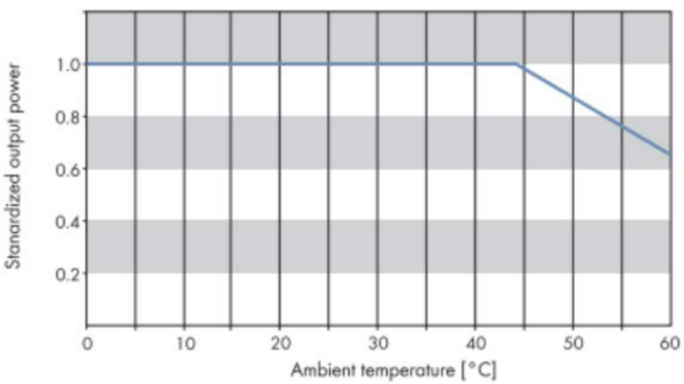
Thermal Design Considerations

- Critical Thermal Management Components
  - IGBT's/MOSFET's (Flicker et. al, 2012)
    - Latch-Up
    - Bond Lift-Off
  - Capacitors
- Direct Active Cooling Issues
  - Dust, Salt Build-Up and Fouling
- Conjugate Heat Transfer Issues
- Derate Operation

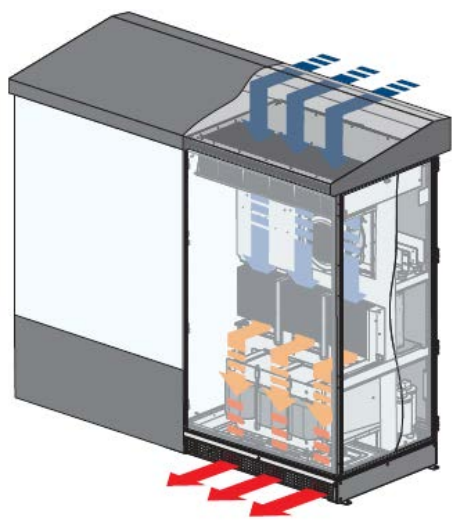


(Saddik, 2013)





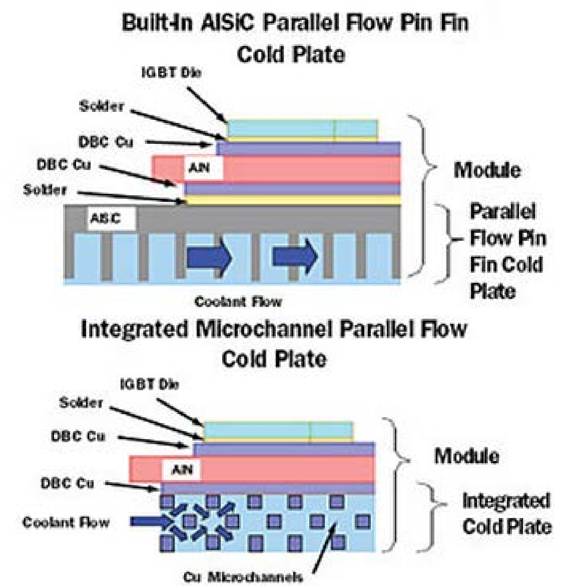
(Saddik, 2013)

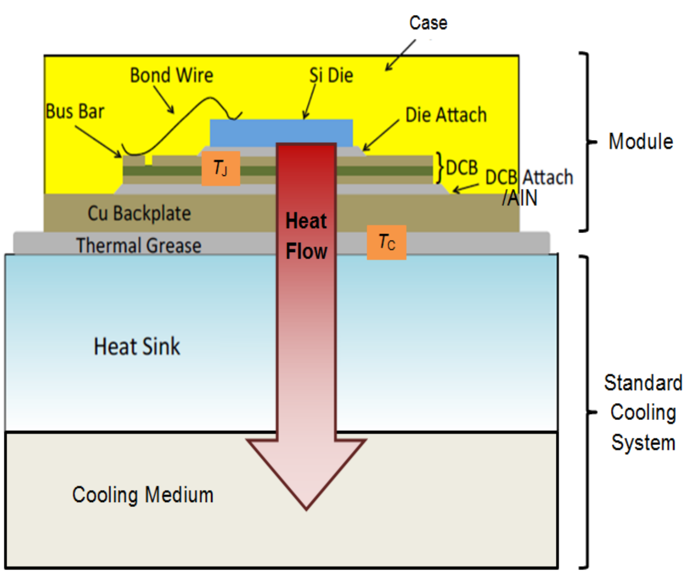


(http://www.sma.de)

Power Electronics

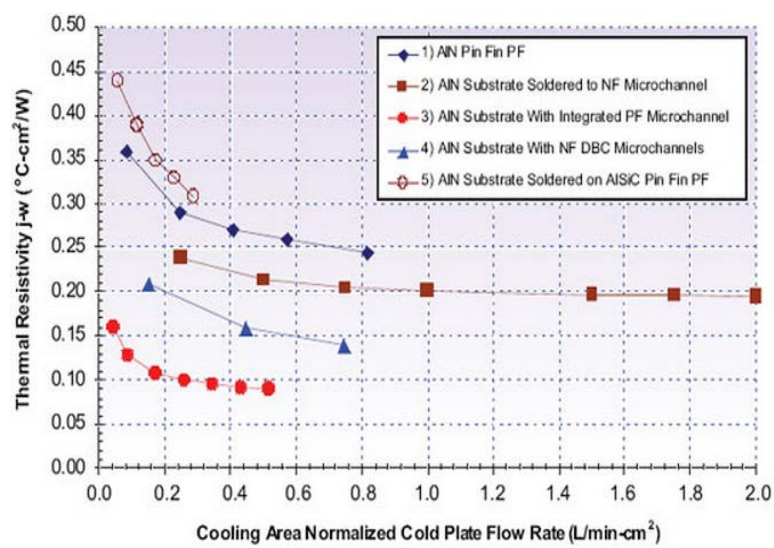
- Greater Number of Layers Increases R_{th} with Standard Configurations Capable of Thermal Dissipation Densities Up to 250-300 W/cm^2
- Power Cycling Degradation Impacts
  - Material Degradation and Micro-Fracturing
- CTE Mismatch Impacts
- Power Diss. = $\text{Loss}_{\text{Switching}} + \text{Loss}_{\text{Conduction}}$





(Leslie et. al., 2013)

Layer	Thermal Conductivity (W/mK)	Thermal Resistivity (°C-cm^2/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



Accelerated Testing

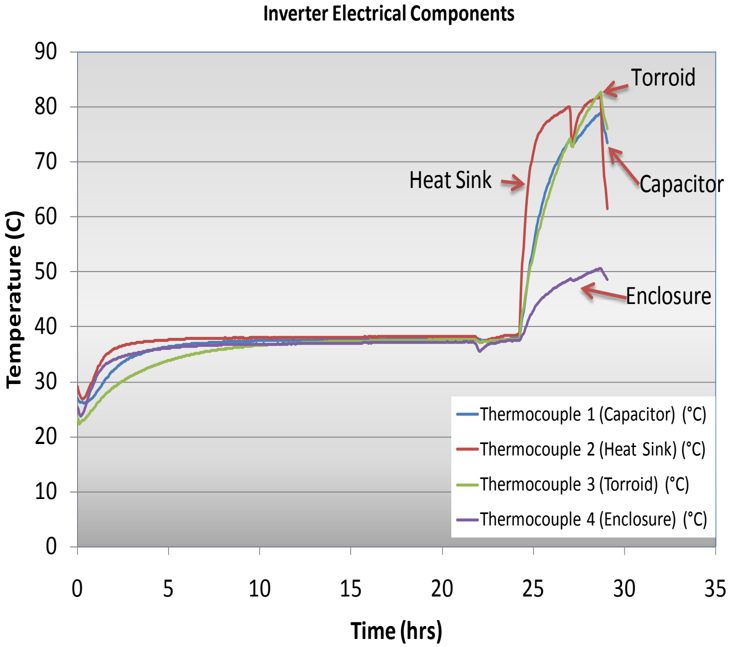
- Thermal cycling
  - Determines the ability of parts to resist extremely low and high temperatures, as well as their ability to withstand cyclical extremes. Stress resulting from cyclical thermomechanical loading accelerates fatigue failures.
- Humidity Freeze
  - This test serves as a mechanical strength 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 Lifetime Testing (ALT)
- Accelerated Stress Testing (AST)
- Highly Accelerated Life Testing (HALT)
- Highly Accelerated Stress Screening (HASS)
- 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



Laboratory testing provides vital information for PV system reliability

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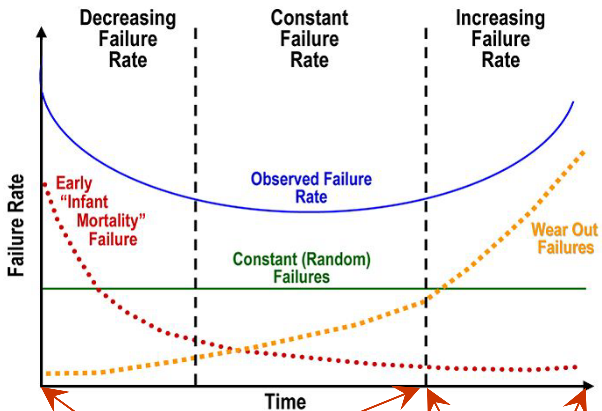
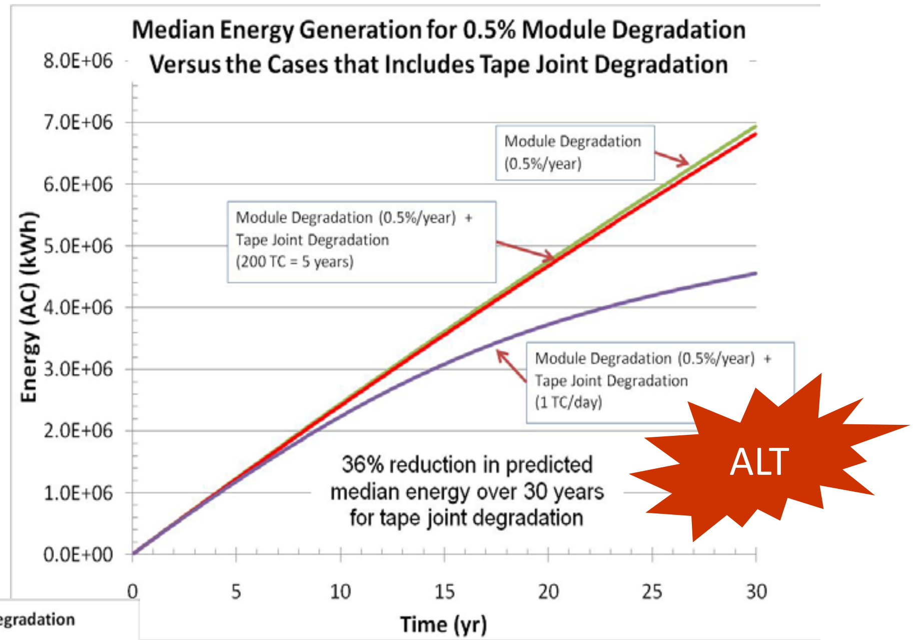
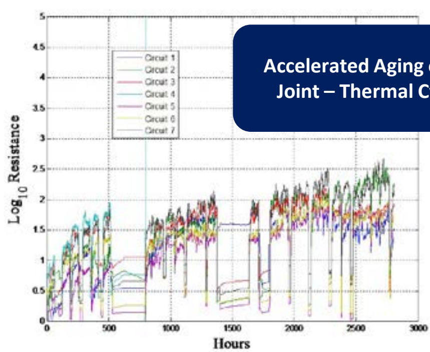
System performance model must include wear out (end of life) information



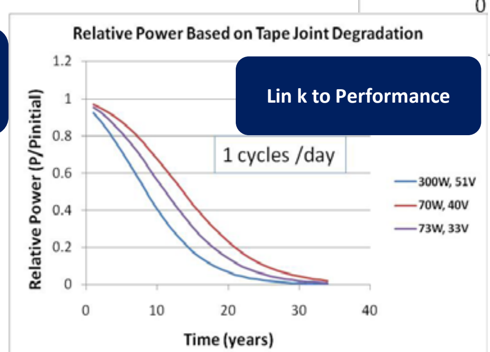


Field Data (O&M, Failures, etc.)

Accelerated Testing / Lab Tests



Accelerated Aging of Tape Joint – Thermal Cycling

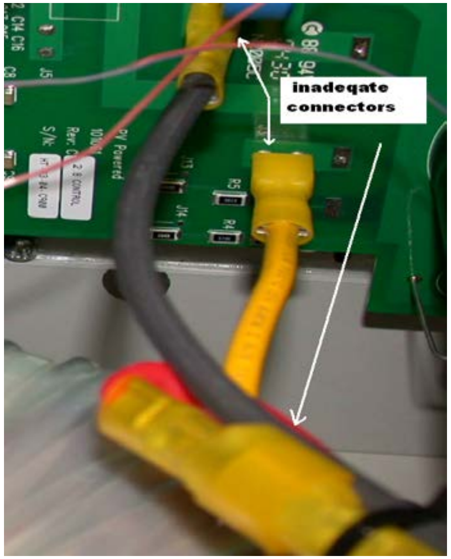


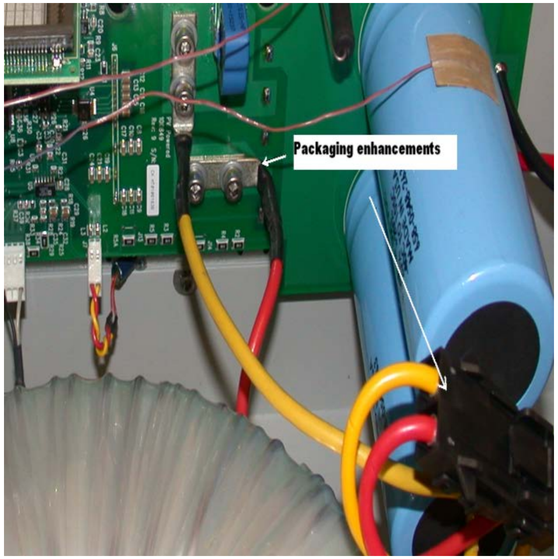
Lin k to Performance

Acceleration Factors

Accelerated Aging for Inverters

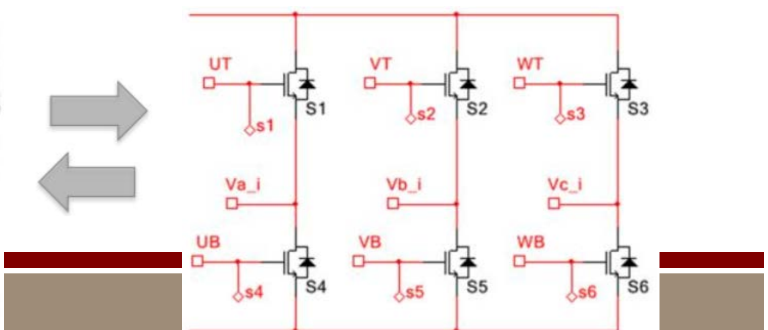
- No specific industry Qual standard exists
  - IEC 61215 is the “de-facto” spec
- HALT testing is spotty; independently applied by inverter manufacturers
  - Data in most cases proprietary
- Separate needs identified for residential and commercial scale inverters
- Failure modes identified but not in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

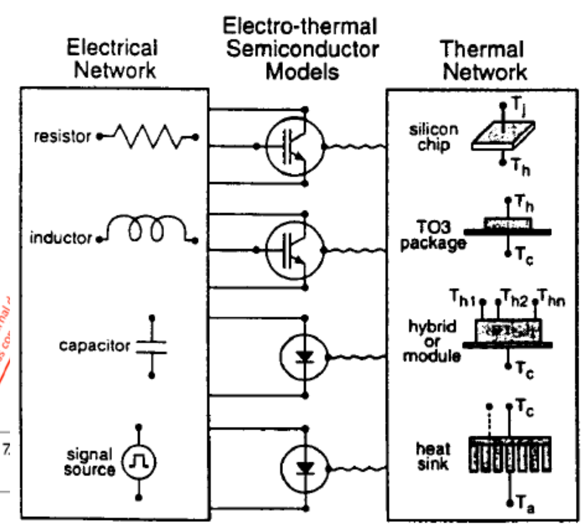




Electro-Thermal Modelling Platforms

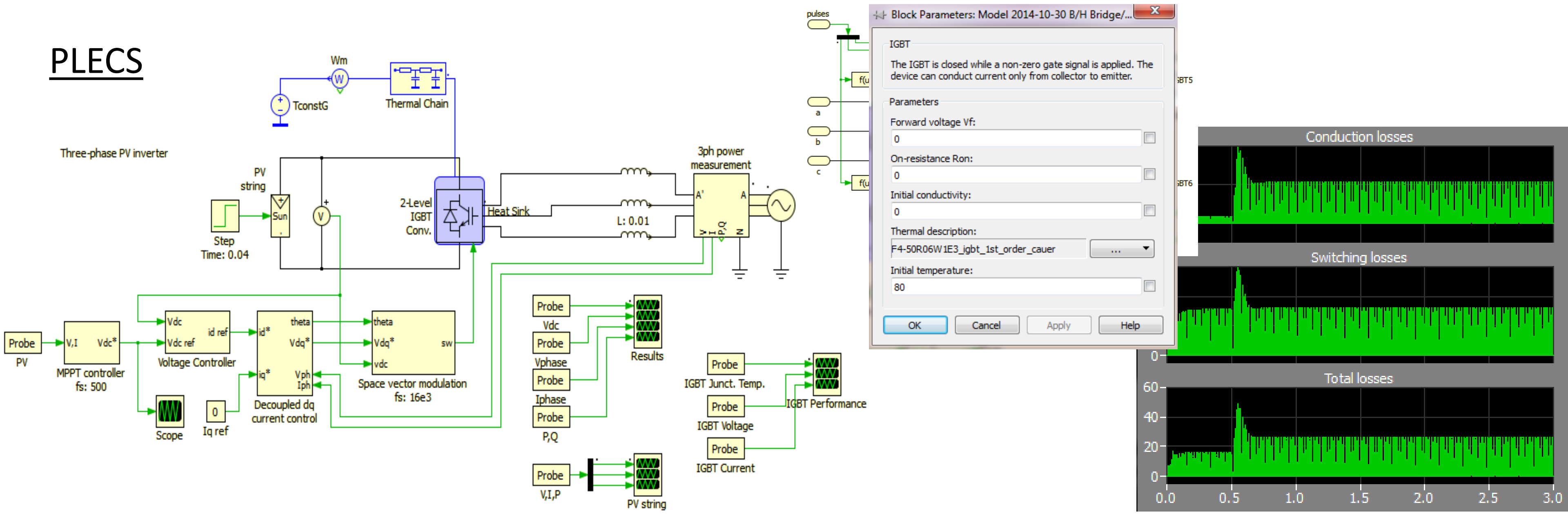
- SPICE
    - General electronic circuit simulator, used for design & to check behavior.
- PLECS
    - Idealized power electronics simulator, used in conjunction with look-up tables.
- COMSOL/ANSYS
    - FEA-level circuit simulation based on fundamental principles.
- Matlab/Simulink
    - SimPowerSystems
        - Graphical block-diagram paradigm to create models of dynamic systems.
    - SimElectronics
        - SPICE-Level Modelling with Non-Ideal Characterization.

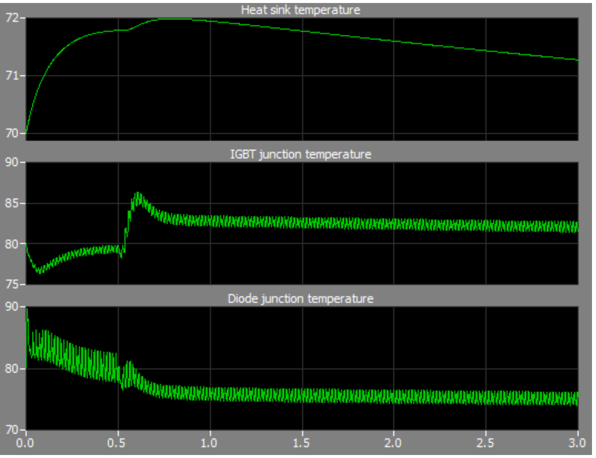


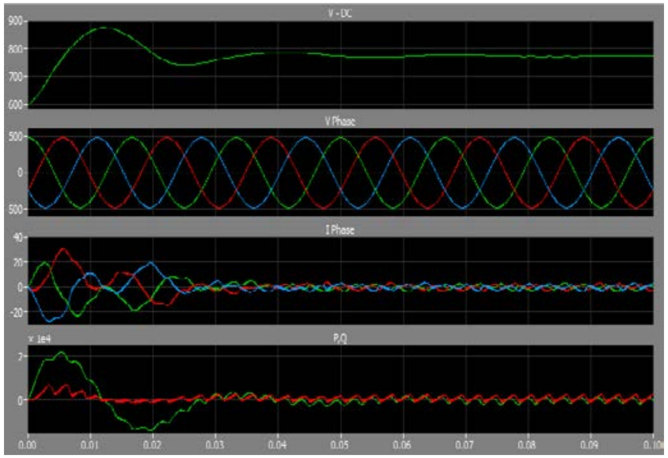


Inverter Modelling Platforms

PLECS

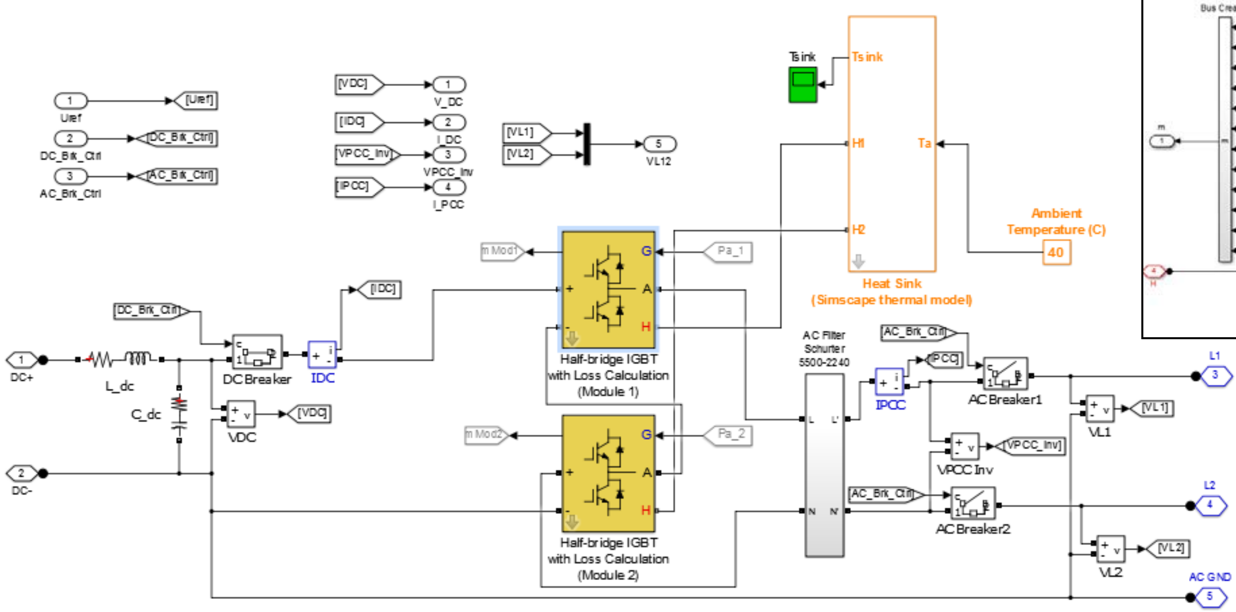


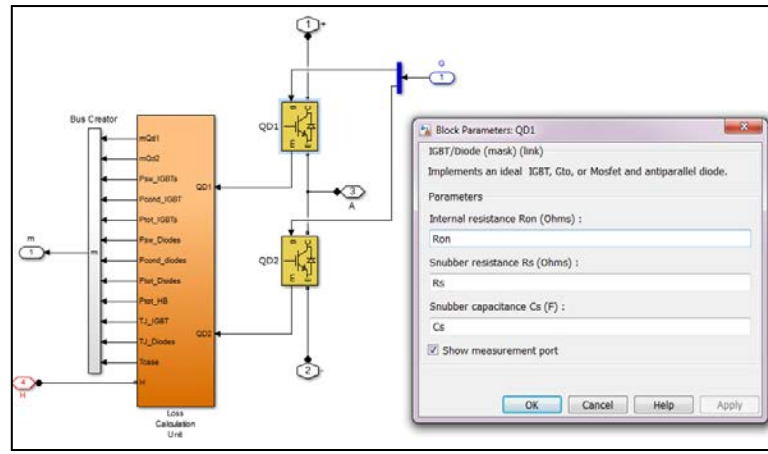




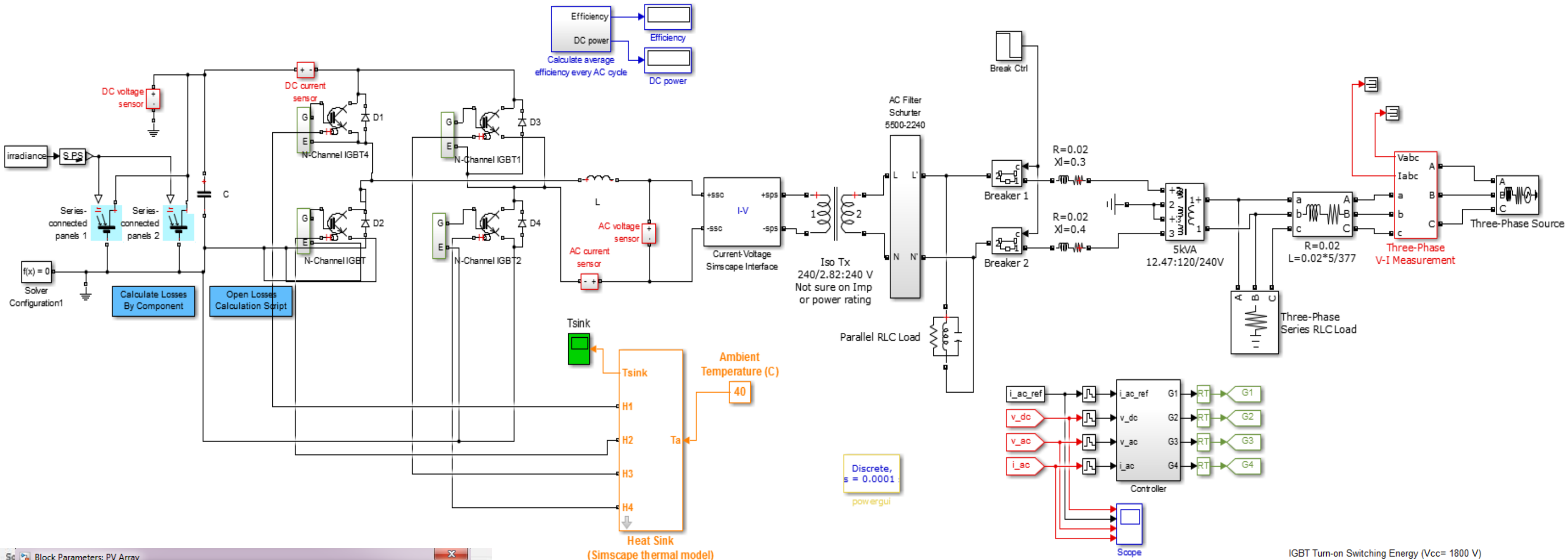
Matlab/Simulink SimPower Systems

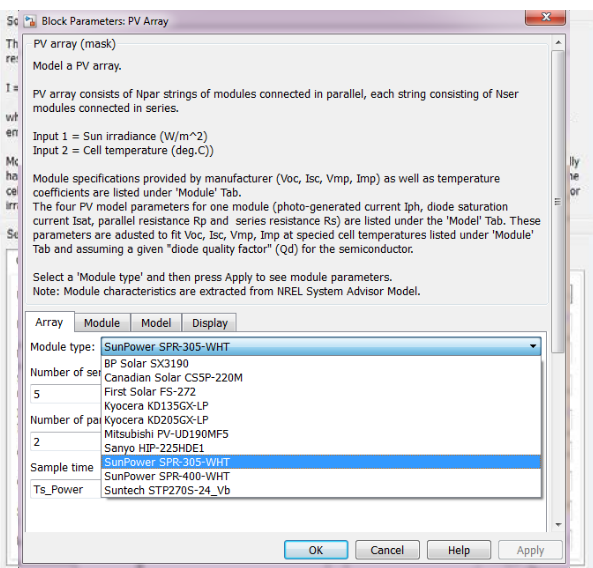
- Simulink
  - Block-Diagram Platform for analyzing continuous, multi-rate, discrete systems
- SimPower Systems PV Examples
  - Electrical – System simulation described by a combination of basic functions, connected using lines representing common variables.
  - Thermal – Modelling based on resistor and capacitor thermal circuits

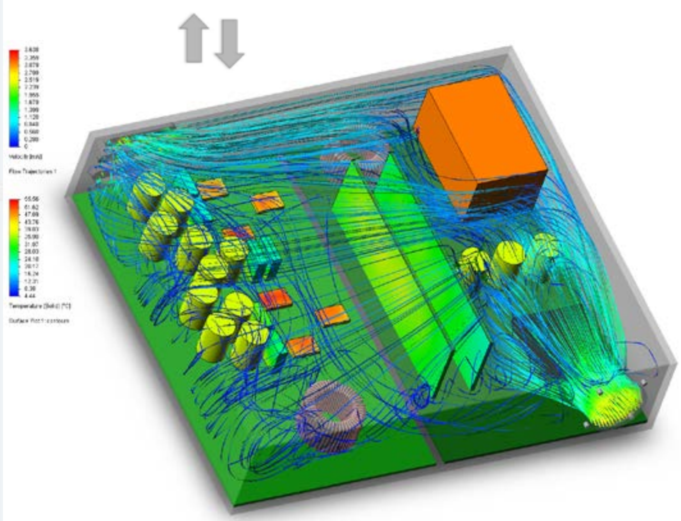


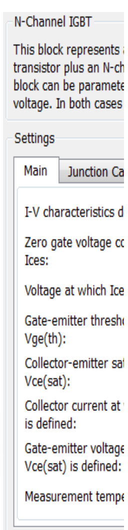


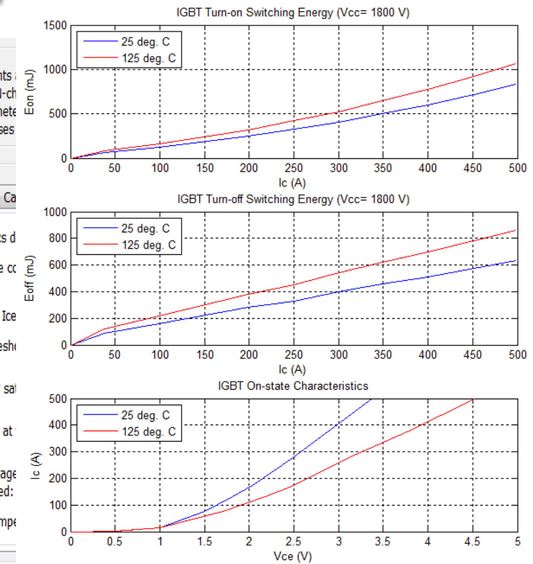
SimElectronics Model





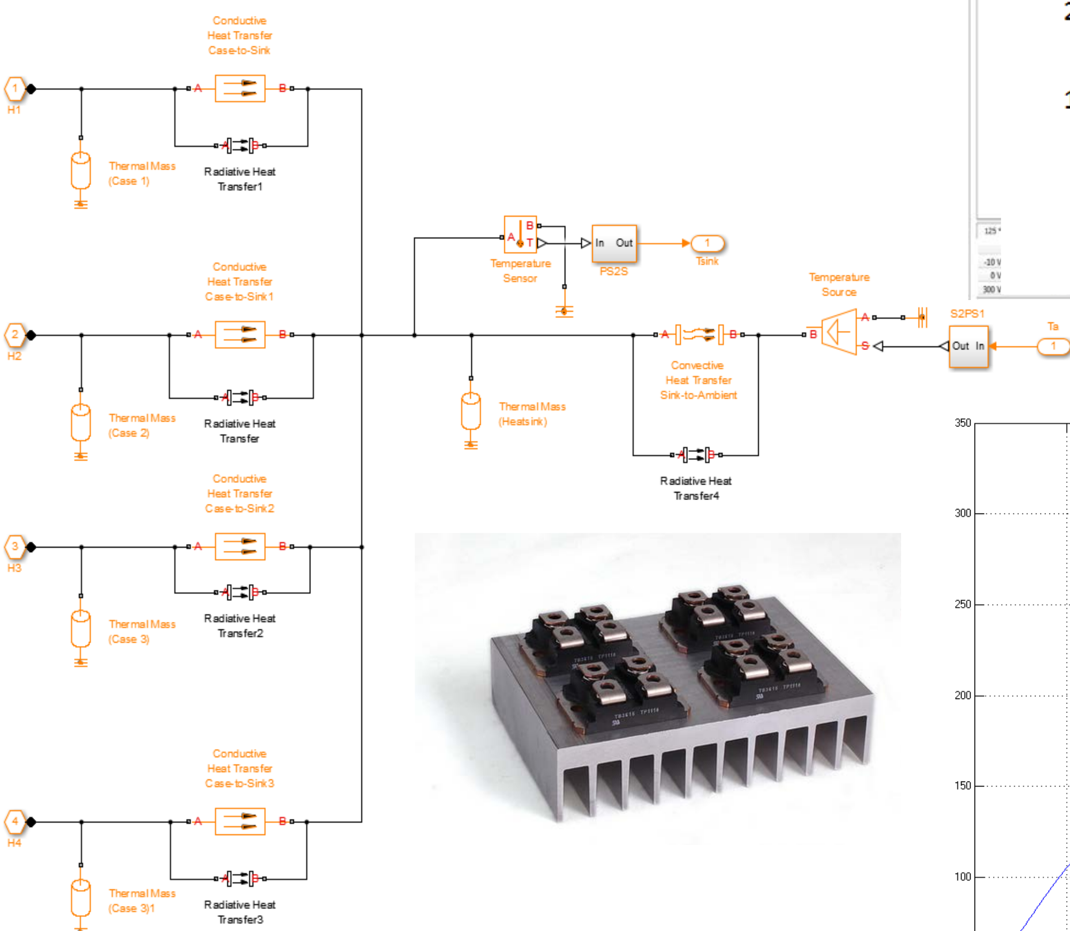


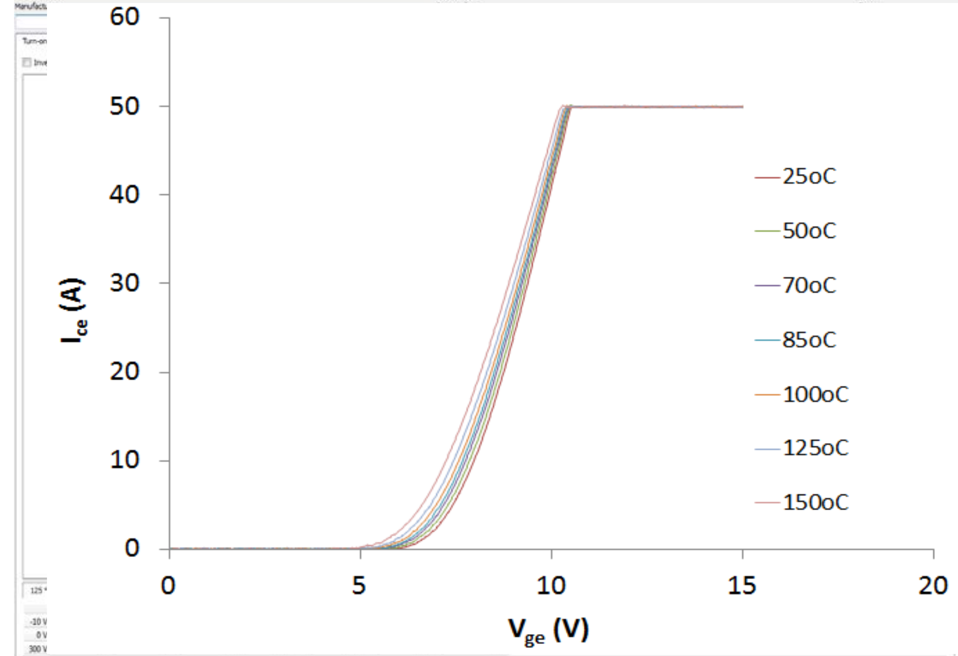




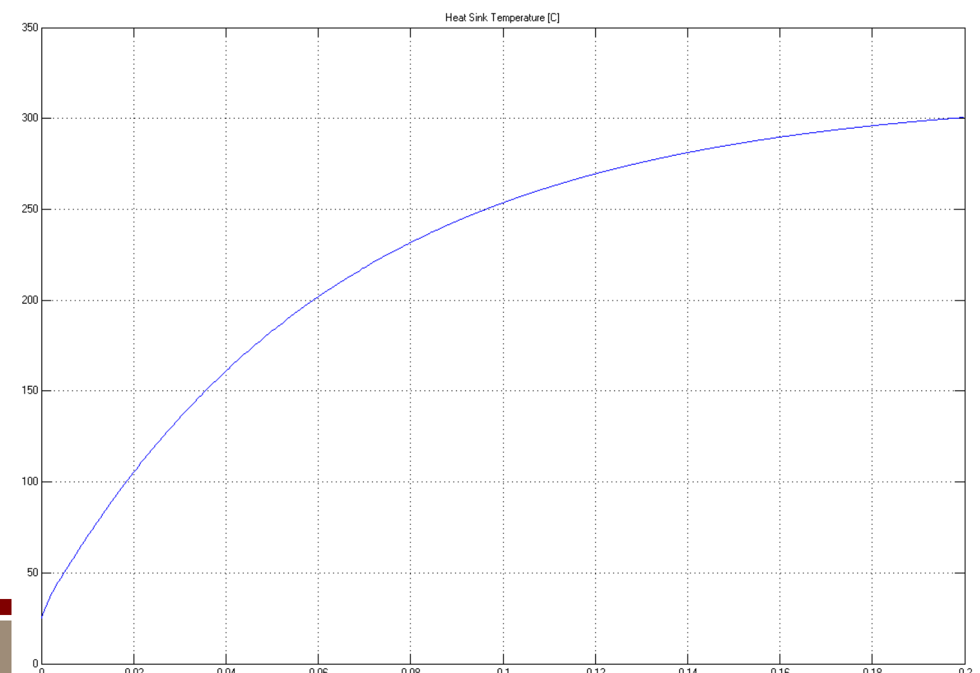
Thermal Sub-Model

Heat Sink Thermal Model

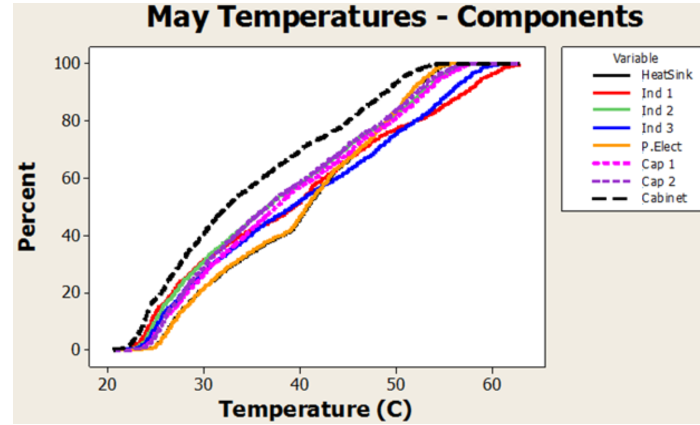


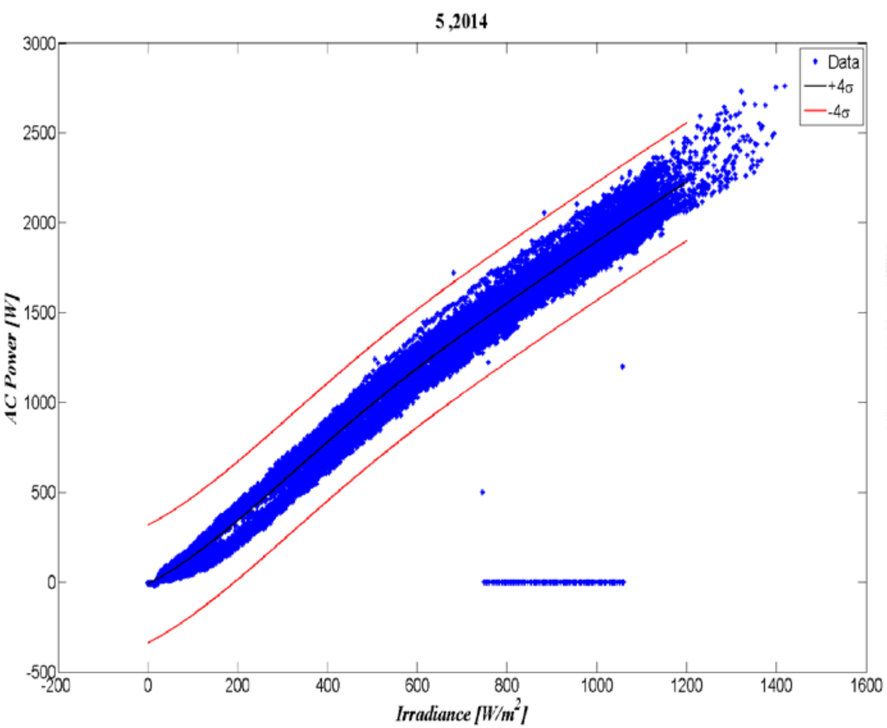


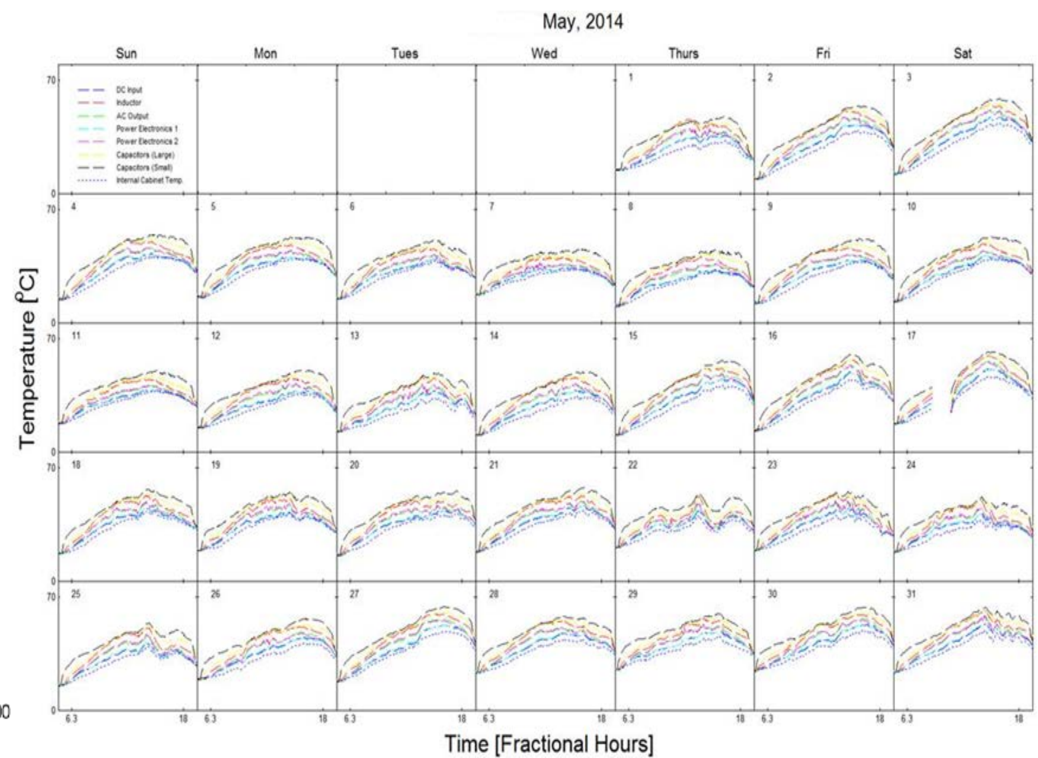
Heat Sink Thermal Profile Results



Fielded Studies Validation

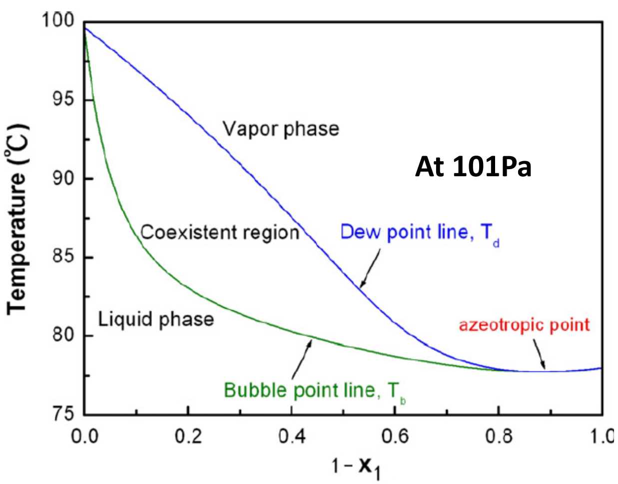


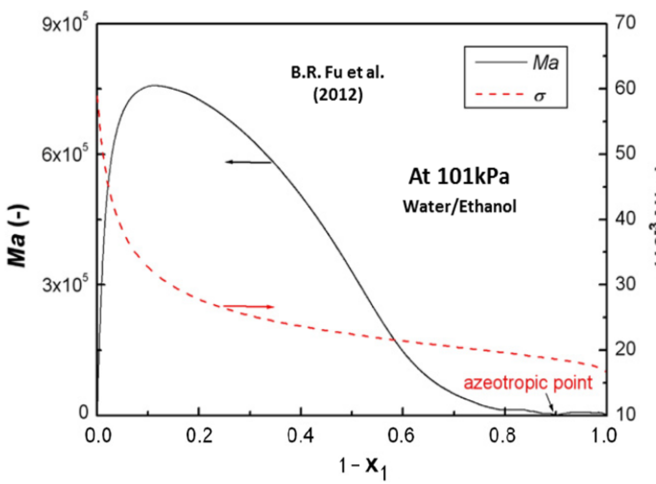


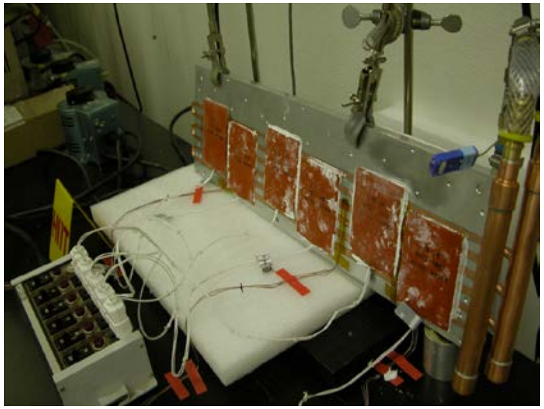


Heat Exchanger Cooling Plate

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







Conclusions

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- Reliability issues still remain with inverters, especially with larger inverter systems.
- Enhanced power electronics have new thermal management challenges.
- Newer topologies & electronics densities are creating new reliability challenges.
- Various methods for accelerated testing:
  - ALT
  - HALT
  - HASS
  - Etc.
- Various electro-thermal modelling platforms exist with limitations.
- SimElectronics interfaced with CFD analysis has much potential!

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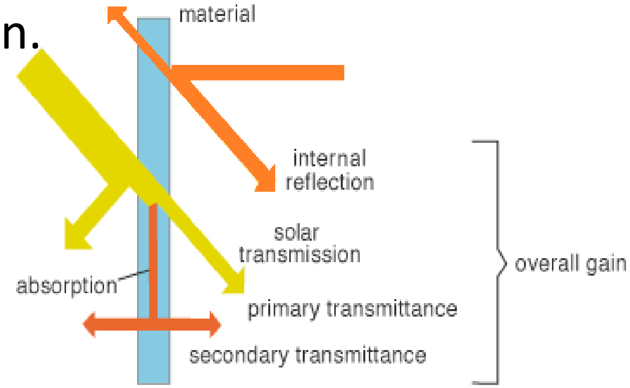
SAND No. 2011–XXXXP.

Extra Slides

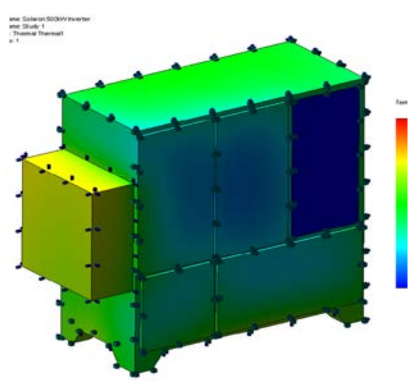
Solar Gain & Thermal Gain

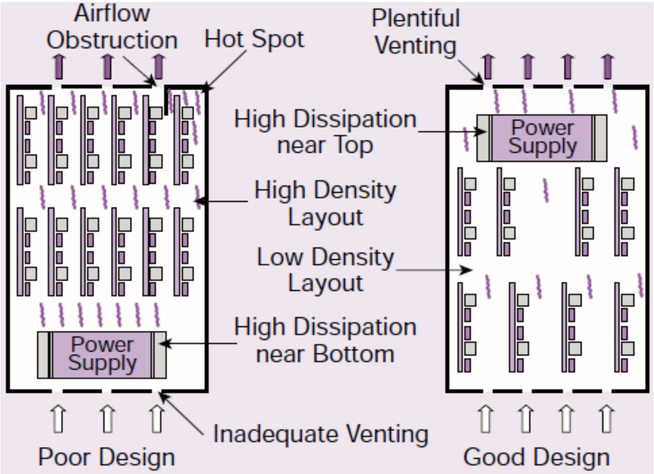
- Thermal gain from solar radiation in an object, space or structure, which increases with the strength of the sun, and with the ability of any intervening material to transmit or resist radiation.

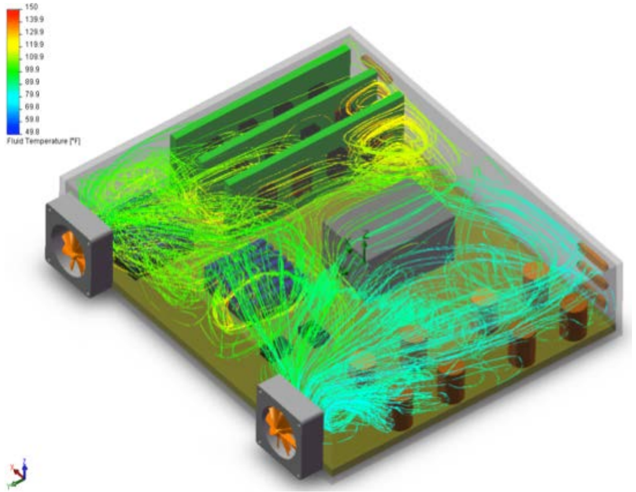
Radiative Energy Balance:



- FEA/CFD Impact Analysis of Internal Comps.







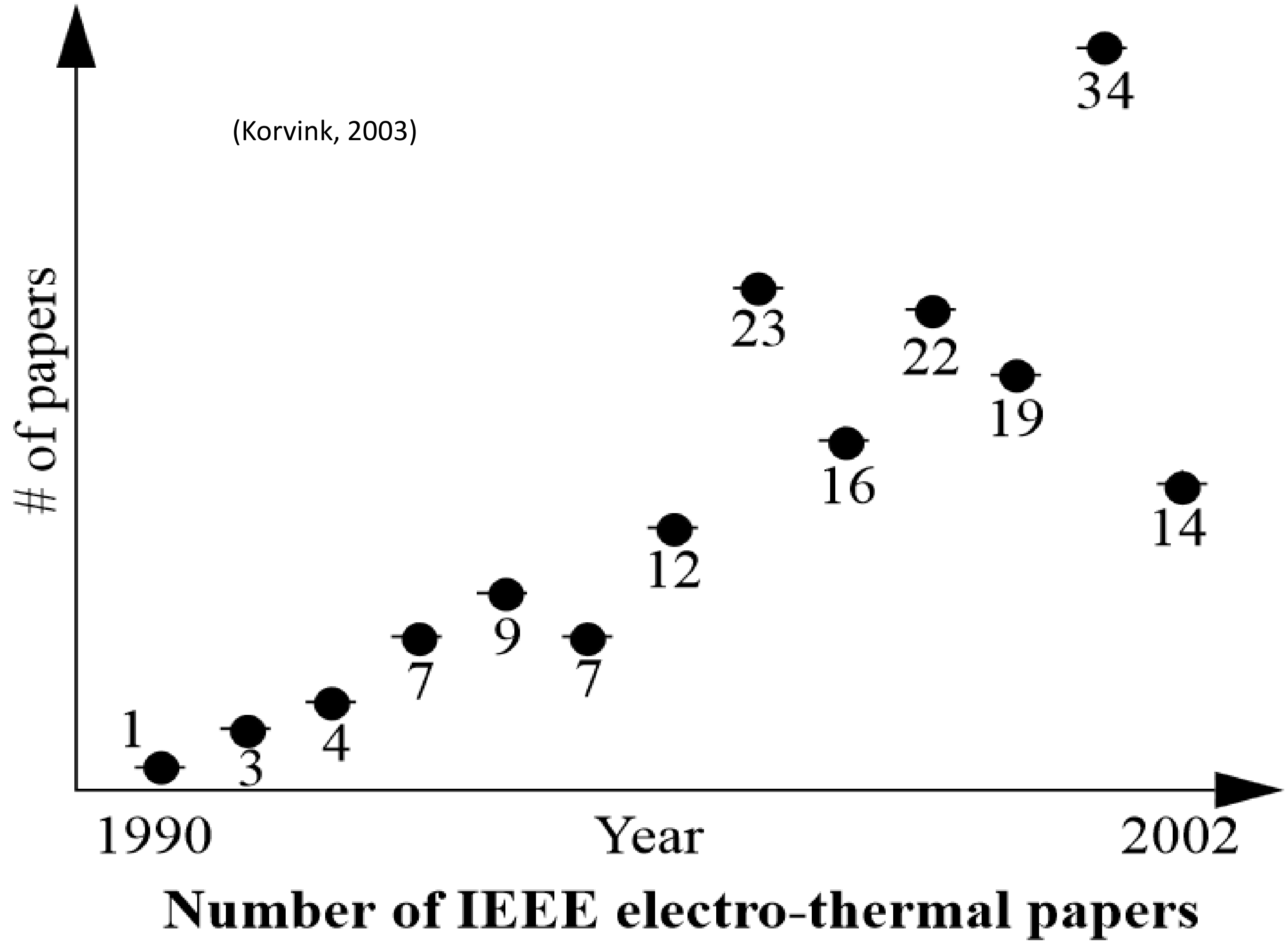
Overview & Need for Electro-Thermal Modeling

- **Research Goal:** Develop robust, reliable 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.

Necessity of an Inverter Thermal-Performance Model

- Just like the electronics industry, inverters are reaching performance limitations.
- Need for a scalable model to determine heat transfer modes occurring at respective residential and utility-scale operations.
- Higher power conversion designs are creating an industry push to leverage liquid-cooled heat exchangers, from traditional fan-cooling
- Industry need for a standardized inverter thermal performance model for determining appropriate thermal management design options that will balance costs
- Knowledge gaps exists concerning inverter failure rates vs. cooling rates and impacts on IGBT switching and overall inverter performance

Title



(Korvink, 2003)
# of papers
1
3
4
7
9
7
12
23
16
22
19
34
14
1990
Year
2002
Number of IEEE electro-thermal papers

What is ALT & why? Issues with ALT:

What?

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

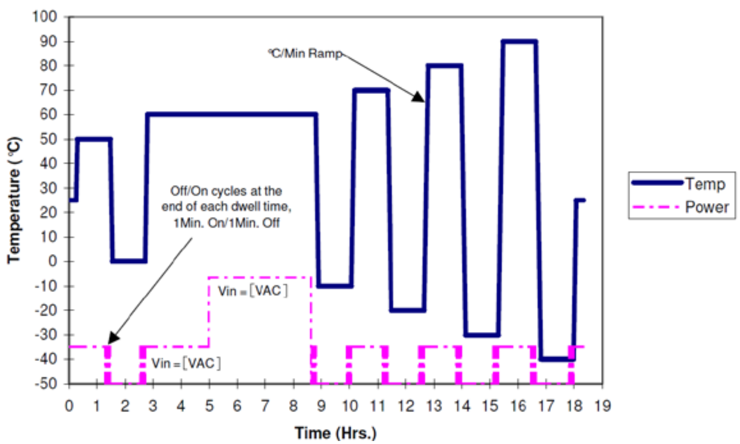
Why?

- 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

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