NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Air Cooling Technology for Advanced Power Electronics and Electric Machines

U.S. Department of Energy Annual Merit Review

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NREL/PR-540-45785 **APE-12**

Overview

Timeline

- Project start date: FY06
- Project end date: FY12
- Percent complete: 40%

Barriers

- 15 year life requirement
- High parasitic power
- ***Larger volume***

Budget

- Total project funding
  - DOE share: $1350k
  - Contractor share: $0.00
- FY08 Funding: $350k
- FY09 Funding: $350k

Partners

- Interactions
  - FreedomCAR Electrical & Electronics Technical Team
  - Delphi, PowerEx, Semikron
- Project lead: NREL

Project Objectives

- 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.
- Enable heat rejection directly to the sink, namely, ambient air. Simplify the system.
- Maintain die temperature below specified operating limits to assure long-term reliability.

Project Milestones

FY2008

- **Milestone:** Conduct tests with prototype test articles and validate CFD models – Submit a report on findings

AN ASSESSMENT OF AIR COOLING FOR USE WITH AUTOMOTIVE POWER ELECTRONICS

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FY2009

- **Milestone:** Incorporate air cooling in power electronic modules and test and validate models – Report due September 2009.

Challenges and 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.

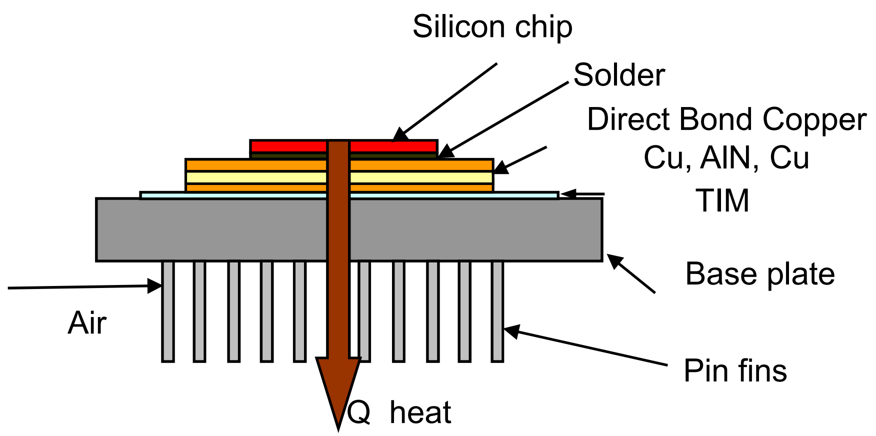
Drawbacks

Air has a low specific heat.

Air is a poor heat-transfer fluid.

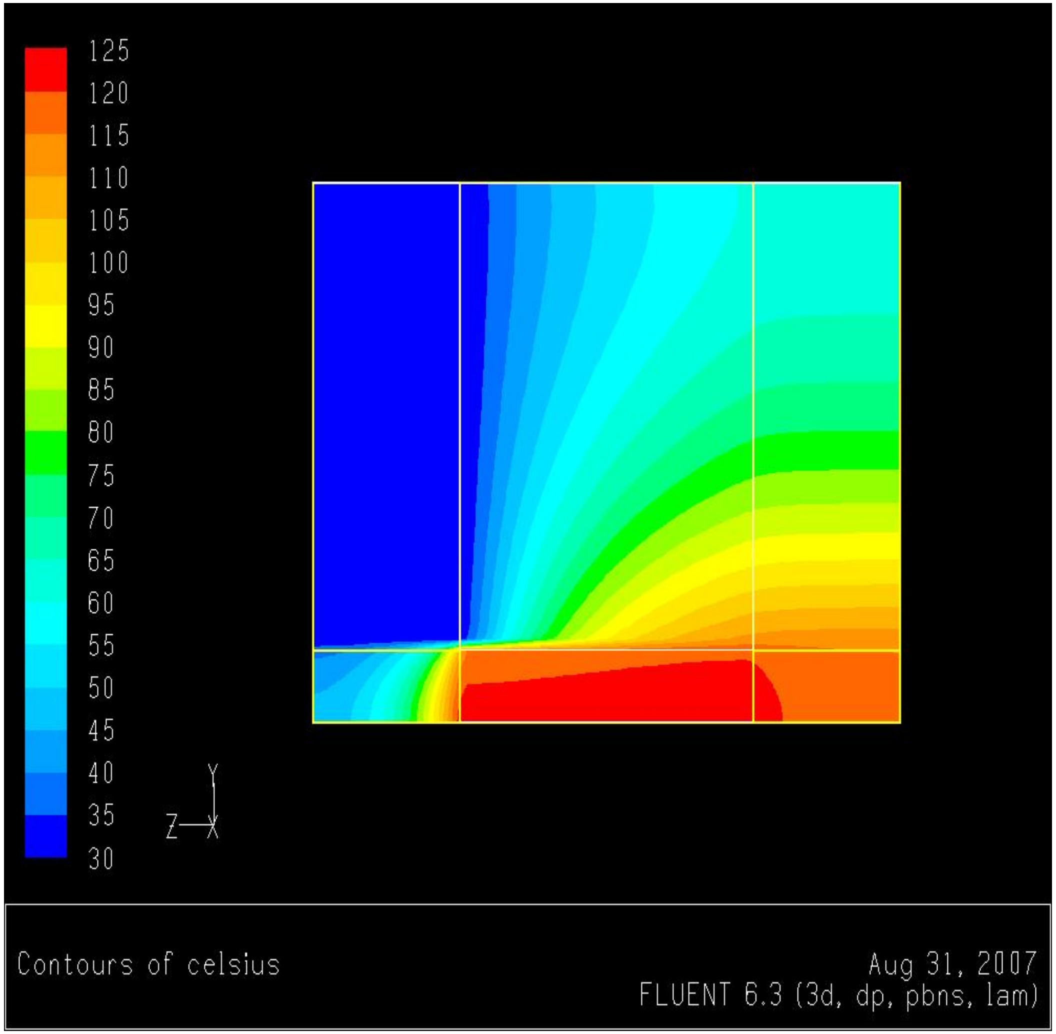
Air density is low.

Cross flow of air complicates heat transfer.



Project Objective for FY09

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

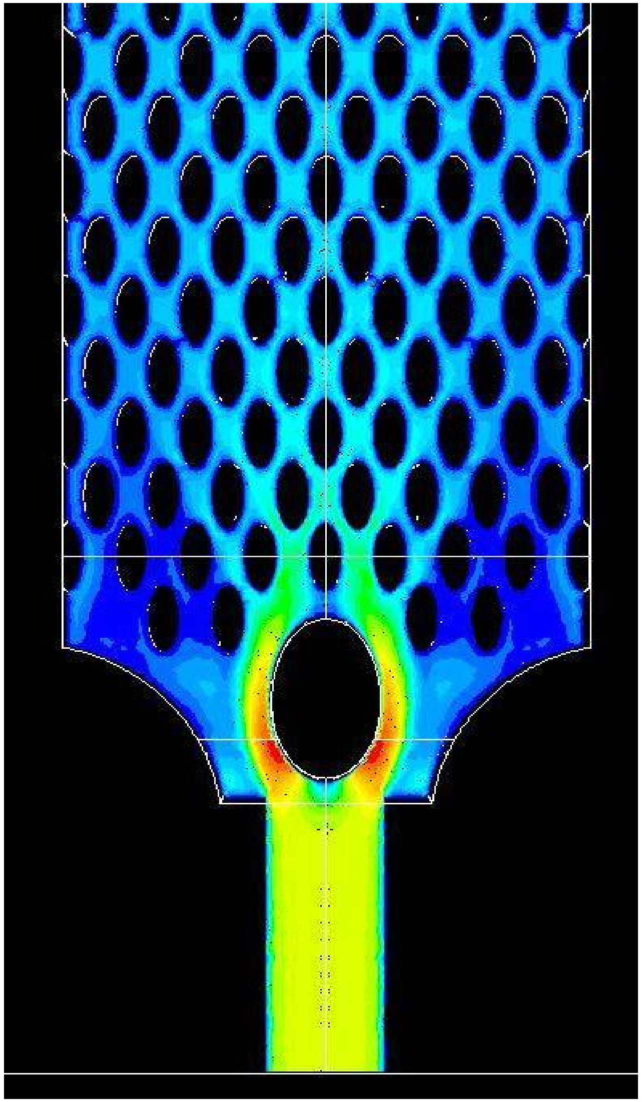


The Problem

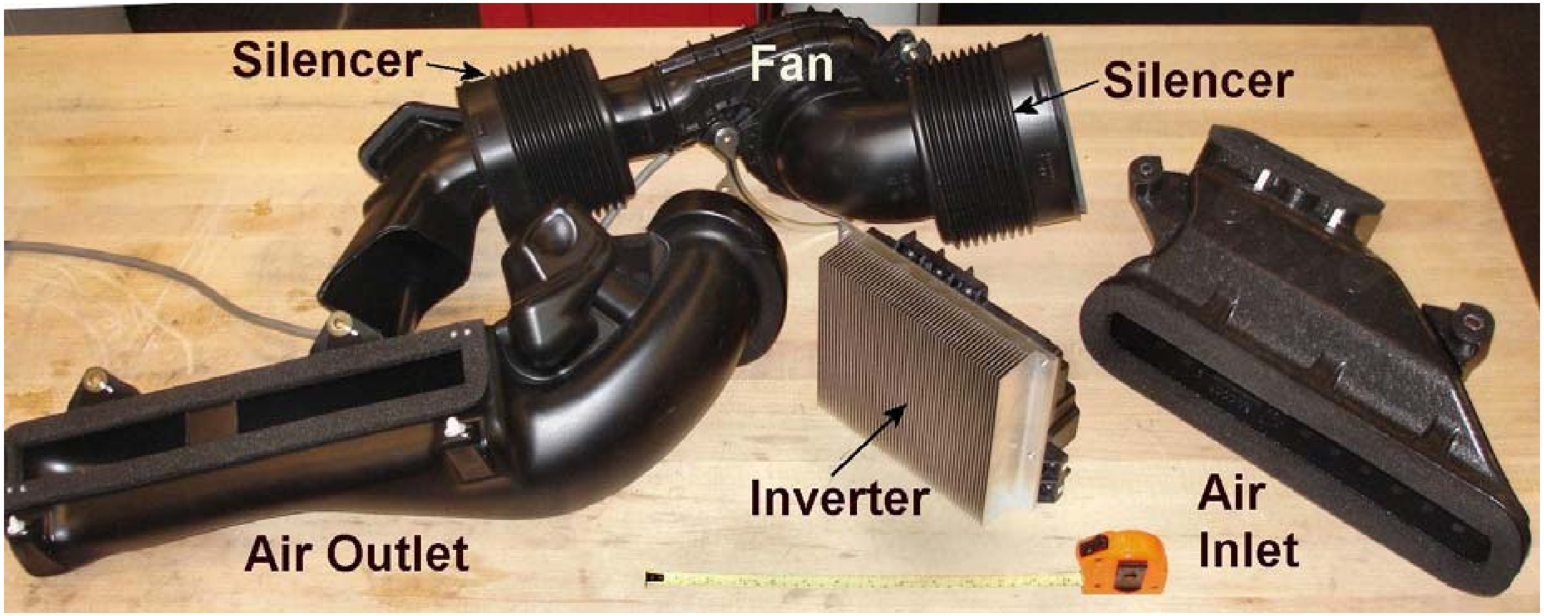
- Reduce cost and complexity of cooling system for power electronics by using ambient air
- Air is the ultimate cooling medium
- Prior work has resulted:
  - in demonstrating high performance for air cooling and
  - in establishing cost reduction potential for air cooling
- Air cooling is essential for long-term cost reduction

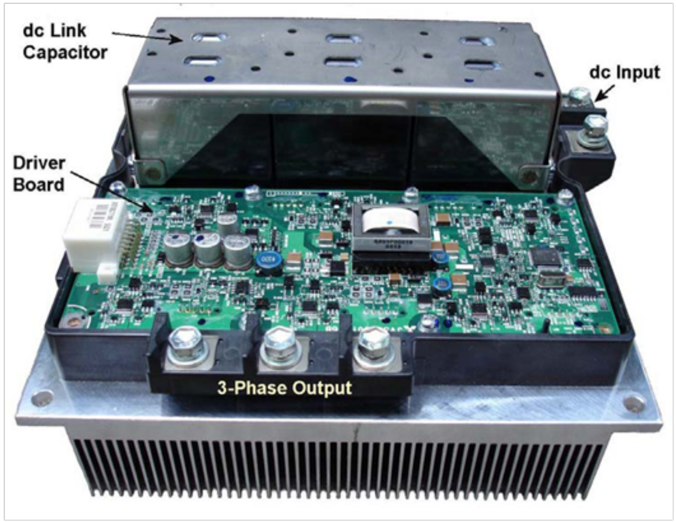
Technical Approach

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



Honda – Air-cooled Inverter Package





Power Rating 12 to 14 kW

Active air cooling

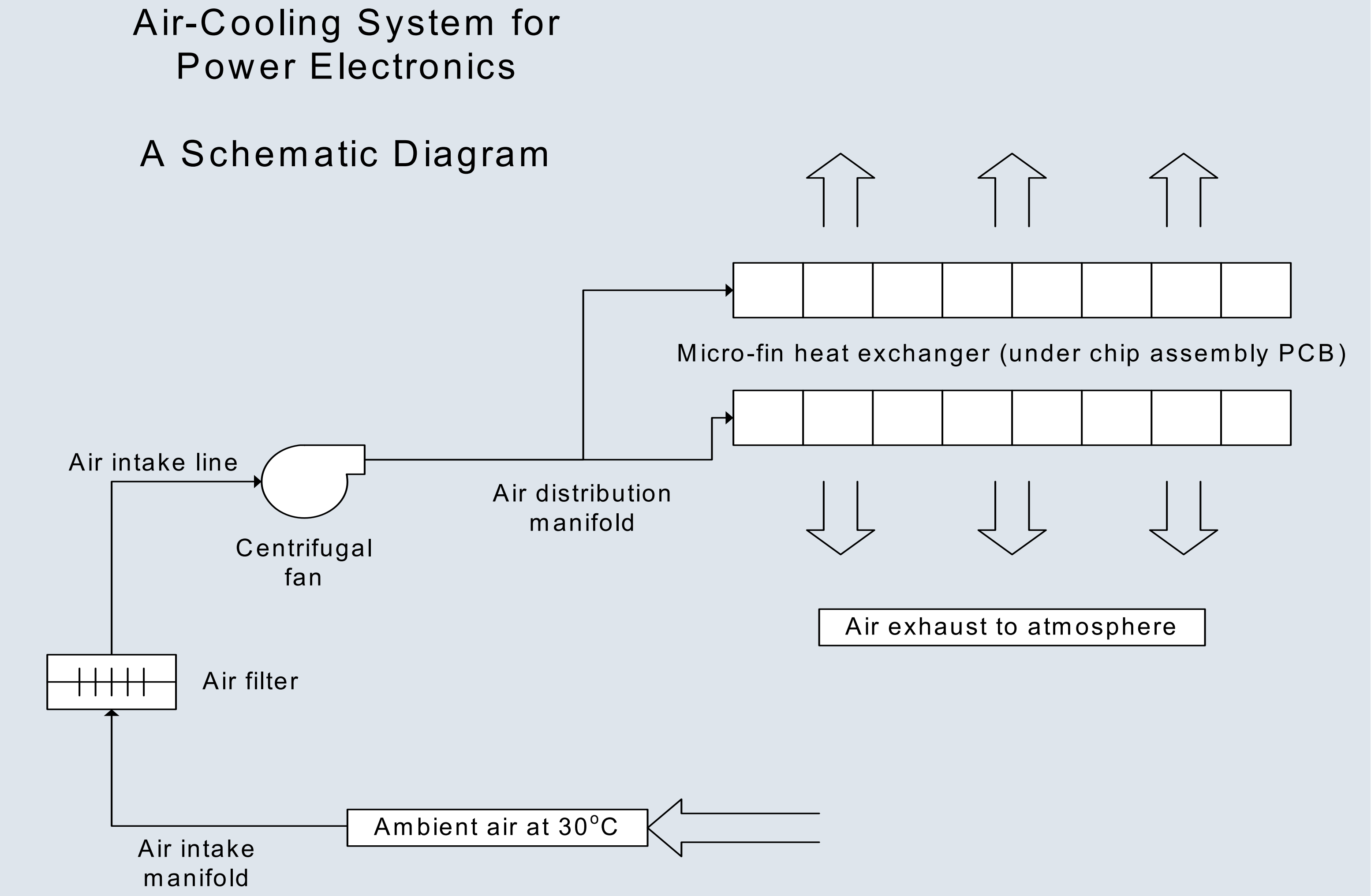
Electric blower ~ 120 W

Heat load ~ 700 W

Uniqueness and Impacts

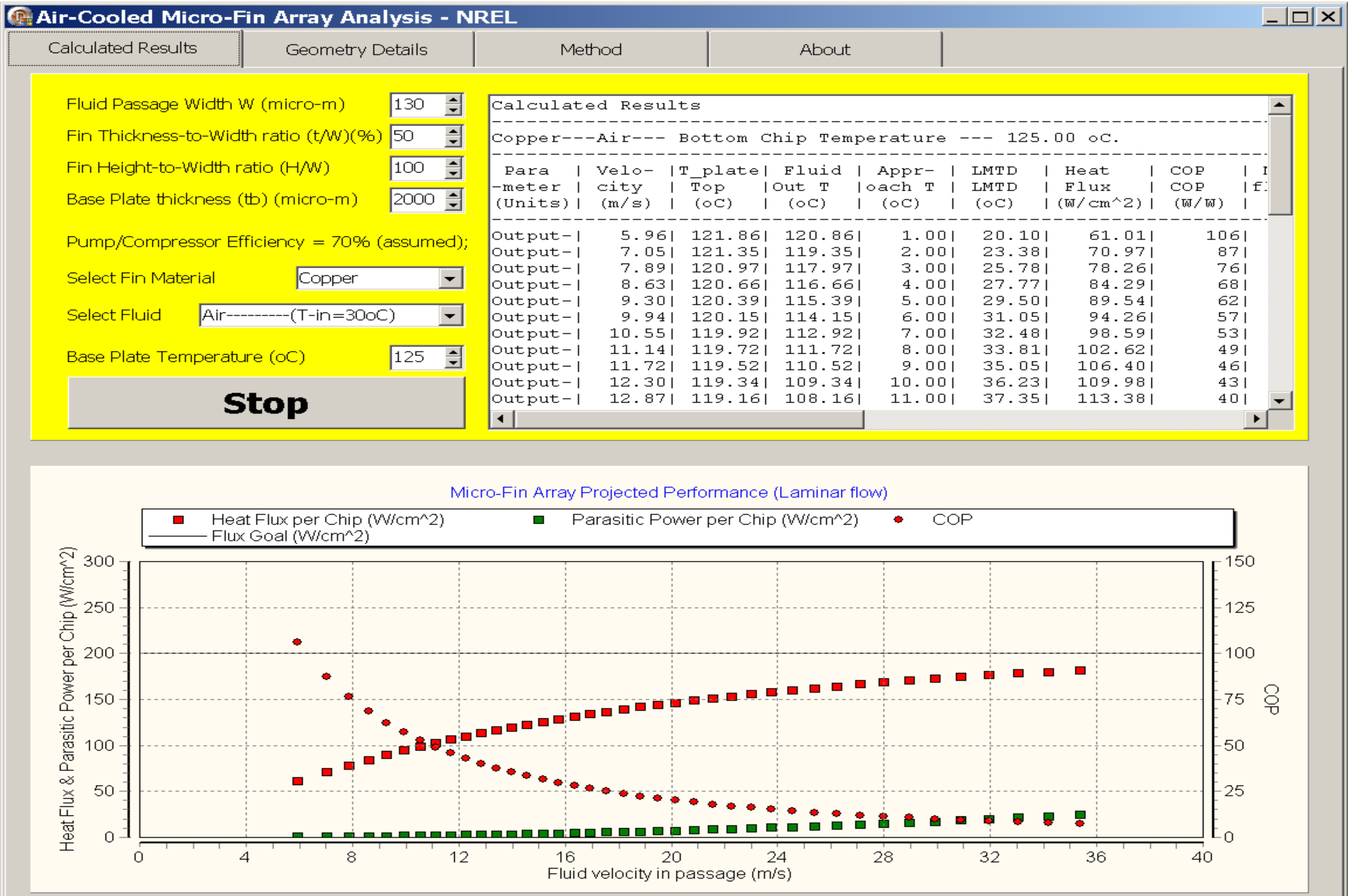
- Our approach aims for simple thermal solutions.
- We offer viable heat rejection fluxes directly to the sink.
- We aim to minimize pressure drop and parasitic power.
- Air cooling offers least number of components and lower cost.
- Air cooling offers high degree of reliability.
- Potential for flow modulation exists.

Accomplishments



ASPEN model for system trade-offs

Accomplishments



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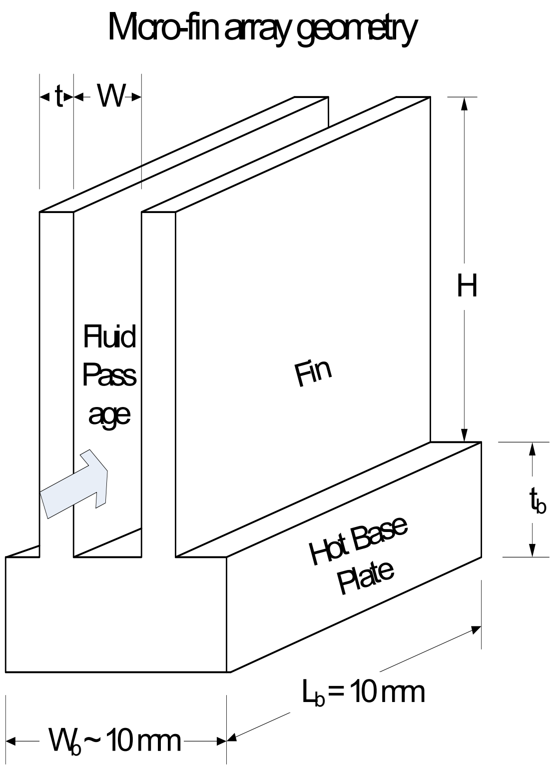
Quick estimator for micro-fin design

Accomplishments



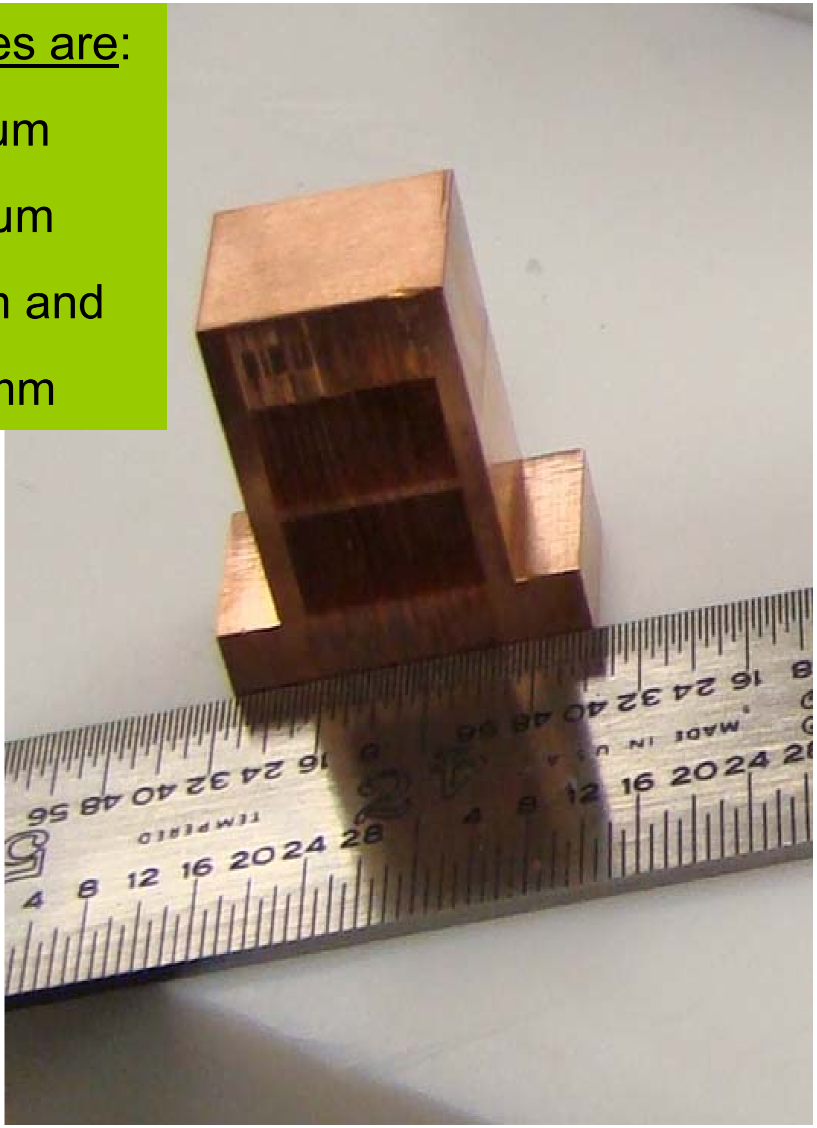
Typical values are:

W=130 μm

t = 65 μm

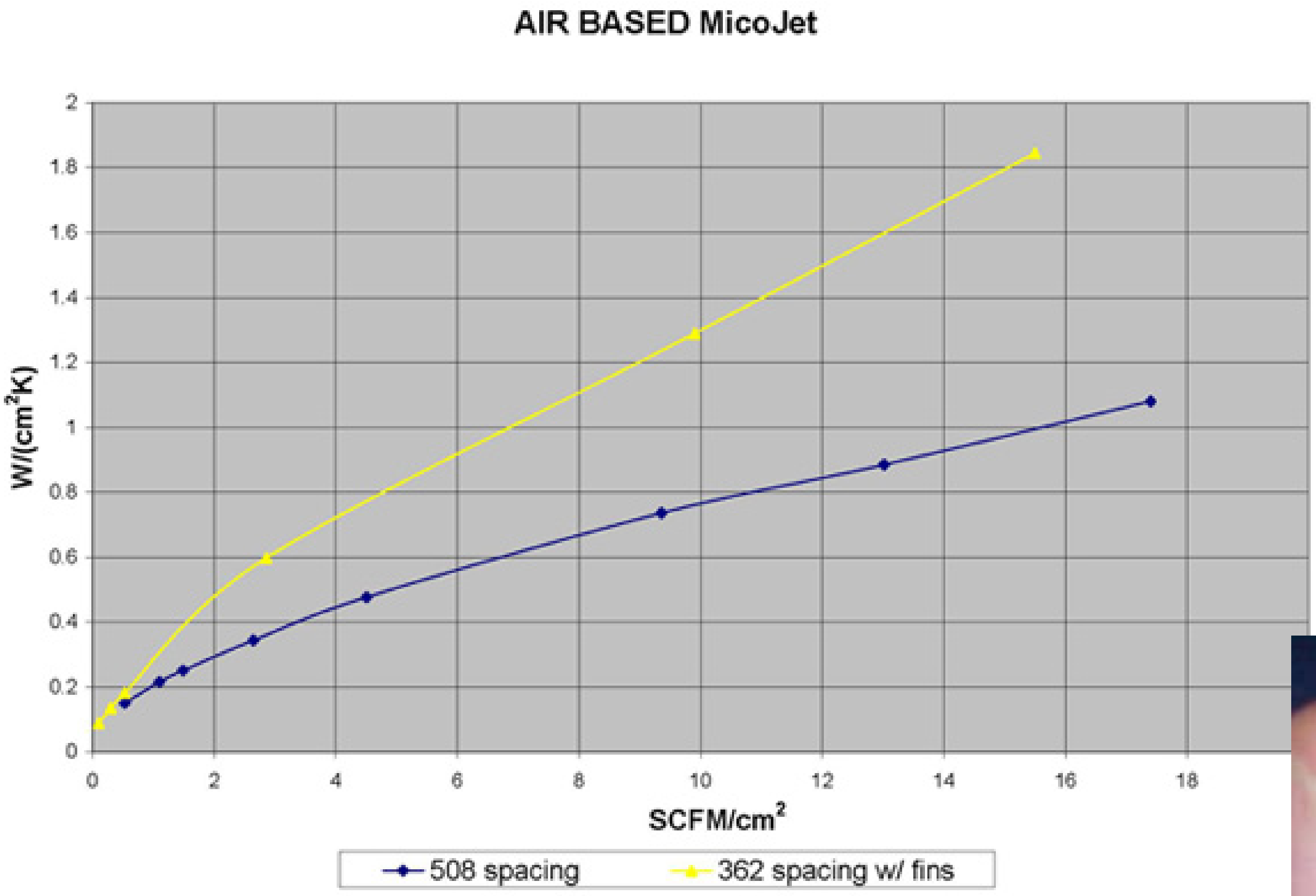
H = 13 mm and

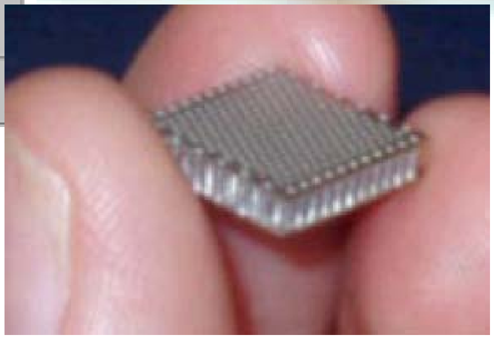
t_b = 1 mm



Prototype fabrication, testing, and validation

Accomplishments





Accomplishments

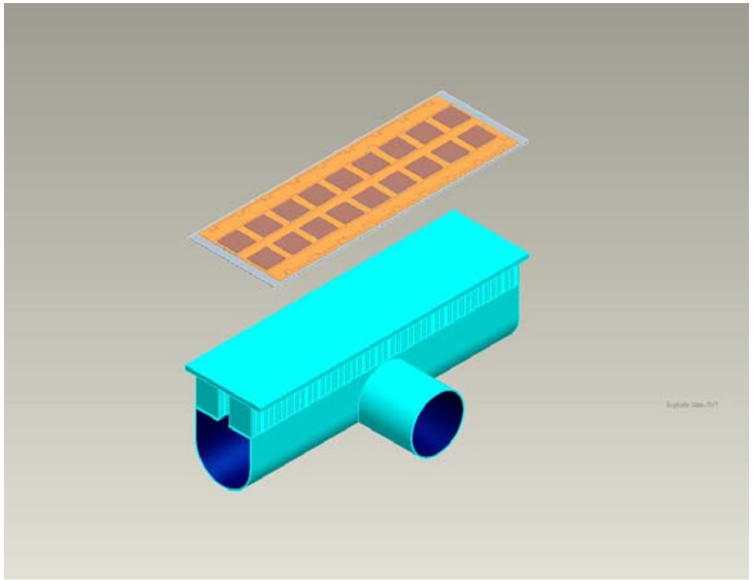
Models show that:

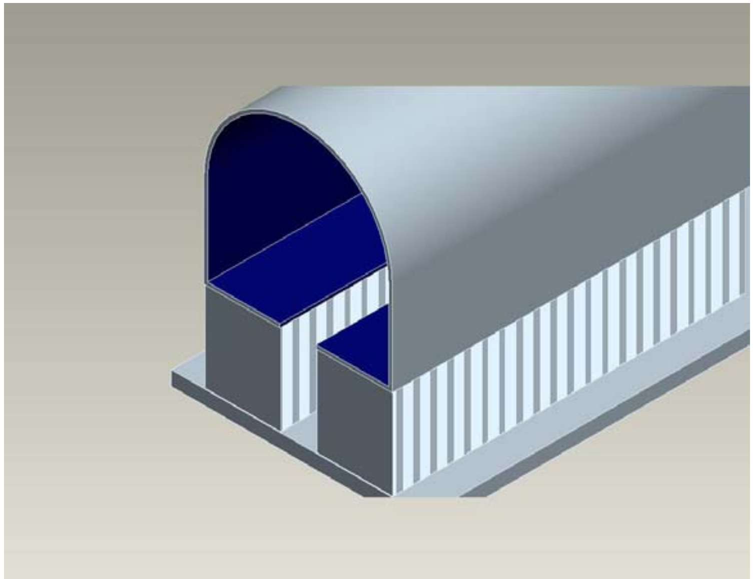
- Air cooling can remove fluxes up to 150 W/cm^2 for Silicon-based devices.
- Higher chip operating temperatures will increase the flux close to programmatic goal of 200 W/cm^2.

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

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

Accomplishments





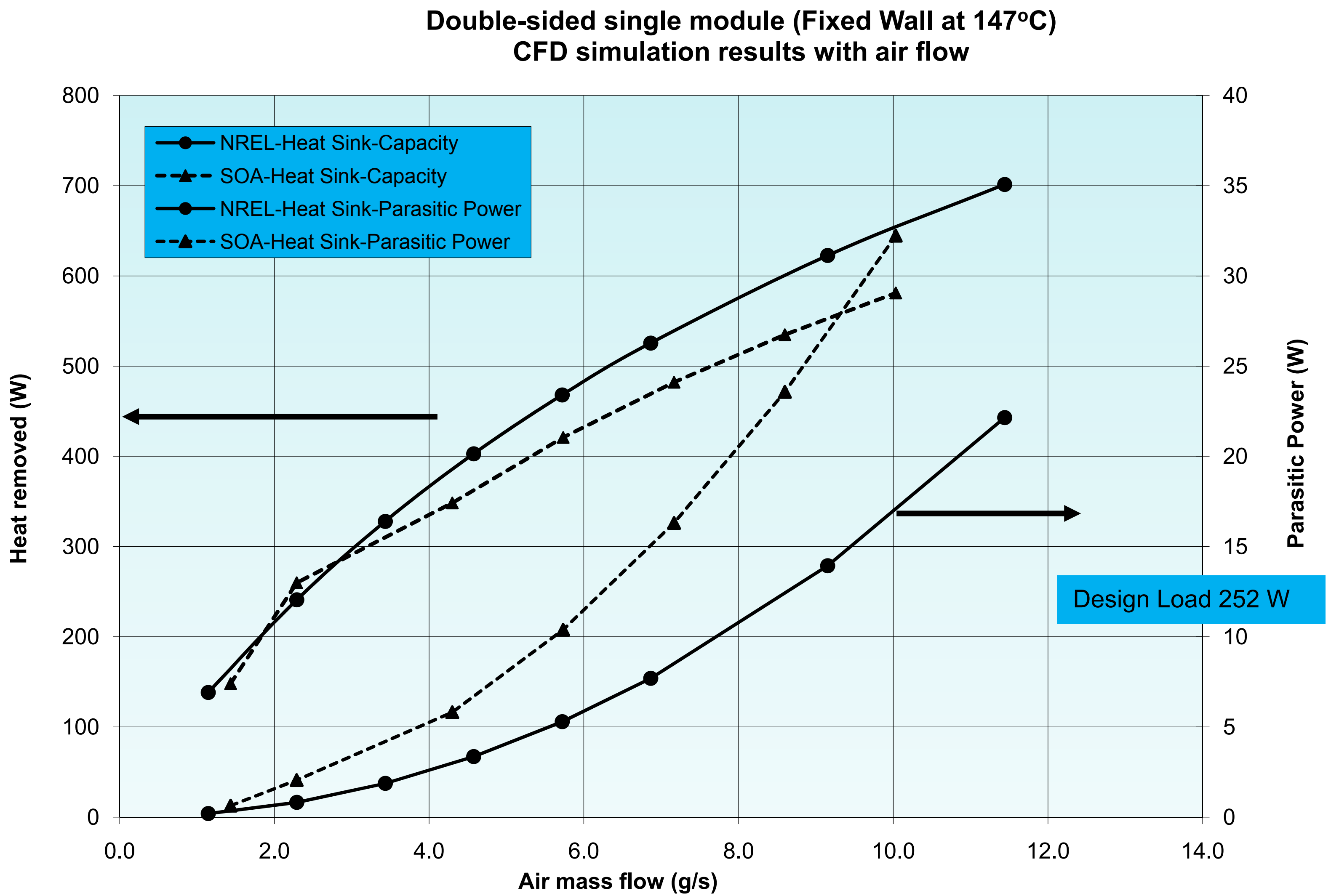
Innovative designs developed for PE packages

Accomplishments

NREL has developed innovative air-cooled heat sink geometry that improves the SOA:

1) Heat transfer surface available is doubled.
2) Flow pressure drop is reduced by 50%.
3) Colder air is directed toward the hot areas near the source.
4) Air flow over the geometry is streamlined.
5) CFD models indicate substantial increase in performance.

Projected Performance Comparisons



Other system related issues – NREL addresses

- Flow configuration
- Fin material and geometry
- Fan configuration and efficiency
- Filtering requirements
- Aerodynamic passages for ducting
- Cooling capacitors
- Extension of novel concepts to motor cooling

Future Work: FY2009 & FY2010

- The cost related to air supply and exhaust system may be comparable to the inverter.
- Manufacturers would rather sell more inverter than an option for air cooling.
- Examples: Due to the high risk nature of this research, industry has been reluctant to embrace the approach.

Summary

DOE Mission Support

- Overcome barriers to adoption of low-cost air-cooled heat sinks for power electronics and motors; air remains the ultimate sink.

Approach

- Create and validate models of air-cooled heat sinks; generate prototype designs for sinks and overall system; demonstrate viability on performance, long-term reliability and competitive costs.

Summary

Technical Accomplishments

- Created prototype designs
  - CFD performance estimation
  - Experimental validation of performance
  - Innovative designs to improve performance
  - Addressing system issues regarding flow, filter, ducting, and air distribution

Collaborations

- Collaborating with industry & partners
  - Interacting with Auto OEMs and suppliers for test data, review, and validation activities
  - Interacting with ORNL, ONR, and NASA
  - Conferring with Jason Lai of VPI.

Critical Assumptions and Issues

Value Added to the Program

- Air-cooled heat sinks are simple and highly reliable. System cost is comparable to liquid-cooled systems.
- Air-cooled heat sinks will track improved technologies offering higher temperatures, such as trench devices, SiC and GaN. Under these cases, the temperatures may be too high for liquid systems in case of failure.
- Air cooling keeps liquids away from electronics! (a big relief for electronics engineers)
- Simple flow of intake air around capacitors will cool them – leading to higher ripple current carrying capacity.

Model Validation

- Heat sink system cost approaches that of the electronic device!
- System issues point to next generation for improving air movers with higher overall efficiency.
- Improvements relating to air duct and distribution need to be incorporated.

Publications and Presentations

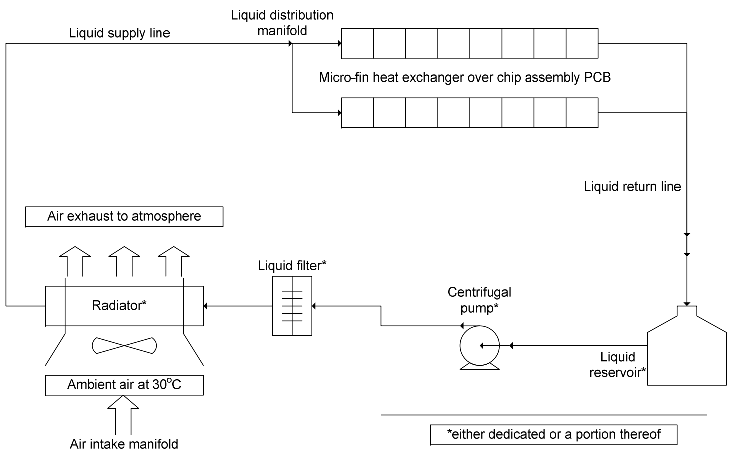
FY08

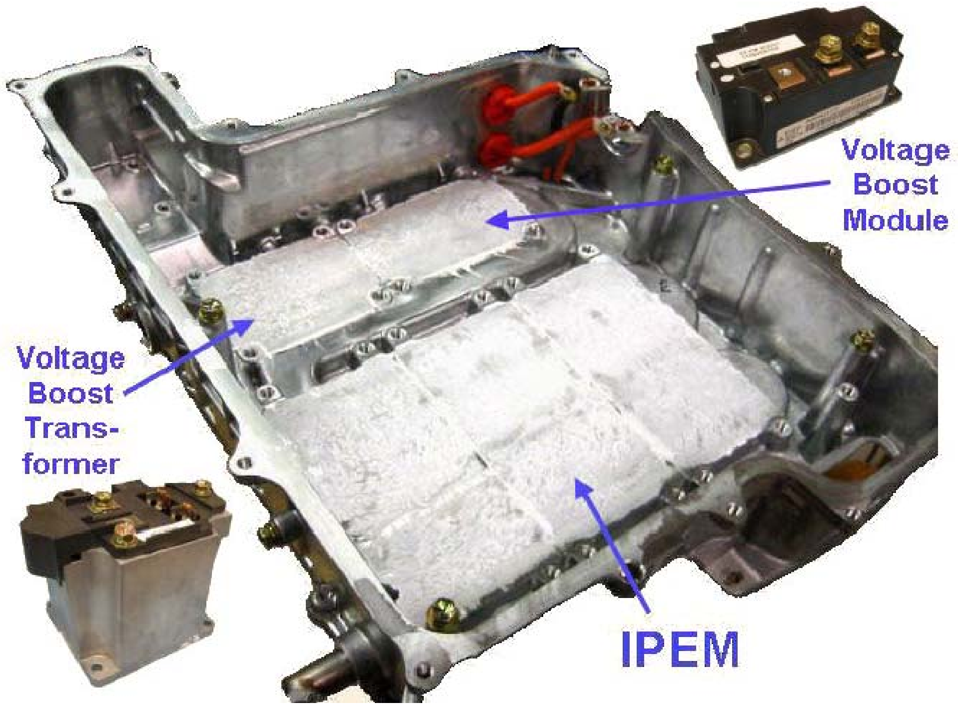
- DOE Milestone: "Air-cooling for power electronics: Status Report" September, 2008.
- ITHERM paper on air cooling for power electronics – July, 2008.

FY09 (Planned)

- DOE Milestone: "Report on results of air-cooling for diode packages " September, 2009.
- Potential Conference Papers (TBD).

Typical Liquid-cooled PE System (Prius)





System Level Comparisons (3kW load)

Quantity	Air Cooling	Liquid Cooling
System mass (kg)	**1.4**	**3.8**
Volume (cc)	**7000**	**3800**
Parasitic Power (W)	**80**	**28**
MPG penalty for excess power	**- Negligible -**	**- Negligible**
MPG penalty for excess mass	**- Negligible**	**- Negligible**
Relative component and system fabricated costs ($)	**48**	**78**
Number of components	+++	
Reliability	+++	
Maintenance Ease	+++	
Feedback to customer	+++	+++
Simplicity in installation	+++	
Overall comparison	+++	