“Everything on a vehicle is air cooled...
“Everything on a vehicle is air cooled... ultimately”
Challenges and Barriers – Relevance

- In current designs, heat is transferred from the source through a heat exchanger to a liquid, which is pumped to a remote location, and then the heat is rejected to air through another heat exchanger
- Air cooling has the potential to improve thermal management system cost, weight, volume, and reliability, helping to meet Advanced Power Electronics and Electric Motors (APEEM) technical targets

The Challenge
- Air is a poor heat-transfer fluid
  - low specific heat
  - low density
  - low conductivity
- Parasitic power
- Perception and novelty

Advantages
- Everything on a vehicle is ultimately air-cooled
- 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
It Can Be Done….When?….How?

Honda Insight
Power Rating 12 to 14 kW

AC Propulsion AC-150
Power Rating 150 kW

Photograph references: Left 1st row [1], Left 2nd row [2], Right 1st row [3], Right 2nd row [4]
Overview

Timeline
• Phase I start date: FY06
• Phase II start date: FY10
• Project end date: FY14
• Phase II complete: 25%

Budget
• Phase II funding
  – DOE share: $1,100K
  – Contractor share: $0.00
• FY10 Funding: $400K
• FY11 Funding: $700K

Barriers
• Cost – Eliminate need for secondary liquid coolant loop and associated cost and complexity
• Weight – Reduce unnecessary coolant, coolant lines, pump and heat exchangers for lower system level weight
• Performance – Maintain temperatures in acceptable range while reducing complexity and system level parasitic losses

Targets
• Cost, Specific Power, and Power Density

Partners (NREL project lead)
• Oak Ridge National Laboratory
• GE, Momentive™ Performance Materials, and Thermacore
Project Objectives – Relevance

- Develop air-cooled thermal management system solutions that help meet DOE’s 2015 technical targets by 2014
- Enable heat rejection directly to ambient air, simplifying the system by eliminating liquid coolant loops, thereby improving weight, volume, cost, and reliability
- Develop and demonstrate the viability of innovative thermal management methods that maintain power electronics within acceptable temperature limits while reducing cost, weight, and volume
- FY11
  - Identify promising advanced cooling technologies, such as enhanced surfaces, synthetic jets, and advanced heat spreaders
  - Develop balance-of-system and module-level testing capability
  - Conduct system-level analysis to understand the air-cooling design space and the potential of advanced cooling technologies for thermal management improvement
  - Analyze thermal management feasibility of a high-temperature, air-cooled inverter concept (ORNL collaboration)
Project Milestones – Relevance

**FY2010**

- Completed preliminary review of synthetic jet technology (3/10)
- Created the Air Cooling Technology Characterization Platform (6/10)
- Found equivalent or better performance of synthetic jets than steady jets under tested flow regime (8/10)
- Developed system-level thermal analysis of air-cooled system (9/10)

**FY2011**

- Established high-temperature, air-cooled inverter work plan with ORNL (2/11)
- Applied system thermal analysis approach to full inverter and evaluated air cooling design space (4/11)
- Completed synthetic jet performance comparison to steady jets (5/11)
- Complete balance-of-system test stand (6/11)
- Finish initial surface enhancement screening (7/11)
- Complete high-temperature, air-cooled 30 kW continuous, 55 kW peak, inverter thermal management feasibility study (8/11)
Approach

- **Thermal Environment**
  - Inverter Location
  - Air Source

- **Device Type**
  - Max Temperature
  - Efficiency

- **Vehicle Context**
  - Power/Duty Cycle
  - Volume/Weight Limits

- **Balance of System**

- **Package**

- **Cooling Technology**

Analytical & Experimental Methods
Approach

FY10 – Fundamental Heat Transfer

Air Cooling Test Bench

FY11 – System R&D

Future Test Bench

FY12 – Application

FY13 – Demonstration

Photograph references from left to right: 1. Top [1], Right [2]; 2. Bottom [3]; 3. [4], 4. [5]
Cooling Technology – Accomplishment

Air Cooling Technology Characterization Platform

- Air flow rate control
- High accuracy heat transfer measurement
- Velocity field characterization
- Automated control and data acquisition

Photograph references: Top [1], Bottom [2a]
Cooling Technology – Accomplishment

Air Cooling Technology Characterization Platform

- Air flow rate control
- High accuracy heat transfer measurement
- Velocity field characterization
- Automated control and data acquisition

Photograph references: Top [1], Bottom [2b]
Cooling Technology – Accomplishment

Air Cooling Technology Characterization Platform

- Air flow rate control
- High accuracy heat transfer measurement
- Velocity field characterization
- Automated control and data acquisition

Photograph references: Top [1], Bottom [2c]
Cooling Technology – Accomplishment

Air Cooling Technology Characterization Platform

- Air flow rate control
- High accuracy heat transfer measurement
- Velocity field characterization
- Automated control and data acquisition

Photograph references: Top [1]
Air Cooling Technology – Accomplishment

Screening a large design space

See end of presentation for references
Synthetic Jets – Accomplishment

*Advanced technology research*

- Fully pulsatile jet
  - Near field: vortex rings/pairs
  - Far field: laminar/turbulent Jet
- Zero net mass flux
- Vorticle structures transfer momentum
- Simple fabrication

**Suction**

**Ejection**

[1] Evolution (Ejection Stroke)

Impinging + Cross-Flow  Leading Edge + Cross-Flow  Interior + Cross-Flow

[2]
Synthetic Jet Compared to Steady Jet – Accomplishment

*Synthetic jets equal or better heat transfer with simpler design*

![Graph showing heat transfer comparison between Synthetic Jet and Continuous Jet](image)

- Synthetic Jet
- Continuous Jet

The graph illustrates the heat transfer coefficient ($h$) in W/m²/K as a function of the Reynolds number (Re). The Synthetic Jet shows equal or better heat transfer compared to the Continuous Jet, particularly at higher Reynolds numbers.
Steady Jet Characterization – Accomplishment

*Fundamental heat transfer research collaboration, example results*

- Characterized steady slot jets for comparison to synthetic jets
- Synthetic jet data to be provided by industry partner
Package Mechanical Design – Accomplishment

**Package design thermal impacts**

- Leverage work on the thermal system and performance task
- Finite element model of packages for system analysis
Balance-of-System – Accomplishment

Understand parasitic loads and system COP

- General high level coolant system model
- Wide range of prime mover performance
- Expanding experimental capabilities

System Test Bench

- Package” – Heat Source
- “Region” – Flow path subdivision
- “Branch” – Flow path

Diagram showing flow paths and pressure differences with labels for temperature (T), pressure (P), and differential pressure (∆P).
System Level Analysis – Accomplishment

20 kW DC-DC converter with air cooled fins case study

Case 1

Case 2

Thermal Demands Met
50 L/s air
Collaborations

• ORNL (High Temperature Air Cooled Inverter)
  – FY11: Thermal feasibility
    o NREL will continue its system level air cooling thermal design including cooling technology, balance-of-system, and high-level package thermal analysis
    o NREL will complete high temperature air-cooled inverter thermal management and balance-of-system feasibility study
    o ORNL will focus its work on wide-band-gap materials in preparation for FY12 high-temperature air-cooled inverter design
  – FY12: Module design phase
    o NREL to improve heat transfer design and experimentally evaluate simulated heat load module thermal management system
    o ORNL to complete module electrical design and build initial prototype for validation
  – FY13: System design phase
    o ORNL to build and test low power inverter prototype
    o NREL to build and test thermal management system with low power inverter
  – FY14: System build and demonstration
    o NREL to build and test full system thermal management system
    o ORNL to build full inverter and test
    o High-temperature air-cooled inverter performance characterized and reported

• Other interactions
  – Electrical & Electronics Technical Team
  – GE, Momentive, and Thermacore
Future Work

• FY11
  – Design and build system-level air-cooling test bench. Use test bench to implement most promising technology on a multi-heat source array
  – Explore other novel air-cooling technologies and surface enhancements
  – Address balance-of-system questions, developing knowledge and solutions for fans, filters, and ducting
  – Complete high-temperature air-cooled inverter thermal management and balance-of-system feasibility study

• FY12
  – Thermal management design of high-temperature air-cooled inverter module (ORNL collaboration)
  – Test simulated heat module for validation of thermal management design
  – Research advanced air-cooling technologies, such as enhanced surfaces, boundary layer perturbation, synthetic jets, heat spreaders, and advanced fin design
  – Analyze system level designs and evaluate balance-of-system solutions
Summary

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

- Create system-level understanding and designs addressing advanced cooling technology, balance-of-system, and package thermal interactions; developing solutions from fundamental heat transfer, then system level design, to application – culminating in vehicle-level viability demonstration with research partners.
**Summary**

**Technical Accomplishments**
- Developed system-level analysis approach for power electronics air cooling
- Established more direct collaboration with ORNL
- Found equivalent or better performance of synthetic jets than steady jets under tested flow regime
- Developed the Air Cooling Technology Characterization Platform for advanced cooling technology research

**Collaborations**
- Established collaboration plan with ORNL to develop needed thermal system knowledge for FY12 high-temperature inverter project
- Researching advanced air-cooling technology in collaboration with GE, Momentive, and Thermacore
- Interacting with auto OEMs and suppliers for test data, review, and validation activities
Acknowledgements and Contact

Acknowledgements:
Susan Rogers,
U.S. Department of Energy

Team Members:
Carson Bates
Kevin Bennion
Xin He
Charlie King
Gopi Krishnan
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References

Slide 4
1. Honda Insight photograph: John P. Rugh, NREL
2. Honda power electronics photograph: Oak Ridge National Laboratory
4. AC Propulsion AC-150 photograph: Jason A. Lustbader & Dean Armstrong, NREL

Slide 9
1. Synthetic jet photograph: Gopi Krishnan and Charlie King, NREL
2. Micro-fin photograph: Charlie King, NREL
3. Inverter photograph: Mark Mihalic, NREL
4. Inverter photograph: Mark Mihalic, NREL
5. Prius photograph: NREL PIX15141

Slides 10-13
1. Test bench photograph: Gopi Krishnan and Dean Armstrong, NREL
2. a. Laminar flow element detail; b. Settling chamber and target; c. Constant Temperature Anemometer, Jason Lustbader, NREL

Slide 14
1. Stream function from a computation fluid dynamics (CFD) calculation of a steady slot jet, Gopi Krishnan, NREL
2. High speed capture of the emergence of a synthetic jet, Gopi Krishnan, NREL
3. Velocity contours from a CFD calculation of vortex ring formation in cross flow, Gopi Krishnan, NREL
4. Velocity contours from a CFD calculation of two steady jets, Gopi Krishnan, NREL
5. Pin fin heat sink from Cool Innovations, Gopi Krishnan, NREL
6. Porous carbon foam under a microscope, Mark Mihalic, NREL
7. Micro fin heat exchanger, Charlie King, NREL
8. MicroCool Surface from Wolverine, Mark Mihalic, NREL
9. A heat pipe, Jason Lustbader, NREL
10. IR image of a thermally conductive material, Charlie King, NREL
11. Aluminum heat sink/spreader, Gopi Krishnan, NREL
12. Ionic wind device, Jason Lustbader, NREL

Slide 15
2. Synthetic jet flow visualization photographs: Gopi Krishnan and Charlie King, NREL