NREL National Renewable Energy Laboratory
*Innovation for Our Energy Future*

# Thermal Stress and Reliability for Advanced Power Electronics and Electric Machines

*U.S. Department of Energy*
*Annual Merit Review*

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**National Renewable Energy Laboratory**

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Program and Vehicle Technologies Program
Annual Merit Review & Peer Evaluation Meeting
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**NREL/PR-540-45772** **APE-14**

# Overview

## Timeline

- Project start date: FY08
- Project end date: FY11
- Percent complete: 40%

## Barriers

- 15 year life requirement
- The time & cost required to validate the reliability of new technology can ***delay*** and ***even prevent its introduction***

## Budget

- Total project funding
  - DOE share: $655k
  - Contractor share: $0.00
- FY08 Funding: $280k
- FY09 Funding: $375k

## Partners

- Interactions
  - FreedomCAR Electrical & Electronics Technical Team
  - Dr. E. Suhir of UC Santa Cruz, Oak Ridge National Laboratory, AES, J. Didion of NASA, Others
- Project lead: NREL

# Thermal Stress/Reliability Project Objectives

- Develop validated models and tools to ***assess*** the ability of power module concepts to meet the 15 year program life requirement

- Investigate how ***variation*** and ***uncertainty*** affect reliability of APEEM R&D concepts

- ***Apply*** the tools & techniques of ***robust design*** to APEEM R&D early in the design stage to increase technology robustness and chance of adoption

# Project Milestones

## FY2008

- **Milestone:** Develop research plan for conducting thermal stress and reliability assessment

## FY2009

- **Milestone:** Report on status and results of the thermal control technology R&D

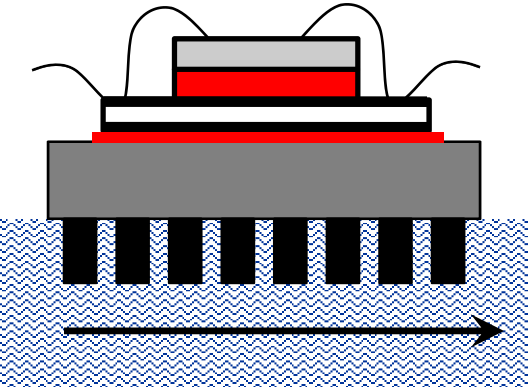
# Technical Approach

- Compare reliability of 3 APEEM packages
  - Boundary conditions, properties obtained, geometry based on existing systems
  - Focus on die attach and DBC attach
- Examine the effect of variability on results
- Obtain validation data via APEEM industry contracts and DOE testing activities
- Review results with FreedomCAR EETT
- Redesign APEEM technology for reliability
- Transition models and methods to industry

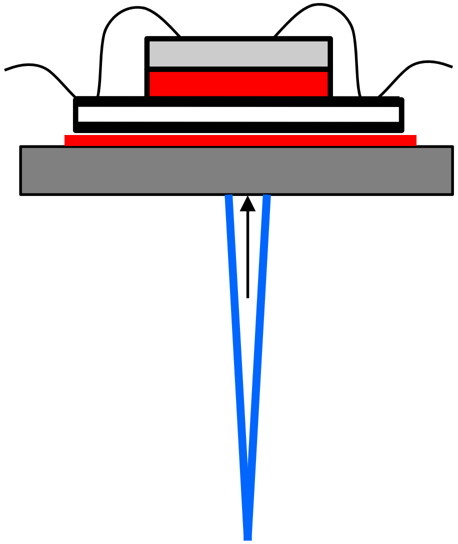
# Will These Cooling Concepts Last the Life?

Failure sites of concern:

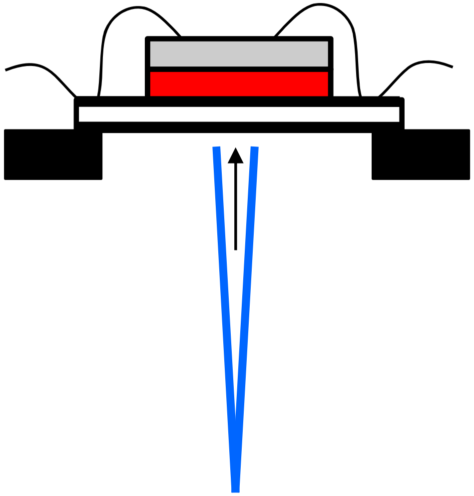
1. Wire bonds
2. Bonded joints (die attach & DBC attach)



**Baseline Pin-fin Heat Exchanger**



**Indirect Jet Impingement on Baseplate**



**Indirect Jet Impingement on DBC**

decreasing thermal resistance (increased stress?)

# Simulation Process for Reliability Assessment

Applying techniques from physics of failure, design for six sigma, optimization, and advanced modeling to R&D

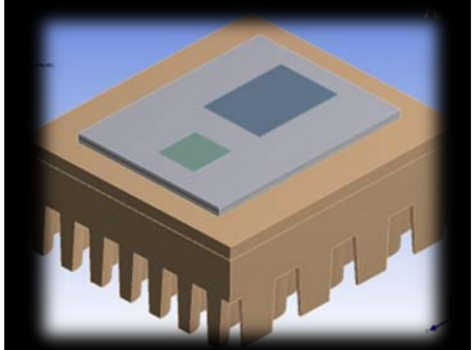
## Input Parameters

**Geometry**
dimensions, topology, etc.

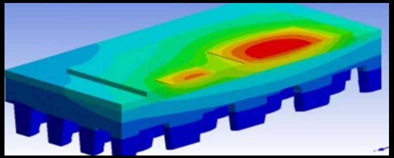
**Materials**
**kinds of materials, properties**

**Loading**
**heat input, test procedure**

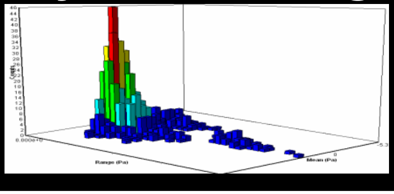
**CAD Model**



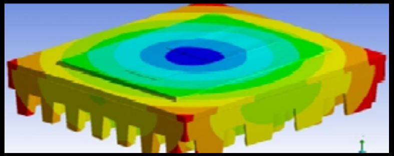
**Thermal Simulation**



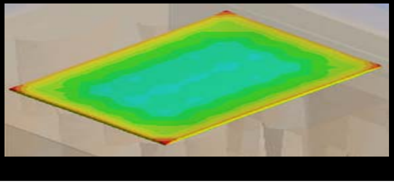
**Cycle Counting**



**Structural Simulation**



**Fatigue Analysis**



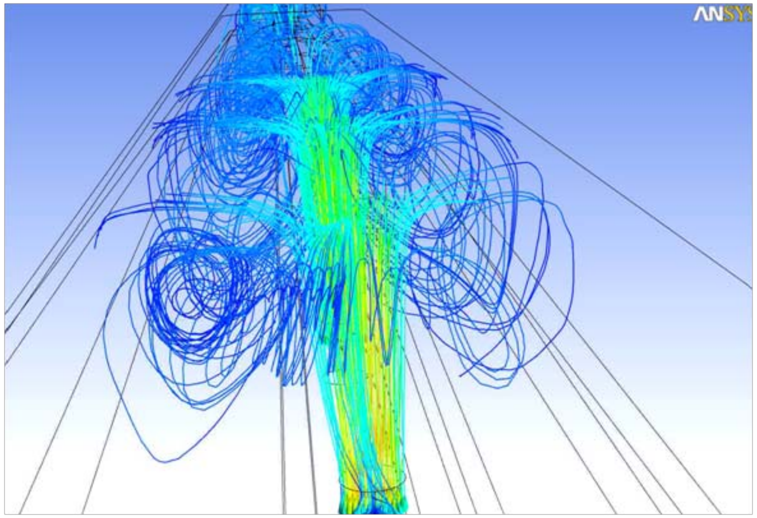
## Output Parameters

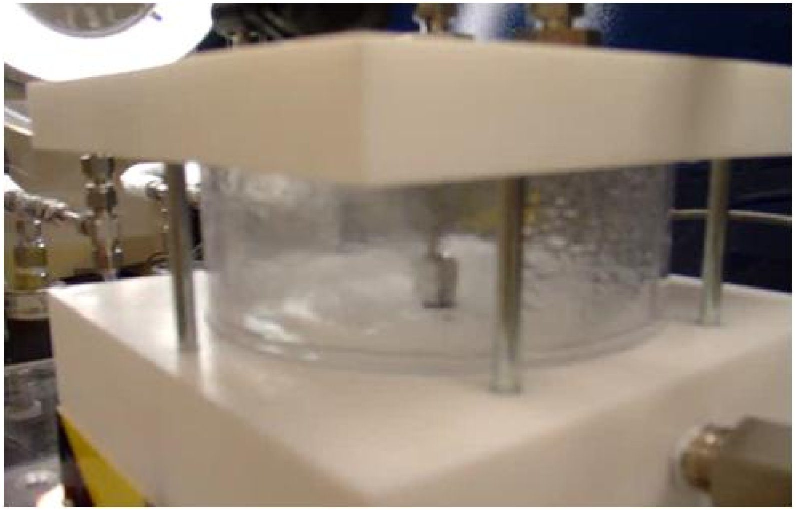
**Thermal**
max temperature, temperature range

**Mechanical**
max and min stress, strain

**Life**
fatigue life of component x

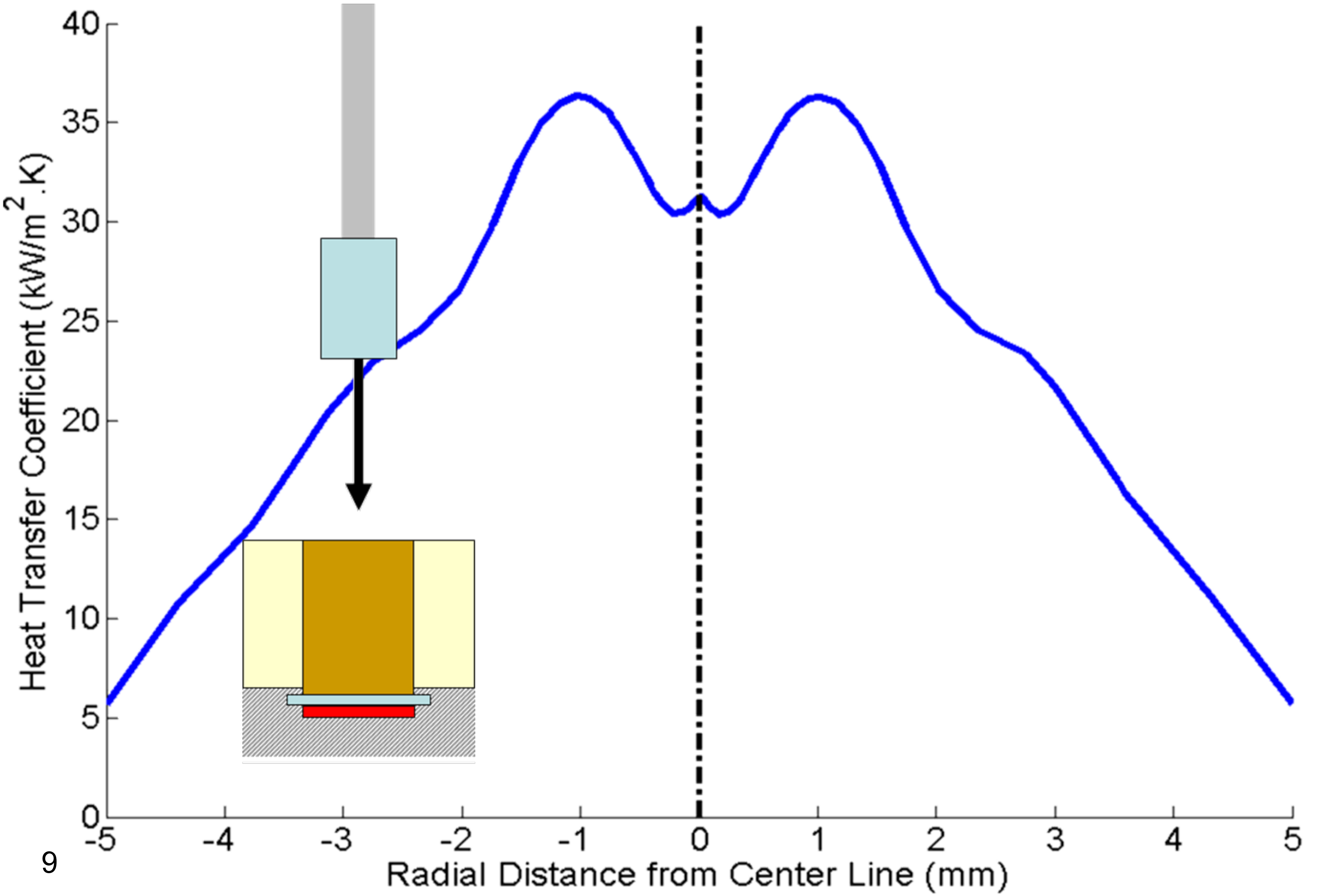
# Validation of Jet Boundary Conditions





| Parameter | Value via CFD | Value via Test |
|---|---|---|
| heat transfer coefficient ($W/m^2.K$) | 18,350 | 18,481 |

# Jet Boundary Condition Varies over Surface



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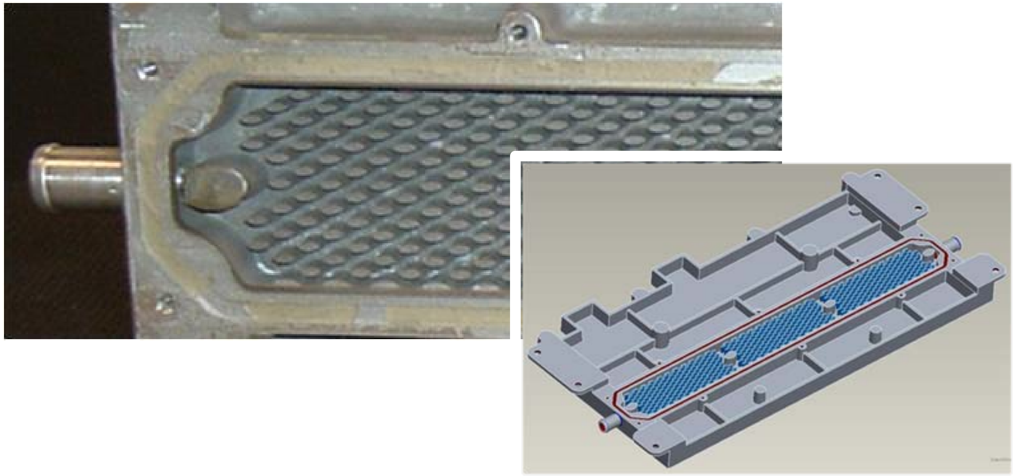
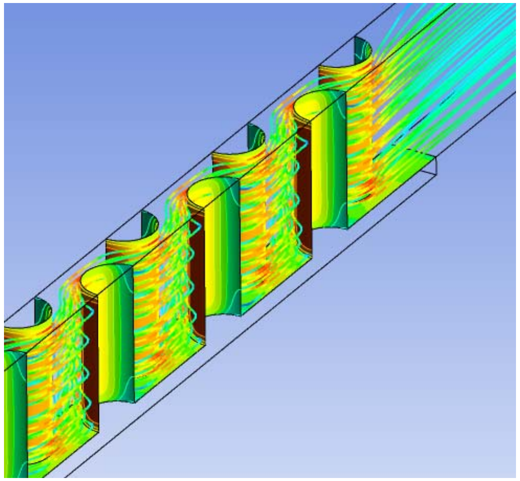
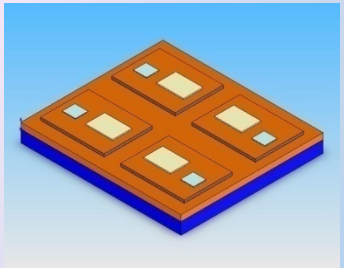
# Validation of Pin-Fin Boundary Conditions

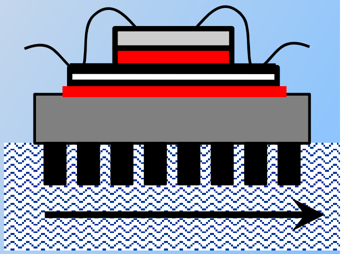




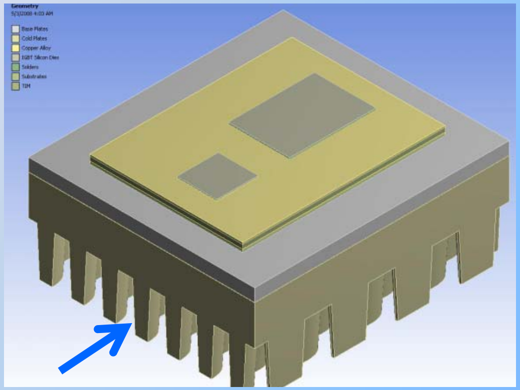
| Pin Type | Parameter | Value via Empirical Correlation | Value via CFD Analysis |
|---|---|---|---|
| Circular | heat transfer coefficient ($W/m^2.K$) | 9501 | 9941 |

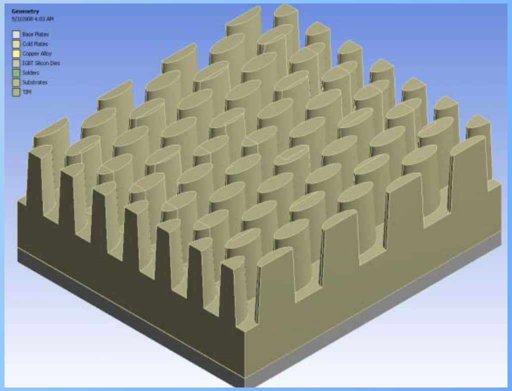
# Solid Models of Three Topologies Created



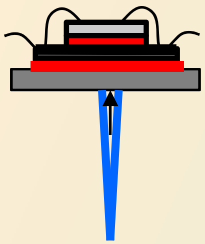


**Topology 1**

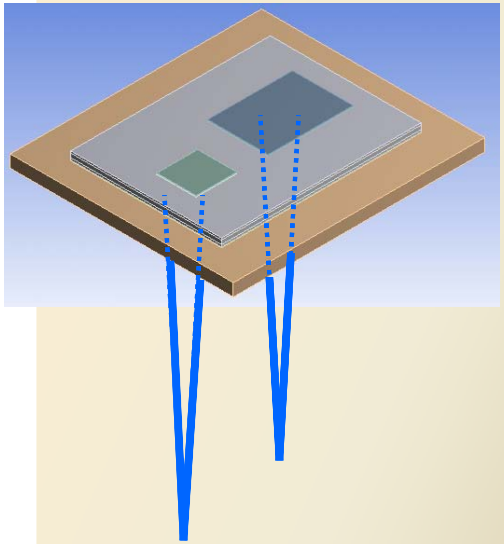




Baseline Pin-Fin

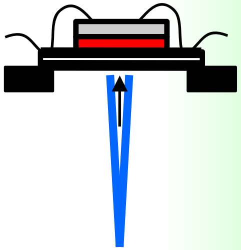


**Topology 2**

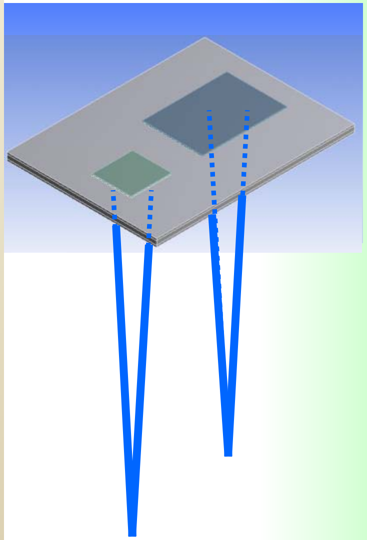


Jets on Baseplate

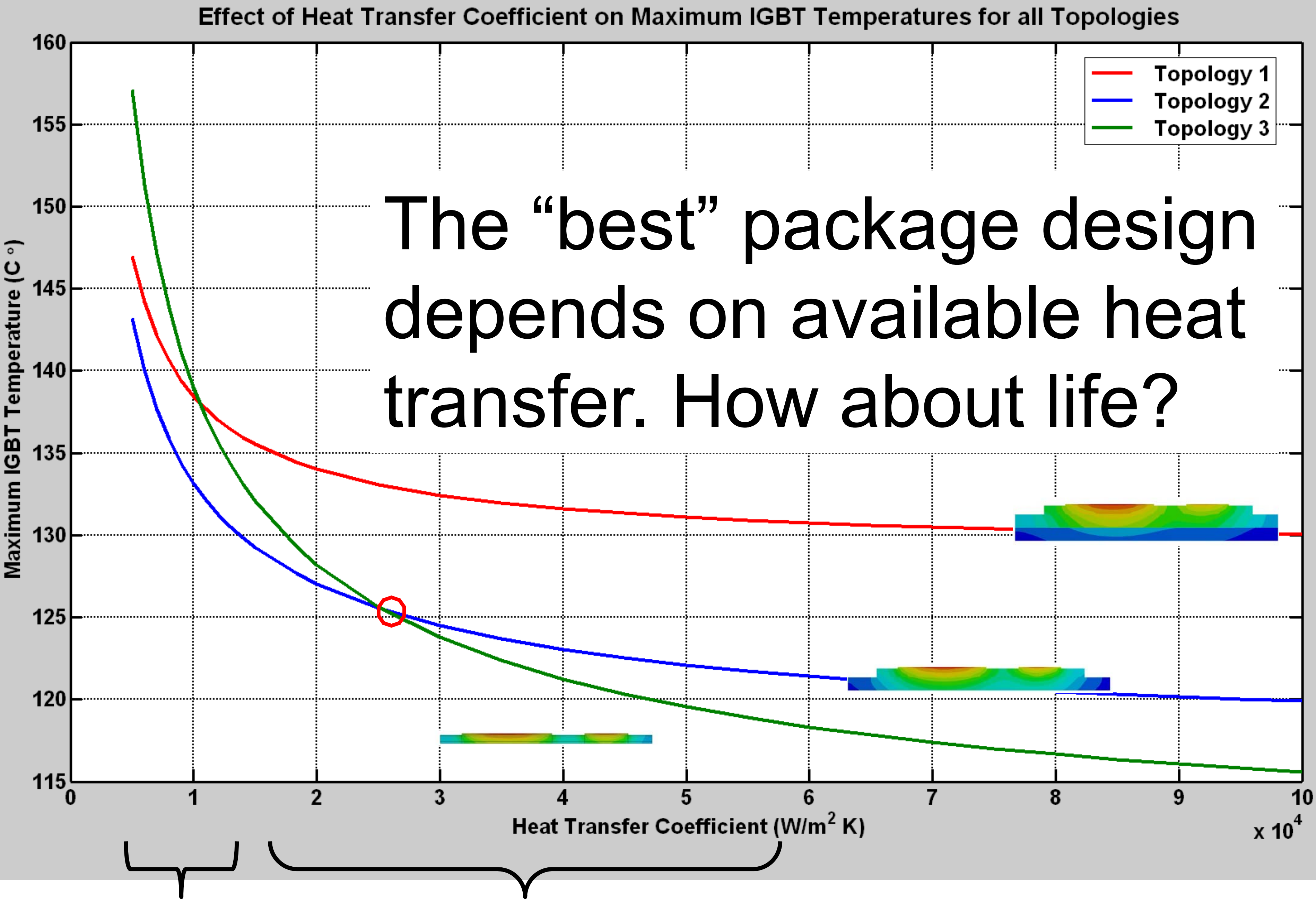
Two jets (one per chip)
Jet Velocity: 4.5 m/s
Nozzle diameter: 1.4 mm



**Topology 3**



Jets on DBC



The “best” package design depends on available heat transfer. How about life?

**pin-fin performance** **jet performance**

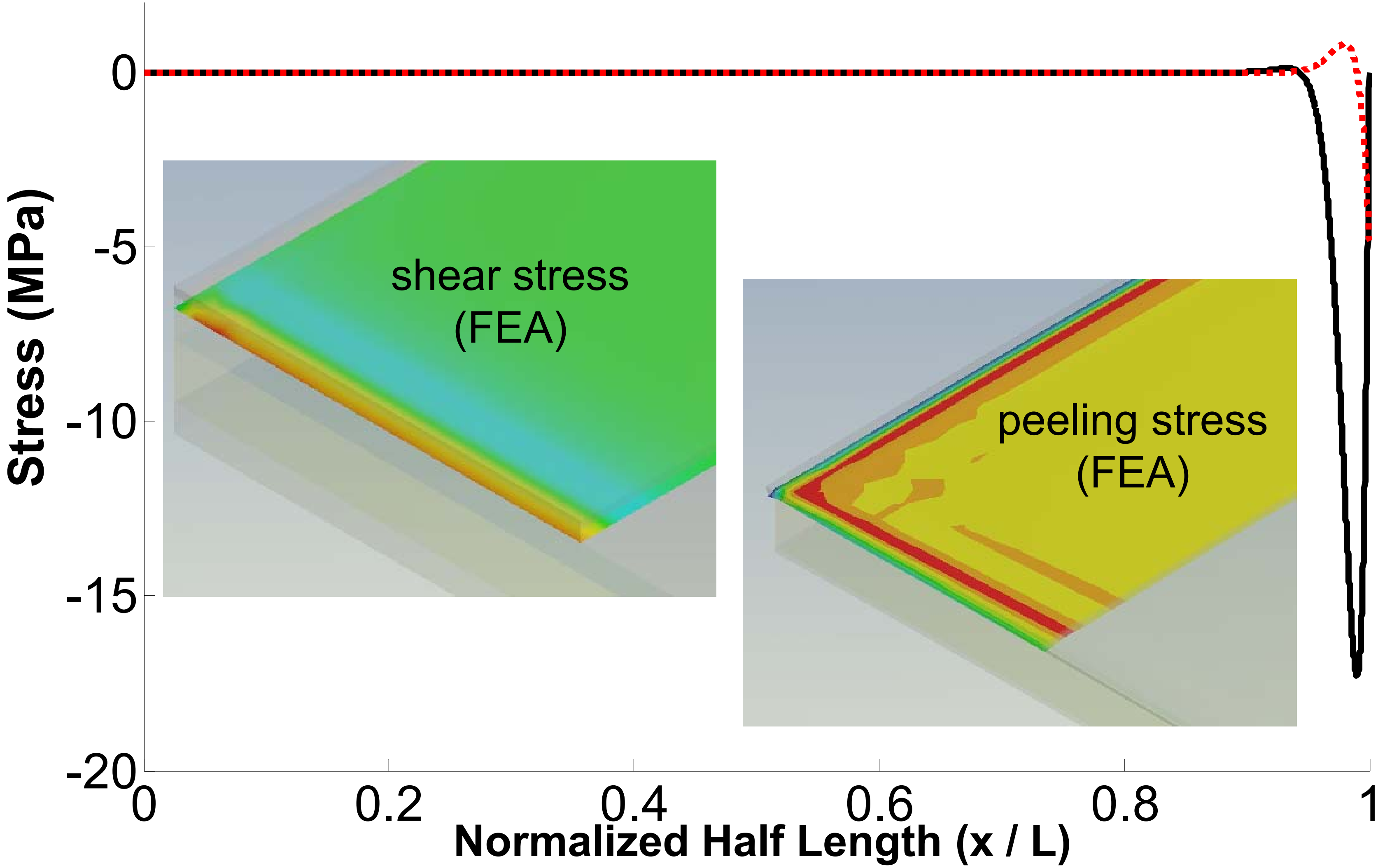
# Analytical Models Add Confidence to FEA Results

| Parameter | FEA | Analytical (bi-metal thermostat) |
|---|---|---|
| Axial Stress in IGBT (MPa) | 87.7 | 79.2 |
| Axial Stress in DBC (MPa) | 130.4 | 137.8 |

**analytical model based on:**

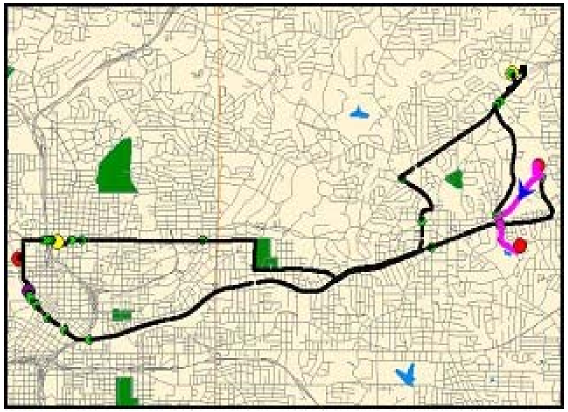
Suhir, E. (1986). “Stresses in Bi-Metal Thermostats”. *Journal of Applied Mechanics.*

# Analytical Stress Add Confidence to FEA Results

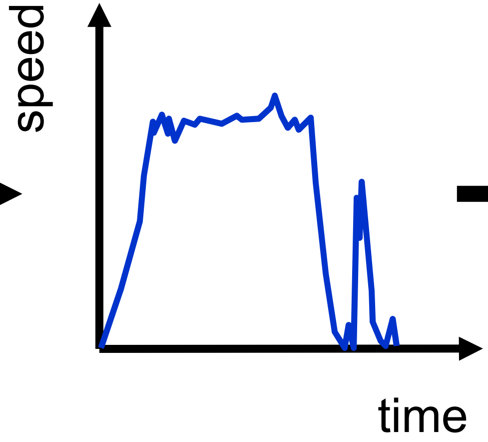


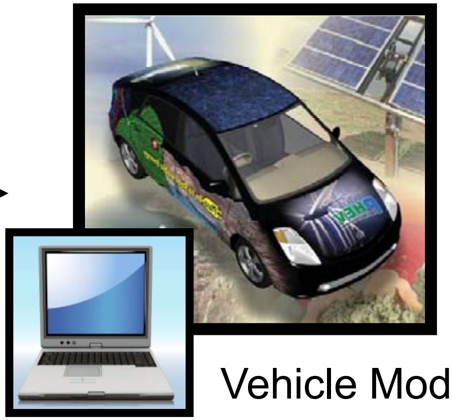
**source:** Ru, C.Q. (2002). “Interfacial Thermal Stresses in Bimaterial Elastic Beams: Modified Beam Models revisited”. *Journal of Electronic Packaging.*

# Connecting Reliability to Mission Profile

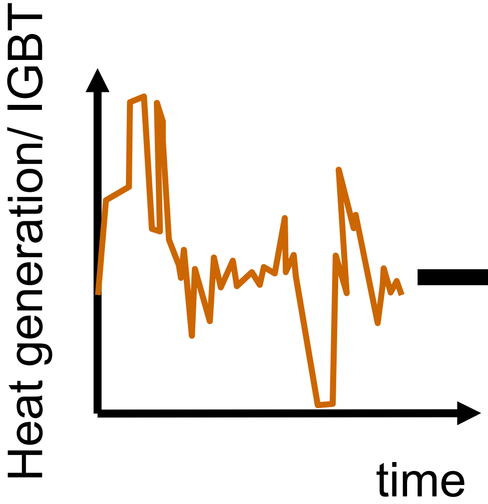


Driving/ Travel Survey Database

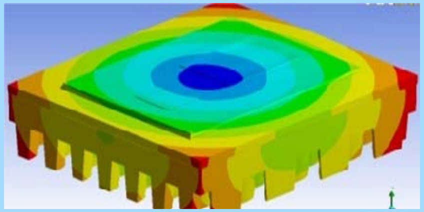




Vehicle Model

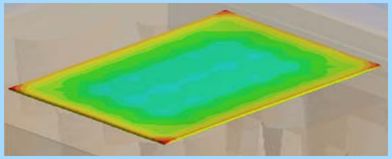


Transient Strain from Structural Simulation

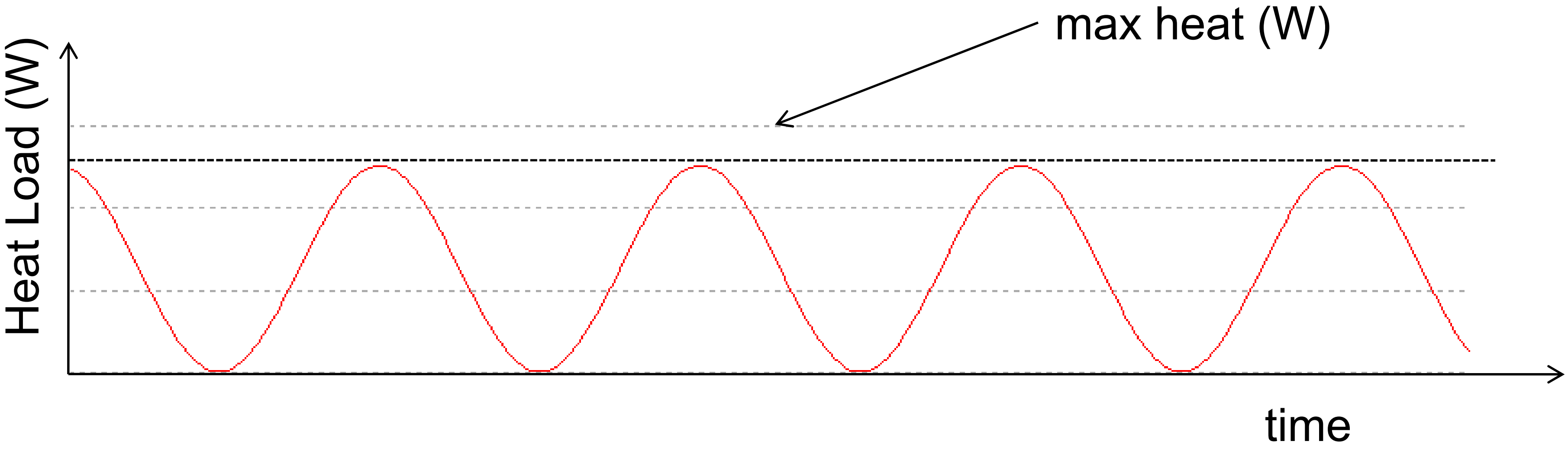


**Reliability Assessment**

Fatigue Life of Component x



# Power Cycling Test to Generate Fatigue Damage



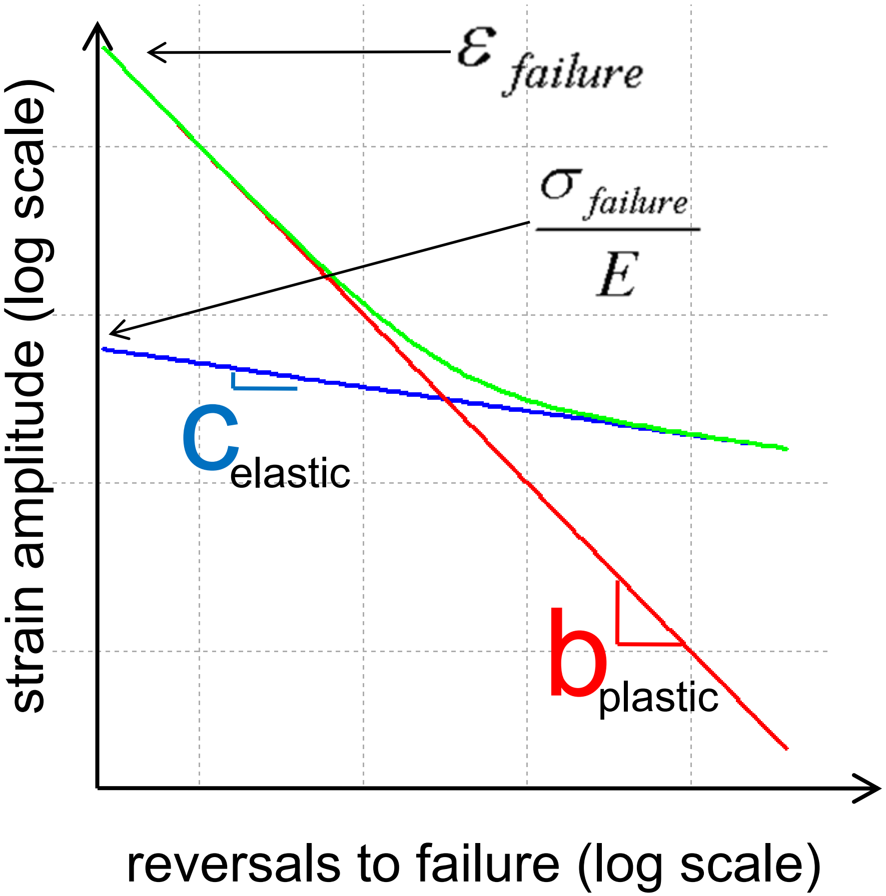
- The IGBT & diode heat generation has constant amplitude and cycles between 0 and maximum
- The max temperature appears at the IGBT
- Thermal and stress/strain gradients are maximized between adjacent layers

# Thermal Fatigue Simulation

1. Uses empirical models that predict fatigue life of solder joints from elastic/plastic strains and temperatures

2. The Manson-Coffin relation is used within the FEA simulation to account for elastic and plastic strain damage

3. Fatigue constants for strain-life approach are determined from the literature and fitting of experimental data



$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_{failure}}{E} \cdot \left[2 \cdot N_{failure}\right]^{b} + \varepsilon_{failure} \cdot \left[2 \cdot N_{failure}\right]^{c}$$

# Future Work: FY2009 & FY2010

- Validate model prediction against test
- Investigate the effect of uncertainty & variation on reliability predictions
- Design APEEM R&D for reliability
- Review results and methods with industry
- Milestone in May: Report on FY09 modeling activity to date

# Summary

**DOE Mission Support**

- Overcome barriers to adoption of low-cost petroleum saving PEEM technology by using CAE tools to design-for-reliability including the effects of variability on our R&D
    - guide R&D decisions, reduce deployment time, identify barriers to meeting life/reliability goals, increase R&D robustness

**Approach**

- Create and validate parametric solid models of technologies of interest to the DOE program (advanced cooling strategies chosen this year). Use standard design practices to enhance robustness of the concepts.

# Summary

**Technical Accomplishments**

- Created parametric solid models of 3 packages
  - thermal boundary conditions analyzed & created
  - material properties identified
  - bonded joint fatigue (soldered & sintered interface)
  - in-process of validating model versus test data
  - relative comparison of life implications of packages

**Collaborations**

- Collaborating for expertise and validation
  - interacting with Auto OEMs and suppliers for test data, review, and validation activities
  - interacting with other national laboratories (ORNL), other government institutions, and academic institutions on reliability, modeling, and technology

# Publications and Presentations

**FY08**

- DOE Milestone: “Thermal Stress and Reliability for Advanced Power Electronics: Current Status and Future R&D Activities.” July, 2008.
- DOE FY2008 Annual Progress Report on Advanced Power Electronics and Electric Machinery, “Thermal Stress & Reliability for Advanced Power Electronics & Electric Machines”.

**FY09 (Planned)**

- DOE Milestone: “Report on Reliability Modeling for Advanced Power Electronics.” June, 2009.
- DOE Milestone: “Report on Status and Results of Thermal Stress & Reliability R&D.” September, 2009.
- Conference Papers:
  - “Reliability Impacts of Cooling Strategies for Power Modules in Electric Traction Drive Vehicles.” 5th IEEE Vehicle Power and Propulsion Conference, 2009. (Paper in Progress).
  - “Sensitivity of Bonded Joint Fatigue to Sources of Variation in Advanced Vehicular Power Electronics Cooling.” ASME International Mechanical Engineering Congress, November 2009. (Paper in Progress).

# Critical Assumptions and Issues

**Value Added to the Program**

- The application of computer aided engineering (CAE) tools to design reliability into a concept is a critical aspect of deploying novel laboratory technology into the marketplace.

**Model Validation**

- Models must be validated to “earn our way out of testing”.
- This activity should be coordinated with other DOE power electronics testing activities to best leverage the funding on expensive testing activities.
  - This activity can add value to testing by anticipating test results and thus help to set up an optimal test, allow for the investigation of phenomena that cannot be directly measured during testing, and assist with the interpretation of test results.
- It will be important to define “standards” for reliability testing and simulation within the DOE program  such that results from one investigation can be compared against work from others.