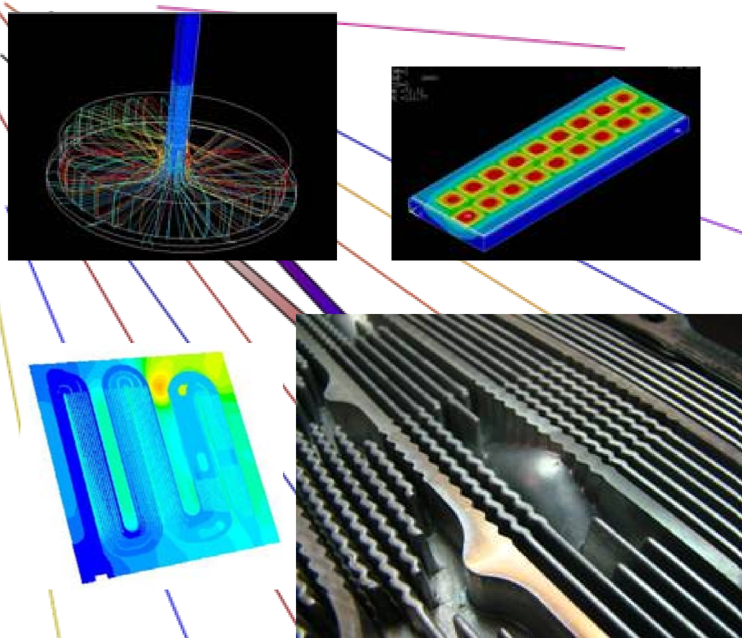
Advanced Thermal Control



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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

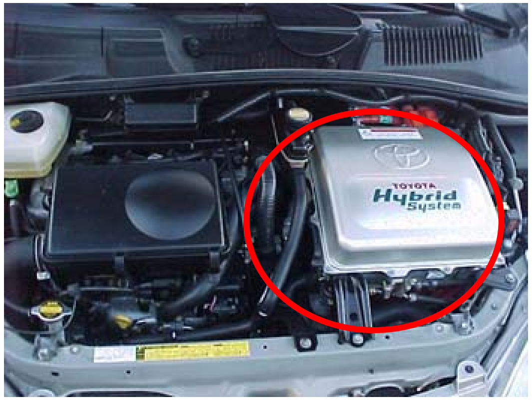
APEEM Thermal Control

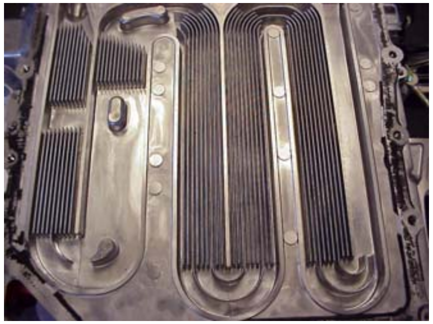
- **Excessive heat can degrade the performance, life, and reliability of power electronic components.**
- **Advanced thermal control technologies are critical to enabling higher power densities and lower system cost.**

EE Tech Team Goal:

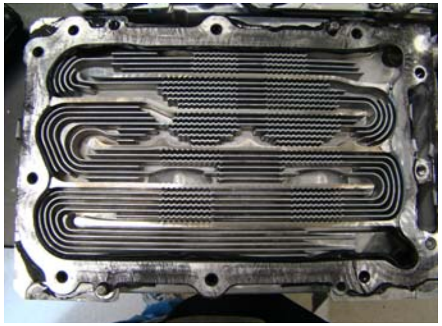
Electric Propulsion System with a 15-year life capable of delivering at least 55 kW for 18 seconds and 30 kW continuous at a system cost of $12/kw peak with a 105°C inlet coolant temperature by 2015.

Industry trend:
- increased power density and more aggressive cooling

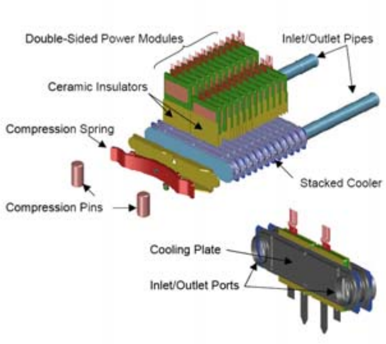




Prius PE
Heat Exchanger (MY 2004)
- Single sided-cooling with straight serpentine fins



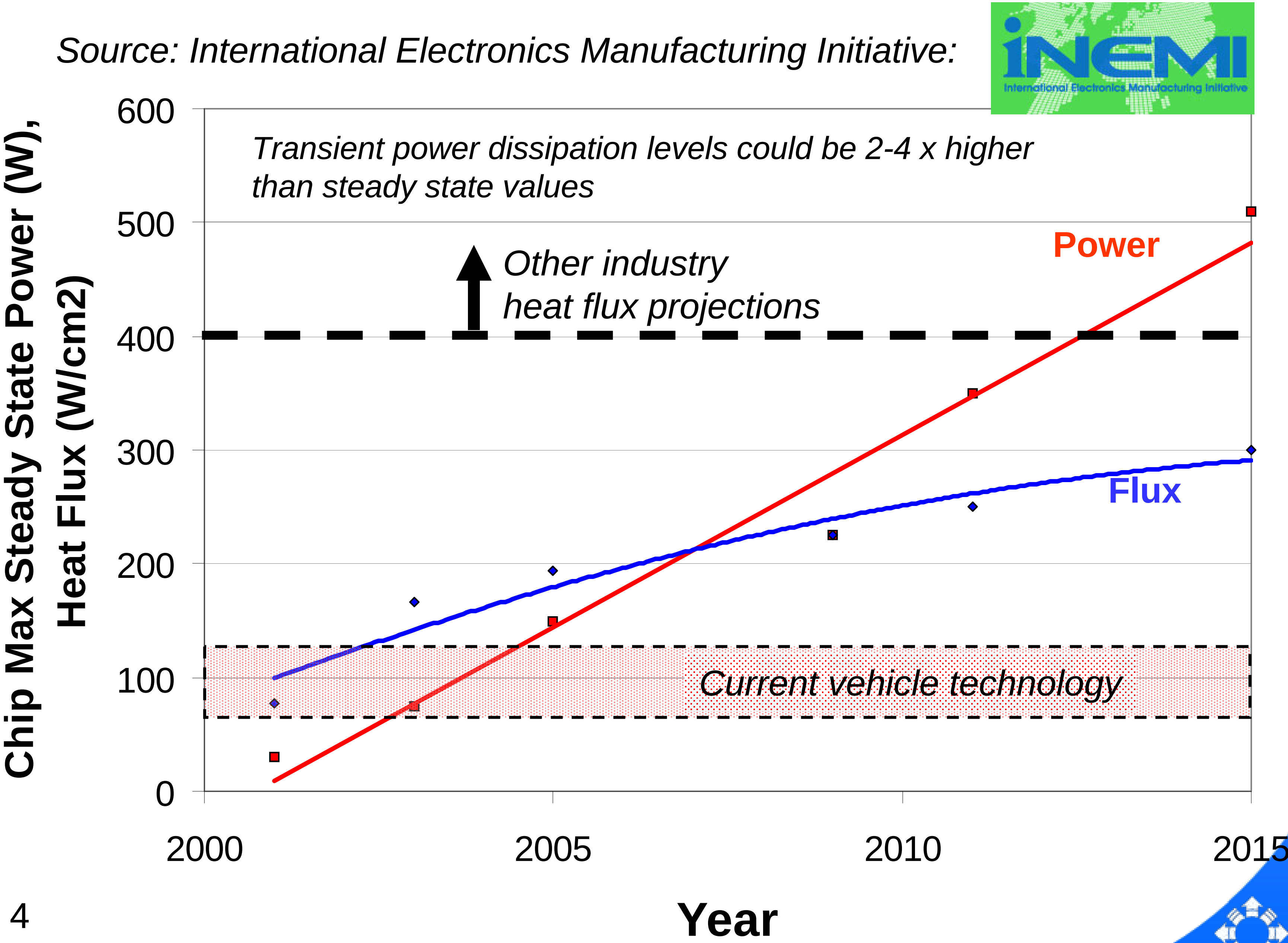
Camry PE
Heat Exchanger (MY 2007)
- Single sided-cooling with enhanced serpentine fins

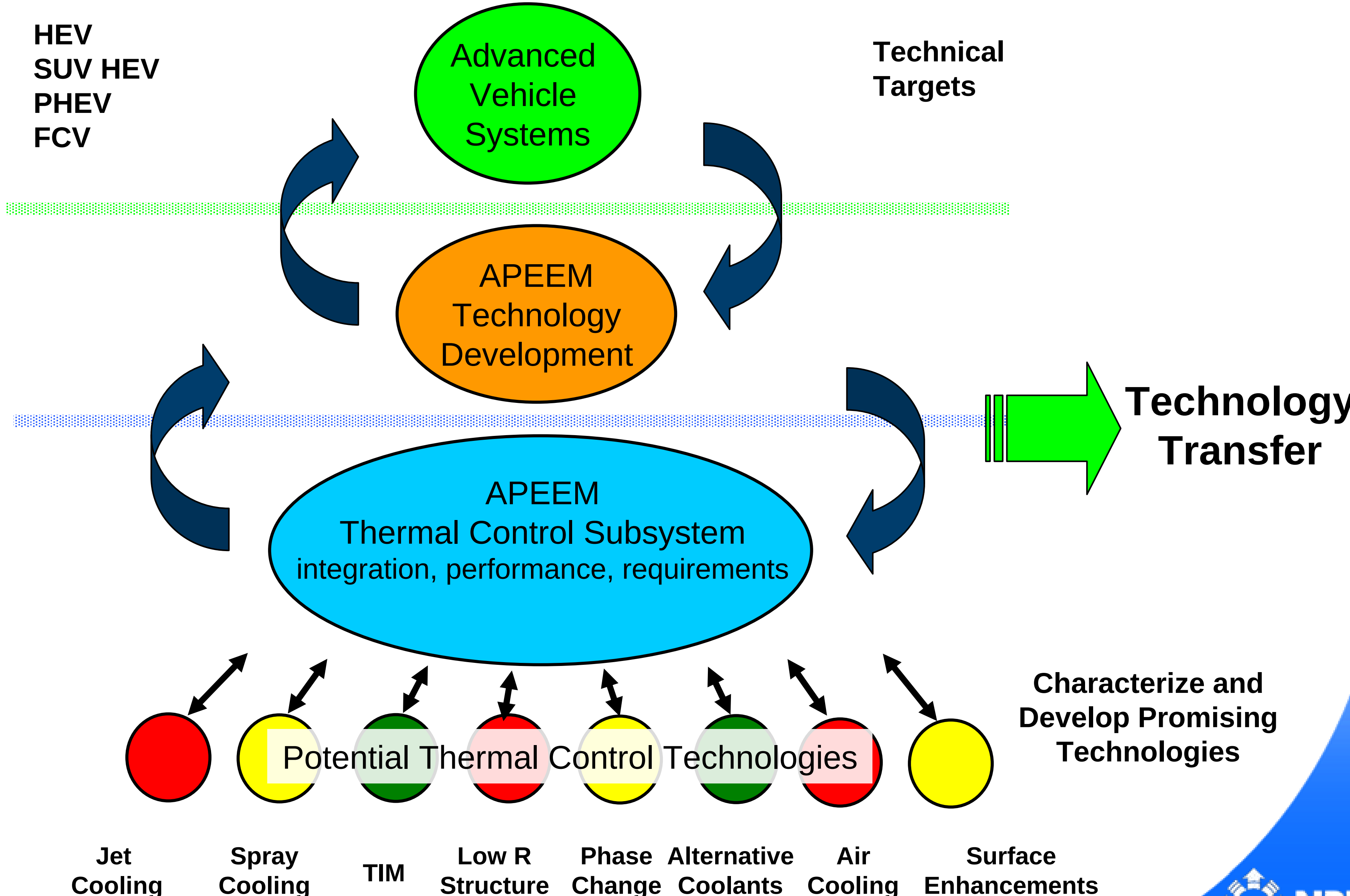


Lexus PE
Heat Exchanger (MY 2008)
Double-sided cooling with complex stacked cooler system – enables increased power density

Thermal Control Requirements

Source: International Electronics Manufacturing Initiative:

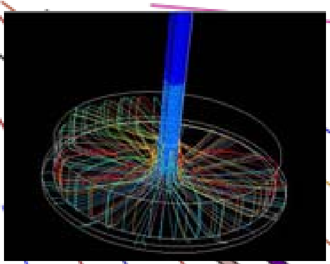


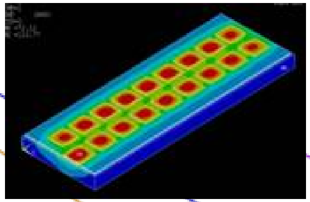

HEV
SUV HEV
PHEV
FCV
Advanced Vehicle Systems
Technical Targets
APEEM Technology Development
Technology Transfer
APEEM
Thermal Control Subsystem
integration, performance, requirements
Potential Thermal Control Technologies
Characterize and Develop Promising Technologies
Jet Cooling
Spray Cooling
TIM
Low R Structure
Phase Change
Alternative Coolants
Air Cooling
Surface Enhancements

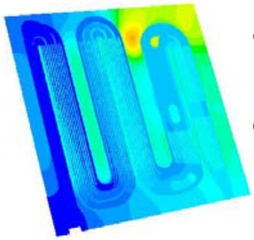
FY08 Thermal Control R&D Projects

Project \ Focus Area	thermal resistance	thermal materials	heat transfer	surface area	thermal models	power density	cost	lifetime
Advanced Thermal Interface Materials	★	★				★	★	★
Advanced Heat Transfer Technologies	★	★	★	★	★	★	★	★
Air Cooling	★		★	★	★	★	★	★
Thermal System Performance and Integration		★			★	★	★	★
Thermal Stress and Reliability					★	★	★	★
Direct Cooled Substrates	★	★	★	★	★	★	★	★

Thermal Interface Materials for Power Electronics







Principal Investigator: Sreekant Narumanchi

Agreement: 13298

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

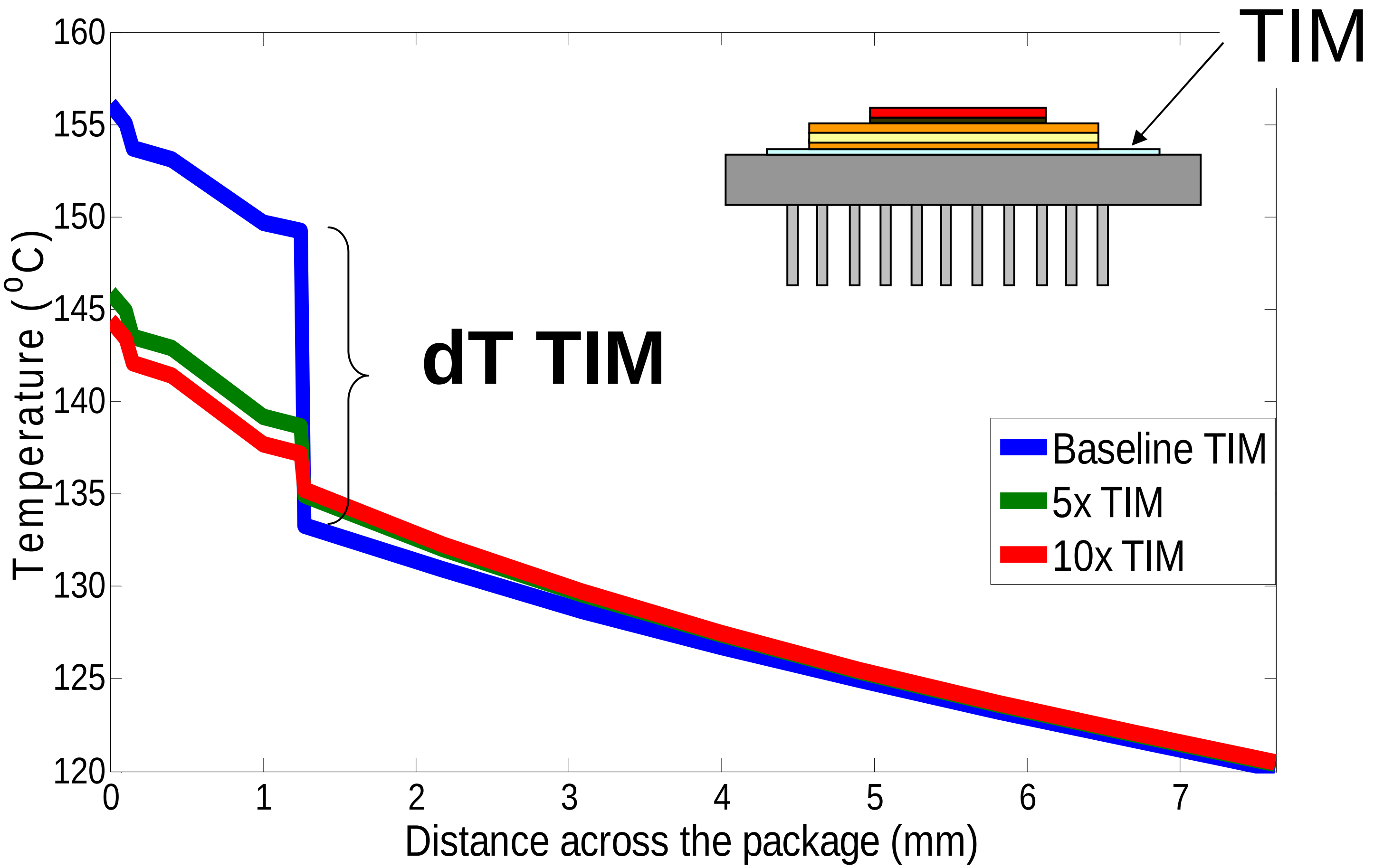
DOE Vehicle Technologies Program
Overview of DOE VTP APEEM R&D

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.



Barriers

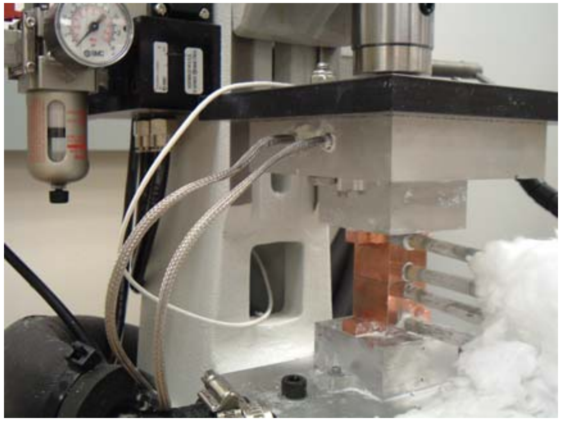
- Thermal grease used in commercially available inverters accounts for 30-50% of the package thermal resistance.
- Problems with greases include: non-uniform application, pump out (due to thermal cycling), and dry out (over time as solvent evaporates/separates).
- Inconsistent test methodologies and performance data.
- Lack of detailed understanding of the in-situ performance.

Response to Previous Reviewer's Comments

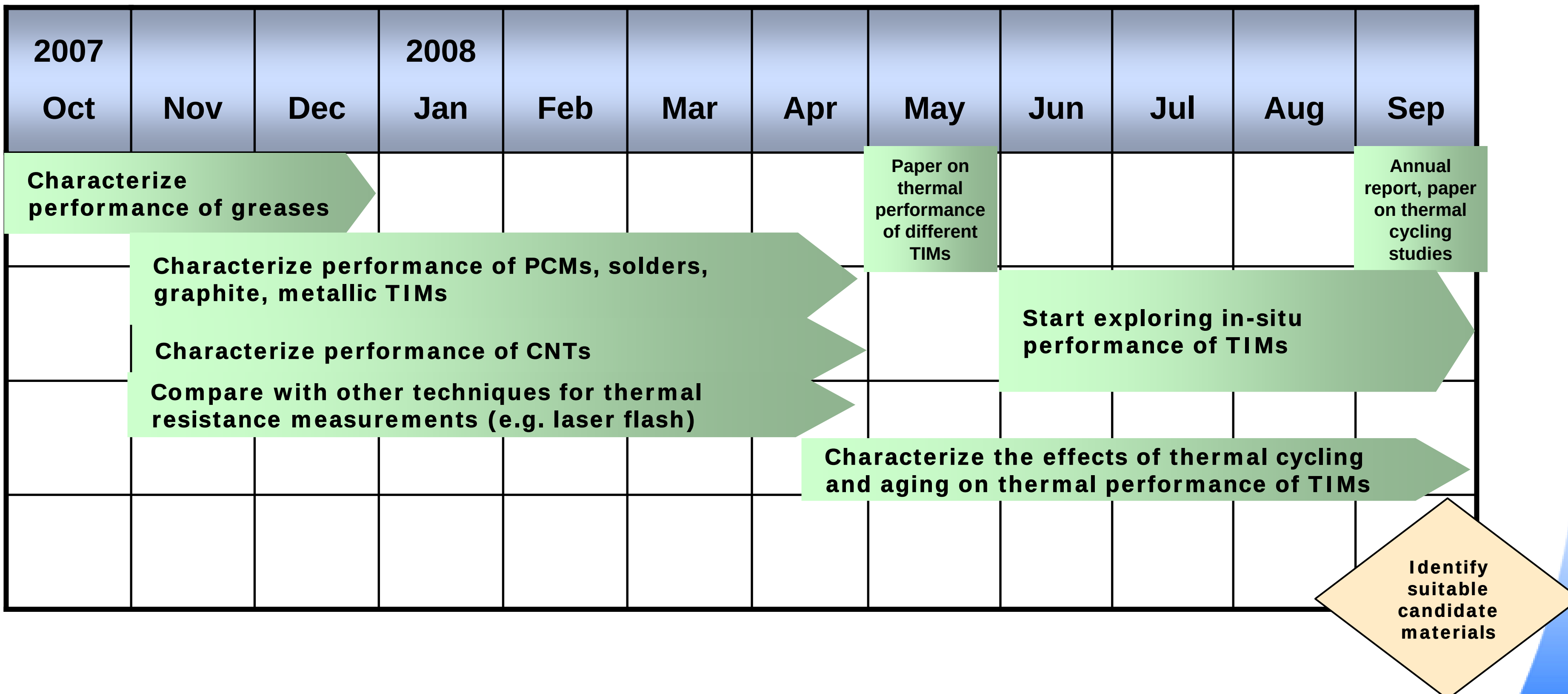
- Improving thermal interface materials is important
  - *Improved thermal interface materials are key to meeting the program target.*
- There may be simpler/cheaper alternatives to carbon nanotubes (CNTs)
  - *We are exploring greases, phase change materials, graphite, thermoplastics and filler pads.*
- 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.

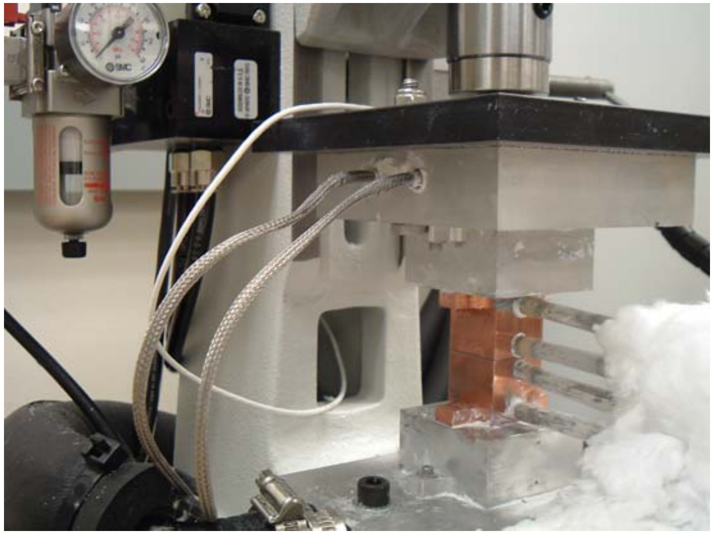


Timeline for FY08



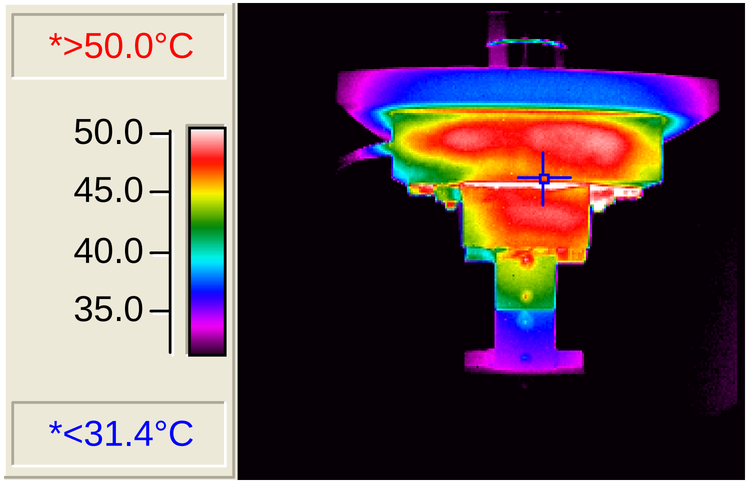
Technical Accomplishments FY08

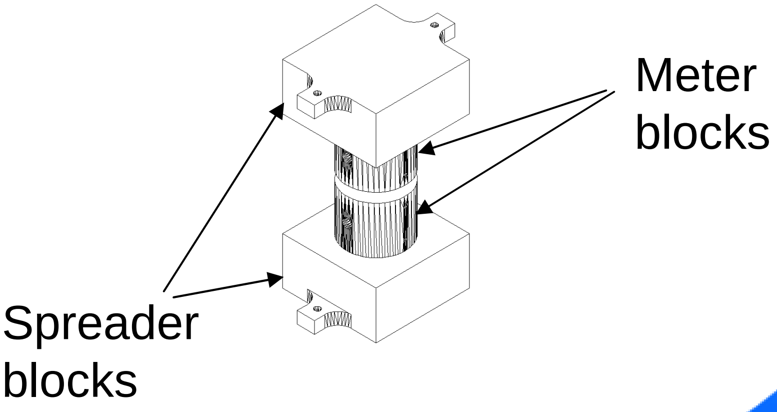
1. Experimental setup



- 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.

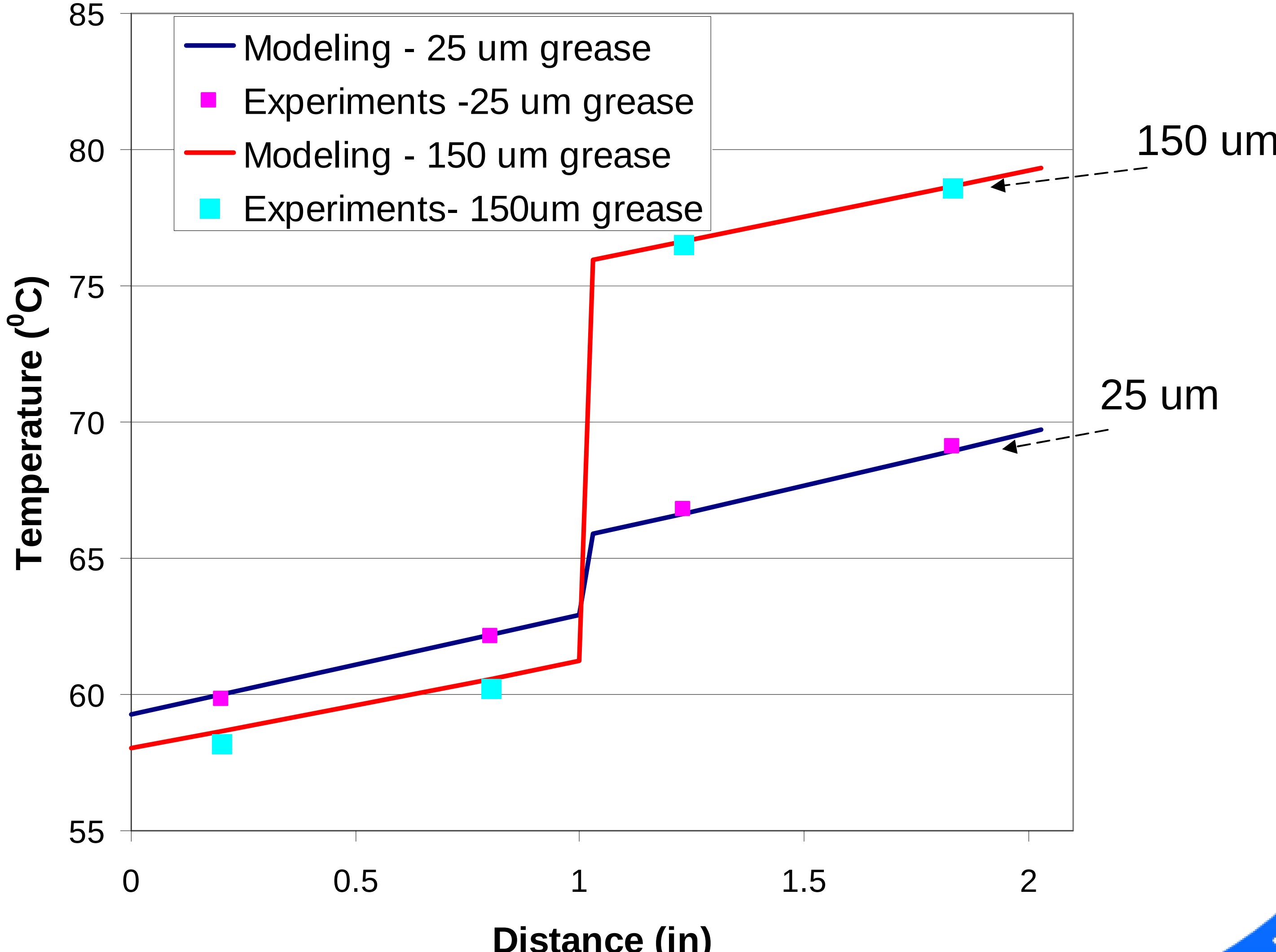
Infrared image of apparatus under test





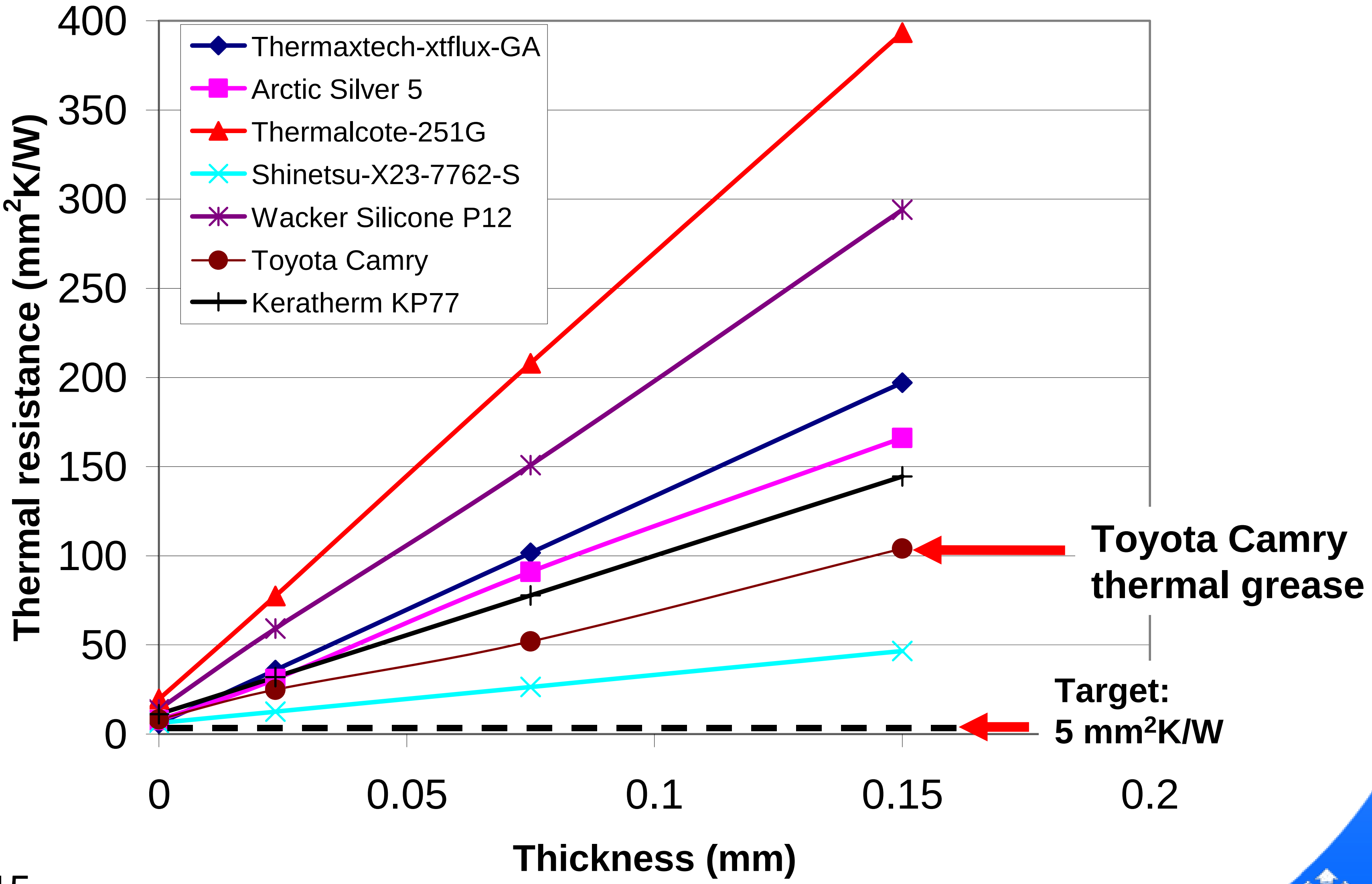
Technical Accomplishments FY08

2. Comparison of FEA modeling and experiments



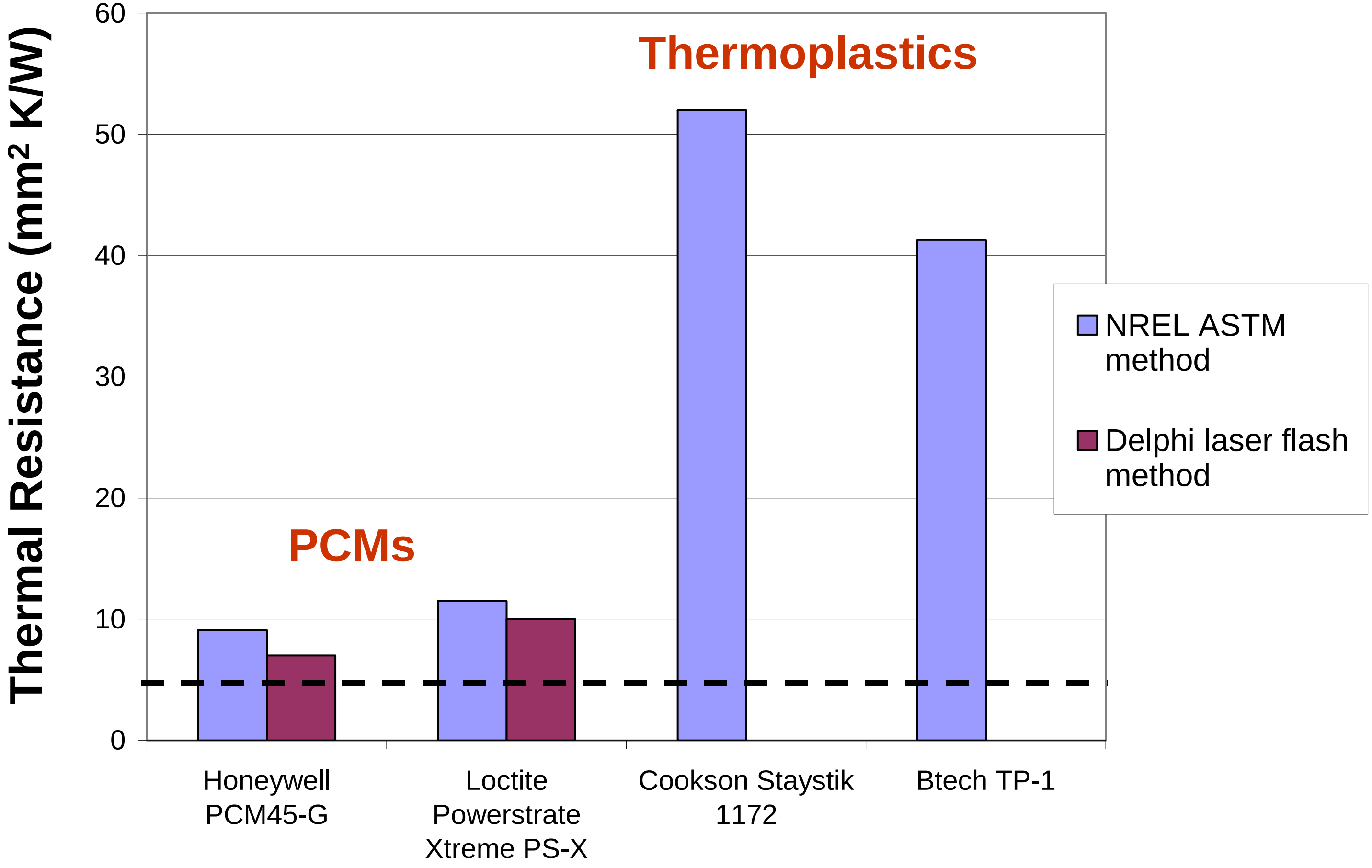
Technical Accomplishments FY08

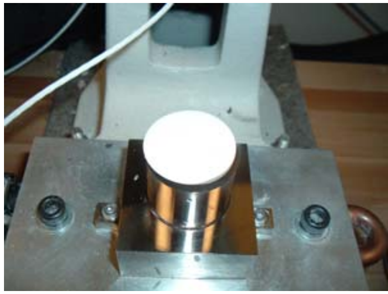
3. Experimental thermal resistance results for various greases

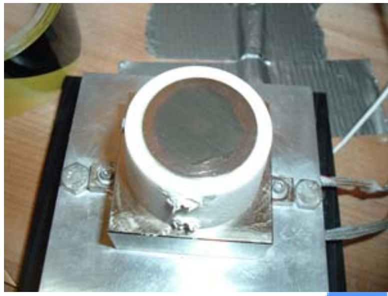


Technical Accomplishments FY08

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

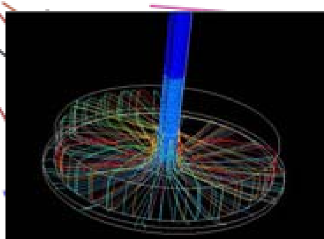
- Narumanchi, S.V.J., et al., 2008, “Characterization of thermal interface materials for advanced power electronics cooling applications”, paper submitted to the 2008 ITherm conference, May 28-31, 2008, Orlando, FL.
- Narumanchi, S. V. J., 2007, “Advanced thermal interface materials for power electronics cooling applications”, NREL technical report, NREL/MR-540-36085, September 2007.
- Narumanchi, S.V.J., et al., 2006, “Advanced Thermal Interface Materials to Reduce Thermal Resistance”, NREL Technical/Milestone Report, NREL Report No. TP-540-40617.

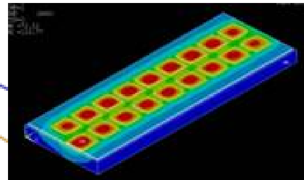
Presentations

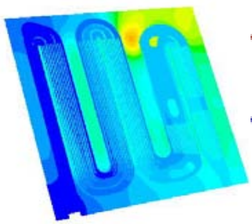
- Narumanchi, S.V.J., 2006, “Advanced thermal interface materials to reduce thermal resistance”, 2006 DOE FreedomCAR APEEM Annual Review, Pollard Technology Conference Center, Oak Ridge, TN, August 17, 2006.
- Narumanchi, S.V.J., 2007, “Advanced thermal interface materials for power electronics”, FY08 Kickoff Meeting, DOE FreedomCAR and Vehicle Technologies Program, APEEM Projects, National Transportation Research Center, Knoxville, TN, November 8, 2007.


Questions
?

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

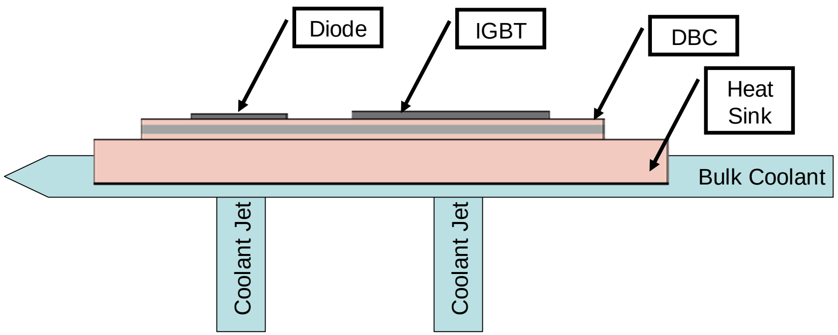
- Dedicated coolant loop at 70°C is costly relative to the overall FreedomCAR goals
- Increasing the coolant inlet temperature decreases the thermal potential available for removing heat
  - increase heat transfer coefficient
  - increase surface area
  - improve device efficiency (reduce heat generation)
  - 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.*

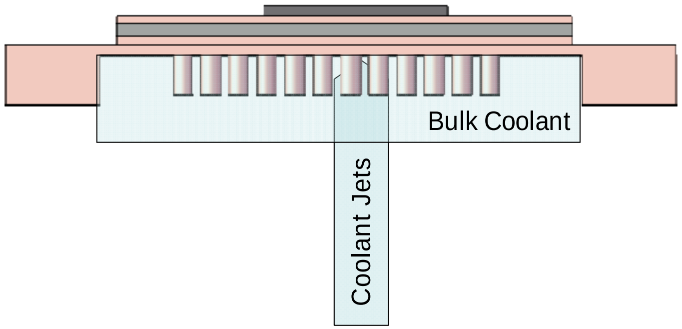
Approach

1. Maximizing Heat Transfer Coefficient, h



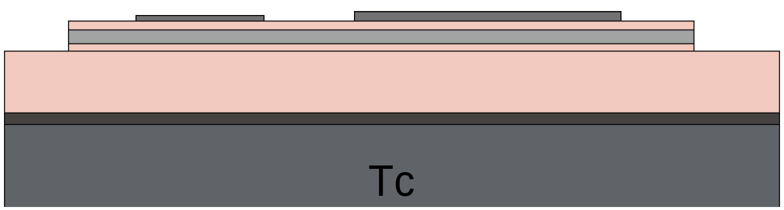
Assessing existing technologies like spray, oscillating jets, direct back side cooling, etc.

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

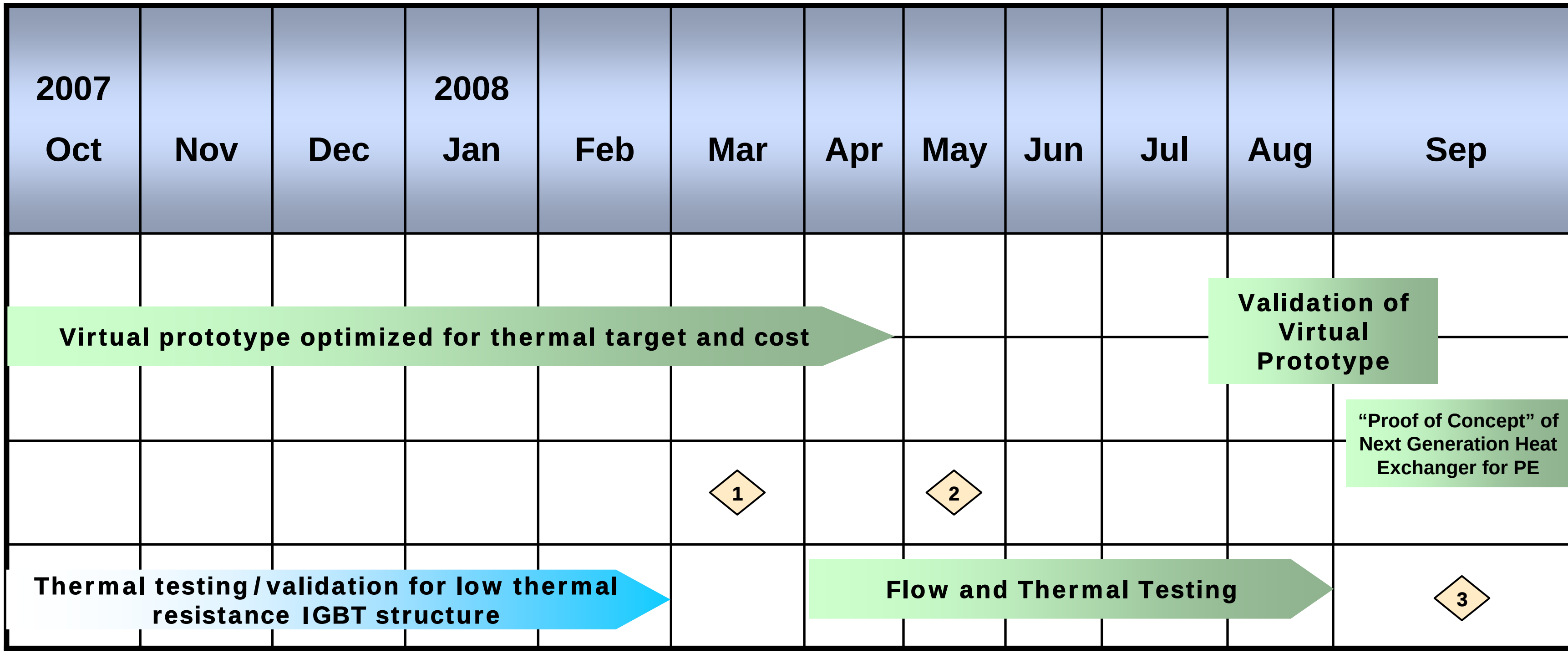


Explore the impact of alternate materials to improve thermal performance and reduce system cost

4. Concurrent Engineering

Close collaboration with ORNL team and industry partners to drive cost reduction

Timeline for FY08

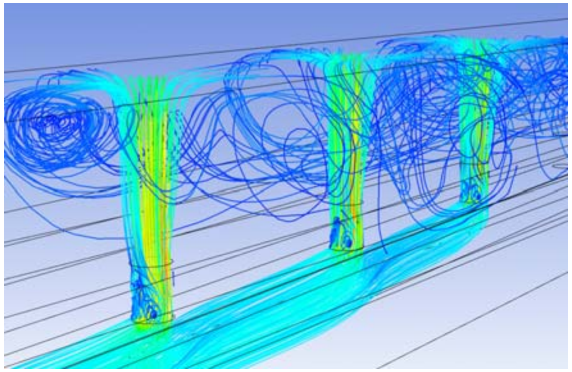


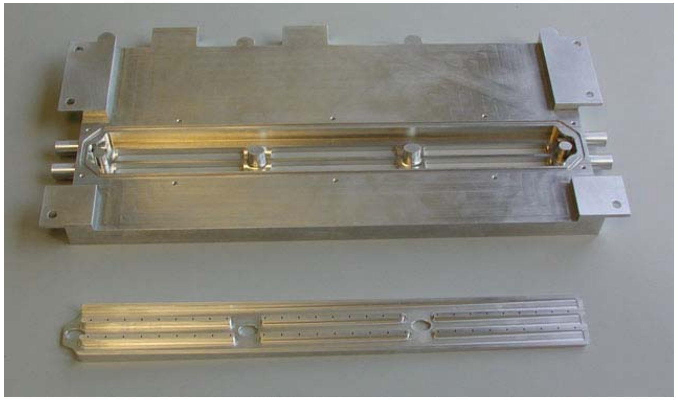
- **Publish**

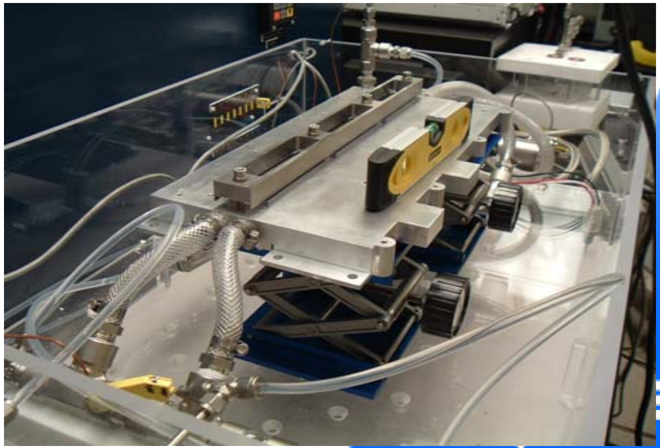
1. **Self-oscillating jet paper (Semitherm, co-authored with Bowles Fluidics), 3/08**
2. **Two-phase experiments with numerical results (ITherm, co-authored with Mudawar Thermal Systems), 5/08**
3. **Submit a conference paper on Low Thermal Resistance IGBT Structure (9/08)**

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

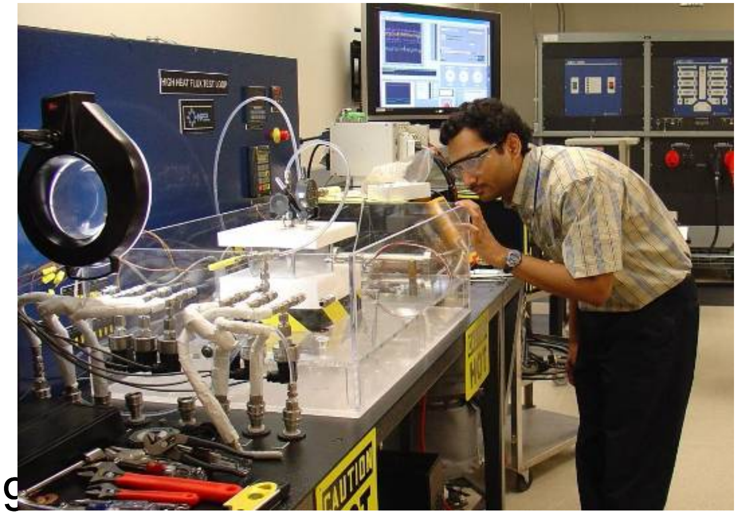
Characterized the Thermal Performance of Self-Oscillating Jets

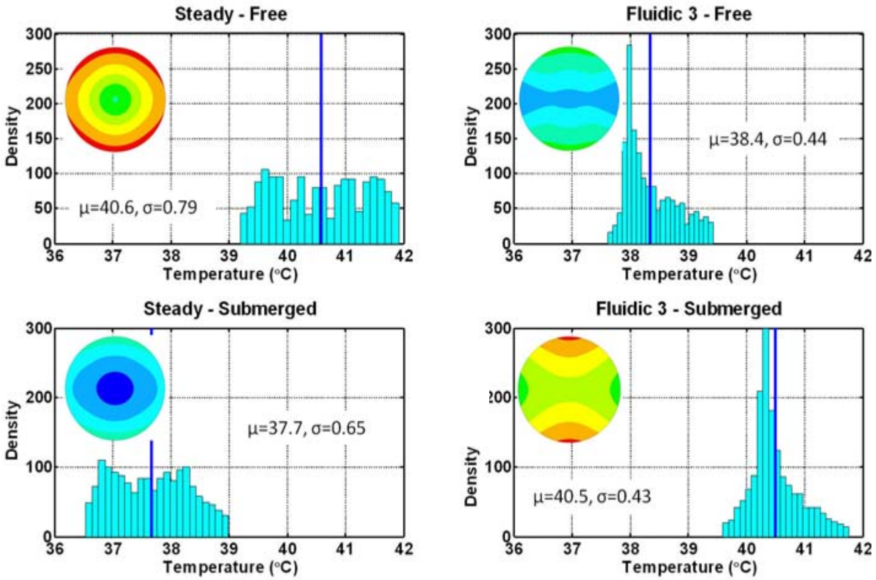
Status

- 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





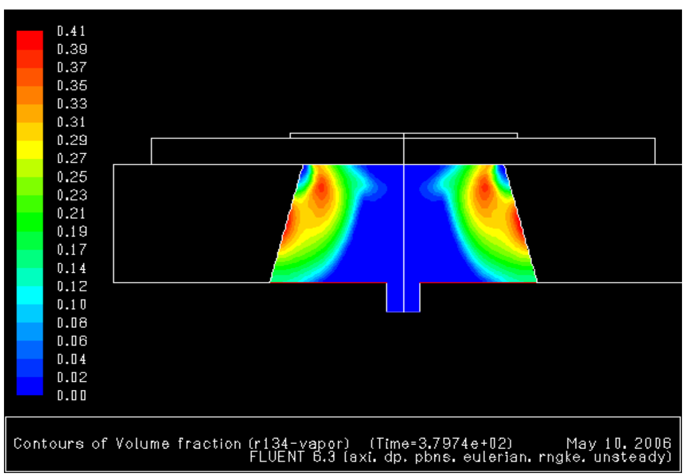
Technical Accomplishments FY08

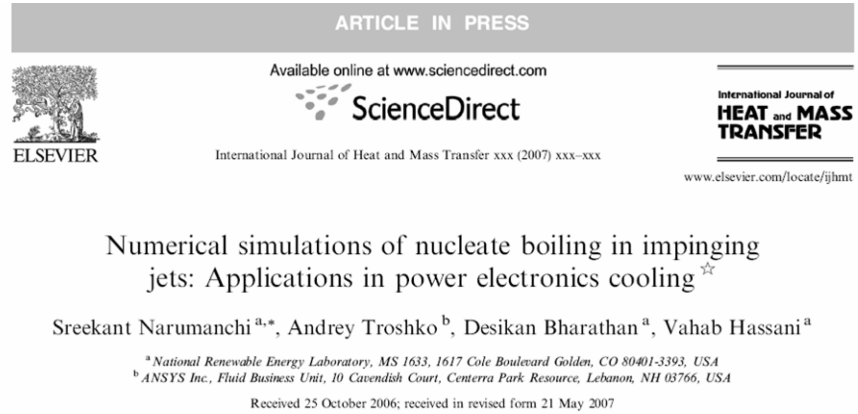
Two-phase Jet Impingement Modeling

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/cm^2 while keeping the die temperature close to 125^{o}C

Simulations with R134a jet

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

Sreekant Narumanchi [a,*], Andrey Troshko [b], Desikan Bharathan [a], Vahab Hassani [a]

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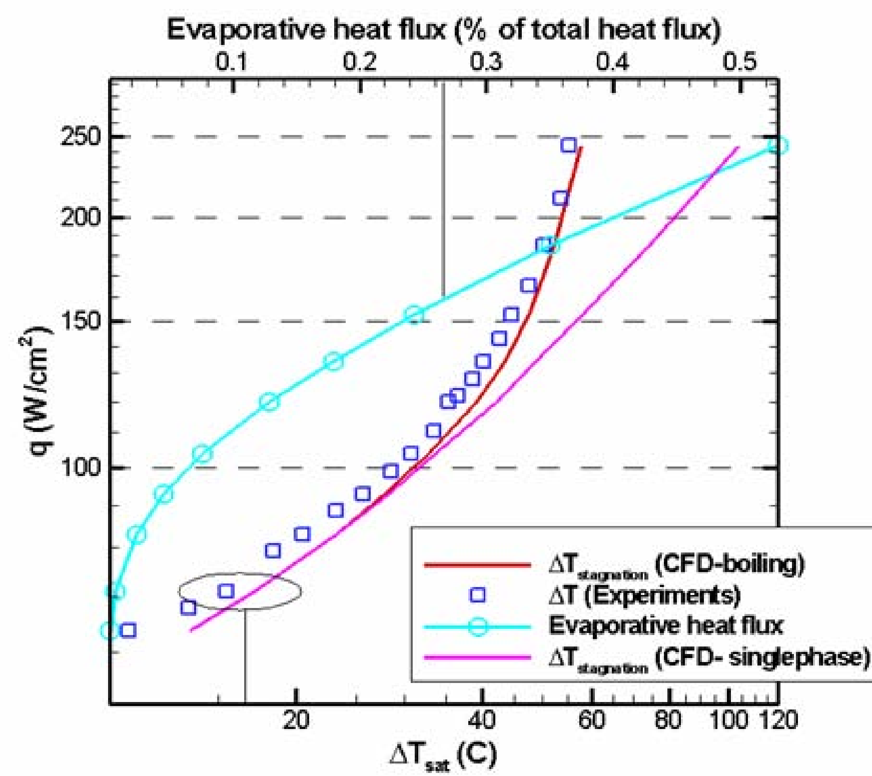


Technical Accomplishments FY08

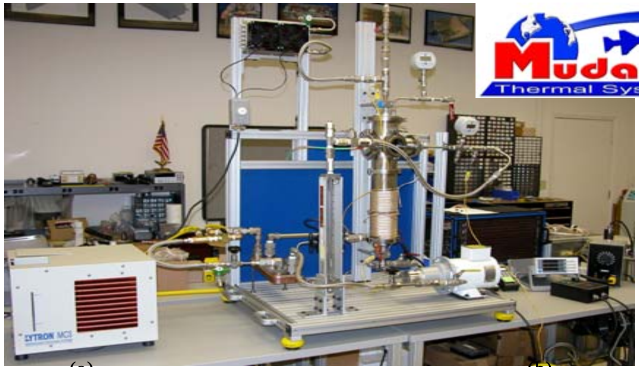
Two-phase Jet and Spray Cooling

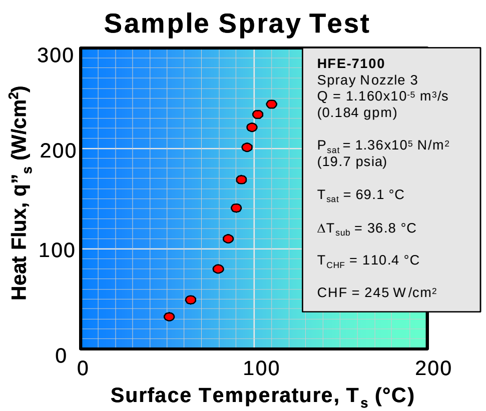
<u>Status</u>

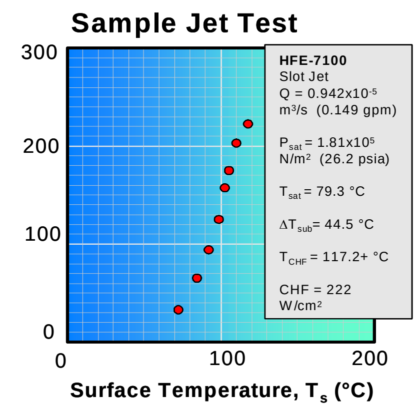
- Mudawar Thermal Systems has constructed the test apparatus for two-phase jet and spray cooling
- Nucleate boiling curves have been established for HFE-7100 using jets and sprays
- Demonstrated conditions with two-phase dielectric coolant that could achieve > 200 W/cm^2 heat flux while maintaining 125^o C chip temperature

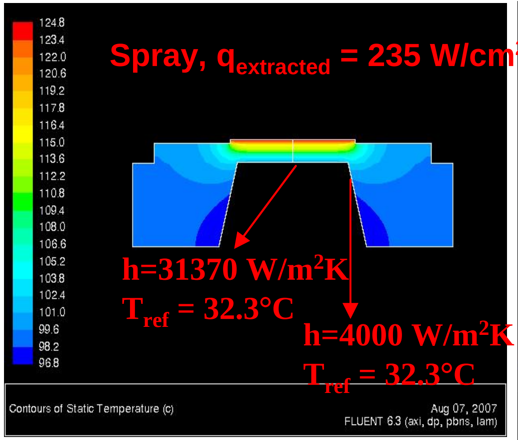
<u>Benefits</u>

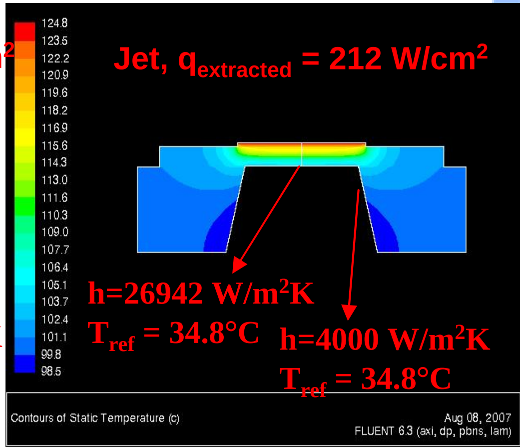
- Two-phase heat transfer provides an alternative means for achieving high heat flux requirements


(a) (b)









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 105ºC 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 a 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

Publications

- Narumanchi, S.V.J., Troshko, A., Hassani, V., and Bharathan, D., 2008, "Numerical simulations of nucleate boiling in impinging jets: applications in power electronics cooling", International Journal of Heat and Mass Transfer, Vol. 51, pp. 1-12.
- Narumanchi, S.V.J., et al., 2008, “Single phase self oscillating jets for enhanced heat transfer”, Proceedings of the Semitherm Conference, March 2008, San Jose, CA.
- Narumanchi, S.V.J., Bharathan, D., and Hassani, V., 2005, "Comparison of different single-phase liquid jet impingement cooling configurations in the context of thermal management in power electronics", Paper No. IPACK2005-73407, Proceedings of IPACK2005, San Francisco, CA.
- Narumanchi, S.V.J., 2007, “Jet and spray impingement for power electronics cooling applications”, NREL technical report, NREL/MR-540-36085, September 2007.
- Narumanchi, S.V.J., et al., 2006, “Modeling Two-Phase Spray and Jet Impingement Cooling”, NREL Technical/Milestone Report, NREL Report No. TP-540-40618.
- Narumanchi, S.V.J., Hassani, V., and Bharathan, D., 2005, "Modeling single phase and boiling liquid jet impingement cooling in power electronics", NREL Technical Report, NREL/TP-540 38787.

Presentations

- Abraham, T. (Nov. 2007), “Characterization and Development of Advanced Heat Transfer Technolgies”, FY08 Kickoff Presentation, National Transportation Research Center, Knoxville, TN.
- Narumanchi, S.V.J., 2006, “Modeling two-phase spray and jet impingement cooling/modeling”, 2006 DOE FreedomCAR APEEM Annual Review, Pollard Technology Conference Center, Oak Ridge, TN, August 16, 2006.

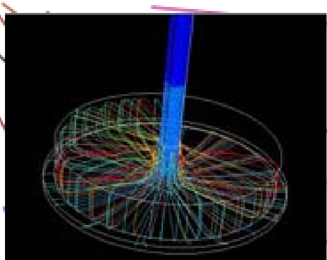
Patents

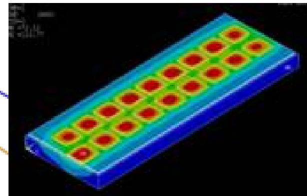
- Hassani, V., Vlahinos, A., Bharathan, D., 2007, “Low Thermal Resistance Power Module Assembly”, US Patent # 7190581, March 13, 2007.

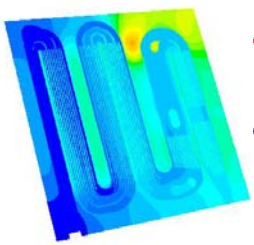
Questions

?

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

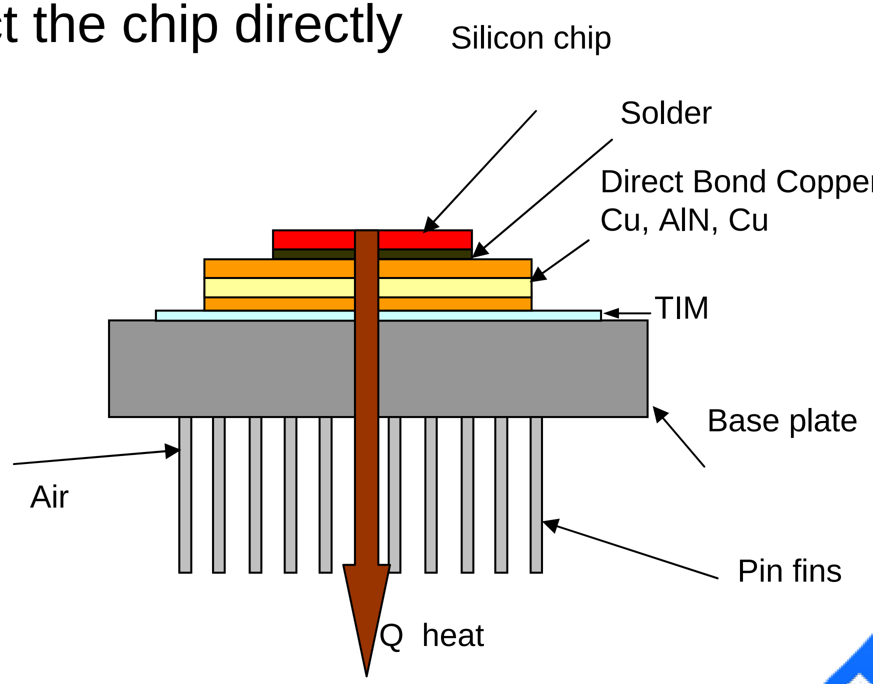
Advantages

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

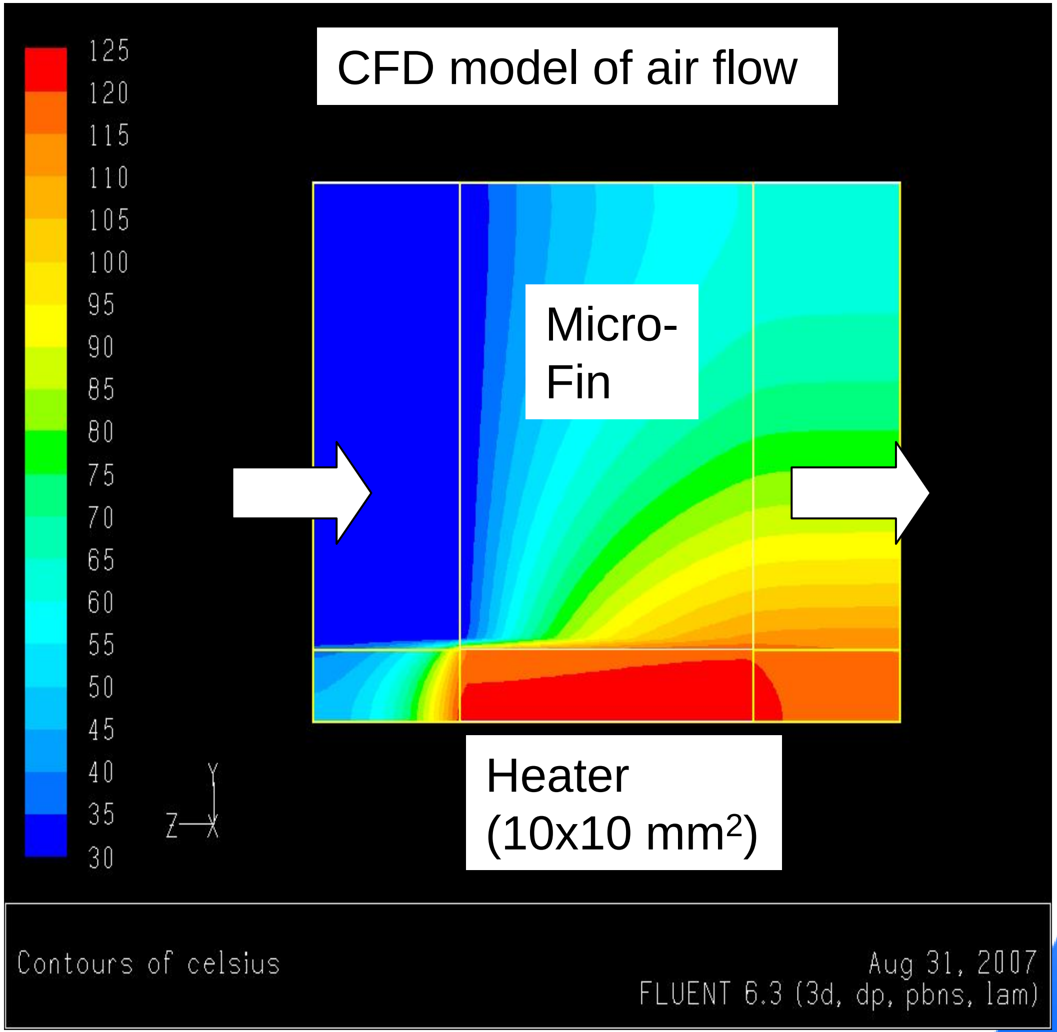
Response to Previous Reviewers' Comments

- **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/cm² 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.*

NREL

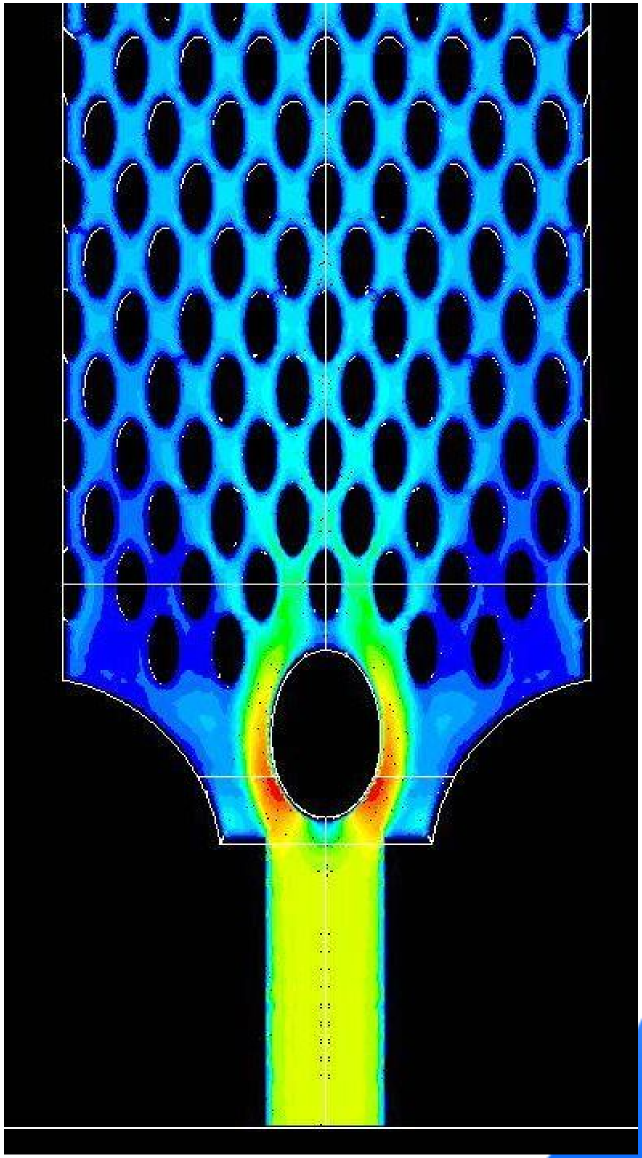
Project Objectives for FY08

- **Implement air cooling**
  - **demonstrate technology on a working inverter**
- **Validate models and design approach.**
- **Contribute to advanced PE development cooling options**
  - **meet programmatic goals.**



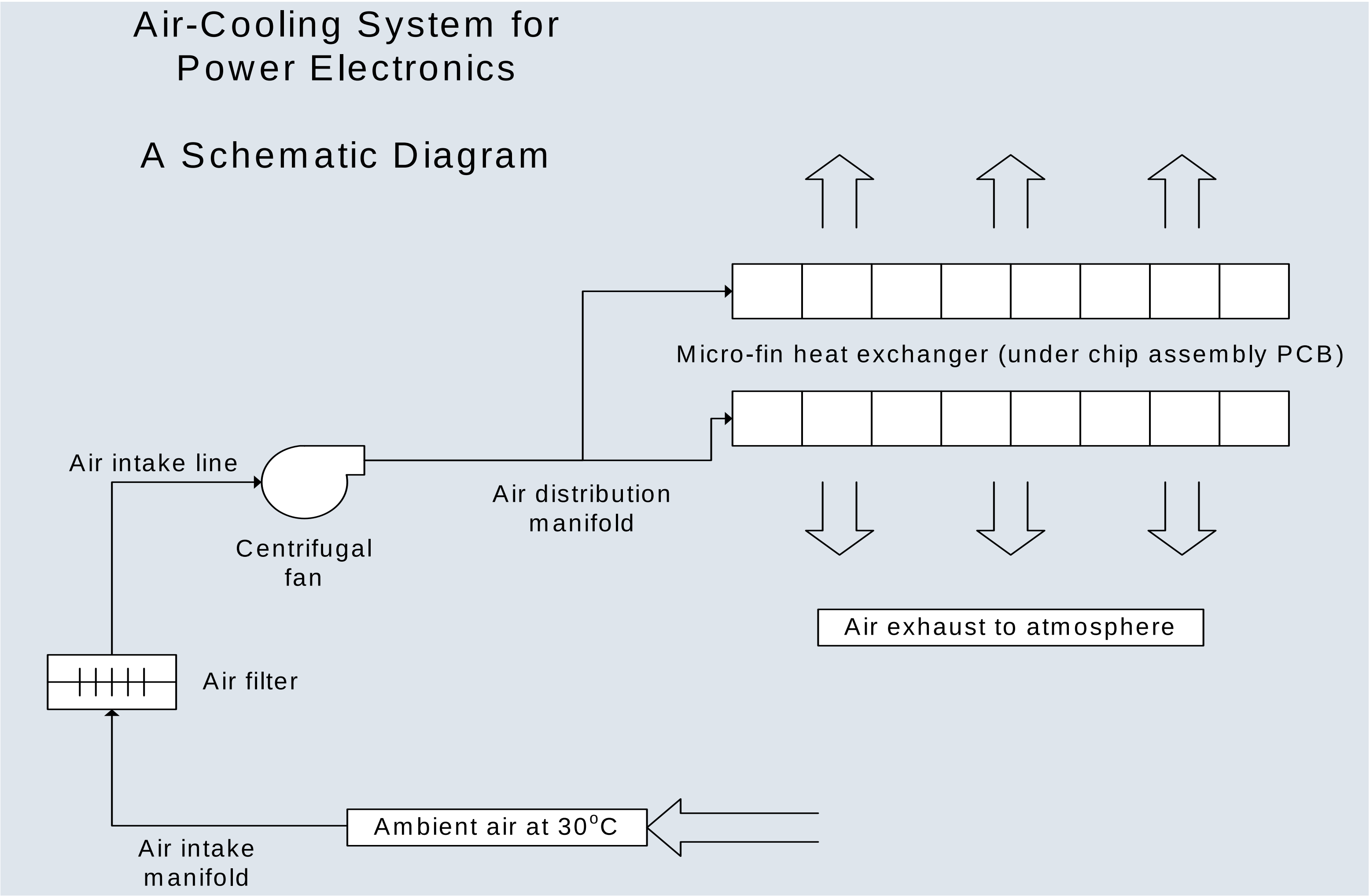
Technical Approach

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**
6. **Develop guidelines for performance estimation, cost, volume, weight, and other measures for industry.**
7. **Develop second iteration design and demonstrate air-cooling**



Accomplishments

Developed ASPEN System Model to Evaluate System Tradeoffs



Accomplishments

Developed Estimator Model to Evaluate Micro-fin Design Tradeoffs

Air-Cooled Micro-Fin Array Analysis - NREL

Calculated Results | Geometry Details | Method | About

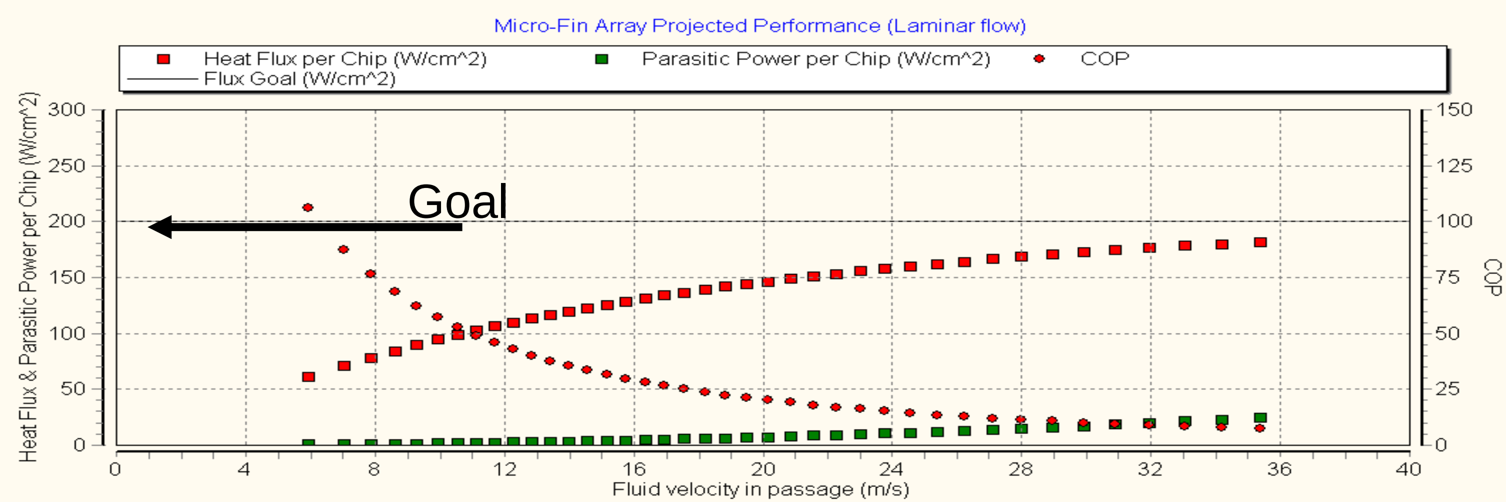
Fluid Passage Width W (micro-m): 130
Fin Thickness-to-Width ratio (t/W)(%): 50
Fin Height-to-Width ratio (H/W): 100
Base Plate thickness (tb) (micro-m): 2000
Pump/Compressor Efficiency = 70% (assumed);
Select Fin Material: Copper
Select Fluid: Air---------(T-in=30oC)
Base Plate Temperature (oC): 125

Stop

Calculated Results

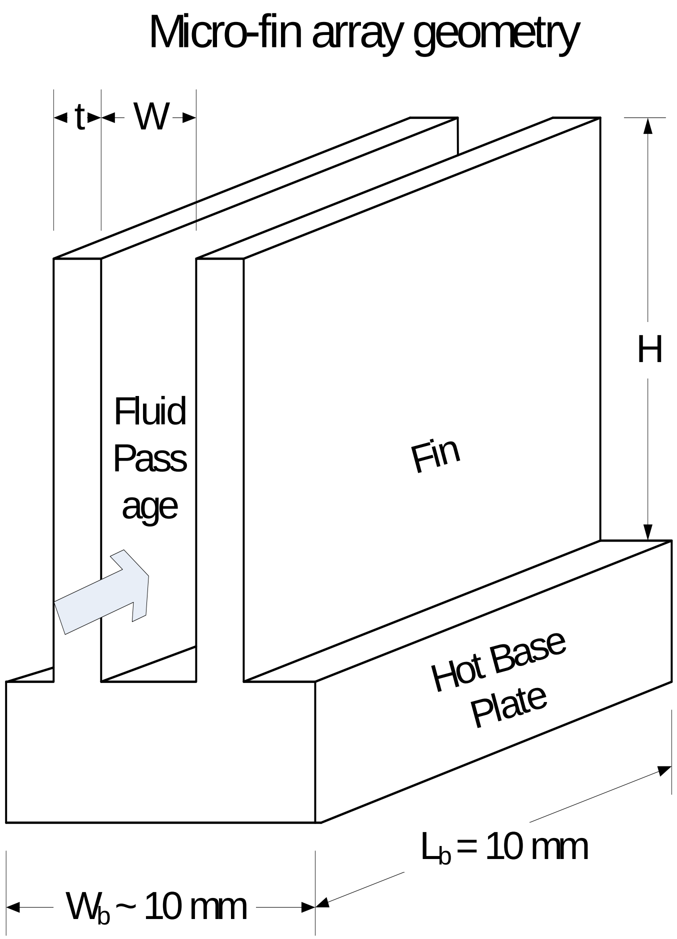
Copper---Air--- Bottom Chip Temperature --- 125.00 oC.

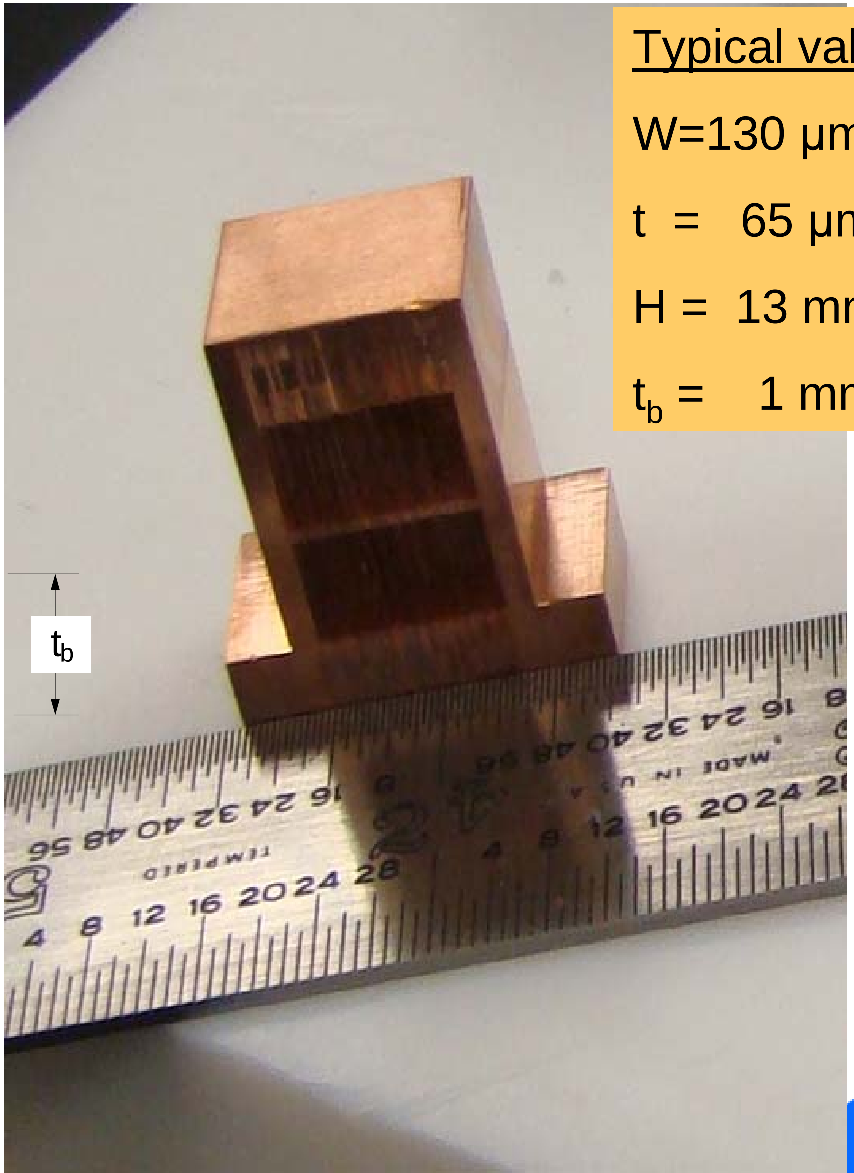
Para-meter (Units)	Velo-city (m/s)	T_plate Top (oC)	Fluid Out T (oC)	Appr-oach T (oC)	LMTD LMTD (oC)	Heat Flux (W/cm^2)	COP COP (W/W)
Output-	5.96	121.86	120.86	1.00	20.10	61.01	106
Output-	7.05	121.35	119.35	2.00	23.38	70.97	87
Output-	7.89	120.97	117.97	3.00	25.78	78.26	76
Output-	8.63	120.66	116.66	4.00	27.77	84.29	68
Output-	9.30	120.39	115.39	5.00	29.50	89.54	62
Output-	9.94	120.15	114.15	6.00	31.05	94.26	57
Output-	10.55	119.92	112.92	7.00	32.48	98.59	53
Output-	11.14	119.72	111.72	8.00	33.81	102.62	49
Output-	11.72	119.52	110.52	9.00	35.05	106.40	46
Output-	12.30	119.34	109.34	10.00	36.23	109.98	43
Output-	12.87	119.16	108.16	11.00	37.35	113.38	40



Accomplishments

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





Typical values are:

W=130 μm

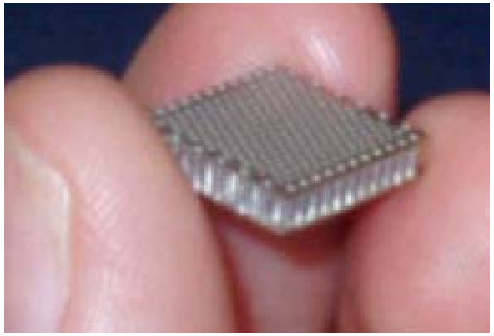
t = 65 μm

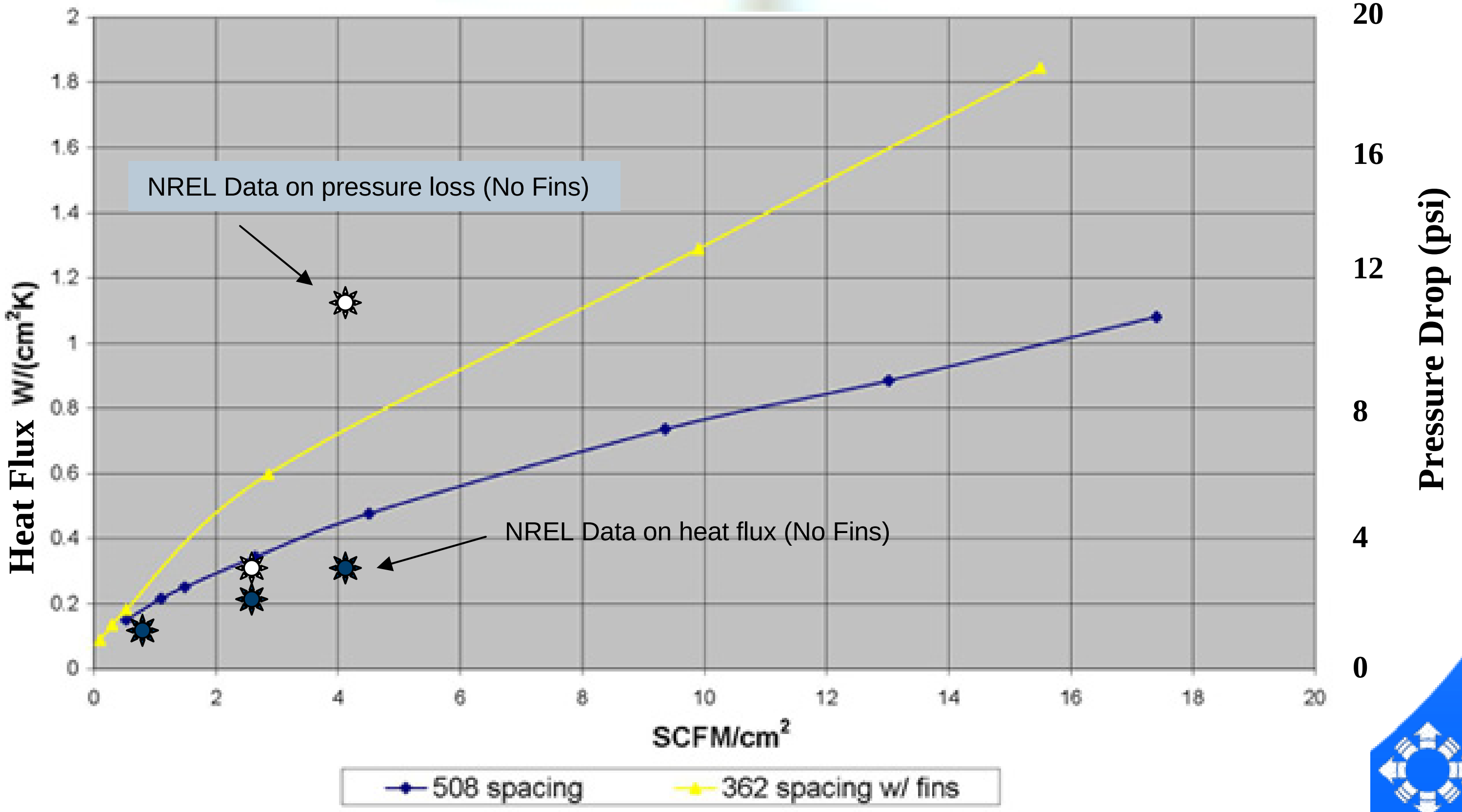
H = 13 mm and

t_b = 1 mm

Accomplishments

Experimental Evaluation of vendor heat exchanger





Accomplishments

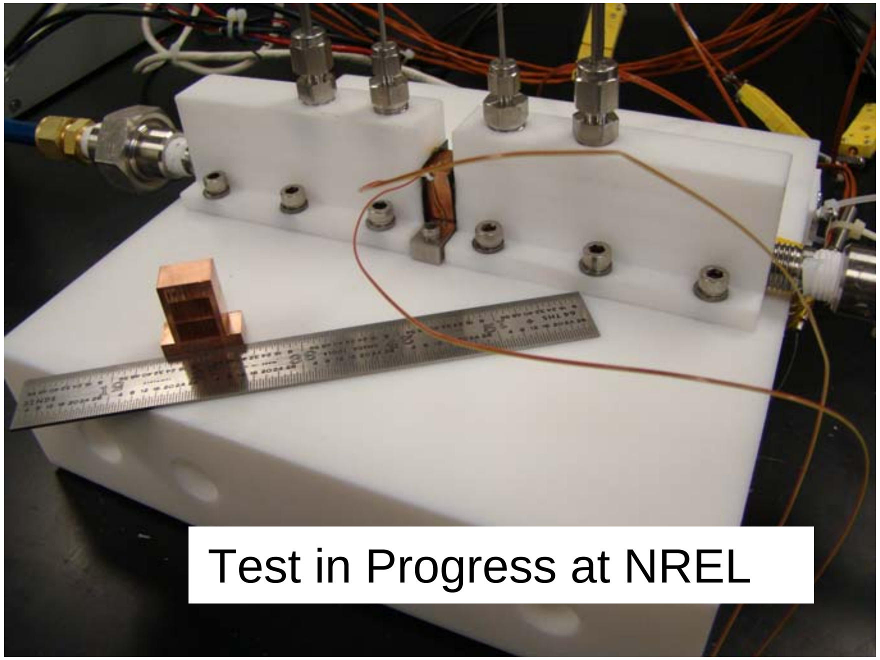
Models show that:

• 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.

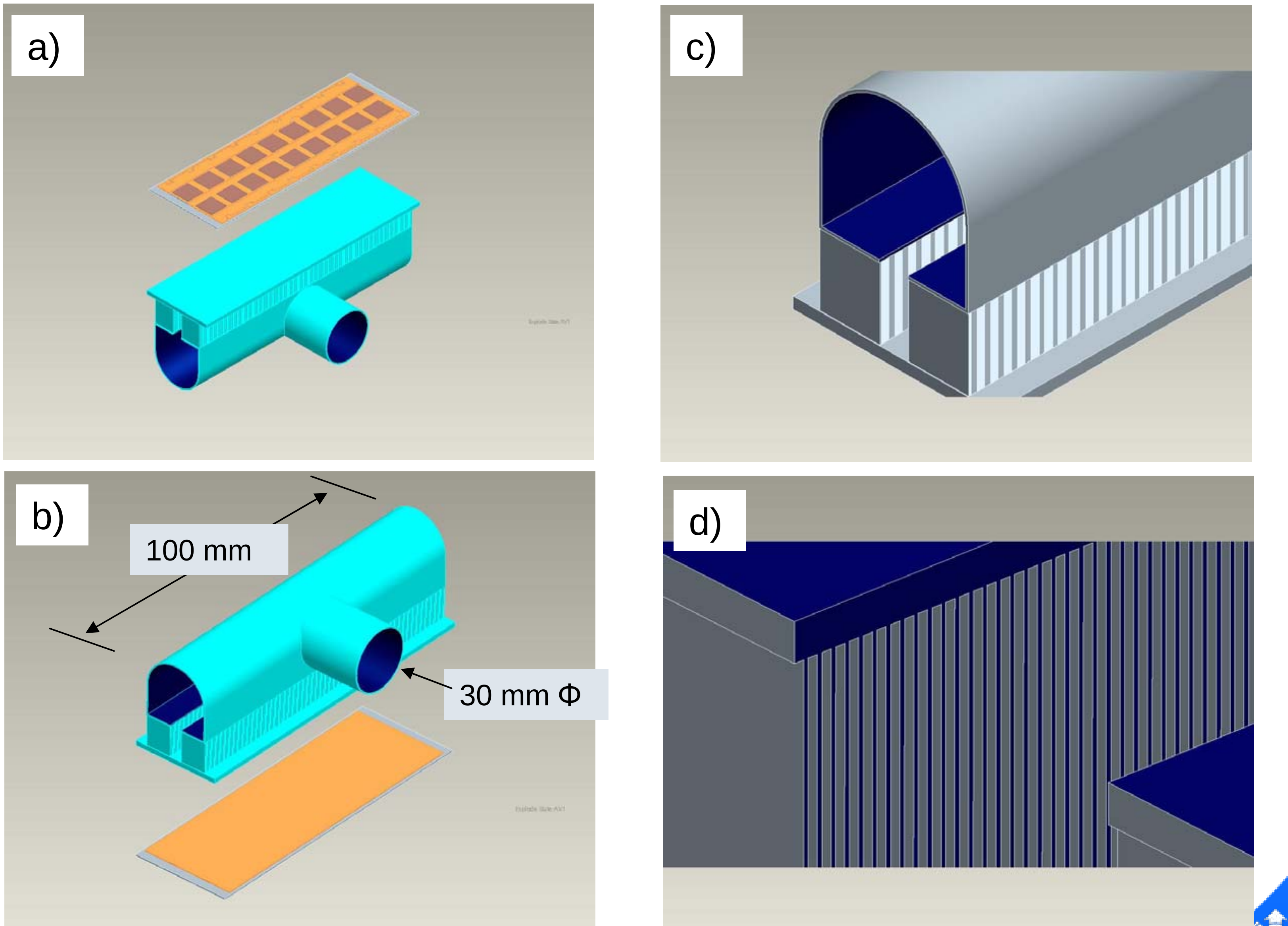
Comparison with the use of an intermediate liquid cooling loop indicate that:

• Air cooling is simple, less costly, and reliable.

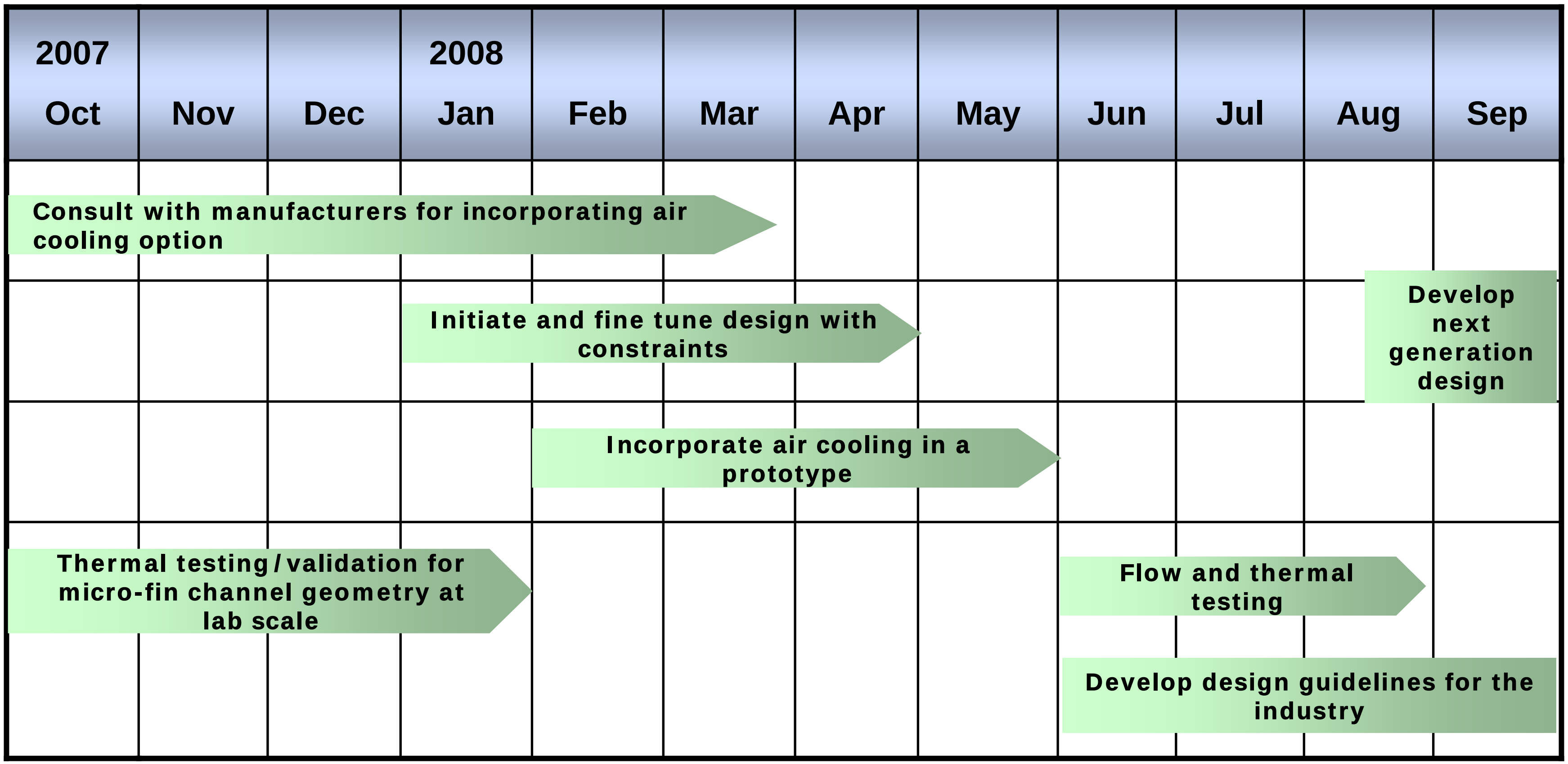


Test in Progress at NREL

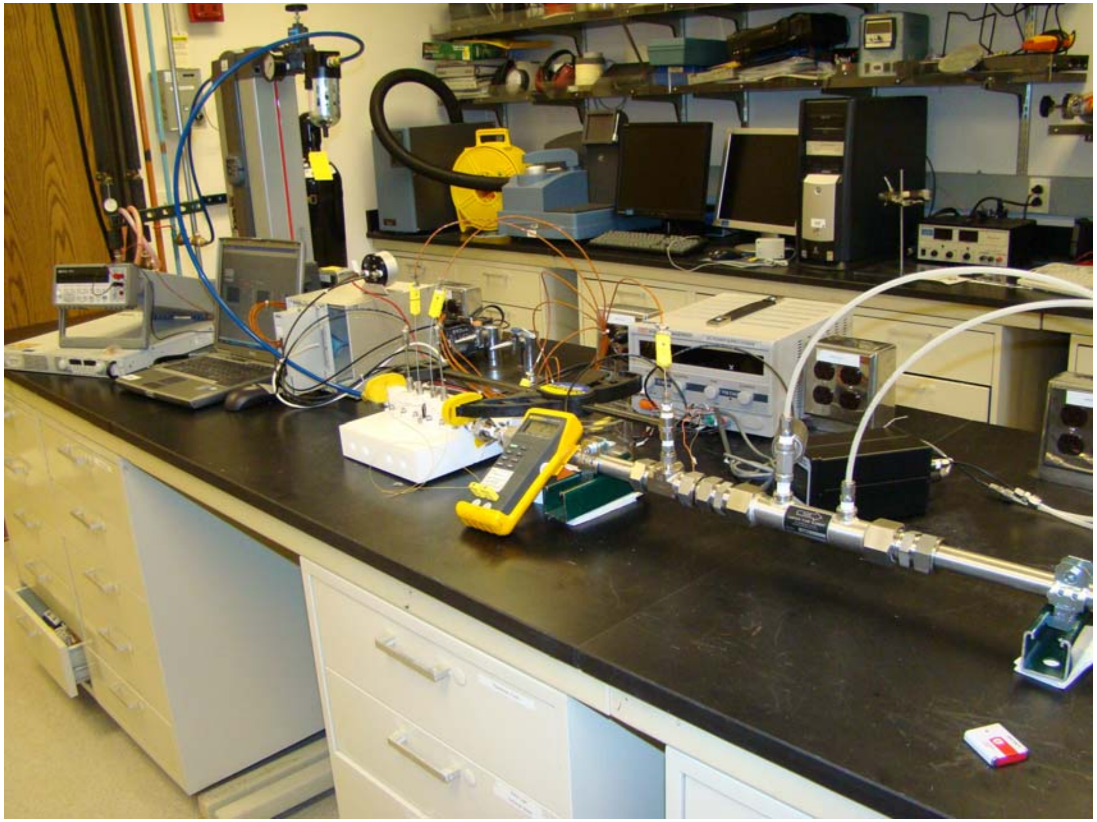
Accomplishments



Timeline

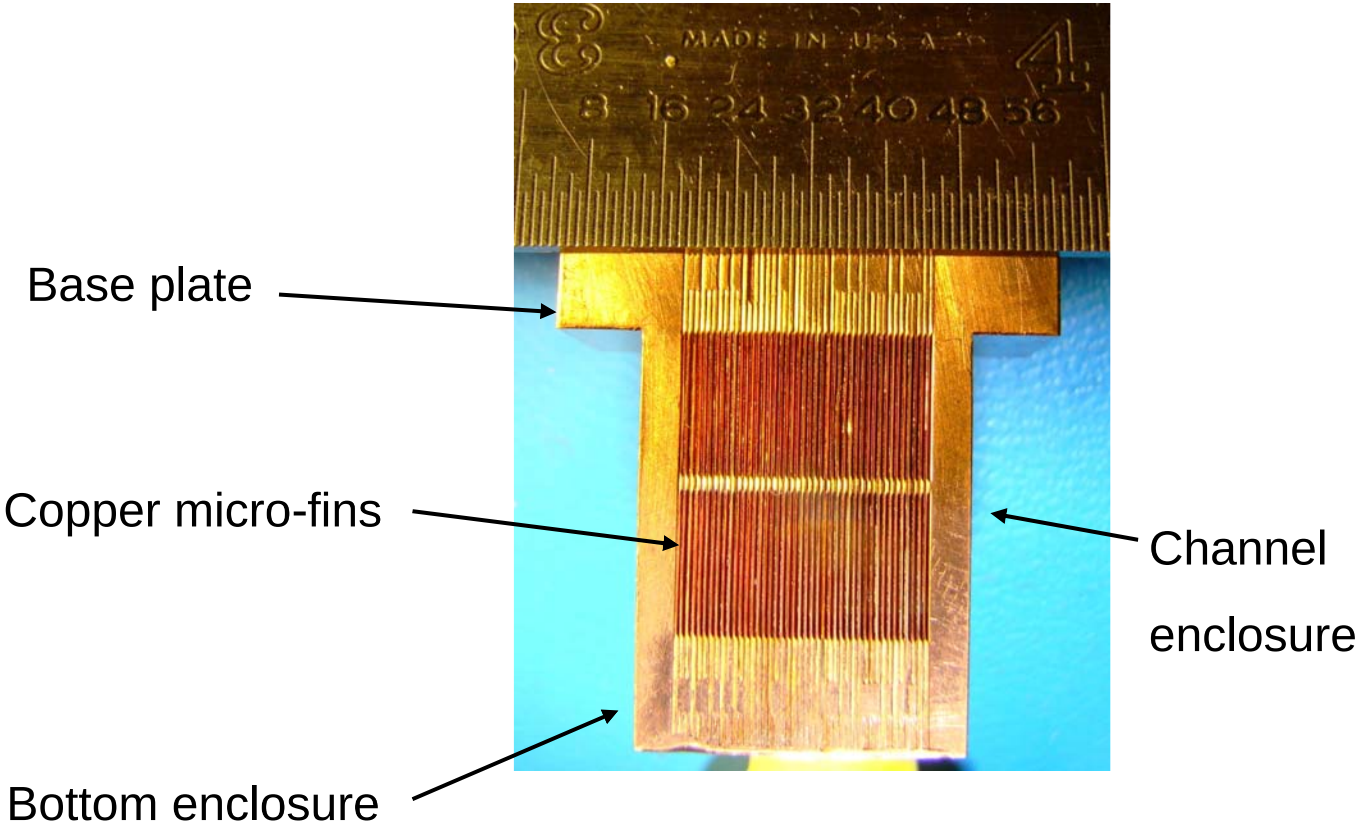

2007
Oct
Nov
Dec
2008
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Consult with manufacturers for incorporating air cooling option
Initiate and fine tune design with constraints
Develop next generation design
Incorporate air cooling in a prototype
Thermal testing / validation for micro-fin channel geometry at lab scale
Flow and thermal testing
Develop design guidelines for the industry

Beyond FY08 -- Integrate the developed thermal control technology with reliability tasks based on a systems level approach

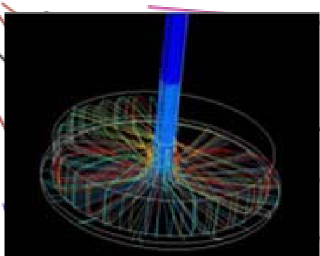


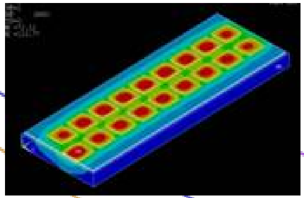
- Analyze pulsed systems to power
- Generate a design tool for air cooling
  - Provide industry with an easy-to-use tool to evaluate all aspects of performance and specifications.

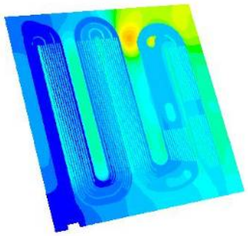
Questions


MADE IN U.S.A.
4
8 16 24 32 40 48 56
Base plate
Copper micro-fins
Channel
enclosure
Bottom enclosure

Power Electronic Thermal System Performance and Integration







Principal Investigator: Kevin Bennion

Agreement: 13298

Project Duration: FY06 – FY10
FY08 Funding: $280k

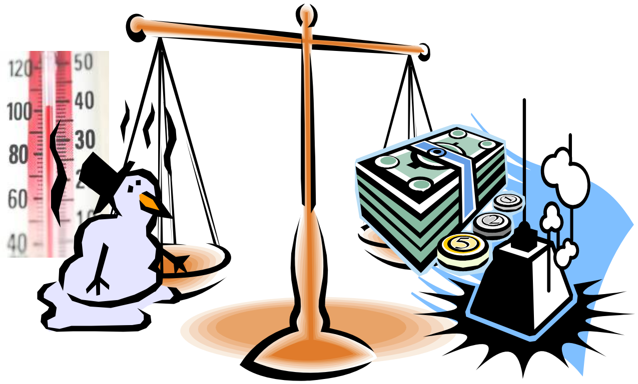
DOE Vehicle Technologies Program
Overview of DOE VTP APEEM R&D

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.

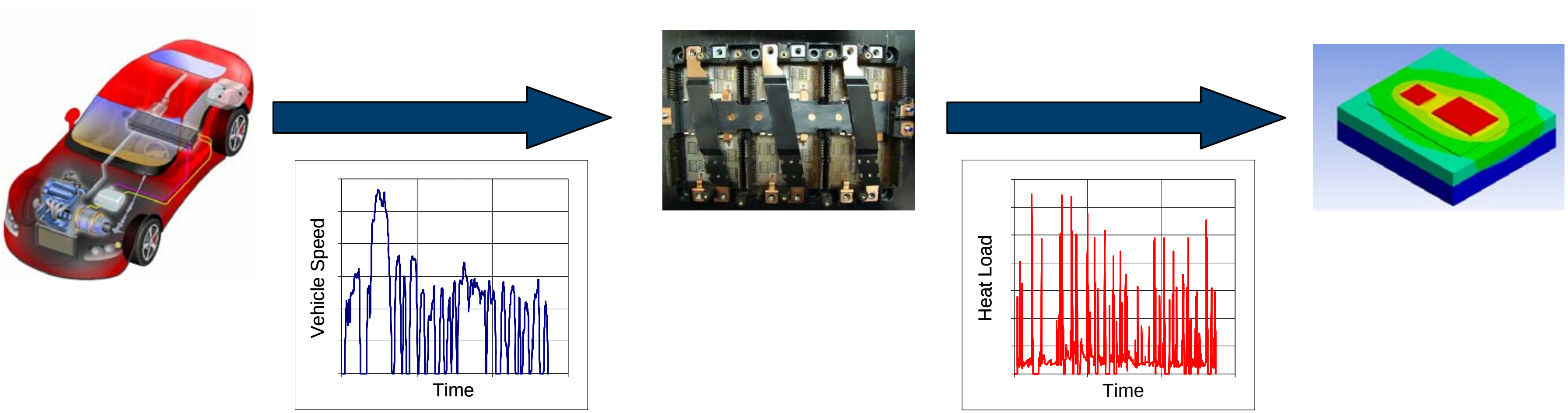
- **What are viable system design directions?**
- **What analysis tools can speed up R&D evaluations?**

How close are breakthrough technologies to meeting system targets?

NREL

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.

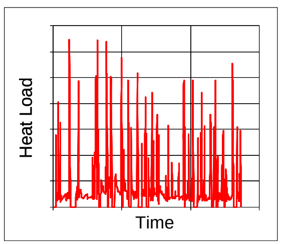


- **Comment: "Need experimental data for validation"**
  - We are leveraging data available from other tasks, labs, and principle investigators.

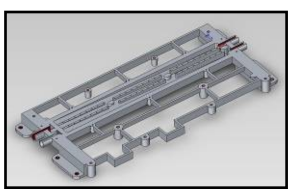
Barriers

- System thermal performance is a multi-dimensional problem.

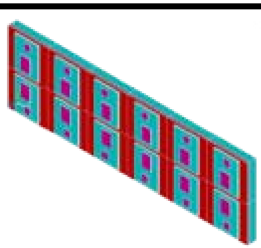
Vehicle Type
HEV/PHEV
FCV



Component Use
Peak
Continuous
Dynamic



Cooling System
Coolant Temperature
Convection Coefficient
Heat Exchanger Effectiveness

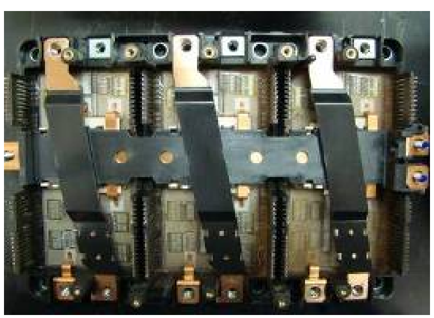


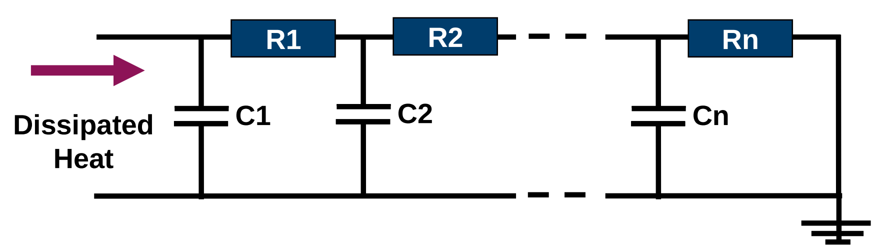
PE Package
Topology
Materials

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.

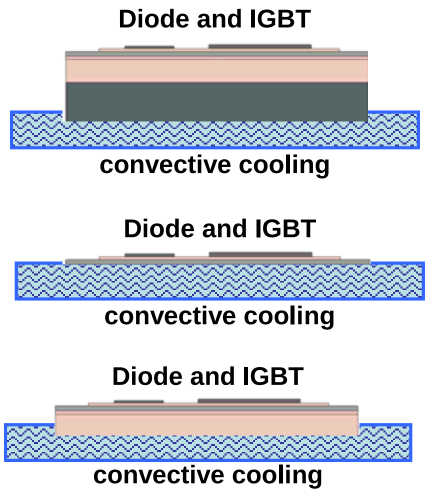


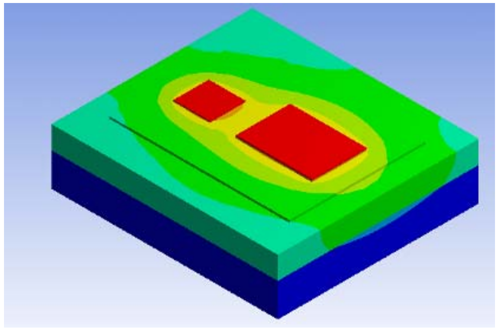


Technical Approach for FY08

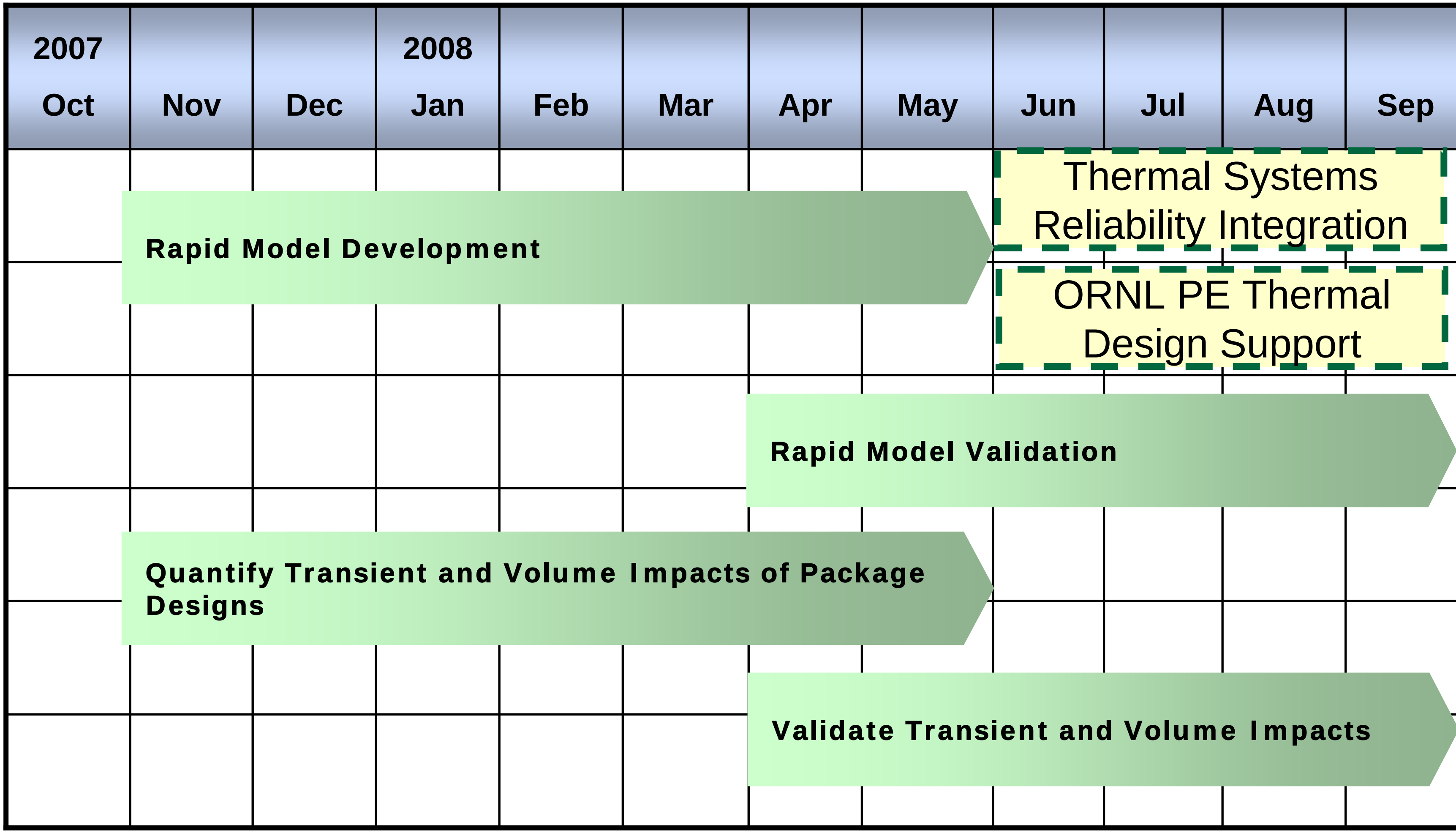
2) <u>Power Electronics Thermal Control and Packaging Tradeoffs</u>

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



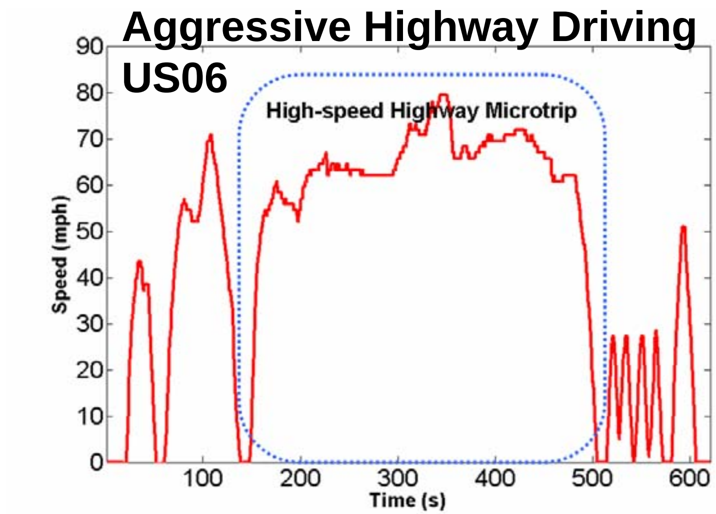


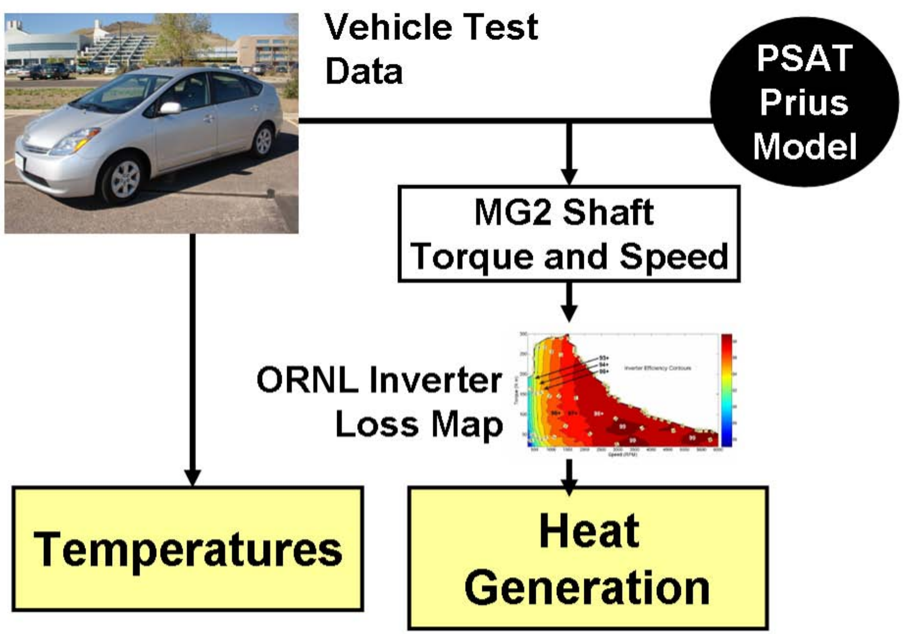
Timeline for FY08

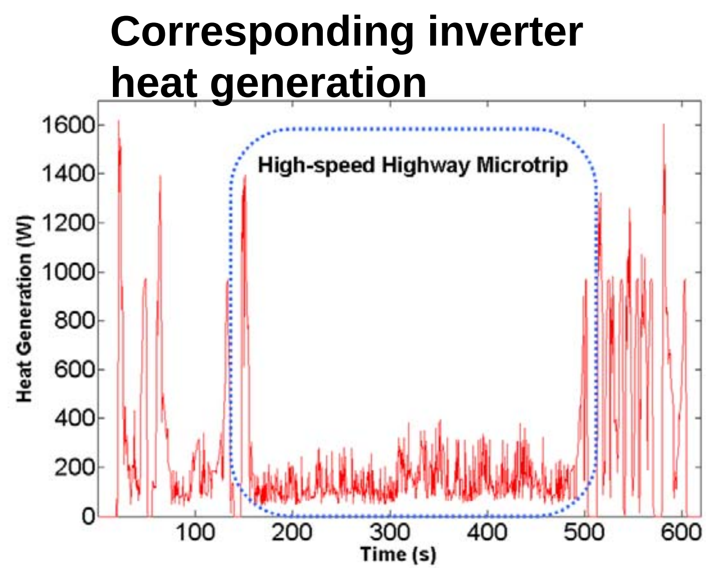


Accomplishments

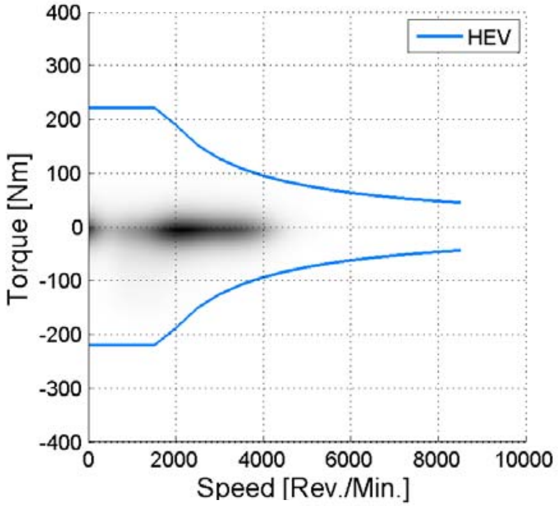
- Evaluated thermal duty cycle for Toyota Prius motor inverter.
  - Vehicle Test Data.
  - Vehicle Systems Analysis PSAT Model.
  - ORNL Benchmark Data.
- Transient heat loads are significantly higher than average heat load.

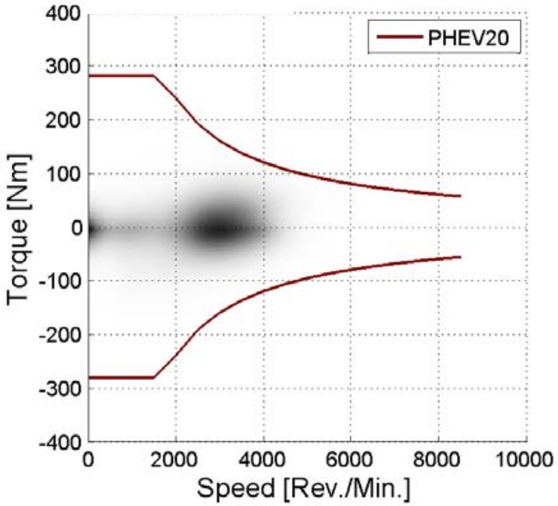




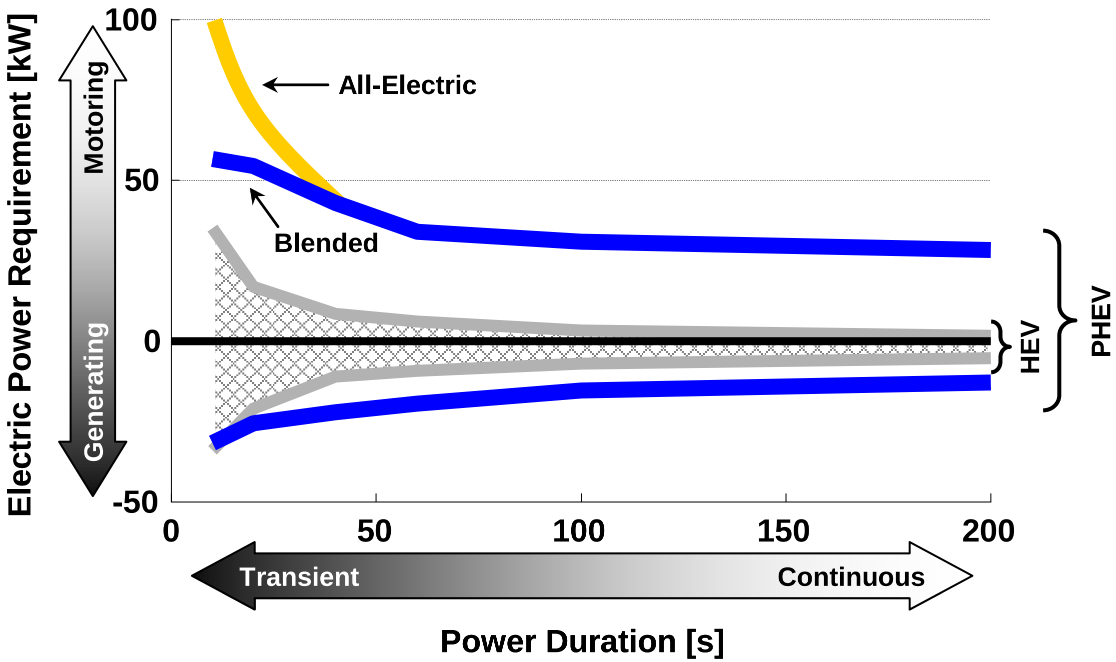


Accomplishments





- 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.

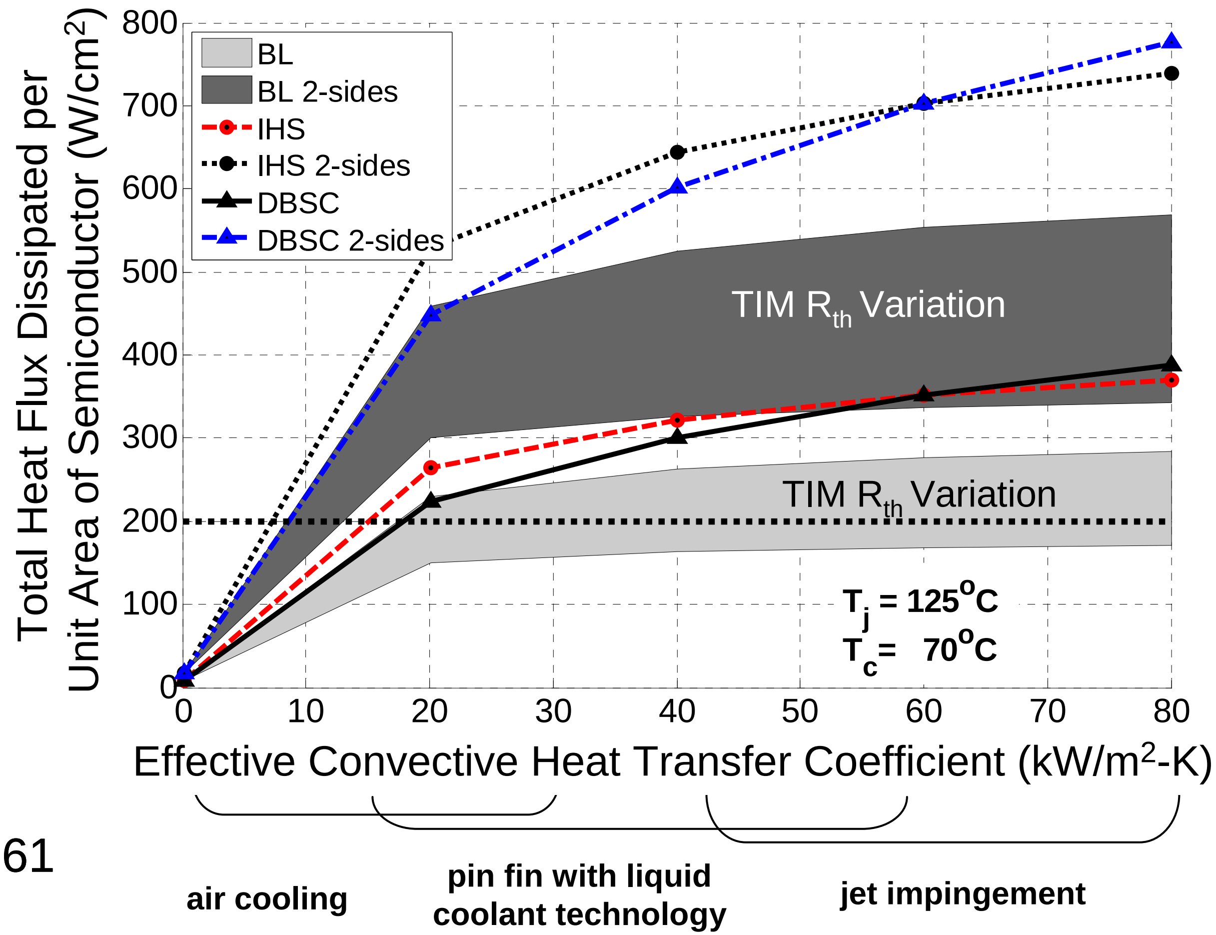


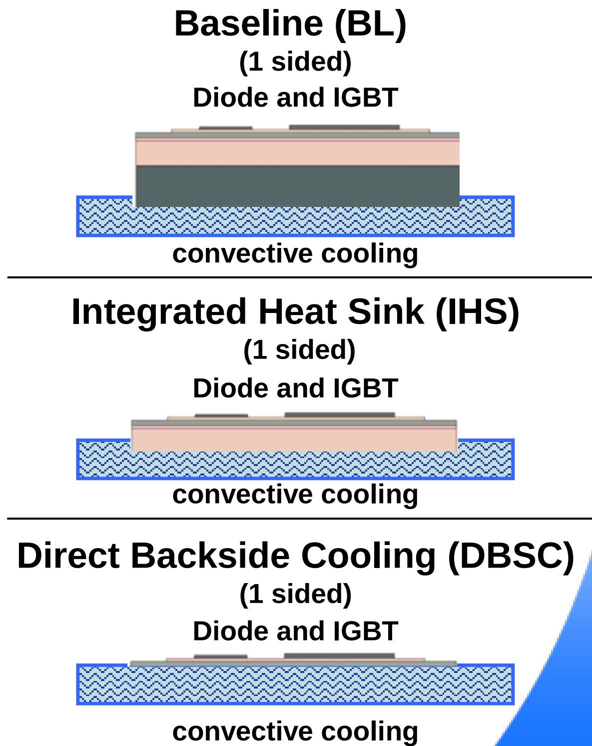
1) J. Gonder, T. Markel, A. Simpson, and M. Thornton, "Using GPS Travel Data to Assess the Real World Driving Energy Use of Plug-In Hybrid Electric Vehicles (PHEVs)," presented at the Transportation Research Board (TRB) 86th Annual Meeting, Washington, D.C. , Jan. 21-25, 2007.

Accomplishments

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

Packages: TIM, Integrated Heat Sink, Direct Backside Cooling, Double Sided.
Thermal: Fins, Jet Impingement, Air, TIM, Coolant Temperatures, Junction Temperatures.



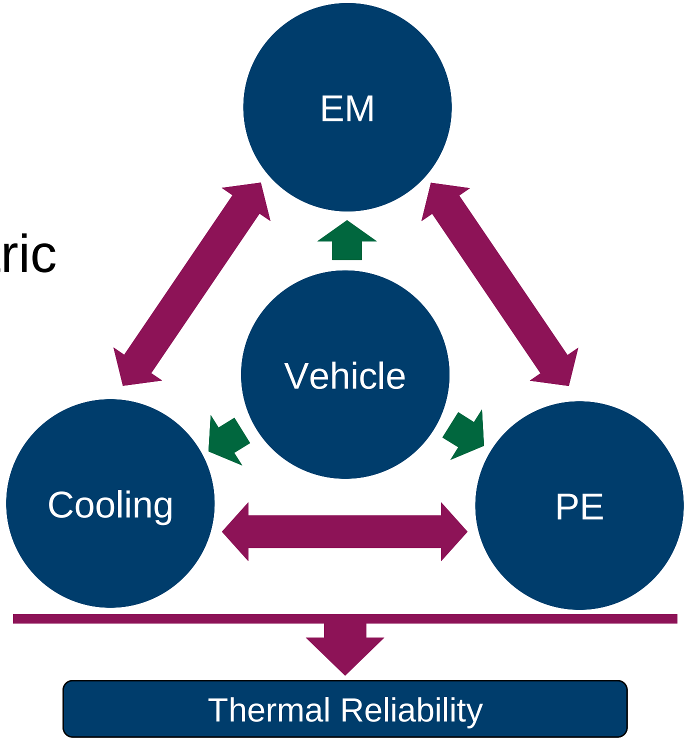


Technology Transfer

- **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.

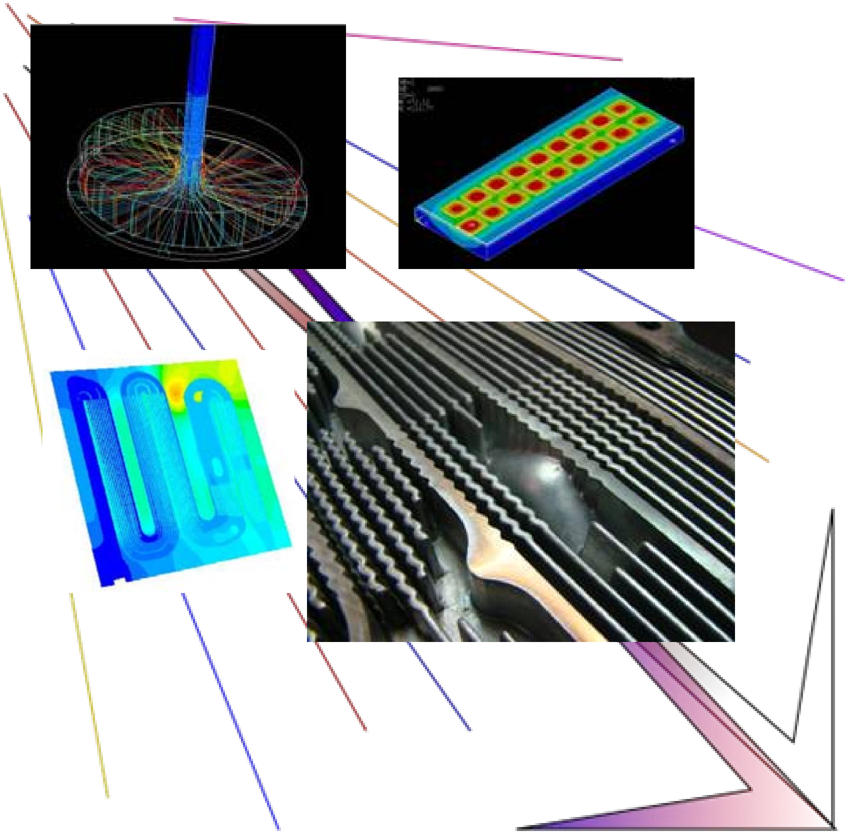
Publications, Presentations, Patents

- M. O'Keefe, G. Albright, K. Bennion, "HEV Inverter Thermal Duty Cycles," Milestone Report, June, 2007.
- M. O'Keefe, K. Bennion, "Comparison of Hybrid Electric Vehicle Power Electronics Cooling Options," in Vehicle Power and Propulsion Conference, Arlington, TX, Sept., 2007.
- K. Bennion, "Plug-In Hybrid Electric Vehicle Impacts on Power electronics and Electric Machines," presentation to EETT, Detroit, MI, Oct., 2007.
- K. Bennion, "Power Electronic Thermal System Performance and Integration," FY08 Kickoff Presentation, National Transportation Research Center, Knoxville, TN, Nov., 2007.
- K. Kelly, T. Abraham, K. Bennion, D. Bharathan, S. Narumanchi, M. O'Keefe, "Assessment of Thermal Control Technologies for Cooling Electric Vehicle Power Electronics", in 23rd International Electric Vehicle Symposium (EVS-23), Anaheim, CA, Dec., 2007.

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

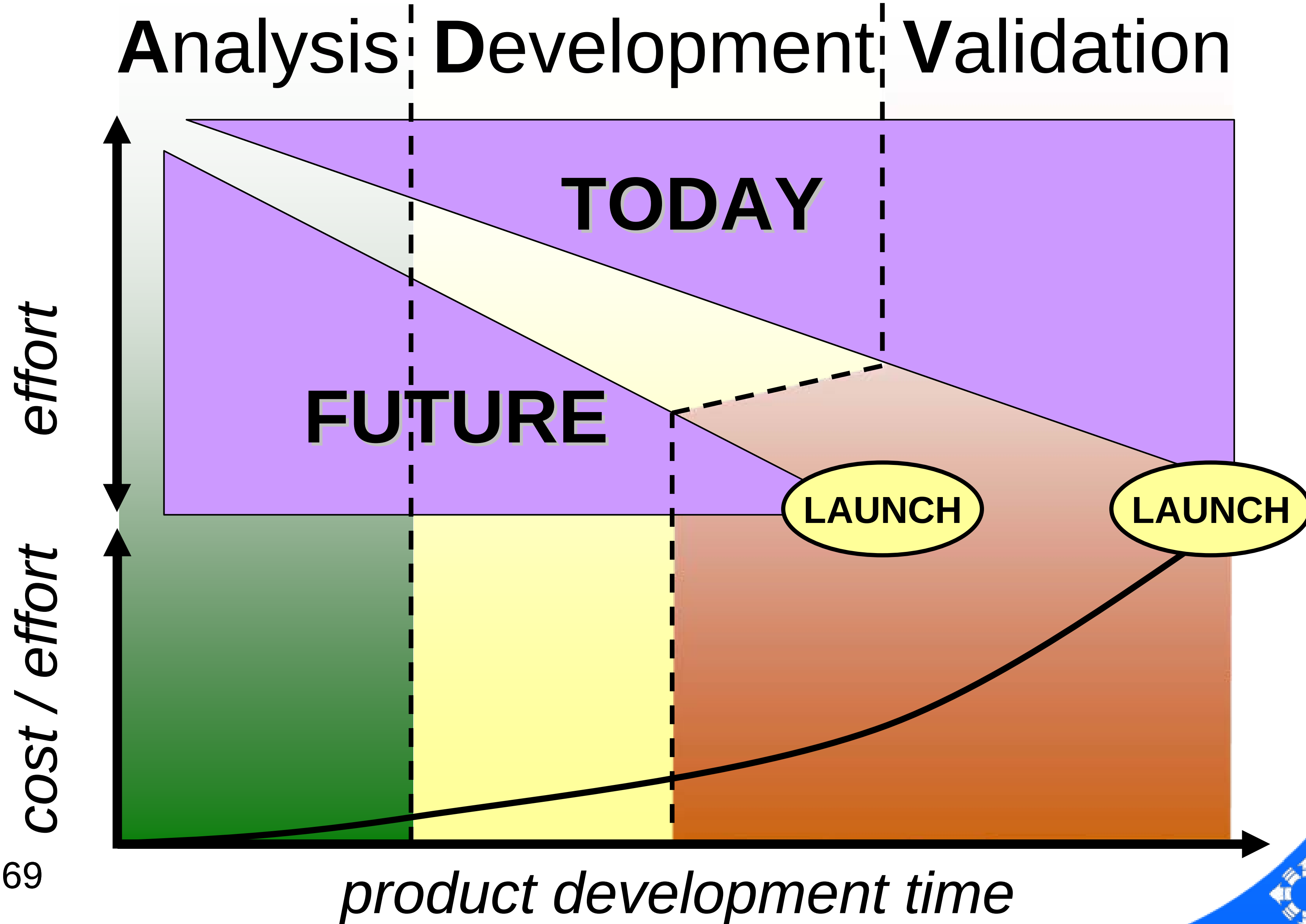
North Marriott Hotel and Conference Center
Bethesda, Maryland

February 28, 2008

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



The Challenges/Barriers

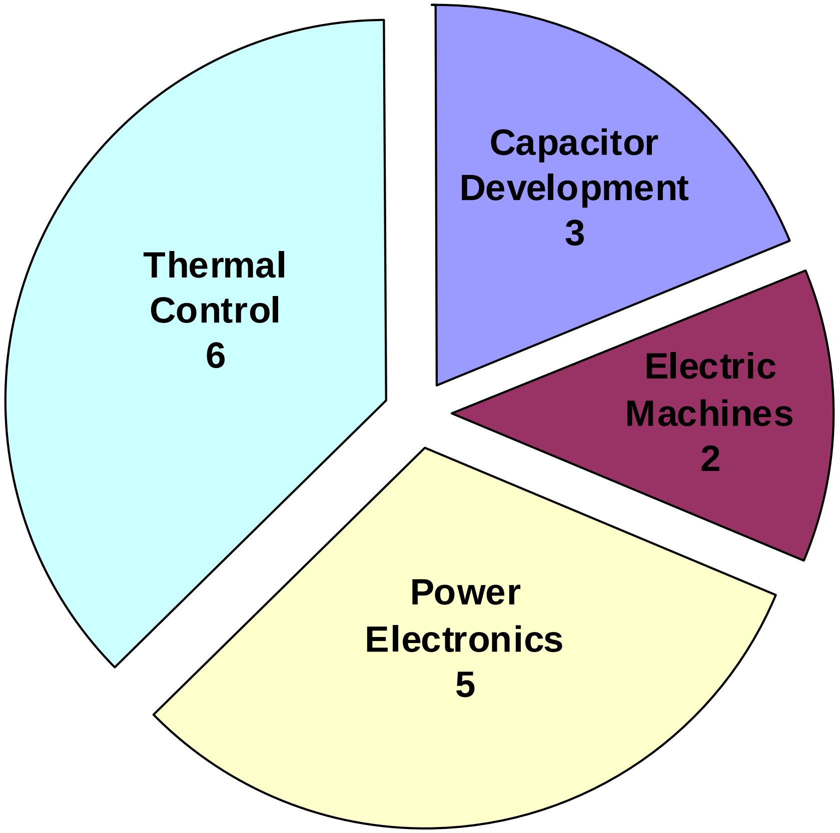
- **Integration and coordination of various engineering software tools**
- **Validation of models (availability of data)**
- **Complexity of problem**
- **Validation of predictions**

Reviewer comments

New project in FY08

Suggested by industry partners

Allows DOE to assess reliability targets



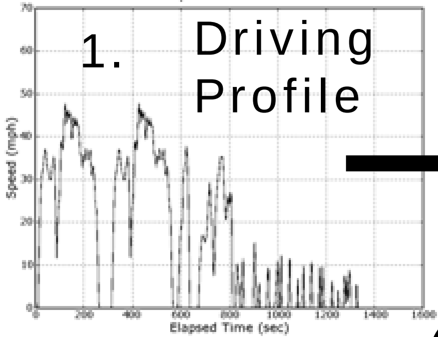
2006 APEEM Reviewer Comments that mention "Reliability"

Approach

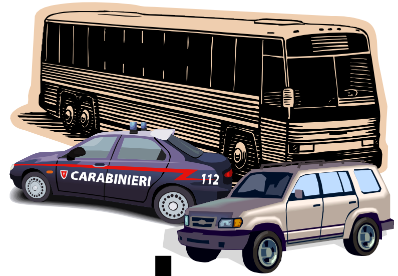
- **Develop critical areas not currently being addressed**
- **Integrate, leverage, and coordinate**
  - **testing at ORNL, ANL, and INL**
  - **thermal modeling at NREL**
  - **national physics of failure expertise**
  - **knowledge and data from automotive OEMs and suppliers**
- **Impacts**
  - **Assess 15 year life target for DOE R&D**
  - **Empower researchers to consider life/ reliability earlier in the design cycle**

Approach

1. Driving Profile



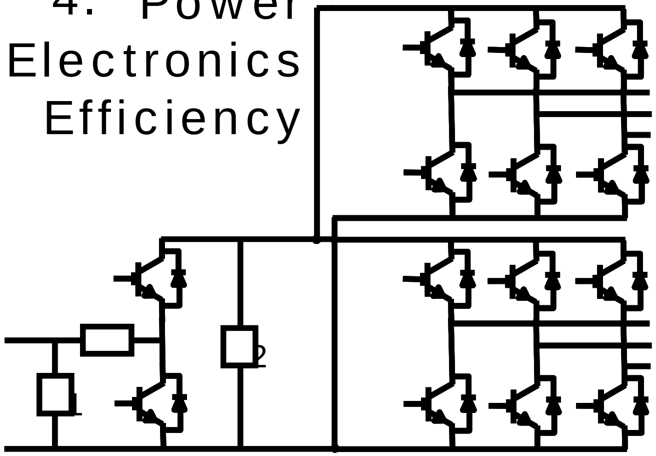
2. Vehicle Level Model



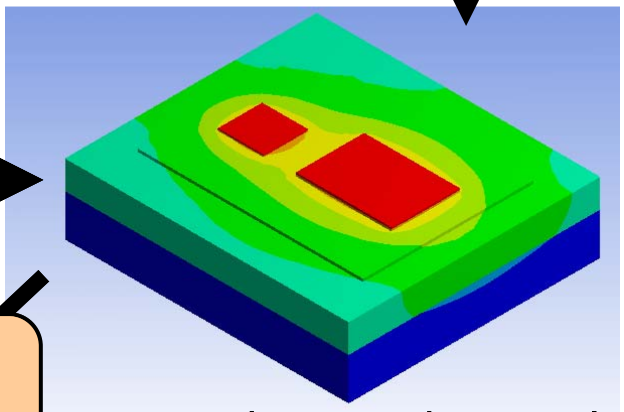
Power Electronics USAGE Profile (Duty Cycle)

3. Power Module Package/Circuit Design

4. Power Electronics Efficiency



Heat Generation



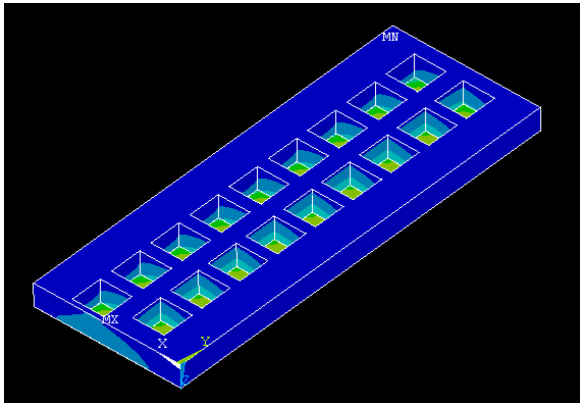
5. Package Thermal Models (FEA)

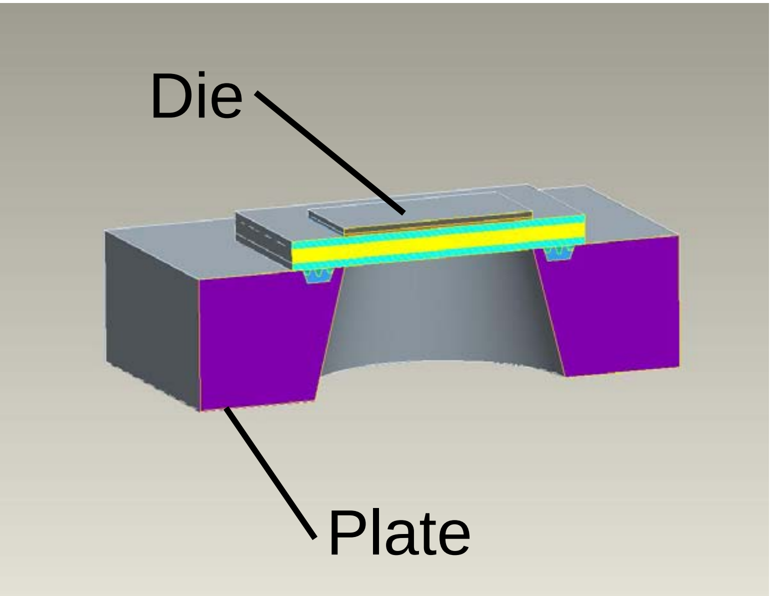
Stress & Temperatures

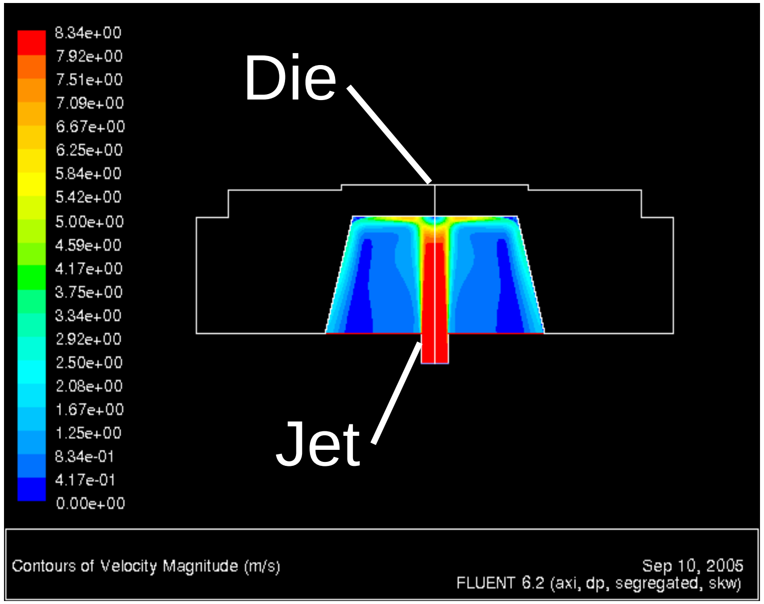
6. Physics of Failure Models & Analysis

Approach

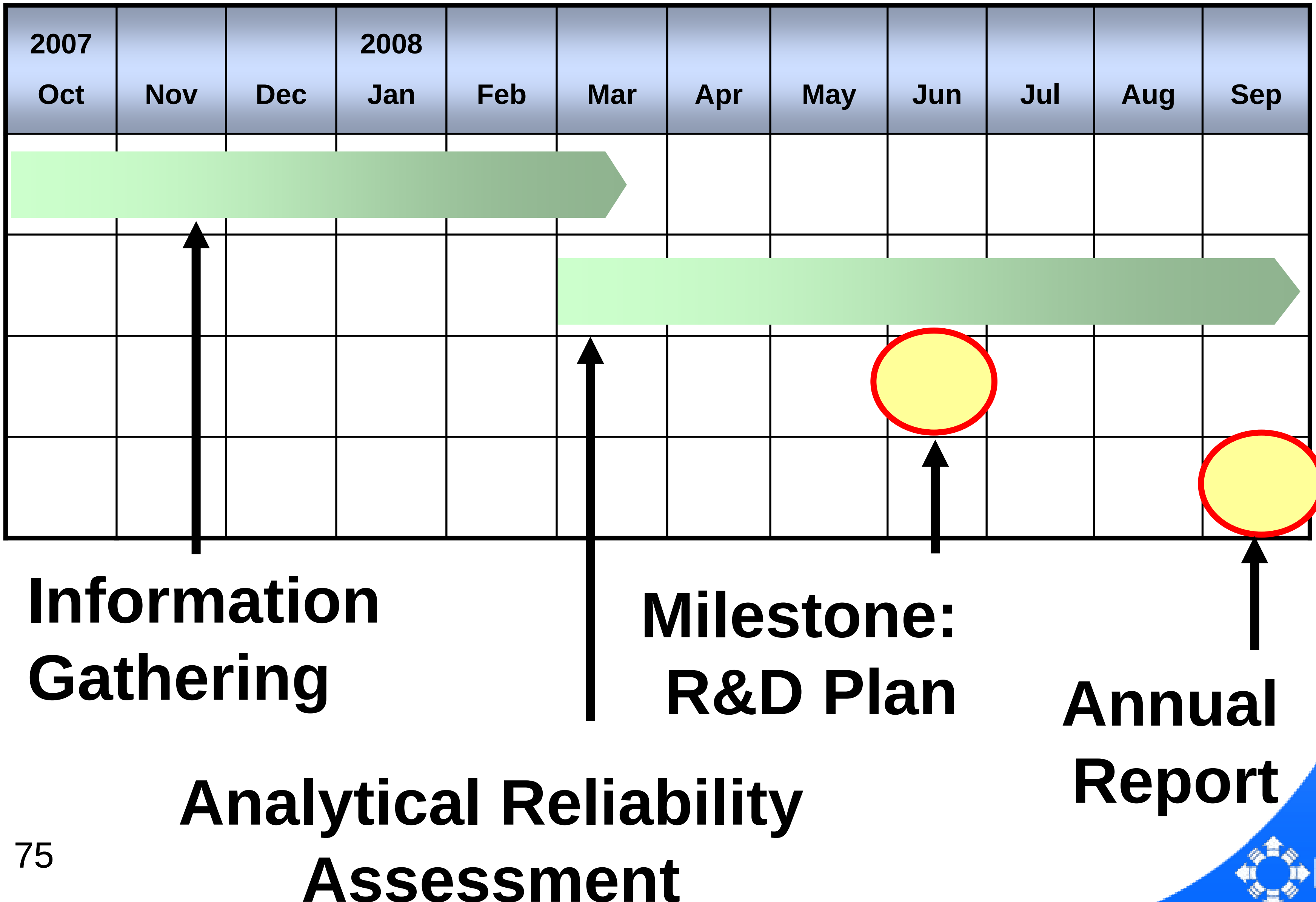
Assess reliability implications of existing DOE projects







Timeline for FY08



Technical Accomplishments

- **We've spoken to/ met with many experts**

Maxwell Tech.

US Navy

University of Maryland CALCE

Virginia Tech CPES

DfR Solutions

Ford

Delphi

GM

ASTR 2007 Workshop

US Air Force

Hobbs Engineering HALT/HASS Training

BAE Systems

Reliability Information Analysis Center

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**

Publications, Presentations, Patents

- **O'Keefe, M. (Nov 2007). "PEEM Thermal Stress and Reliability", FY08 Kickoff Presentation, National Transportation Research Center, Knoxville, TN.**
  - **http://www.nrel.gov/vehiclesandfuels/powerelectronics/pdfs/42341.pdf**

Questions

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