Integrated Traction Drive Thermal Management

Keystone Project 3

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June 21, 2022

DOE Vehicle Technologies Program
2022 Annual Merit Review and Peer Evaluation Meeting

Project ID # elt217

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Overview

Timeline

- Project start date: October 2018
- Project end date: September 2024
- Percent complete: 70%

Budget

- Total project funding: $1,000,000
  - DOE share: $1,000.000
- Funding for FY 2021: $250,000
- Funding for FY 2022: $250,000

Barriers

- Barriers addressed
  - Cost
  - Power density of a traction drive/system
  - Reliability and lifetime

Partners

- Research institutions
  - Oak Ridge National Laboratory (ORNL)
  - University of Wisconsin-Madison
  - Ames Laboratory

Relevance

Objectives:

- Research and evaluate motor-integrated power electronics packaging technologies and thermal management approaches.
- Develop thermal management system and its subcomponents to enable integrated electric drive DOE power density targets in collaboration with project partners.
- Support activities of DOE's Electric Drive Technologies (EDT) consortium members, ORNL, and University of Wisconsin research teams in thermal management component design and thermal modeling of their integrated traction drives.
- Identify candidate driveline fluids suitable for direct cooling of traction-drive components and high-voltage power electronics and evaluate their convective cooling performance.

Project Impact:

- Identify pathways enabling high-performance, compact, and reliable integrated electric drives.
- Help achieve DOE 2025 target of 33-kW/L system power density for an electric traction drive.

FY 2022 Milestones

Milestone Name/Description	Criteria	End Date	Status
Manufacture and evaluate performance of developed select key subcomponents and/or subcomponent assemblies of integrated traction drive thermal management system.	Heat removal performance meets thermal loads of key motor and/or inverter components at the rated design power output.	09/30/2022	On Track

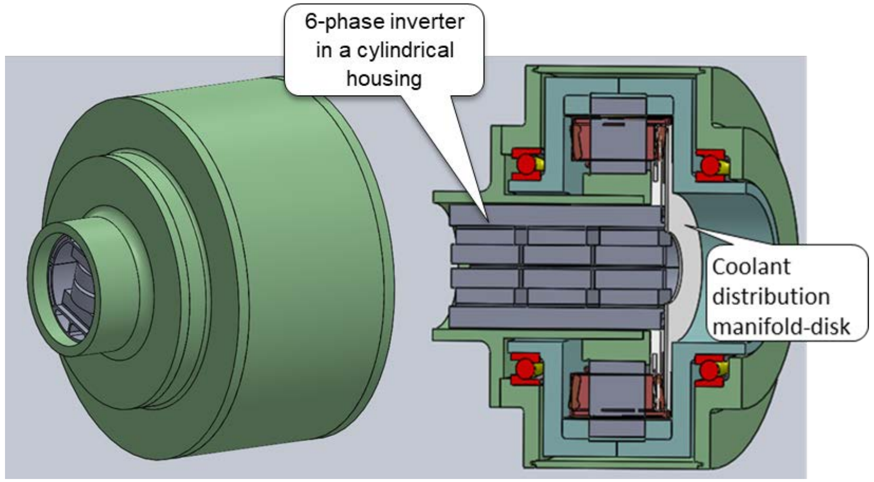
Approach

- Use combination of various cooling strategies for most efficient heat removal from integrated traction drive components.
- Support design of a thermal management solution appropriate to each collaborating (ORNL and University of Wisconsin) team's selected integrated drive concept:
  - Support design of a combined thermal management system and its subcomponents for electric motor and integrated power electronics cooling.
  - Preferably use a single fluid loop approach to enable the integrated cooling system for inverter + motor.
  - Select appropriate materials for the cooling system components (i.e., heat exchangers for ORNL drive):
    - Transparent for electromagnetic field to minimize interference with electric motor operation
    - Electrically isolating to avoid short-circuiting electrically sensitive parts and ensure reliable phase separation of windings
    - Thermally conductive to improve heat removal from heat-generating components of the integrated drive.
  - Employ thermal modeling tools: finite element analysis (FEA) and computational fluid dynamics (CFD) to inform design solutions.
- Design, model and test thermal management system components to reduce thermal resistance of the motor and power electronics packaging stack-up to help increase system power density.

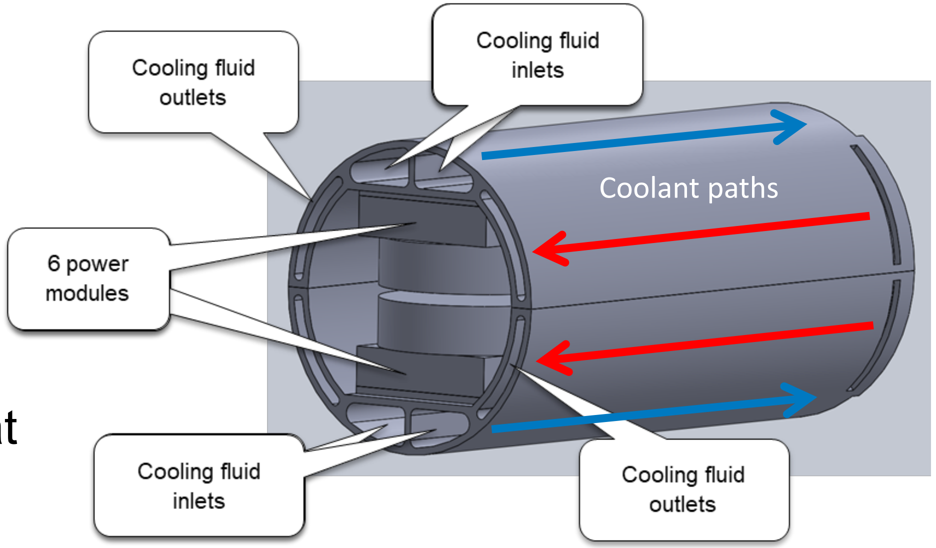
Technical Accomplishments and Progress

ORNL integrated traction drive

- Features a single loop cooling concept for ORNL outer-rotor motor with integrated power electronics in its central cavity.
- Designed a cylindrical housing for power electronics integration into central cavity of the electric motor. Completed number of design revisions.
  - Features internal channels for coolant flow.
  - Serves a dual purpose for:
    - Removing heat from power electronics and stator's internal cylindrical surface.
    - Providing coolant to phase-separator T-shape heat exchangers embedded in the windings, removing heat from thermally critical area of the stator.



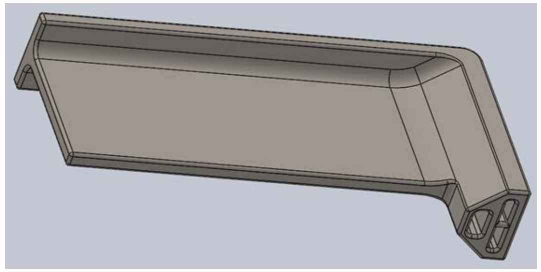
Design concept of ORNL's integrated traction drive with inverter in central cavity. CAD design by Randy Wiles, Jon Wilkins, Tsarafidy Raminosoa, Mostak Mohammad (ORNL) and Bidzina Kekelia (NREL)



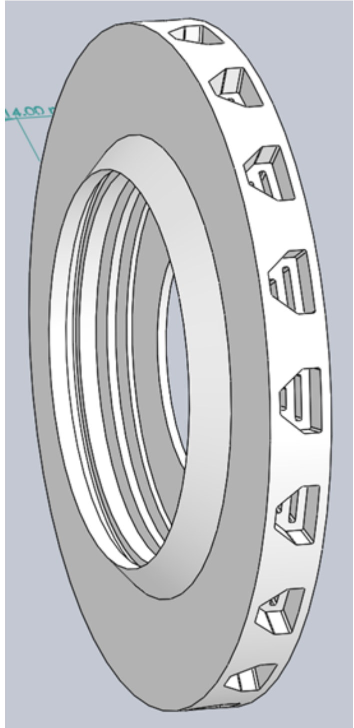
Design concept of a cylindrical inverter housing with cooling fluid channels in the walls. CAD design by Bidzina Kekelia (NREL)

ORNL integrated traction drive (continued)

- Completed several design revisions of T-shape heat exchanger embedded between winding phases.
- Completed number of design revisions for coolant distribution manifold-disk.
- Evaluating options for manufacturing cooling system components:
  - Extruded aluminum for inverter housing
  - 3D-printing T-shape heat exchangers from:
    - High thermal conductivity polymer/resin (8–10 W/m·K)
    - Al_2O_3 Ceramic (28–35 W/m·K)
  - 3D-printing fluid distribution manifold from polymer



Phase separator T-shape heat exchanger. CAD design by Bidzina Kekelia and Emily Cousineau (NREL)



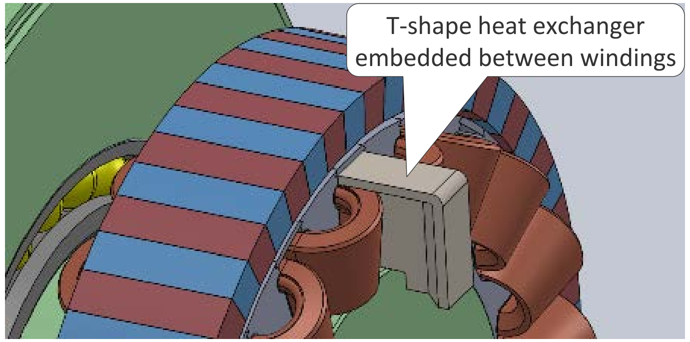
Coolant distribution manifold-disk.
CAD design by Bidzina Kekelia (NREL)

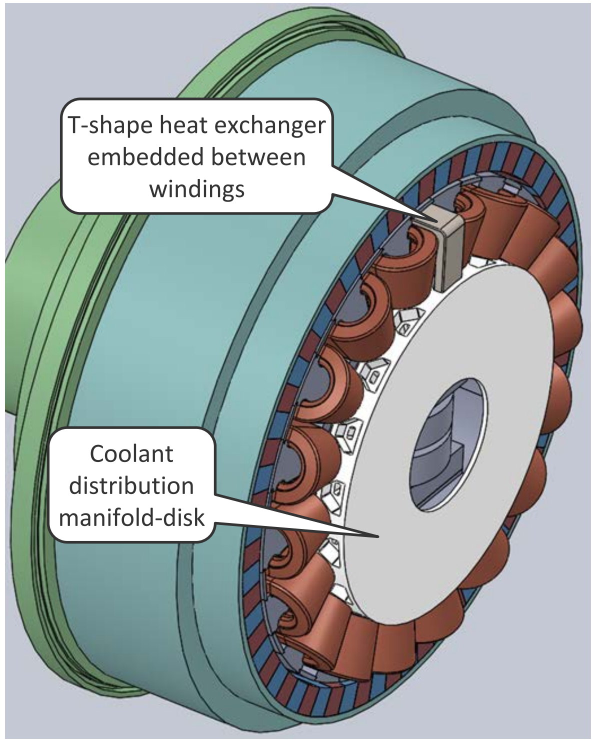
Technical Accomplishments and Progress

ORNL integrated traction drive (continued)

- Next Steps:
  - Together with NREL's and ORNL's teams, finalize T-shaped heat exchanger prototype design:
    - Optimize heat exchange surfaces through thermal modeling
    - Select material and manufacture (3D print) and experimentally measure its thermal performance.
  - Finalize coolant distribution manifold-disk design, manufacture and experimentally test it.
  - Finalize prototype design, manufacture and test thermal performance of cylindrical aluminum housing for the inverter.
  - Assemble core thermal management system components and test their combined performance.

Any proposed future work is subject to change based on funding levels.

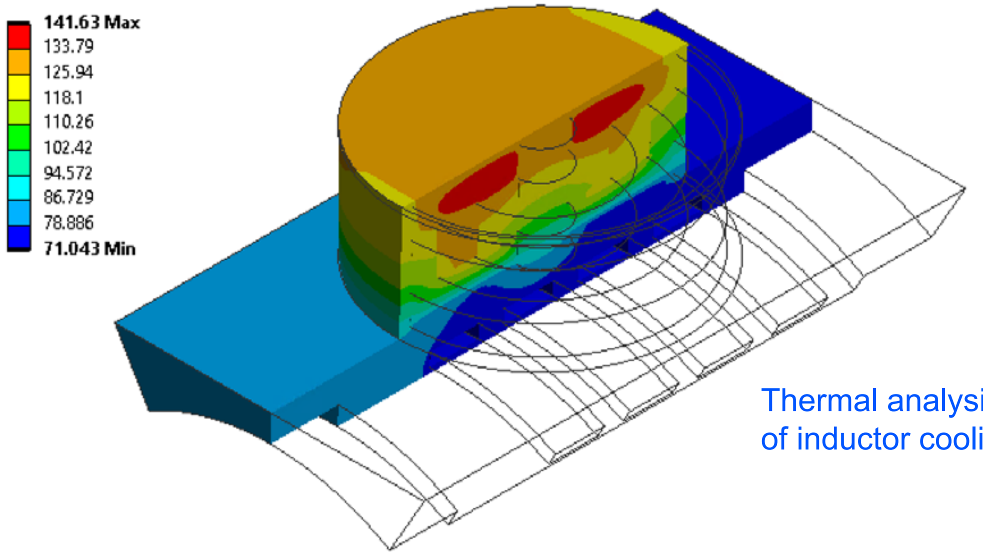




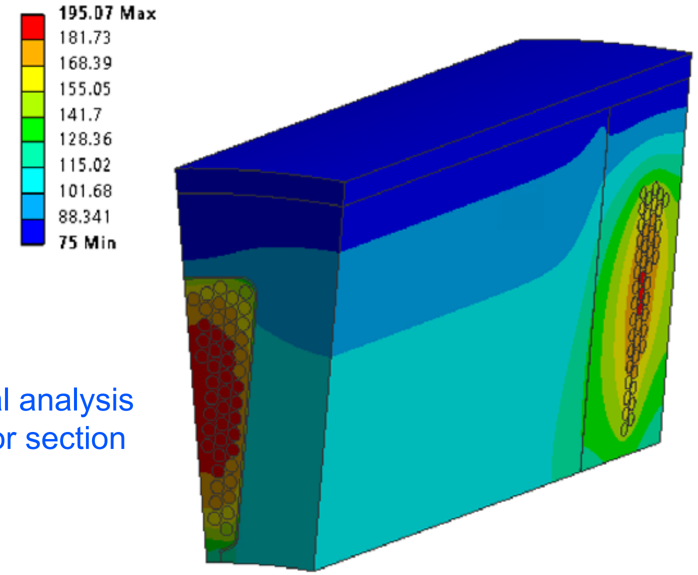
Key components of thermal management system assembly for ORNL's outer-rotor integrated drive.

University of Wisconsin integrated traction drive

- Providing technical support, thermal data, and material information to support integrated thermal management system design for cooling electric motor and power electronics.
- Ongoing regular discussions and consultations on thermal management system design aspects for Wisconsin's integrated traction drive concept.



Thermal analysis of inductor cooling



Thermal analysis of stator section

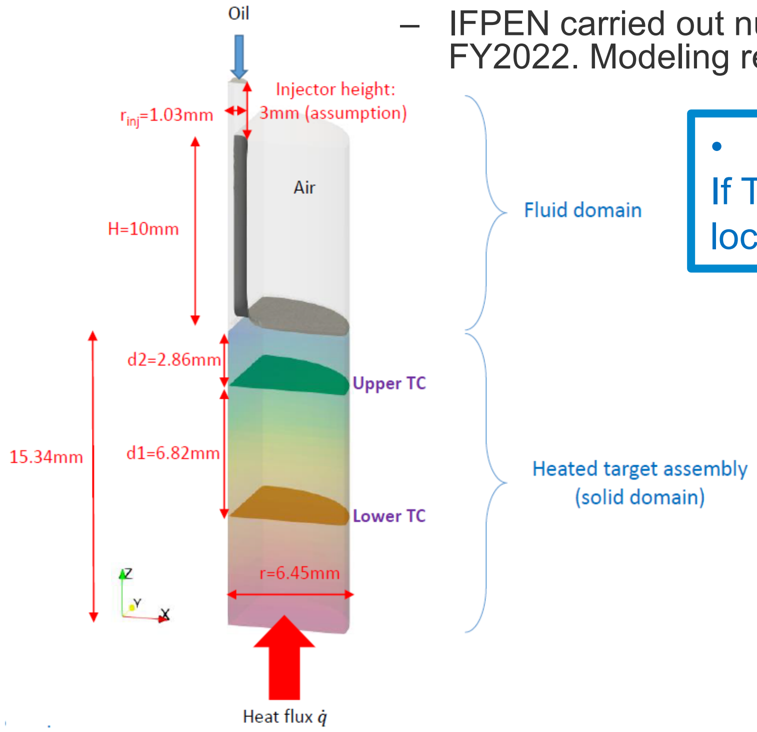
Inductor (left) and stator section (right)'s temperature distribution at the end of 30s peak power operation (100 kW) from steady-state of continuous power operation (55 kW). Results show capability of maintaining peak temperature below each part's thermal limit: 155ºC for inductor, and 220ºC for stator winding. Figures by University of Wisconsin.

Driveline Fluids:

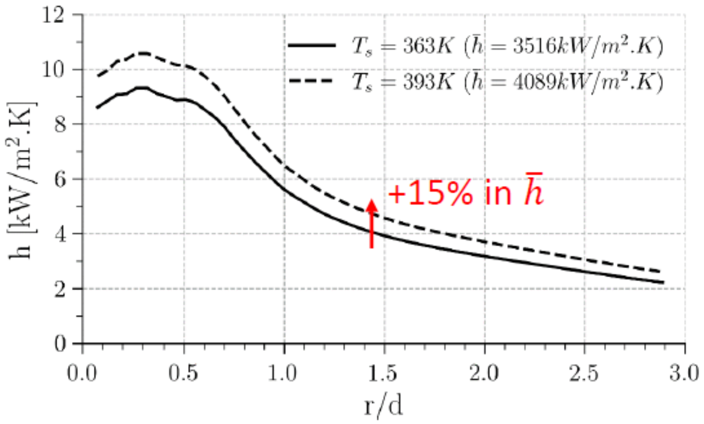
- Collaborative publication[1] with French public research institute **IFP Energies Nouvelles**[2] on ATF jet impingement cooling of electric traction drives.
  - NREL experimentally characterized automatic transmission fluid (ATF) jet impingement heat transfer coefficients (HTC) in FY 2015–2019.
  - IFPEN carried out numerical simulations of ATF jet impingement cooling in FY2021-FY2022. Modeling results showed excellent agreement with NREL's experimental findings.

ATF jet impingement on a heated target. Photo by Bidzina Kekelia (NREL)

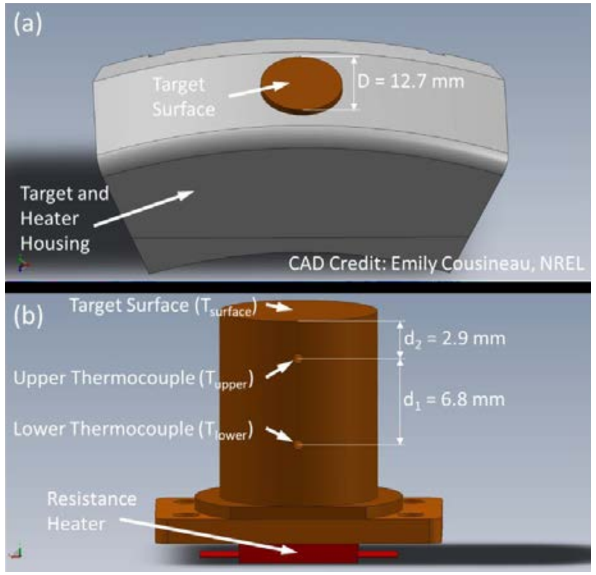
- Increasing surface temperature increases heat transfer:
If Ts↗, film temperature↗, ν↘, flow velocity↗(as film thickness↘) => local Re↗, δ↘, δt↘ (despite Pr↘) => h↗



Computational domain. Figure by Adèle Poubeau (IFPEN).



HTC dependence on cooled surface temperature. Figure by Adèle Poubeau (IFPEN).



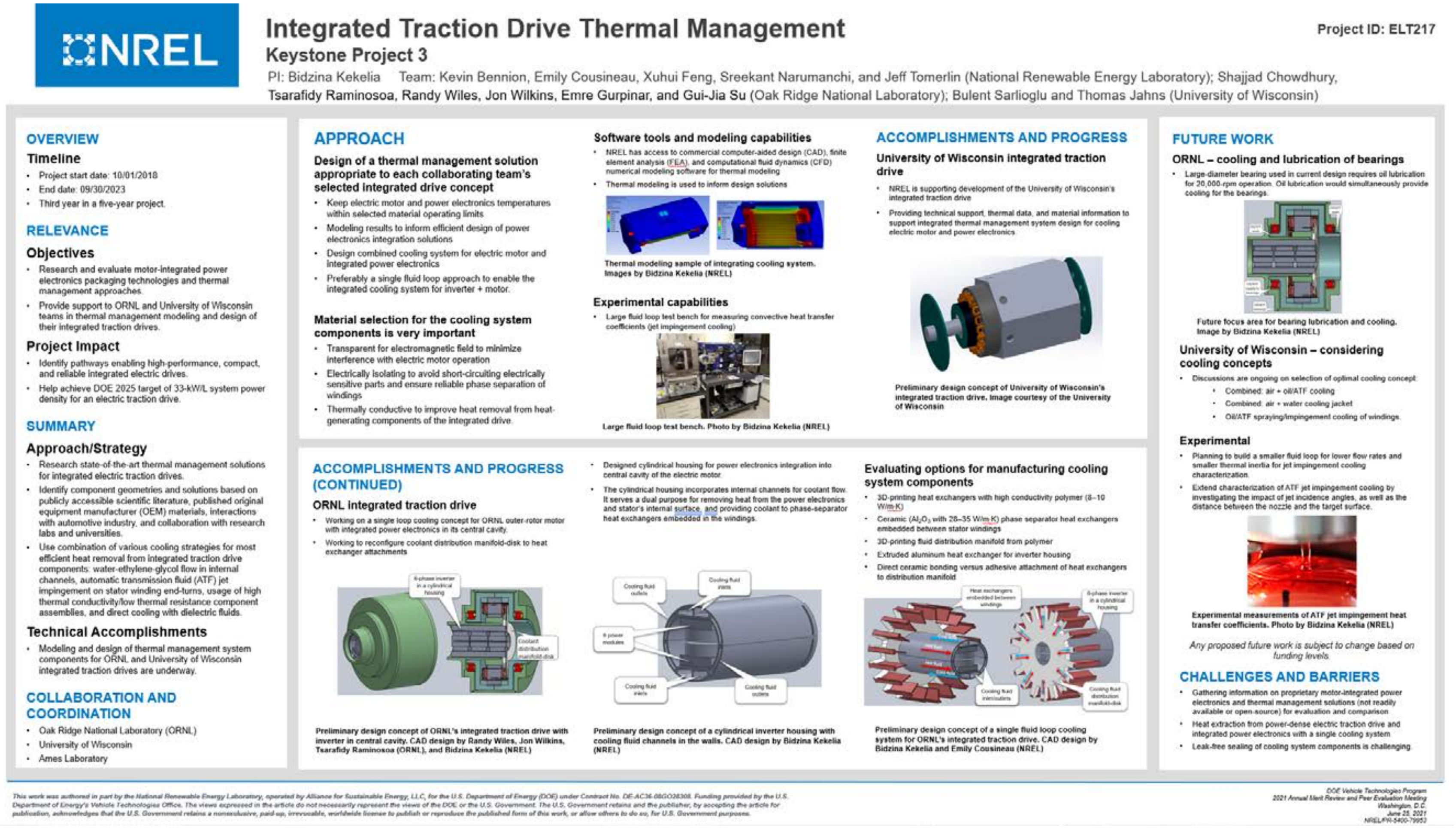
Heated target assembly: (a) assembled housing with exposed top surface of the target, (b) copper target with thermocouple locations and resistance heater mounted on its bottom. CAD design by Emily Cousineau (NREL).

1 Poubeau, A, Vinay, G, Kekelia, B, and Bennion, K, "Conjugate heat transfer simulations of high Prandtl number liquid jets impinging on a flat plate." International Journal of Heat and Mass Transfer. Manuscript submitted in March 2022. Available at SSRN: http://dx.doi.org/10.2139/ssrn.4059091

2 IFP Energies Nouvelles is a public research, innovation and training organization in the fields of energy, transport and the environment. https://www.ifpenergiesnouvelles.com/

Responses to Previous Year Reviewers' Comments

- This project presented a poster at the 2021 AMR and was therefore not reviewed.



Collaboration and Coordination

Collaborations within EDT consortium:

- Collaborating with ORNL's integrated drive team through regular meetings and exchange of design data, thermal modeling results and relevant information.
- Supporting University of Wisconsin's integrated drive team through regular meetings, providing technical advice on design, thermal modeling and component material data. Discussions and technical exchanges are held between University of Wisconsin, ORNL, Ames Lab and NREL researchers.

Collaboration outside EDT consortium:

- Collaborating with IFP Energies Nouvelles (French public research institute in the fields of energy, transport and the environment) on direct jet impingement cooling of electric machines with driveline fluids.

Remaining Challenges and Barriers

- Design of a single thermal management system for power electronics and electric motor would require cooling fluids with appropriate physical, thermal and dielectric properties.
- Material selection for cooling system components: ceramics versus thermally enhanced polymers.
- Coefficient of thermal expansion (CTE) mismatch between components of cooling system poses a problem when thermally cycling electric drive components.
- Leak-free sealing of cooling system components is challenging.

Proposed Future Research

Planned for FY2022 and FY2023

ORNL integrated traction drive

- Finalize T-shaped heat exchanger prototype design:
  - Optimize heat exchange surfaces through thermal modeling (FY2022)
  - Select material (ceramics versus thermally enhanced polymer) and manufacture (3D print) the heat exchanger (FY2022)
  - Experimentally measure its thermal performance (FY2023).
- Finalize coolant distribution manifold-disk design:
  - Select material and manufacture (3D print) it (FY2023).
- Finalize cylindrical housing prototype design for the inverter:
  - Carry out thermal FEA modeling to confirm its cooling capability (FY2022)
  - Manufacture using extruded aluminum (FY2023).
- Assemble core thermal management system components and test their performance (FY2023)

University of Wisconsin integrated traction drive

- Continue providing technical support trough regular meetings, thermal data, and material information to support integrated thermal management system design for University of Wisconsin integrated traction drive concept (FY2022 through FY2023).

Any proposed future work is subject to change based on funding levels.

Summary

Relevance

- Effective thermal management is essential for high performance, compact (power dense), and reliable integrated electric traction drives to achieve the 2025 DOE system power density target of 33 kW/L.

Approach

- Use combination of various cooling strategies for most efficient heat removal from integrated traction drive components.
- Support design of a thermal management solution appropriate to collaborating EDT consortium member (ORNL and University of Wisconsin) team's selected integrated drive concept.
- Employ thermal modeling tools: FEA and CFD to inform design solutions.

Technical Accomplishments

- ORNL integrated traction drive:
  - Cylindrical inverter housing - completed number of design revisions.
  - T-shape heat exchanger embedded between windings - completed several design revisions.
  - Coolant distribution manifold-disk - completed number of design revisions.
- University of Wisconsin integrated traction drive:
  - Providing technical support, thermal data, and material information to support integrated thermal management system design.
- Published an article in the Electronics Cooling Magazine on comparison of thermal management system concepts for integrated traction drives.

Collaborations

- Collaborating with ORNL's integrated drive team through regular meetings and exchange of design data and thermal modeling results.
- Supporting University of Wisconsin's integrated drive team. Discussions and technical exchanges are held between University of Wisconsin, ORNL, Ames Lab and NREL researchers.
- Collaborated with IFP Energies Nouvelles on direct jet impingement cooling of electric machines with driveline fluids resulting in a joint manuscript submitted to the International Journal of Heat and Mass Transfer.

Acknowledgments

Susan Rogers, U.S. Department of Energy

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Thank You

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NREL/PR-5400-82653

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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Reviewer-Only Slides

Publications and Presentations

Publications

- Kekelia, B, and Narumanchi, S. “Thermal Management of Integrated Traction Drives in Electric Vehicles.” *Electronics Cooling* 2022 Annual Guide https://learn.electronics-cooling.com/electronics-cooling-2022-annual-edition/
- Poubeau, A, Vinay, G, Kekelia, B, and Bennion, K, “Conjugate heat transfer simulations of high Prandtl number liquid jets impinging on a flat plate.” *International Journal of Heat and Mass Transfer*. Manuscript submitted in March 2022. Available at SSRN: http://dx.doi.org/10.2139/ssrn.4059091

Critical Assumptions and Issues

- Material selection for key thermal management system components and their interconnection is critical for the design of effective and reliable cooling system. Coefficient of thermal expansion (CTE) mismatch between components of cooling system poses a problem when thermally cycling electric drive components. This could potentially cause cracks between adhesive-filled joints and coolant leaks in electric machine cavity.
- CTE mismatch should be minimized through material and adhesive selection and thermal cycling testing should be performed to verify reliable interconnections between key cooling system components.