Advanced Thermal Control

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Agreement: 13298

DOE Vehicle Technologies Program
DOE VTP APEEM R&D

North Marriott Hotel and Conference Center
Bethesda, Maryland

February 28, 2008
APEEM Thermal Control

- Excessive heat can degrade the performance, life, and reliability of power electronic components.

- Advanced thermal control technologies are critical to enabling higher power densities and lower system cost.

**EE Tech Team Goal:**
Electric Propulsion System with a 15-year life capable of delivering at least 55 kW for 18 seconds and 30 kW continuous at a system cost of $12/kw peak with a 105°C inlet coolant temperature by 2015.
Industry trend:
- increased power density and more aggressive cooling

Prius PE
Heat Exchanger (MY 2004)
- Single sided-cooling with straight serpentine fins

Camry PE
Heat Exchanger (MY 2007)
- Single sided-cooling with enhanced serpentine fins

Lexus PE
Heat Exchanger (MY 2008)
Double-sided cooling with complex stacked cooler system – enables increased power density
Transient power dissipation levels could be 2-4 x higher than steady state values

Other industry heat flux projections

Current vehicle technology
Advanced Power Electronics

Advanced Vehicle Systems

Technical Targets

APEEM Technology Development

APEEM Thermal Control Subsystem integration, performance, requirements

Potential Thermal Control Technologies

Technologies

Characterize and Develop Promising Technologies

- Jet Cooling
- Spray Cooling
- TIM
- Low R Structure
- Phase Change
- Alternative Coolants
- Air Cooling
- Surface Enhancements

HEV
SUV HEV
PHEV
FCV
## FY08 Thermal Control R&D Projects

<table>
<thead>
<tr>
<th>Project</th>
<th>Focus Area</th>
<th>thermal resistance</th>
<th>thermal materials</th>
<th>heat transfer</th>
<th>surface area</th>
<th>thermal models</th>
<th>power density</th>
<th>cost</th>
<th>lifetime</th>
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</thead>
<tbody>
<tr>
<td>Advanced Thermal Interface Materials</td>
<td>★★★</td>
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<td>Advanced Heat Transfer Technologies</td>
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<td>Thermal System Performance and Integration</td>
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<td>Direct Cooled Substrates</td>
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Thermal Interface Materials for Power Electronics

Principal Investigator: Sreekant Narumanchi

Agreement: 13298

Project Duration: FY06 – FY10
FY08 Funding: $375k

DOE Vehicle Technologies Program
Overview of DOE VTP APEEM R&D

North Marriott Hotel and Conference Center
Bethesda, Maryland

February 28, 2008
Purpose of Work

- Advanced thermal interface material (TIM) is a key enabling technology for the use of 105°C engine coolant and/or air cooling.
Barsriers

- Thermal grease used in commercially available inverters accounts for 30-50% of the package thermal resistance.

- Problems with greases include: non-uniform application, pump out (due to thermal cycling), and dry out (over time as solvent evaporates/separates).

- Inconsistent test methodologies and performance data.

- Lack of detailed understanding of the in-situ performance.
Response to Previous Reviewer’s Comments

• Improving thermal interface materials is important
  – *Improved thermal interface materials are key to meeting the program target.*

• There may be simpler/cheaper alternatives to carbon nanotubes (CNTs)
  – *We are exploring greases, phase change materials, graphite, thermoplastics and filler pads.*

• Need to evaluate degradation, thermal cycling
  – *In FY08, we plan to address these issues.*

• Could purchase CNTs from vendors
  – *We are evaluating CNTs grown on substrates from vendors.*
Technical Approach – FY08

- Establish a consistent, objective database of the thermal performance of different TIMs.

- Characterize impact of thermal cycling and aging effects on thermal resistance.

- Develop an understanding of in-situ TIM behavior.

- Translate experimental results into a TIM behavioral model that will guide the development of a breakthrough TIM.
**Timeline for FY08**

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<thead>
<tr>
<th>2007</th>
<th>Oct</th>
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<td>Characterize performance of greases</td>
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<td>Characterize performance of PCMs, solders, graphite, metallic TIMs</td>
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<td>Compare with other techniques for thermal resistance measurements (e.g. laser flash)</td>
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<td>Paper on thermal performance of different TIMs</td>
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<td>Start exploring in-situ performance of TIMs</td>
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<td>Characterize the effects of thermal cycling and aging on thermal performance of TIMs</td>
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<td>Annual report, paper on thermal cycling studies</td>
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12
Technical Accomplishments FY08

1. Experimental setup

- Obtained ASTM-based TIM test stand.
- Developed a thermal model to evaluate and improve the test apparatus.
- Implemented design changes to improve accuracy and control
  - added spreader blocks.
  - switched to cylindrical meter blocks.
  - added Teflon insulation.
  - increased depth of RTD probes.
  - pressure feedback control.

Infrared image of apparatus under test

| Temperature | Color
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<tr>
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<td>Orange</td>
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<td>40.0-35.0°C</td>
<td>Yellow</td>
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<tr>
<td>&lt;31.4°C</td>
<td>Blue</td>
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Spreader blocks

Meter blocks
Technical Accomplishments FY08

2. Comparison of FEA modeling and experiments

![Graph comparing FEA modeling and experiments](image-url)

- **Modeling - 25 um grease**
- **Experiments - 25 um grease**
- **Modeling - 150 um grease**
- **Experiments - 150 um grease**
Technical Accomplishments FY08

3. Experimental thermal resistance results for various greases

- Thermaxtech-xtflux-GA
- Arctic Silver 5
- Thermalcote-251G
- Shinetsu-X23-7762-S
- Wacker Silicone P12
- Toyota Camry
- Keratherm KP77

Thermal resistance (mm²K/W) vs. Thickness (mm)

Target: 5 mm²K/W
Technical Accomplishments FY08

4. Experimental thermal resistance results for PCMs and thermoplastics

- PCMs have very low thermal resistance.
- Reliability and in-situ performance needs to be proven.
Technology Transfer

- Sample materials obtained from industry collaborators and research organizations.
- Disseminate test results to industry partners.
- Close collaboration with industry partners
  - development and correlation of test methods.
  - understanding performance requirements.
- Industry partners
  - Delphi, Semikron, UQM, FreedomCAR, TIM suppliers.
- Candidate materials will be transferred to industry for evaluation.
Future Work

FY09

- Conduct studies related to reliability – including impact of thermal cycling and aging effects.
- Conduct in-situ testing via transient as well as steady-state approaches.
- Explore fabrication of novel interface materials most suited for automotive applications
  – modeling to understand/predict TIM behavior including contact resistance.

FY10

- Develop novel materials that meet requirements.
- Demonstrate in-situ performance and reliability
- Transfer candidate materials to industry.
Summary

- TIMs are key enabling technology for 105°C and air cooling technical pathways.
- NREL is developing a consistent and objective database of best performing TIM materials.
- A number of samples have been tested
  - greases,
  - PCMs,
  - preliminary CNT samples,
  - indium,
  - thermoplastics.
- The impacts of in-situ performance, thermal cycling and the effects of “aging” will be evaluated.
- NREL will translate experimental results to a model for behavioral mechanisms
  - lead to the development of improved materials.
Publications, Presentations, Patents

Publications


Presentations


Characterization and Development of Advanced Heat Transfer Technologies

Principal Investigator: Thomas Abraham

Agreement: 13298

Project Duration: FY08 – FY11
FY08 Funding: $375k

DOE Vehicle Technologies Program
Overview of DOE VTP APEEM R&D

North Marriott Hotel and Conference Center
Bethesda, Maryland

February 28, 2008
Purpose of Work

• Develop heat transfer technologies that will eliminate the dedicated cooling loop by enabling the use of 105°C coolant.

• Enable improved power density and system cost reductions through effective heat transfer performance.
  – Low cost thermal solutions
  – Reduced device and material cost
Barriers

- Dedicated coolant loop at 70°C is costly relative to the overall FreedomCAR goals

- Increasing the coolant inlet temperature decreases the thermal potential available for removing heat
  - increase heat transfer coefficient
  - increase surface area
  - improve device efficiency (reduce heat generation)
  - develop higher temperature devices

- Increased overall system temperature may adversely affect other power electronics components such as capacitors, wire bonds, and packaging.

- Long term reliability of system components may be degraded.

- Motor cooling will be more challenging with high temperature coolant.
Response to Previous Reviewer’s Comments

- Need measured data to support simulations
  - Next generation prototype is ready for detailed flow and thermal testing.
  - In collaboration with Mudawar Thermal Systems, NREL constructed test apparatus for two-phase jet and spray cooling and also established boiling curves for sprays/jets.

- Need to address long-term performance issues such as sealing, degradation of fluid, contamination, pressure drop, vibration, erosion, pump requirements.
  - We will be evaluating these concerns as part of our prototype demonstration and testing.

- Quantify systems implications – focus on system integration
  - We are developing a thermal sub-system evaluation methodology.
**Approach**

1. **Maximizing Heat Transfer Coefficient, \( h \)**
   - Assessing existing technologies like spray, oscillating jets, direct back side cooling, etc.

2. **Enhancing Surface Area, \( A \)**
   - Surface area is a key parameter for enhancing heat transfer, enabling volume and cost reduction

3. **Optimizing Cold Plate Temperature, \( T_B \)**
   - Explore the impact of alternate materials to improve thermal performance and reduce system cost

4. **Concurrent Engineering**
   - Close collaboration with ORNL team and industry partners to drive cost reduction
### Timeline for FY08

<table>
<thead>
<tr>
<th>2007</th>
<th>2008</th>
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<td>Oct</td>
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- **Virtual prototype optimized for thermal target and cost**
- **Flow and Thermal Testing**
- **Validation of Virtual Prototype**
- **“Proof of Concept” of Next Generation Heat Exchanger for PE**

#### Publish

1. **Self-oscillating jet paper (Semitherm, co-authored with Bowles Fluidics), 3/08**
2. **Two-phase experiments with numerical results (ITherm, co-authored with Mudawar Thermal Systems), 5/08**
3. **Submit a conference paper on Low Thermal Resistance IGBT Structure (9/08)**
Technical Accomplishments FY08

Low Thermal Resistance Power Module

Status

• Awarded patent for “Low Thermal Resistance Power Module Assembly”

• Simplified heat exchanger design and built 2nd generation prototype

• Completed preliminary flow testing

• Baseline Semikron inverter is being tested, prototype heat exchanger ready for assembly with Semikron inverter

Benefits

• Eliminates the need for thermal interface materials

• Weight and cost of power electronics devices can be reduced

• Cooling effectiveness variation between the jets is within 8%
Technical Accomplishments FY08

Characterized the Thermal Performance of Self-Oscillating Jets

Status
• Completed detailed testing of self-oscillating jets for power electronics cooling
• Paper entitled “Single-Phase Self-Oscillating Jets for Enhanced Heat Transfer” submitted to SemiTherm 08
• Demonstrated up to 15-30% heat transfer enhancement for free surface configuration.

Benefits
• Self-oscillating jets have no moving parts and can be used in conjunction with direct backside cooling and have the potential of further improving heat transfer
Technical Accomplishments FY08

Two-phase Jet Impingement Modeling

Status

- Two phase modeling results published in International Journal of Heat and Mass Transfer
- Validation of NREL modeling with experimental data available in the literature
- Demonstrated conditions for two-phase jets with R134a that dissipate 200 W/cm² while keeping the die temperature close to 125°C

Numerical simulations of nucleate boiling in impinging jets: Applications in power electronics cooling

Sreekanth Narumanchi¹*, Andrey Troshko³, Desikan Bharathan³, Vahab Hassani²

¹ National Renewable Energy Laboratory, MS 1031, 1617 Cole Boulevard Golden, CO 80401-3393, USA
² ANSYS Inc., Fluid Business Unit, 19 Easton Park Lane, Canonsburg, Pennsylvania 15317, USA

Received 25 October 2006; received in revised form 21 May 2007

Simulations with R134a jet
Technical Accomplishments FY08

Two-phase Jet and Spray Cooling

Status

• Mudawar Thermal Systems has constructed the test apparatus for two-phase jet and spray cooling

• Nucleate boiling curves have been established for HFE-7100 using jets and sprays

• Demonstrated conditions with two-phase dielectric coolant that could achieve > 200 W/cm² heat flux while maintaining 125°C chip temperature

Benefits

• Two-phase heat transfer provides an alternative means for achieving high heat flux requirements
Technology Transfer

- CRADA with Semikron to develop and demonstrate direct backside cooling technology in an inverter.
- CRADA with Bowles Fluidics to evaluate heat transfer potential of self oscillating jets and develop promising technology.
- Evaluation and development of two-phase jet and spray cooling solutions with Mudawar Thermal Systems.
- Publish research results
  - journal article on numerical modeling of two-phase jets
  - submitted paper on self-oscillating jets at Semitherm
  - submitted paper on two-phase experimental and model validation at ITherm
Future Work

- Select most promising spray or jet technologies to meet thermal targets using 105°C coolant
- Evaluate additional thermal control parameters to enable system cost, weight, and volume reduction
  - Surface area enhancement
  - Materials to improve thermal performance, cost and weight
  - Overall system cost reduction
- Develop optimized/integrated thermal solution
  - Thermal control integrated with PE system
  - Close collaboration with ORNL and industry partners
Summary

- Project is focused on evaluation and development of thermal control technologies to enable improved power density and system cost reductions.
- Supports the APEEM objective to reduce cost by eliminating the dedicated coolant loop and enable 105°C coolant.
- We have worked closely with industry partners and research institutions to evaluate a number of technologies
  - Single phase self-oscillating jets
  - Two phase jets and sprays
  - Direct backside cooling
- The project will now focus on developing an optimized, low-cost integrated thermal solution working in close collaboration with ORNL and industry partners.
- Transfer the low cost thermal solution to the industry.
Publications


Presentations


Patents

Questions
Air Cooling Technology for Power Electronics Thermal Control

Principal Investigator: Desikan Bharathan

Agreement: 13298

Project Duration: FY06 – FY10
FY08 Funding: $350k

DOE Vehicle Technologies Program
Overview of DOE VTP APEEM R&D

North Marriott Hotel and Conference Center
Bethesda, Maryland

February 28, 2008
Purpose of Work

- Develop air cooling technology that will enable overall system cost reductions to meet the FreedomCAR technical targets ($8/kW by 2020).
- Eliminate liquid coolant loops for power electronics.
- Enable heat rejection directly to the sink, namely, ambient air. Simplify the system.
- Maintain die temperature below specified operating limits for long-term reliability.
The Challenges/Barriers

**Advantages**

Air is the ultimate sink

Rejecting heat to air can eliminate intermediate fluid loops

Air is benign and need not be carried

Air is a dielectric, and can contact the chip directly

**Drawbacks**

Air has a low specific heat

Air is a poor heat-transfer fluid

Air density is low
Response to Previous Reviewers’ Comments

- **Ultimate solution**
  - *We believe this may be true*

- **Measured data is needed**
  - *Experimental data will be a key focus point in FY08.*

- **Focus on SiC application**
  - Our focus has been on assessing air cooling technologies with the potential to dissipate up to 200 W/cm\(^2\) of heat while maintaining the required operating temperature. The application to SiC technology will continue to be a priority for the long term, but it appears that air-cooling may have potential for Si trench technology.

- **Quantify systems implications – focus on system integration**
  - *We have developed a thermal sub-system evaluation methodology.*

- **Need experimental results including acoustics**
  - *Experimental validation and evaluations that address the issues above along with developing the necessary thermal sub-systems will be key areas of focus for this project.*
Project Objectives for FY08

- Implement air cooling
  - demonstrate technology on a working inverter

- Validate models and design approach.

- Contribute to advanced PE development cooling options
  - meet programmatic goals.
Technical Approach

1. Complete evaluation of alternative heat exchanger designs and system trade-off study
2. Design an air cooled micro-channel fin heat exchanger for an inverter module
   - In close collaboration with industrial manufacturer
   - Meet performance, cost, volume, and manufacturing constraints
3. Incorporate air cooling device in an actual inverter
4. Test performance of the module
5. Validate design with test data
7. Develop second iteration design and demonstrate air-cooling
Accomplishments

Developed ASPEN System Model to Evaluate System Tradeoffs

Air-Cooling System for Power Electronics

A Schematic Diagram

- Air intake line
- Centrifugal fan
- Air filter
- Micro-fin heat exchanger (under chip assembly PCB)
- Air exhaust to atmosphere
- Ambient air at 30°C
Accomplishments
Developed Estimator Model to Evaluate Micro-fin Design Tradeoffs
Accomplishments

Numerical Evaluation of Micro-channel fins led to prototype test article

Micro-fin array geometry

Typical values are:

- \( W = 130 \, \mu m \)
- \( t = 65 \, \mu m \)
- \( H = 13 \, mm \) and
- \( t_b = 1 \, mm \)
Accomplishments

Experimental Evaluation of vendor heat exchanger

NREL Data on heat flux (No Fins)

NREL Data on pressure loss (No Fins)

![Graph showing heat flux and pressure drop](image)
Accomplishments

**Models show that:**

- Air cooling can remove fluxes up to 150 W/cm$^2$ for Silicon-based devices.
- Higher chip operating temperatures will increase the flux close to programmatic goal of 200 W/cm$^2$.

**Comparison with the use of an intermediate liquid cooling loop indicate that:**

- Air cooling is simple, less costly, and reliable.
Accomplishments

a) 

b) 100 mm  30 mm Φ

c) 

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# Timeline

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<th>2007</th>
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<tr>
<td>Consult with manufacturers for incorporating air cooling option</td>
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<td>Initiate and fine tune design with constraints</td>
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<td>Incorporate air cooling in a prototype</td>
<td>Develop next generation design</td>
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<td>Thermal testing/validation for micro-fin channel geometry at lab scale</td>
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<tr>
<td>Flow and thermal testing</td>
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<td>Develop design guidelines for the industry</td>
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Beyond FY08 -- Integrate the developed thermal control technology with reliability tasks based on a systems level approach

- Analyze pulsed systems to power
- Generate a design tool for air cooling
  - Provide industry with an easy-to-use tool to evaluate all aspects of performance and specifications.
Questions
Power Electronic Thermal System Performance and Integration

Principal Investigator: Kevin Bennion
Agreement: 13298
Project Duration: FY06 – FY10
FY08 Funding: $280k

DOE Vehicle Technologies Program Overview of DOE VTP APEEM R&D

North Marriott Hotel and Conference Center
Bethesda, Maryland

February 28, 2008

This presentation does not contain any proprietary or confidential information
Purpose of Work

**Problem**
- Commercially viable thermal control technologies must minimize system cost, volume, and weight while maintaining performance and reliability.

**Objective**
- Integrate thermal control technologies into commercially viable systems.

- What are viable system design directions?
- What analysis tools can speed up R&D evaluations?

How close are breakthrough technologies to meeting system targets?
Response to Previous Reviewer’s Comments

- Comment: “Need to focus on thermal sub-system and not the whole vehicle system”
  - We are evaluating the thermal control of power electronics at a number of levels to understand how use and design impact cost, weight, performance, and reliability.

- Comment: “Need experimental data for validation”
  - We are leveraging data available from other tasks, labs, and principle investigators.
Barriers

- System thermal performance is a multi-dimensional problem.

**Vehicle Type**
- HEV/PHEV
- FCV

**Component Use**
- Peak
- Continuous
- Dynamic

**Cooling System**
- Coolant Temperature
- Convection Coefficient
- Heat Exchanger Effectiveness

**PE Package**
- Topology
- Materials
Technical Approach for FY08

1) Rapid Power Electronics Transient Thermal Model

- Develop methodology and tools integrating transient thermal simulations with dynamic vehicle systems models.
  - Characterize thermal duty cycles.
  - Evaluate breakthrough technologies and design tradeoffs at system level.
  - Support thermal stress and reliability analysis.

![Diagram of electrical components with dissipated heat labeled]
Technical Approach for FY08

2) **Power Electronics Thermal Control and Packaging Tradeoffs**

- Evaluate advanced packaging and cooling technologies in terms of performance, weight, and transient characteristics.
  - Compare breakthrough technologies at a thermal systems level.
# Timeline for FY08

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- **Rapid Model Development**
- **Quantify Transient and Volume Impacts of Package Designs**
- **Rapid Model Validation**
- **Validate Transient and Volume Impacts**
- **Thermal Systems Reliability Integration**
- **ORNL PE Thermal Design Support**
Accomplishments

- Evaluated thermal duty cycle for Toyota Prius motor inverter.
  - Vehicle Test Data.
  - Vehicle Systems Analysis PSAT Model.
  - ORNL Benchmark Data.

- Transient heat loads are significantly higher than average heat load.
Accomplishments

- Performed preliminary analysis of PHEV impacts to quantify PEEM thermal control implications.
  
  - Vehicle Systems Analysis using “Real World” Data\(^1\).

- PHEV thermal loads are even more challenging as compared to HEVs.

Accomplishments

- Developed parametric FEA thermal model to evaluate performance of advanced inverter cooling concepts.

Thermal: Fins, Jet Impingement, Air, TIM, Coolant Temperatures, Junction Temperatures.
Technology Transfer

- Publish results.

- Communicate with EETT.

- Develop partnerships and interactions with OEM’s and suppliers.
Future Work

- FY09
  - Evaluate cost and parasitic power tradeoffs for power electronics (PE) cooling technologies.
  - Review need for thermal control of electric machines (EM).
  - Support reliability task with systems modeling.

- FY10
  - Apply developed systems analysis techniques to support research in advanced designs.
  - Develop systems analysis abilities for electric machines.
Summary

Problem

- Commercially viable thermal control technologies must minimize system cost, volume, and weight while maintaining performance and reliability.

Method

- Develop methodology to understand impacts of thermal system use and design on:
  - Cost.
  - Weight.
  - Performance.

- Integrate analytical modeling capability with experimental data.

- Collaborate with other labs, principle investigators, and industry.

Accomplishments

- Evaluated component use in a systems context (HEV and PHEV).

- Developed parametric FEA thermal model to evaluate performance of advanced inverter cooling concepts.
Publications, Presentations, Patents

Questions
Thermal Stress and Reliability

Principal Investigator: Michael P. O’Keefe

Agreement: 13298

Project Duration: FY08 – FY11
FY08 Funding: $280k

DOE Vehicle Technologies Program
Overview of DOE VTP APEEM R&D

North Marriott Hotel and Conference Center
Bethesda, Maryland

February 28, 2008

This presentation does not contain any proprietary or confidential information
The Problem

- Fundamental concerns related to PEEM component usage and reliability
- Existing methods of addressing reliability are costly and time intensive
- For the DOE: need a quantitative method to evaluate 15 year life target of new technologies
- Apparent gap between vehicle level requirements and component development
Purpose of Work

Analysis | Development | Validation

TODAY

FUTURE

LAUNCH

LAUNCH

product development time

cost / effort

effort
The Challenges/Barriers

- Integration and coordination of various engineering software tools
- Validation of models (availability of data)
- Complexity of problem
- Validation of predictions
Reviewer comments

New project in FY08
Suggested by industry partners
Allows DOE to assess reliability targets

2006 APEEM Reviewer Comments that mention “Reliability”
Approach

• Develop critical areas not currently being addressed

• Integrate, leverage, and coordinate
  – testing at ORNL, ANL, and INL
  – thermal modeling at NREL
  – national physics of failure expertise
  – knowledge and data from automotive OEMs and suppliers

• Impacts
  – Assess 15 year life target for DOE R&D
  – Empower researchers to consider life/ reliability earlier in the design cycle
Approach

1. Driving Profile
2. Vehicle Level Model

Power Electronics USAGE Profile (Duty Cycle)

3. Power Module Package/Circuit Design

4. Power Electronics Efficiency

Heat Generation

5. Package Thermal Models (FEA)

Stress & Temperatures

6. Physics of Failure Models & Analysis
Approach

Assess reliability implications of existing DOE projects
Timeline for FY08

Information Gathering

Milestone: R&D Plan

Annual Report

Analytical Reliability Assessment
Technical Accomplishments

- We’ve spoken to/ met with many experts

Maxwell Tech.  
Virginia Tech  
GM  
Hobbs Engineering  
Reliability Information Analysis Center

US Navy  
Delphi  
ASTR 2007 Workshop  
US Air Force

University of Maryland CALCE  
DfR Solutions  
Ford  
BAE Systems

Literature Review
Key Messages

Motivation: make informed decisions for higher reliability earlier in product design

Current approach: costly/time-consuming test
Future approach: “robust design” w/ CAE

Knowledge on reliability + sophisticated CAE tools exist; key is integration

NOT advocating to stop testing; advocating to minimize unneeded test and/or retest
Technology Transfer Strategy

• Publish results

• Work with OEMs and suppliers

• Work with SAE Standards committee
Summary

- Develop Automotive PEEM Reliability Tool
- Process:
  - Information gathering
  - Create a working example early on
  - Adjust as we go
  - Identify opportunities to validate
- Review progress periodically
- Apply concepts to DOE program technology
O’Keefe, M. (Nov 2007). “PEEM Thermal Stress and Reliability”, FY08 Kickoff Presentation, National Transportation Research Center, Knoxville, TN.
