Electric Motor Thermal Management

U.S. Department of Energy
Vehicle Technologies Program
Annual Merit Review

PI: Kevin Bennion

May 11, 2011

Project ID: APE030

Overview

Timeline

- Project Start: FY 2010
- Project End: FY 2013
- Percent Complete: 25%

Budget

- Total Funding
  - DOE: $850K
  - Contract: $0K
- Annual Funding
  - FY11: $450K

Partners / Collaboration

- Electrical and Electronics Technical Team (EETT)
- University of Wisconsin (UW) – Madison (Thomas M. Jahns)
- Oak Ridge National Laboratory (ORNL)
- Motor Industry Representatives

Barriers

- Cost
- Weight
- Performance & Life

- Cooling System
- Material Selection
- Vehicle Integration

Cost ($/kW)

Efficiency (%)

- Heat Generation
- Cooling Requirements
- Cooling Efficiency Benefits on System

Weight (kW/kg)

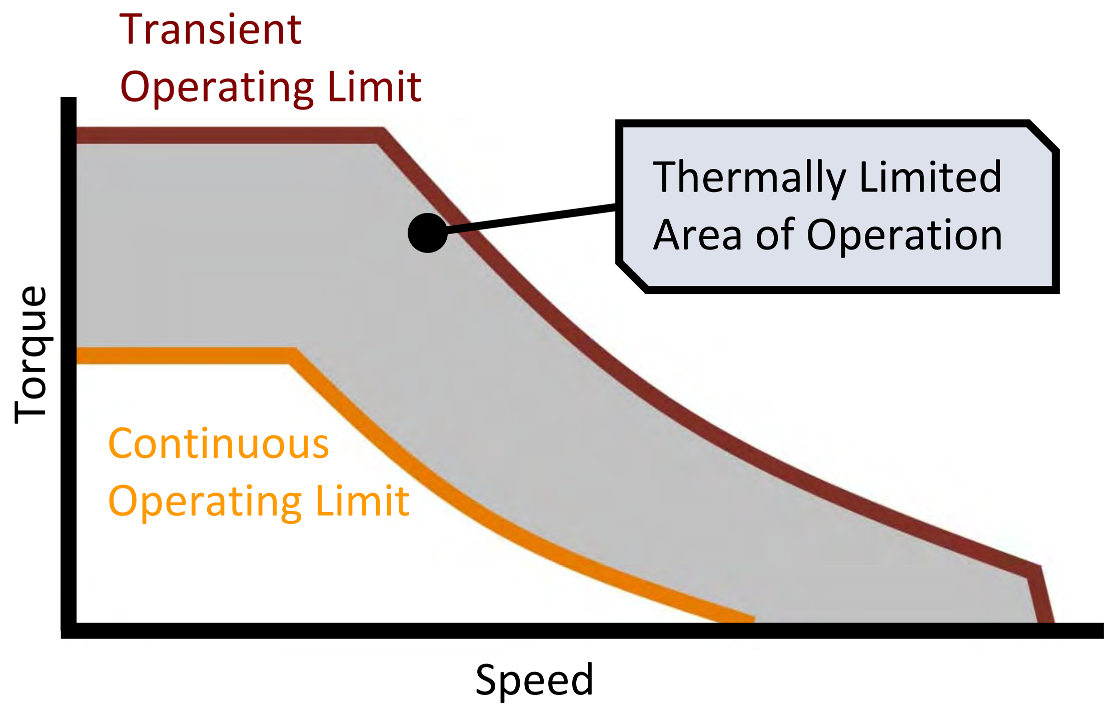
- Materials
- Power Capability

Volume (kW/L)

- Heat Flux
- Heat Exchanger Volume
- Power Capability

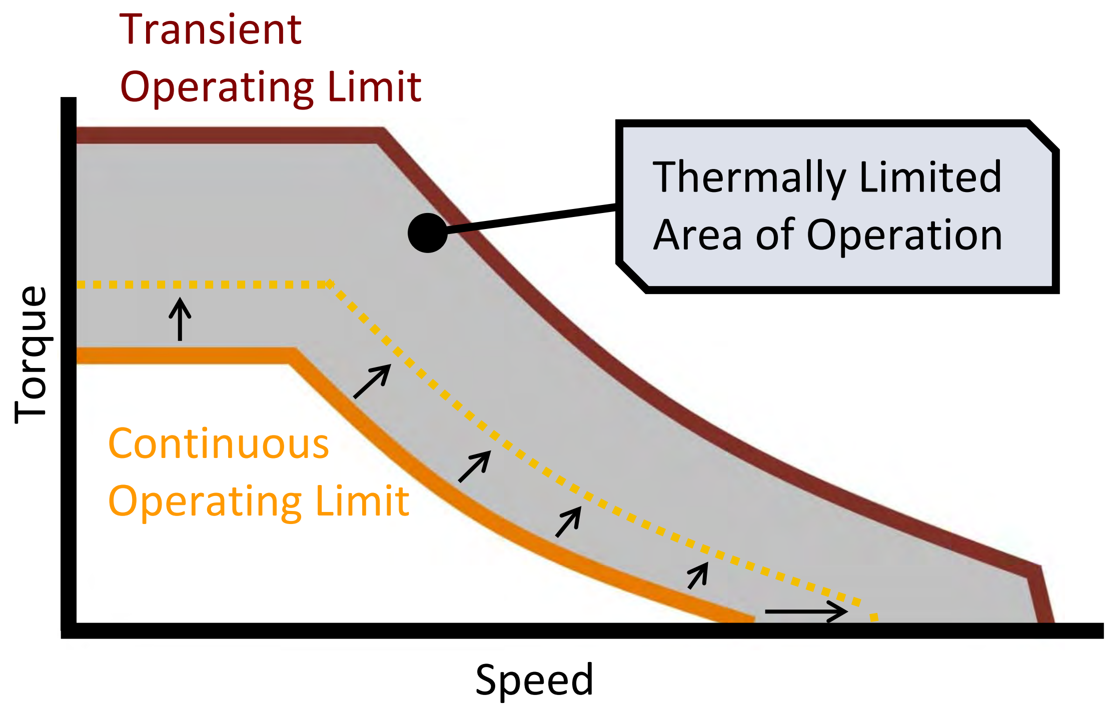
Relevance

Thermal management impacts the continuous power capability of electric machines.



Relevance

The transition to more electrically dominant propulsion systems leads to higher-power duty cycles for electric drive systems.



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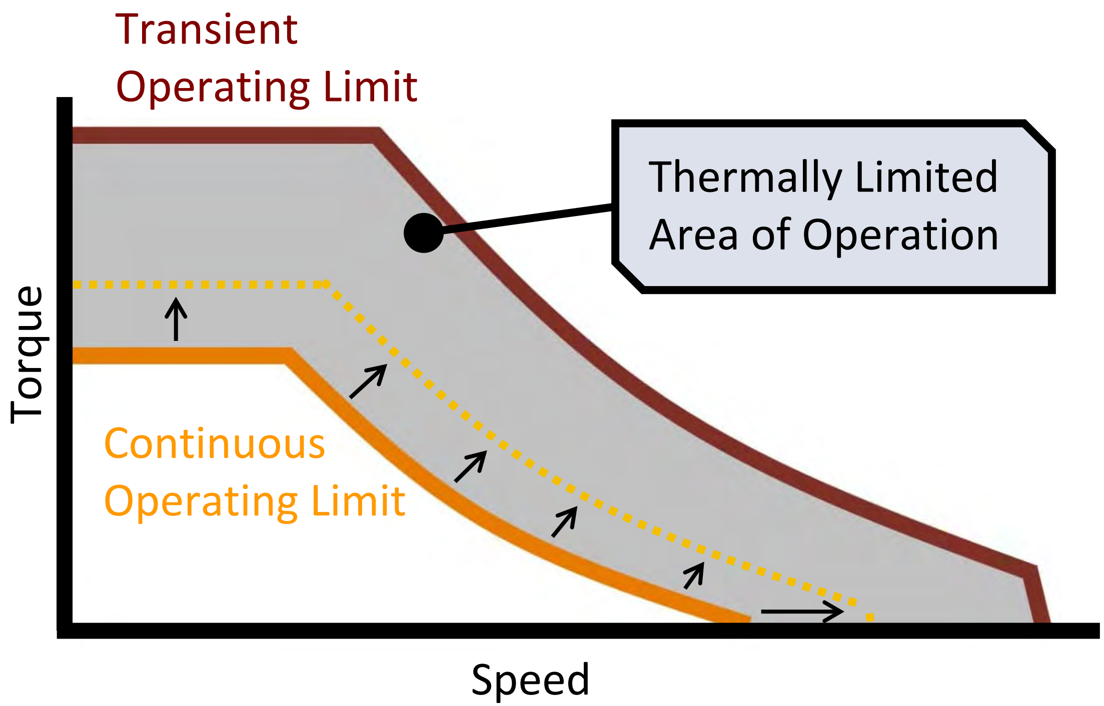

Problem: Heat

Over-sizing the electric machine is one solution to improving performance of electric machines within the thermal constraints [1]

Improving the high-temperature performance of materials is another approach (**dysprosium – rare earth magnets**)

[1] Source: C. Liao, C. Chen, and T. Katcher, "Thermal Analysis for Design of High Performance Motors," ITHERM, May 1998

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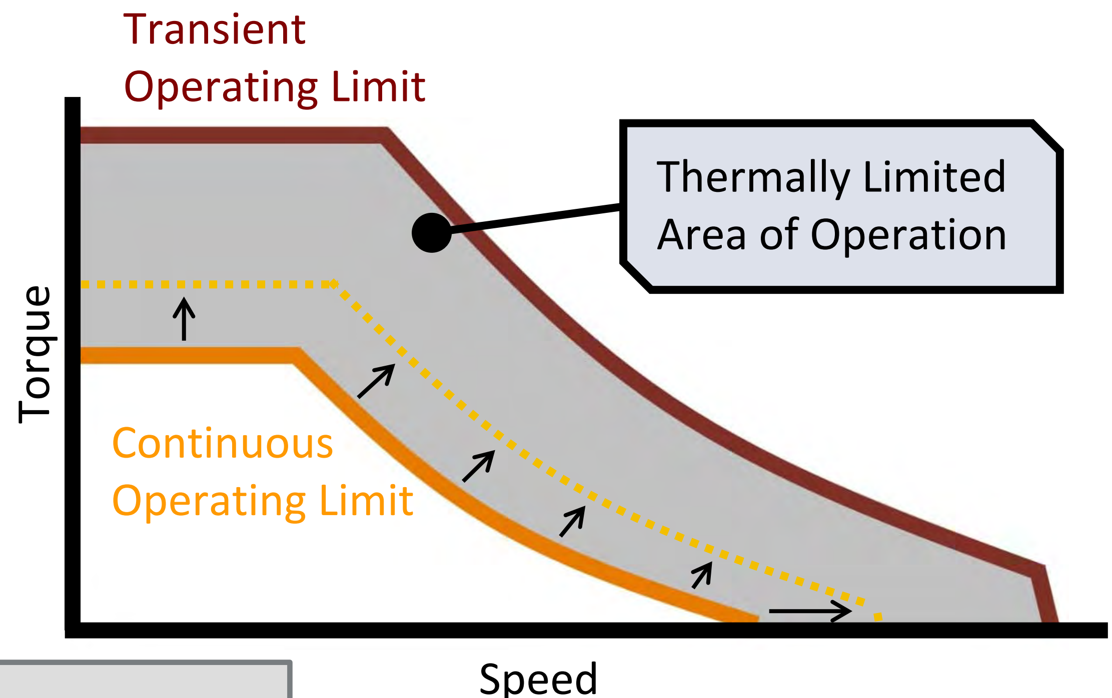

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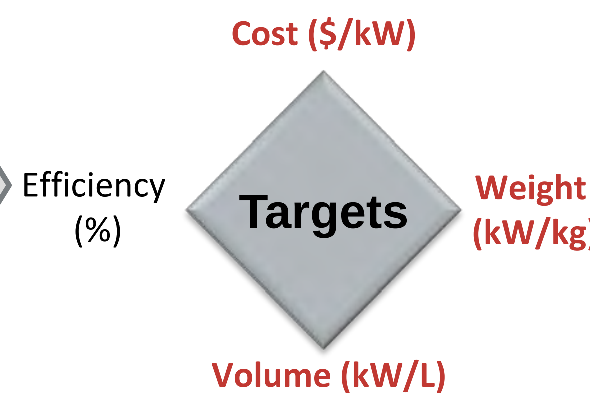

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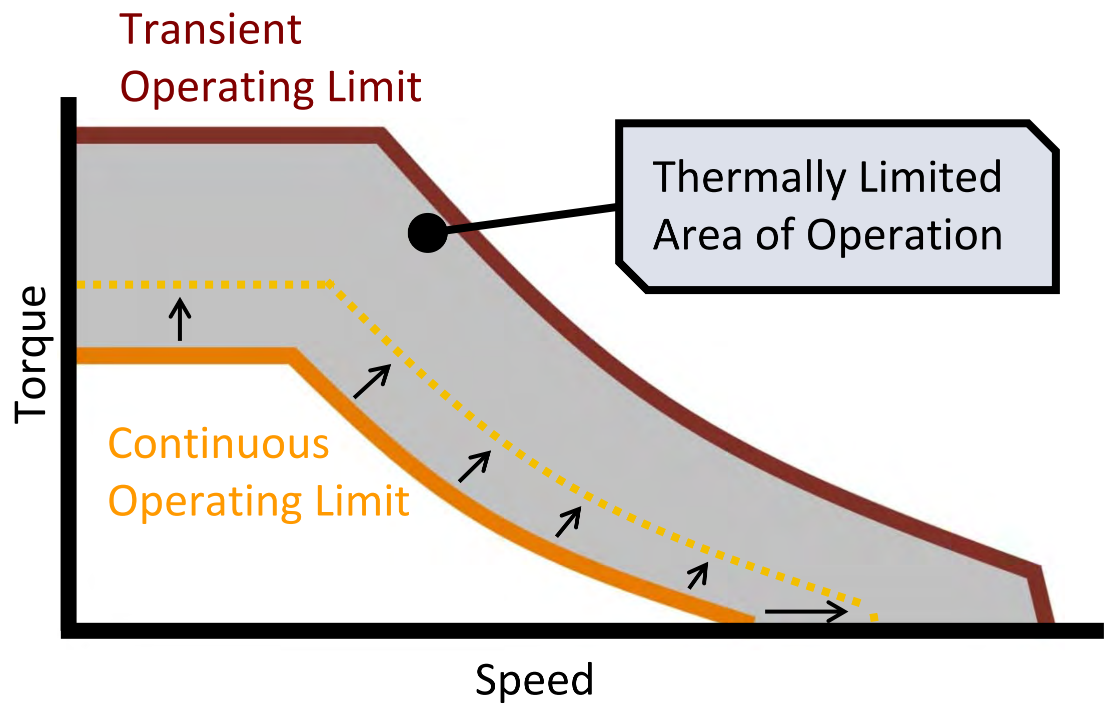


Thermal management is needed to reduce size and improve performance of electric machines [1].

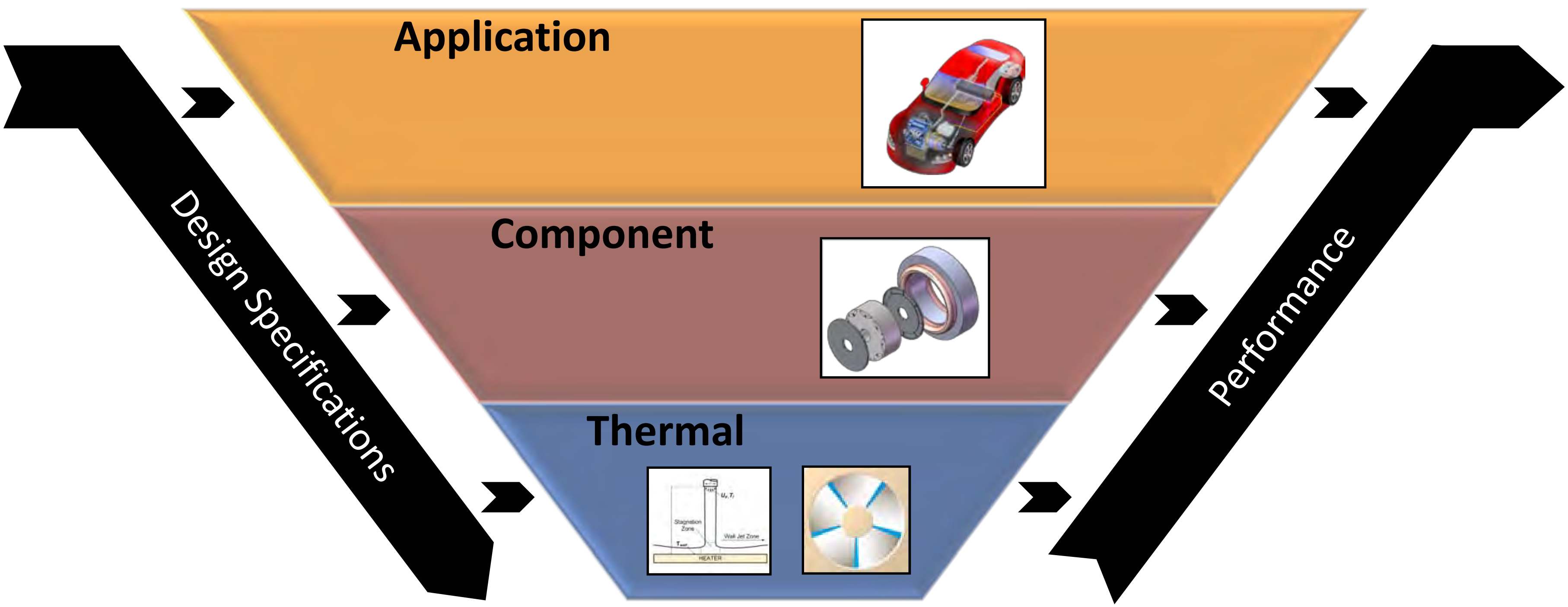
- Meet/improve power capability within cost/efficiency constraints
- Reduce rare earth material costs (dysprosium)

[1] Source: C. Liao, C. Chen, and T. Katcher, "Thermal Analysis for Design of High Performance Motors," ITHERM, May 1998

Relevance: Objective

Optimize selection and development of cooling technologies for motor cooling to maximize impact on Advanced Power Electronics and Electric Motors (APEEM) targets (weight, volume, cost, efficiency).

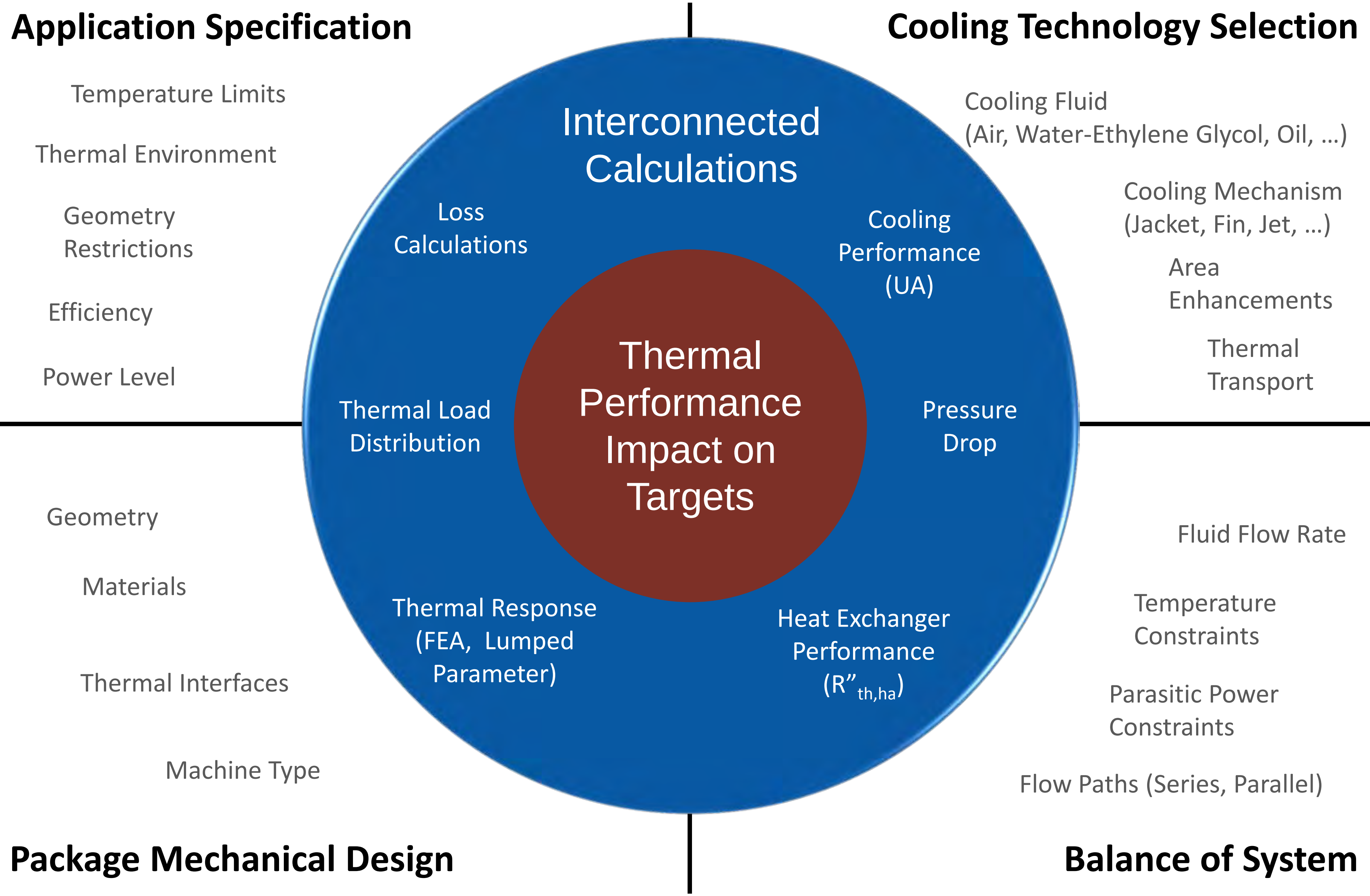
- Quantitatively pinpoint areas for improving and applying new cooling technologies
- Link application and component specifications to thermal design targets
- Link thermal performance to component and application performance



Milestones

Month / Year	Milestone or Go / No-Go Decision Point
October 2010 *Milestone*	• Completed in-depth literature review and characterization of motor cooling and modeling approaches for automotive applications – Machine types, thermal limitations, cooling approaches, materials, and properties – Motor loss approximation methods (finite element analysis [FEA] and lumped parameter) – Thermal analysis methods (FEA and lumped parameter) – Oil jet cooling thermal performance correlations
April 2011 *Milestone*	• Applied parametric FEA thermal analysis methods to initial motor thermal management application • Developed heat load estimation methods to support FEA and lumped parameter thermal models compatible with MATLAB/Simulink
June 2011 *Go/No-Go*	• Evaluate impact of cooling methods on electric machine performance (APEEM goals) to determine if benefit warrants additional effort • Transition promising cooling methods to heat transfer characterization efforts
October 2011 *Milestone*	Annual milestone report – status update (October) • Describe parametric thermal FEA model and lumped parameter models • Report experimental tests to support modeling (thermal interface testing, oil cooling performance and durability experimental test setup)

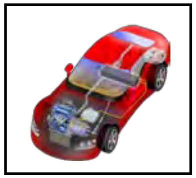
Approach/Strategy



Approach / Strategy

- Develop heat generation model (UW)
- Incorporate thermal load benchmark data (ORNL)

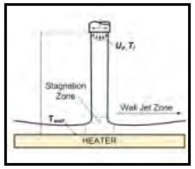
- Characterize cooling technologies
- Identify cooling limitations (durability)



Application Technical Specifications

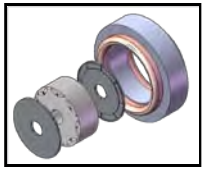
- Link machine specifications and cooling technologies.

Cooling Technology Selection



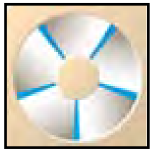
Thermal Design Targets

Thermal Resistance



Package Mechanical Design

Cooling Technology Balance of System



- Create FEA/Lumped thermal models (UW, NREL)
- Perform thermal interface testing (NREL)

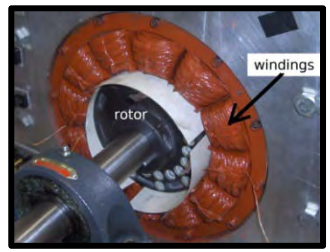
- Collaborate with Vehicle Technologies cross-cut activity for vehicle thermal management – APEEM, Energy Storage Systems (ESS), Vehicle Systems Analysis (VSA)

Technical Accomplishments

Application Technical Specifications

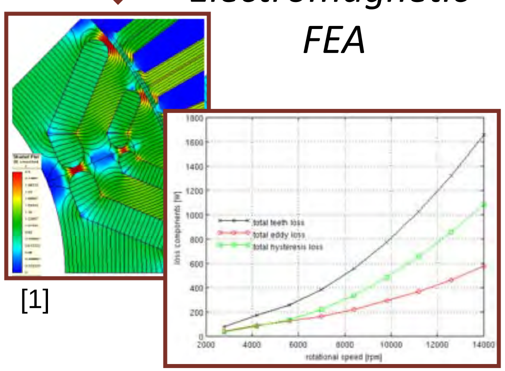
- Obtained thermal heat loads for selected operating points
  - Literature search
  - ORNL : Benchmarking thermal data for Camry and Prius motors
  - UW-Madison: Machine losses for thermal analysis (FEA/lumped parameter)

UW-Madison Thermal Characterization Project



[1]

Electromagnetic FEA



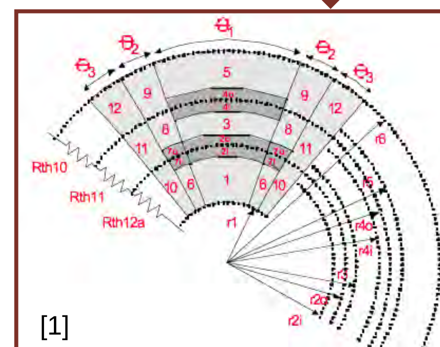
[1]

[1]

Component Losses

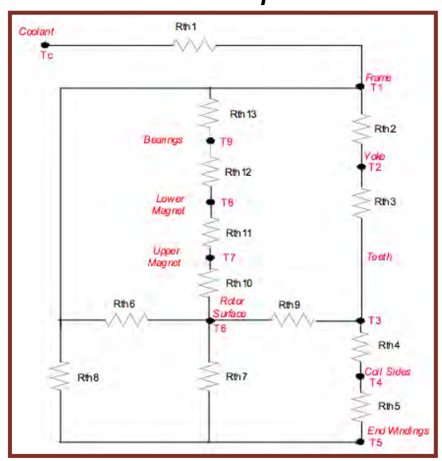
Loss Inputs

Thermal Impedance Mapping



[1]

Machine Thermal Equivalent Circuit



[1]

Thermal Impedance Values

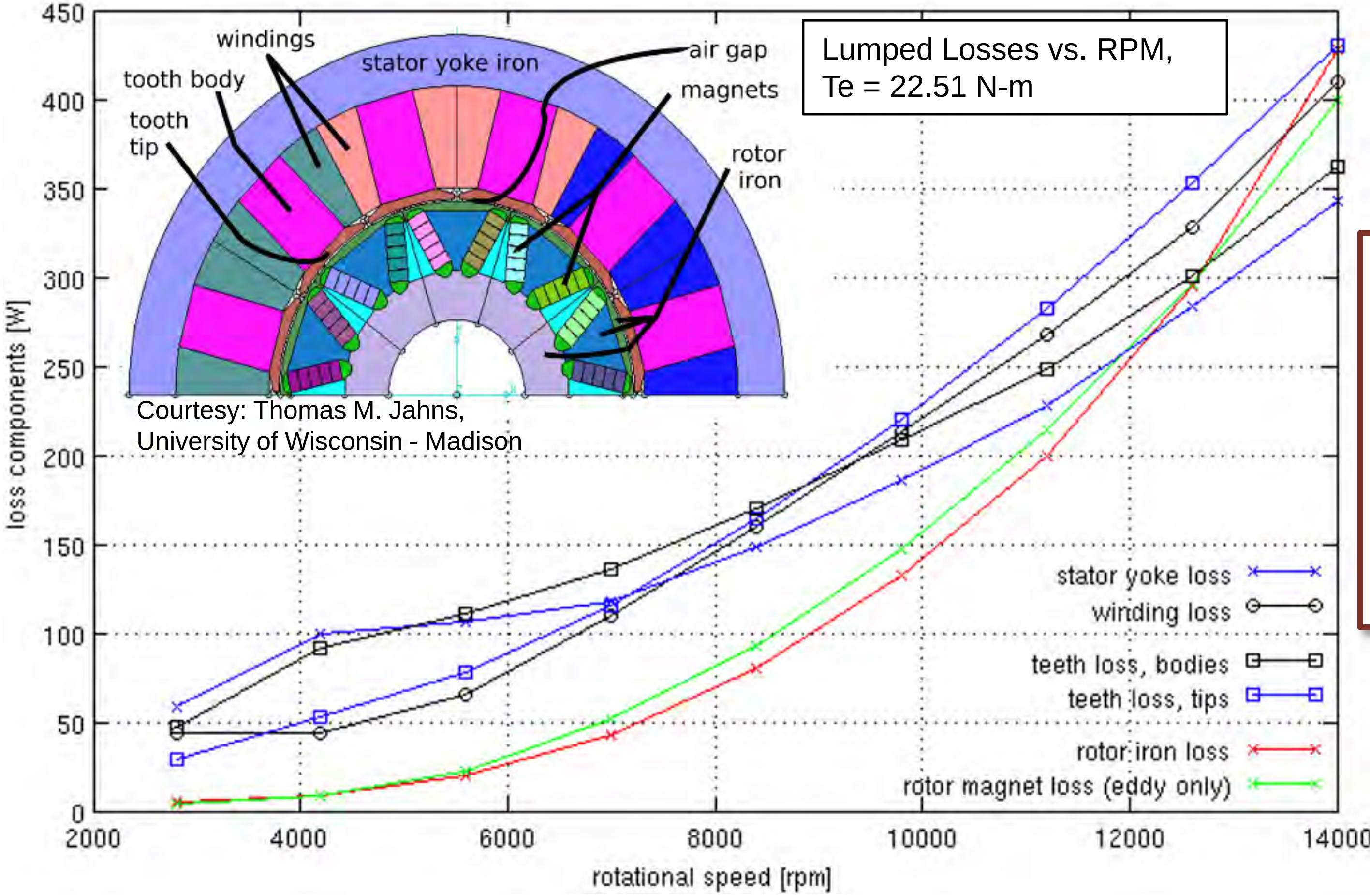
Temperature Predictions

[1] Courtesy of Thomas M. Jahns, University of Wisconsin - Madison

Technical Accomplishments

Application Technical Specifications

UW-Madison Thermal Characterization Project: *FEA-Based Loss Prediction Technique*



Losses can be predicted rapidly for any operating condition

- Electromagnetic FEA used to calculate losses in all major parts of the machine for a given reference speed and direct/quadrature (dq) axis current vector operating point
- Losses calculated for an array of operating points at the same reference speed
- Losses extrapolated for other speeds using physics-based scaling factors

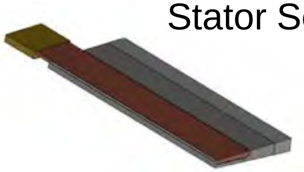
Technical Accomplishments

Package Mechanical Design

- Selected range of permanent magnet (PM) motor configurations
- Applied parametric thermal FEA models to initial motor geometry
- Quantifying thermal interface resistances and lamination material properties

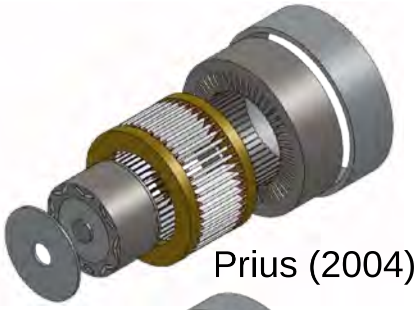
Published PM Motor with Water Jacket

Stator Section



Published Motor Data*
NREL Thermal Modeling

ORNL PM Motor Benchmarking with Oil Cooling

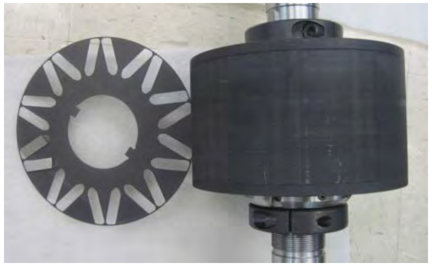


Prius (2004)

Camry

ORNL Data
NREL Thermal Modeling

UW-Madison PM Motor with Concentrated Winding



[1]

[1]

UW Data
UW Thermal Model

*J. Lindström, "Thermal Model of a Permanent-Magnet Motor for a Hybrid Electric Vehicle," Department of Electric Power Engineering, Chalmers University of Technology, Göteborg, Sweden, 1999.

[1] Courtesy: Thomas M. Jahns, University of Wisconsin - Madison

Technical Accomplishments

Package Mechanical Design

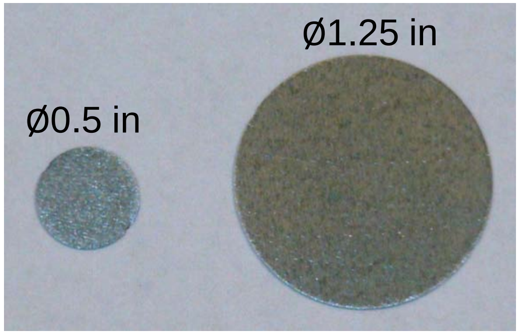
Motor Lamination Stack Effective Thermal Conductivity Testing

Goal

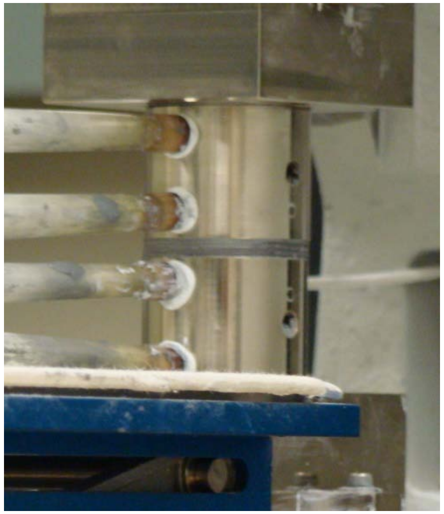
- Utilize developed lab capabilities (ASTM Stand & Xenon Flash) to measure material thermal properties of individual laminations and stacked lamination structures to support thermal modeling efforts.

Status

- Initial material sample testing in progress (M-19)
- Interface tests scheduled once material samples are characterized
- Expand to other material samples



Sample Laminations [1]



ASTM Stand [1]

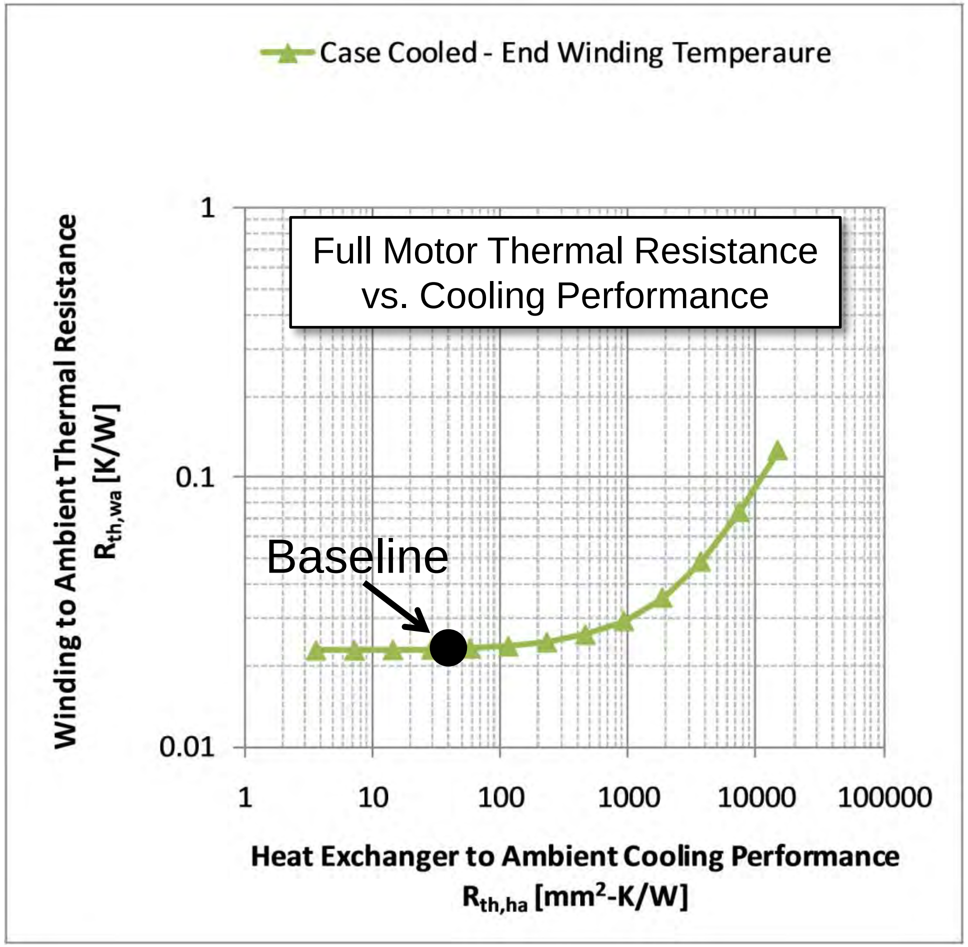
Insulation Type	Lamination Type	Lamination Thickness (mm)	Contact Pressure (psi)	Interface
C-5	M-19 Silicon Steel	0.635, 0.47, 0.356	20 - 100	Air
C-5	Arnon 5,7	0.127, 0.1778	20 - 100	Air
C-5	HF10	0.26	20 - 100	Air

[1] Credit: Kevin Bennion, NREL

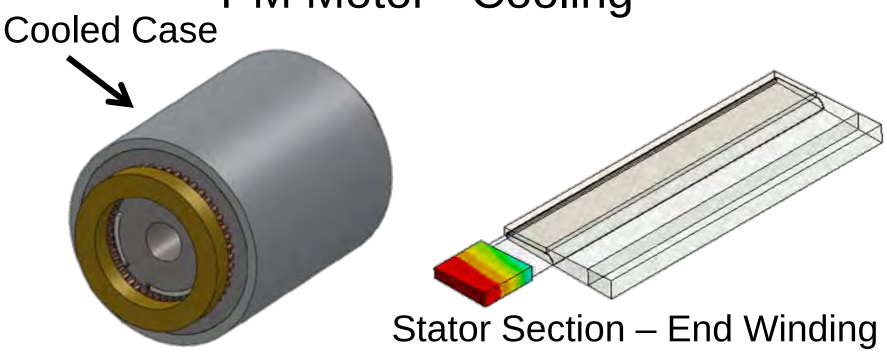
Technical Accomplishments

Thermal Design Targets

- Developed approach to link thermal design elements together to perform thermal performance trade-off studies for motors.
  - Operating point (heat load distribution), materials, mechanical package, and cooling mechanism affect thermal performance curves



PM Motor - Cooling



- Matched case cooling condition against published data with water jacket (baseline)*
  - Material properties
  - Cooling
  - Thermal interfaces

*J. Lindström, “Thermal Model of a Permanent-Magnet Motor for a Hybrid Electric Vehicle,” Department of Electric Power Engineering, Chalmers University of Technology, Göteborg, Sweden, 1999.

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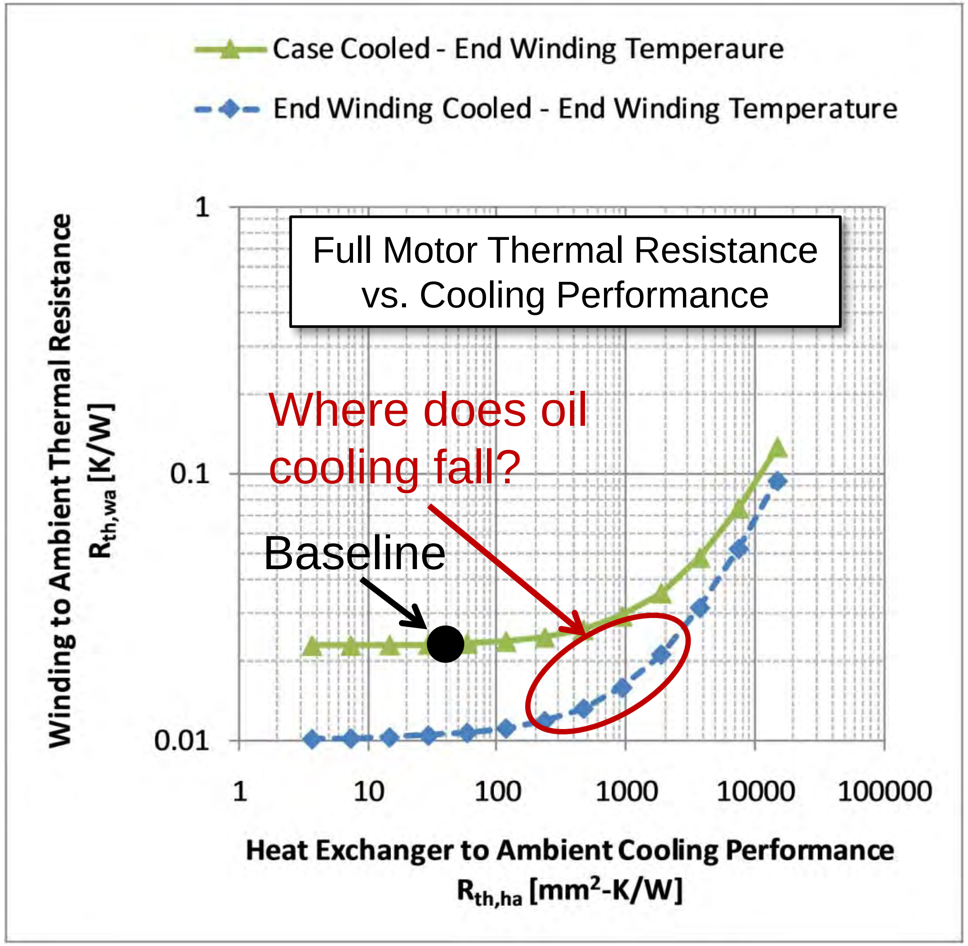

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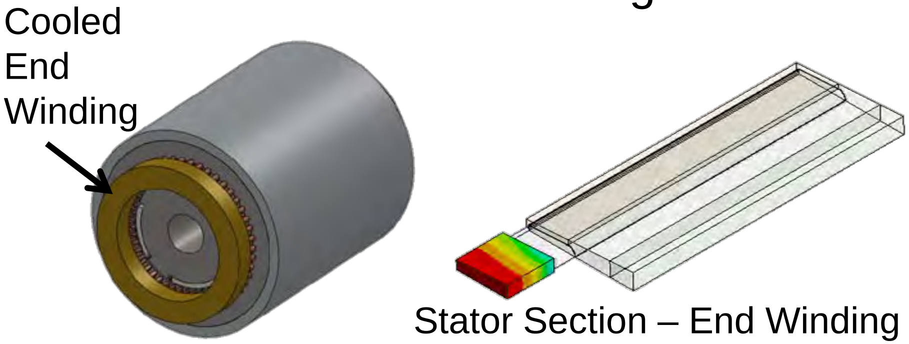

- Compared alternative cooling conditions
  - Cooling applied to case
  - Cooling applied to end windings

Technical Accomplishments

- Developed approach to link thermal design elements together to perform thermal performance trade-off studies for motors.
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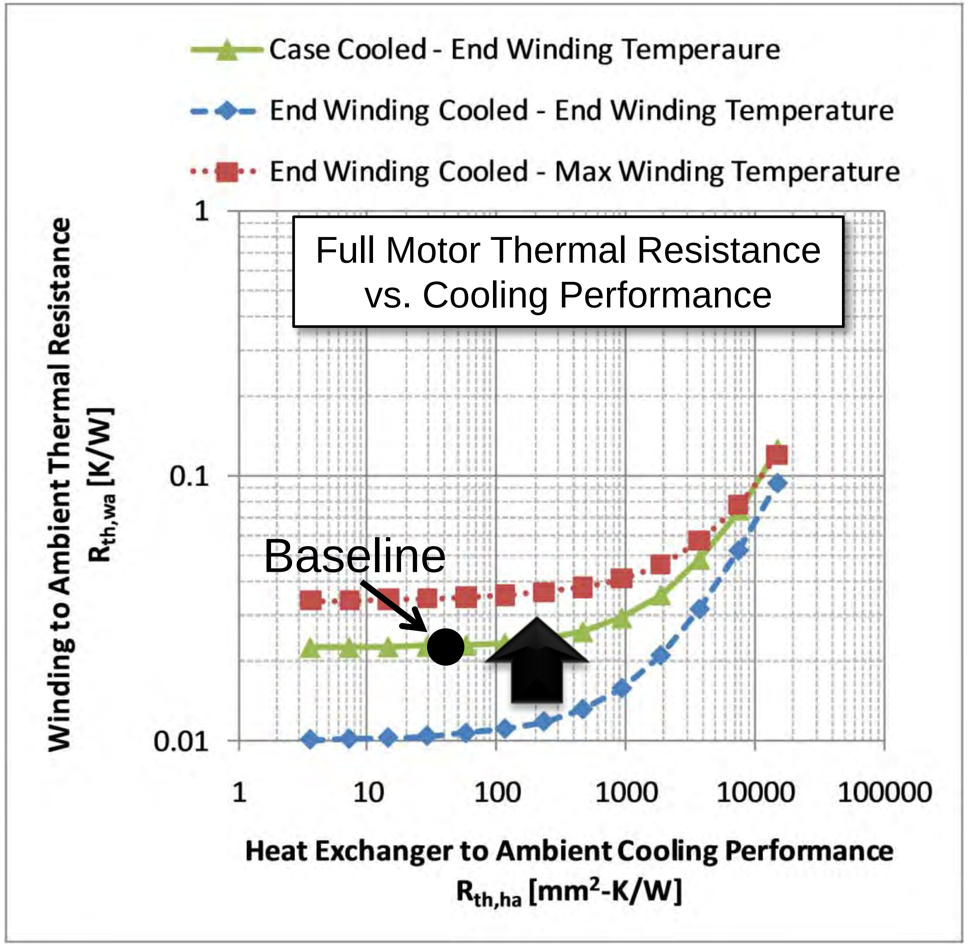
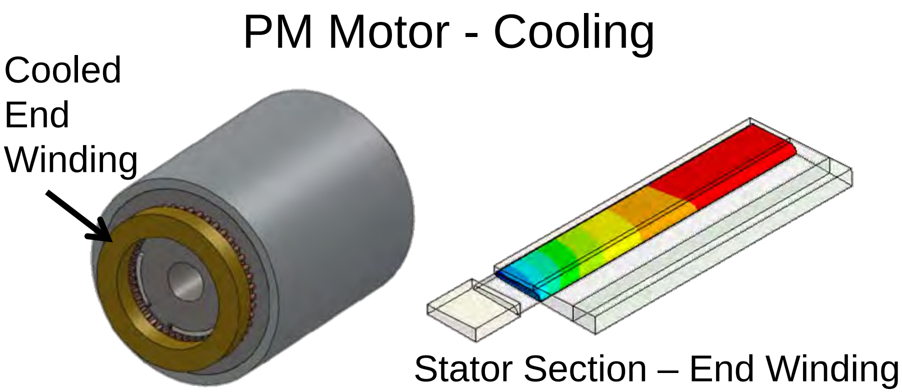
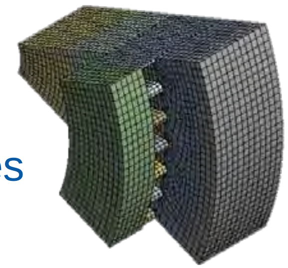




- Shifted peak temperature location
  - Higher temperature in slot
  - Increased thermal resistance (red)

- Next Steps
  - Shorter stack geometry
  - Combined cooling
  - Material sensitivity studies
  - Heat spreading methods



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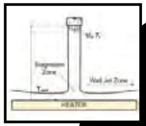
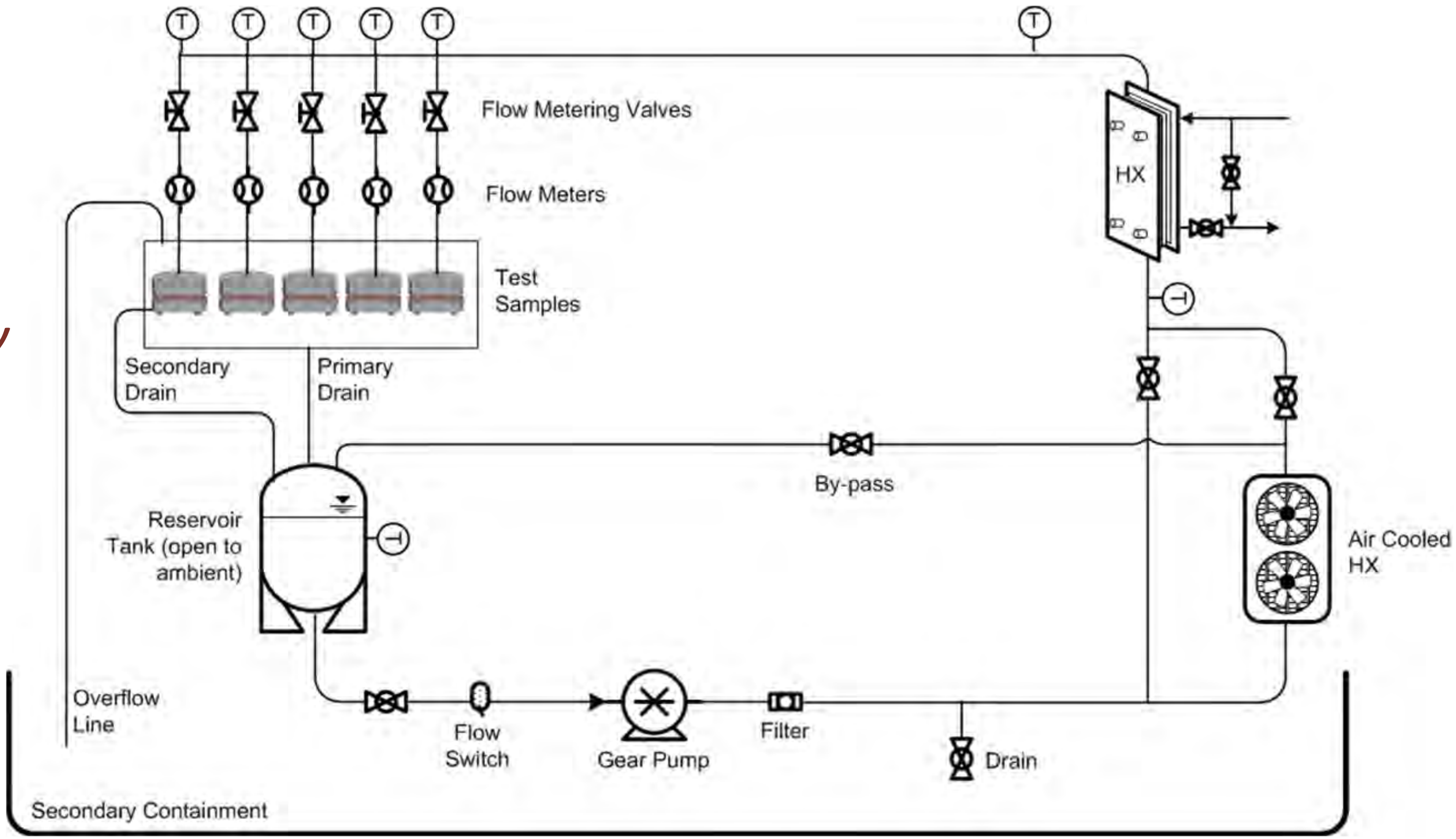


- Initiated efforts to apply experience with jets and sprays to motor cooling
- Developed experimental hardware design for oil-jet cooling characterization and durability evaluation
- Completed literature review and comparison of cooling methods for automotive use

<u>Oil Thermal Loop</u>

Insulation Durability



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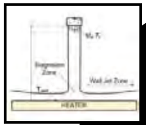

Cooling Technology Selection

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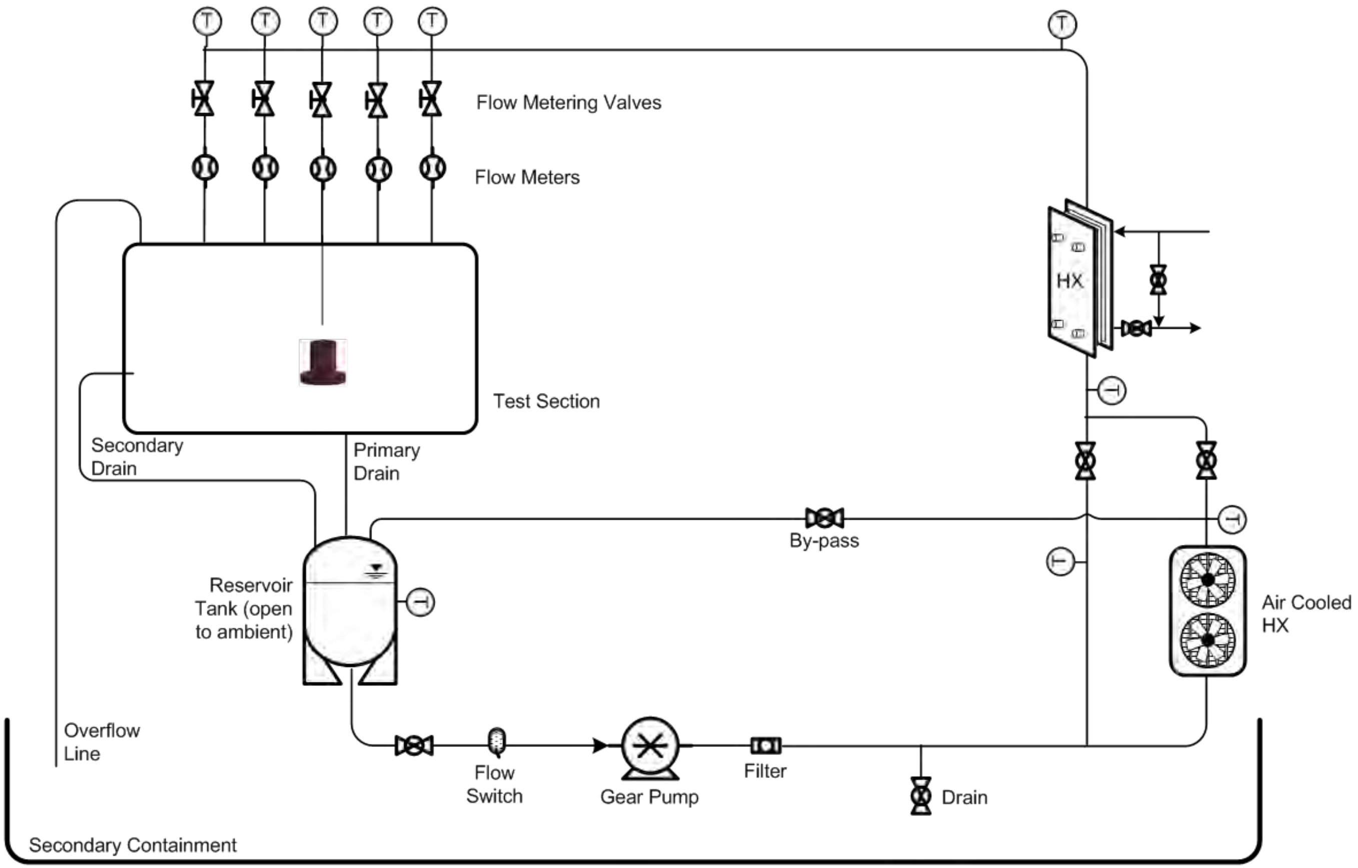
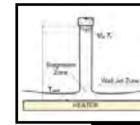
Oil Thermal Loop

Fundamental Cooling Characterization



Technical Accomplishments



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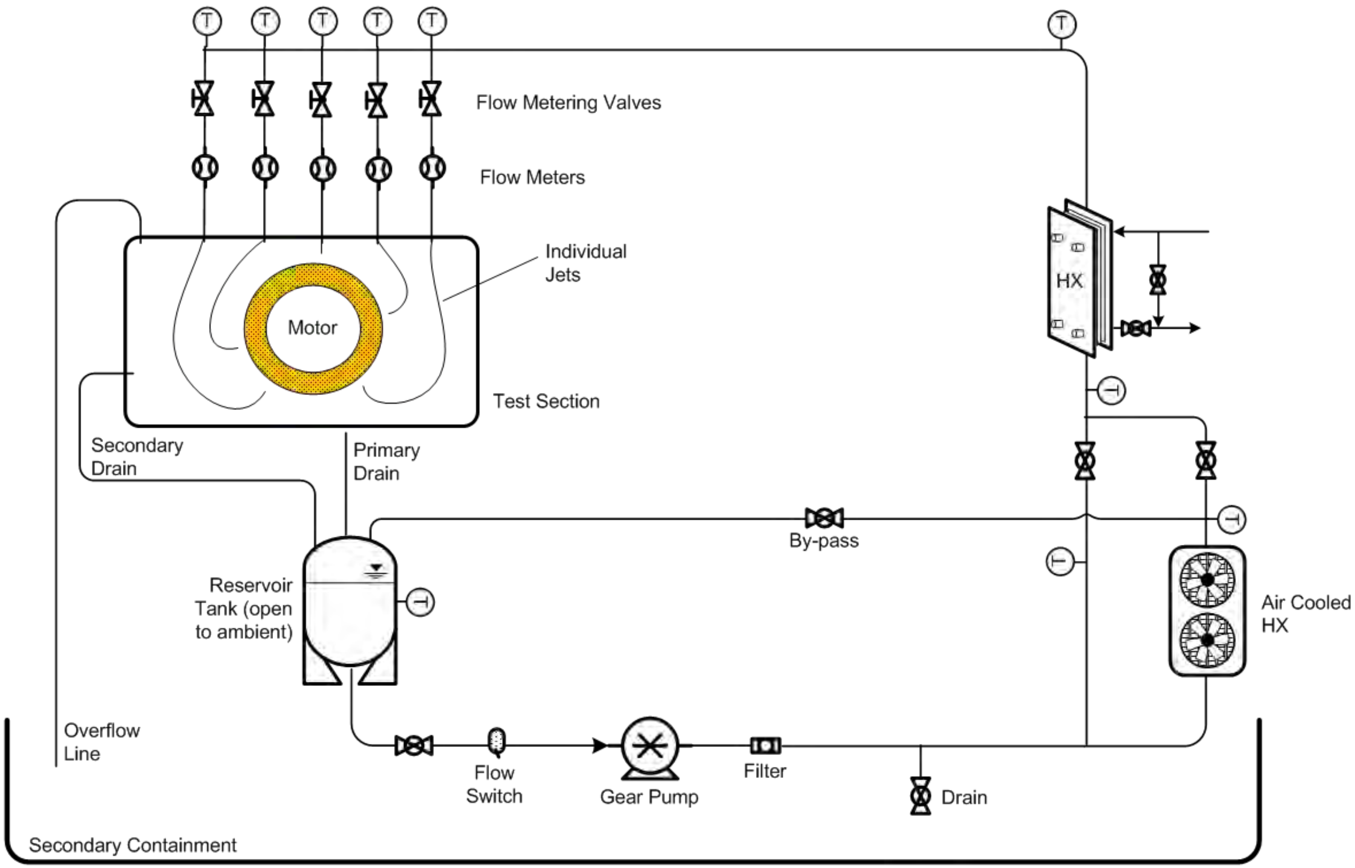
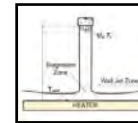
Oil Thermal Loop

System Cooling Characterization



Technical Accomplishments



Cooling Technology Selection

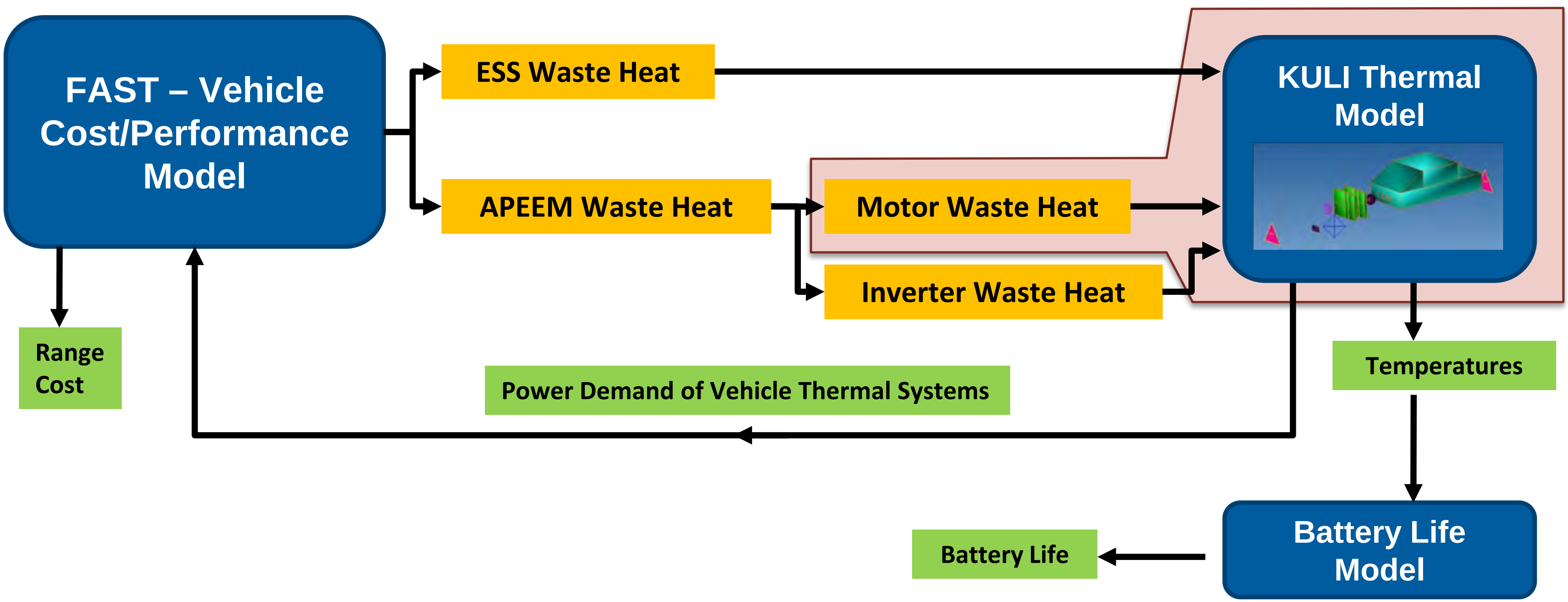
Comparison of Cooling Approaches: Summary

Available Cooling	Induction Motor	PM Motor
Oil	• Allows direct cooling of stator and rotor • **Integrates well with transmission** • Full electric vehicle (EV) without transmission may not have oil available for cooling • **Gravity-fed system has limited flow** • **Flow velocity and dynamic force impacts**	• Allows direct cooling of stator and rotor • Integrates well with transmission • Full EV without transmission may not have oil available for cooling • Gravity-fed system has limited flow • Flow velocity and dynamic force impacts • **Magnet temperature distribution (hot spots)**
Water/ Ethylene Glycol	• Significant heat produced in rotor • **Challenge to remove heat from rotor** • Heat from rotor can impact bearing durability	• Direct rotor cooling may not be as critical for certain designs (potential for lower rotor losses) • **Lower rotor temperature limit because of magnet material (rare-earths, addition of dysprosium)** • May require overdesign of the magnet or machine to ensure operation within thermal limits • Magnet temperature distribution (hot spots)
Air	• Can enable rotor and stator cooling • **Low cost** • Lower heat transfer capacity per volume • Potential for high pumping losses • **Particulate filtering**	• Same as induction with additional magnet concerns (see above)

Technical Accomplishments

Cooling Technology Balance of System

- Linked to Vehicle Technologies Program (VTP) cross-cut project "Combined Heating/Cooling Loops in Advanced Vehicles," which covers APEEM, Energy Storage System (ESS), and Vehicle Systems Analysis (VSA) areas.
  - Supported APEEM integration into vehicle thermal analysis flow model
  - Collaborating to investigate approaches to integrate APEEM cooling with other vehicle thermal management systems



Collaboration and Coordination

University

- University of Wisconsin – Madison (Thomas M. Jahns)
  - Support with electric machine expertise

Industry

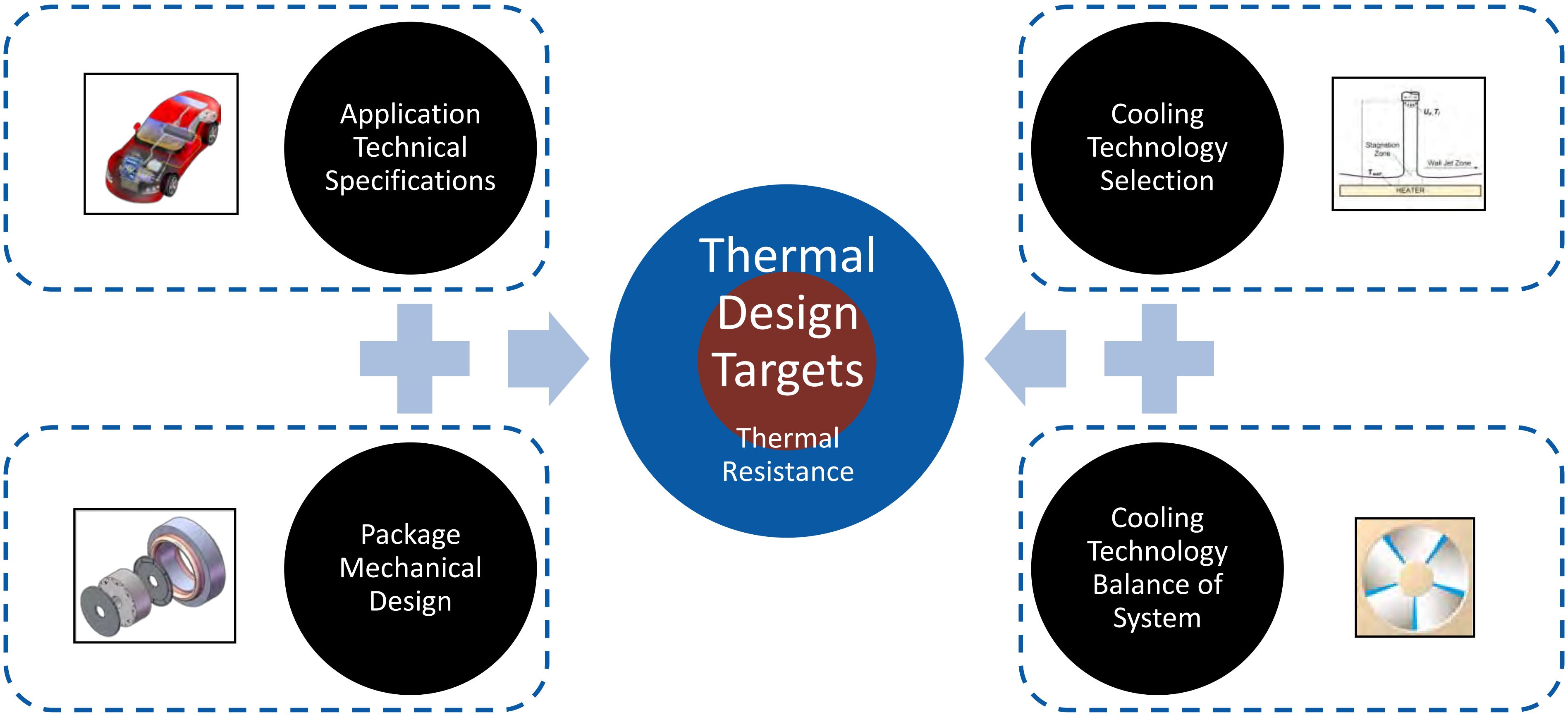
- Electrical & Electronics Tech Team
  - Input on research plans
- Motor industry suppliers, end users, and researchers
  - Input on research and test plans

Other Government Laboratories

- ORNL
  - Support from benchmarking activities
  - Ensure thermal design space is appropriate and modeling assumptions are consistent with other aspects of APEEM research
- Other VTP areas
  - Collaborate with VTP cross-cut effort for combined cooling loops

Proposed Future Work

- Expand heat generation model development for alternative machine configurations with reduced rare earth materials [FY12]
- Test oil cooling durability [FY11-12]
- Perform oil cooling thermal characterization [FY12]
- Develop and test cooling designs [FY12]



- Expand to other machine configurations (winding structures, reduced rare earths, wheel motors) [FY11-12]
- Evaluate heat spreading technologies [FY11-12]
- Refine motor thermal models to support VTP cross-cut activity (APEEM, ESS, VSA) [FY11]

Summary

Relevance

- Impacts the transition to more electrically dominant propulsion systems with higher continuous power requirements
- Enables improved performance of non-rare earth machines
- Supports lower cost through reduction of rare earth materials used to meet temperature requirements (dysprosium)
- Applies experimental and analytical capabilities to quantify and optimize the selection and design of effective motor cooling approaches

Approach/Strategy

- Develop process to evaluate thermal management trade-offs between alternative cooling technologies for electric machines
  - Application Specifications
  - Package Mechanical Design
  - Cooling Technologies
  - Cooling Balance of System

Summary

Technical Accomplishments

- Obtained PM thermal load data: Literature, ORNL, UW-Madison
- Selected range of PM motor configurations for cooling evaluation with available thermal data
- Developed parametric thermal FEA models for thermal trade-off studies
- Started characterization of thermal interface properties to feed model development
- Completing heat load and lumped thermal parameter estimation methods to support vehicle level cooling analysis
- Collaborating with VTP cross-cut activity for vehicle thermal management

Collaborations

- Collaborations established with research and development partners
  - University of Wisconsin – Madison
  - Oak Ridge National Laboratory
  - Motor Industry Representatives: Manufacturers, researchers, and end users (light-duty and heavy-duty)

Acknowledgements:

Susan Rogers, U.S. Department of Energy

Tim Burress, Oak Ridge National Laboratory

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Douglas DeVoto

Gilbert Moreno

Mark Mihalic

Thomas M. Jahns (UW–Madison)

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