Unique Lanthanide-Free Motor Construction

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2015 Annual Merit Review

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Overview

Timeline

Project start date: 10/1/2011

Project end date: 4/30/2016

Percent complete: 80%

Budget

Total project funding

- $3,017K DOE Share
- $1,006K UQM Share

Funding received in FY14: $794K

Funding for FY15: $821K

Barriers Addressed

A: Electric motor cost

B: Elimination of rare-earth elements

E: Efficiency

Partners

Ames Laboratory: improved magnet properties

NREL: motor thermal management

ORNL: motor testing

Coordination provided by UQM Program Manager

Relevance to VTO

- If successful the motor design will meet DOE targets w/o Rare earth magnets
- Utilization of AlNiCo magnets will hedge the volatile pricing of NdFeB and other rare earth constituents.
- Proving out Proof of Concept design motors and confirmed near compliance with VTO specifications and OTS magnet materials
- Motors under development are applicable to a number of vehicle architectures for which the VTO is developing technology, including pure EV, Plug-in EV and many other vehicle architectures.
- The project has shown that non-rare earth motors can be manufactured and demonstrate competitive performance with SOA automotive motors

Approach - Milestones

Month/Year	Milestone or Go/No-Go Decision
02/2013 ✓	Milestone: complete motor assembly concept
04/2013 ✓	Milestone : Complete Period 1 and Enter Period 2
11/2013 ✓	Milestone: motor drawing package complete
04/2014 ✓	Milestone: motor build complete and ready for dynamometer testing
07/2014 ✓	Go/No-Go: UQM dynamometer testing demonstrates technology feasibility
09/2014 ✓	Milestone: delivery of proof of concept motor to ORNL for independent testing
01/2015 ✓	Milestone: Approval to continue into BP3 with enhanced magnet material from Ames

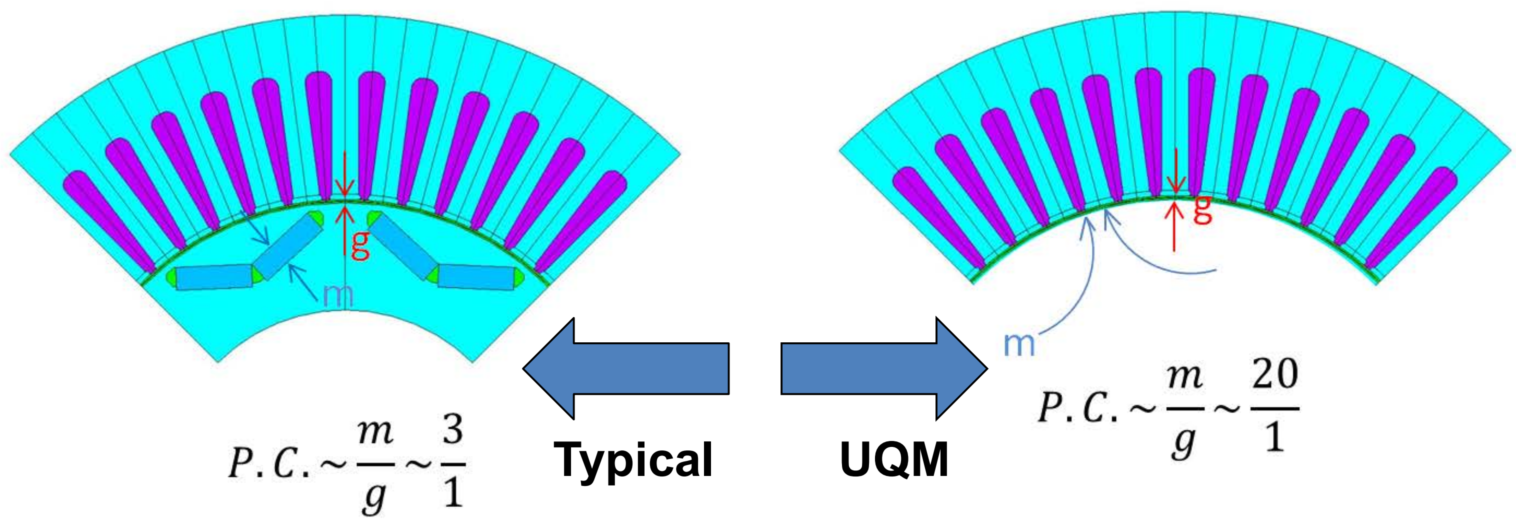
Approach - Milestones

Month/Year	Milestone or Go/No-Go Decision
10/2014 ✓	Milestone: Complete Period 2 and enter Period 3
11/2014 ✓	Go/No-Go: Proceed into BP3 based on ability to correct POC short comings
11/2015	Milestone: Incorporate enhanced magnets into POD motor design
02/2016	Milestone: Build two (2) POD motors
03/2016	Milestone: Dynamometer test at UQM POD motors to validate improvements
04/2016	Milestone: Deliver POD motor(s) to DOE for independent validation
03/2016	Milestone: Complete higher power (120kW) motor design
4/2016	Milestone: Completion of BP3 and project

Approach - Project Strategy

- Non-rare-earth magnet chemistries such as AlNiCo are capable of supporting the high flux densities needed to meet cost, power density, specific power, and efficiency targets
- These magnets are not used because they will demagnetize if used in existing magnetic circuit designs

UQM’s project strategy is to use and refine a magnetic circuit that avoids demagnetization ⇨ high permeance coefficient and low armature reaction fields experienced at the magnets



Coordination and Collaboration with Other Institutions

- Subcontractor: Ames Laboratory, FFRDC within the VT Program, for incremental improvements in high flux, low coercivity magnet materials
  - Enable high loads (current density) and minimize magnet content
- Subcontractor: National Renewable Energy Laboratory, FFRDC within the VT Program, for thermal management
  - Assembly heat rejection for power density and cost
- Subcontractor: Oak Ridge National Laboratory, FFRDC within the VT Program, for testing
  - Confirmatory testing; results to be used for design refinement between Year 2 and 3

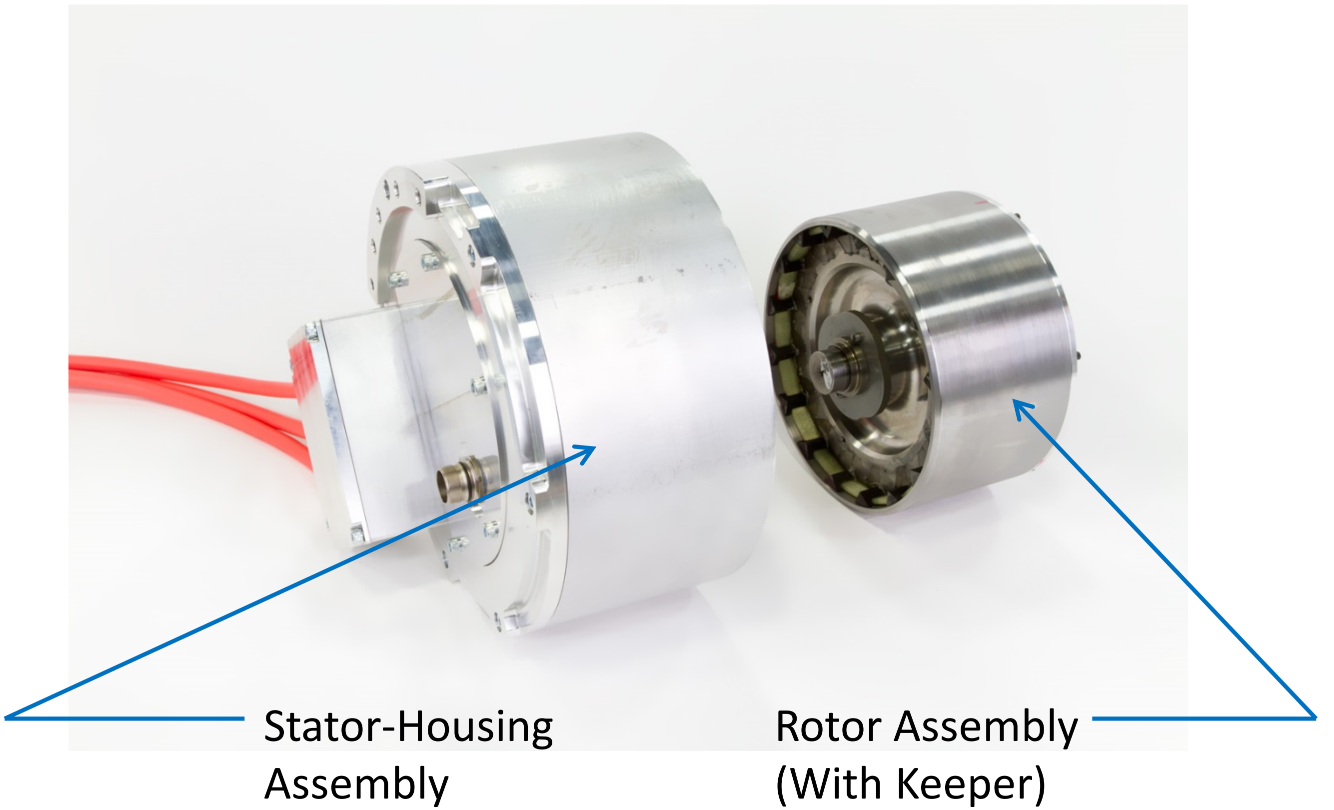
Progress - Key Specifications

Requirement		Value	Model Prediction	POC #1 &2
DOE Requirements	Efficiency	>90%	Analyzed, Comply	Analyzed, Comply
	Peak Power	55 kW	55 kW	55 kW verified at UQM
	Maximum Speed	10,000 rpm	10,000 rpm	Verified at UQM (durability concerns)
	Operating Voltage Range	200-450 VDC 325 VDC Nominal	Analyzed, Comply [1]	Comply [1]
	Maximum phase current	400 A	Analyzed, minimal demagnetization	8% Demagnetization
	Torque	262 N-m	Analyzed, minimal demagnetization	235 Nm verified at UQM
	Total Volume	≤ 9.7 L	9.59 L	9.59 L (actual)
UQM Internal Requirements	Max Stator Diameter	254 mm	250.8 mm	250.8 mm (actual)
	Pole Coverage	50%-90%	55 %	55 %
	Magnet Weight Limit (For Cost)	4.5 kg	4.5 kg	4.5 kg (actual)
	EMF Voltage	83.6-92.4 V/krpm L-L	88 V/krpm L-L	84.25 V/krpm L-L
	EMF THD	< 10%	2.86%	Comply
	EMF Harmonics	< 5% of Fundamental	2.27%	Comply
	Cogging Torque	< 4 N-m	3.85 N-m	Comply
	Specific Power	1.57 kW/kg	1.57 kW/kg	1.44 kW/kg (actual)
	Power Density	5.74 kW/Liter	5.74 kW/Liter	5.74 kW/Liter (actual)

Notes:
1. Complies using voltage boost topology inverter

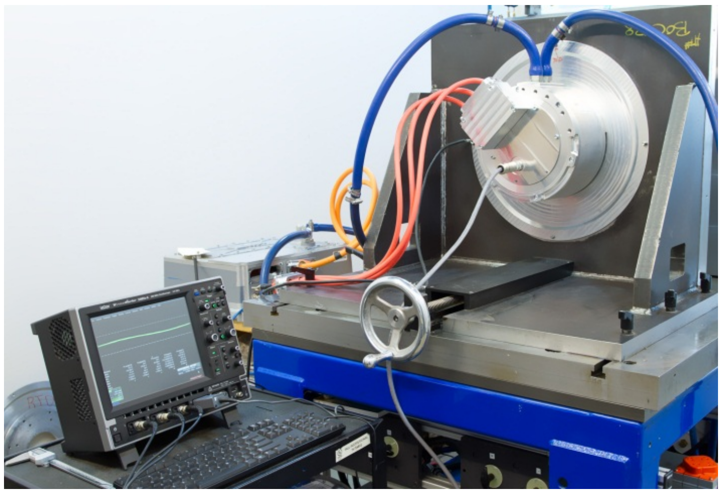
Accomplishments & Progress

Prototype 1 and 2 Motor Build



Accomplishments & Progress

- Motor performance characterization on the UQM dynamometer



✓Back EMF measurements

✓Maximum Torque tests (POC1)

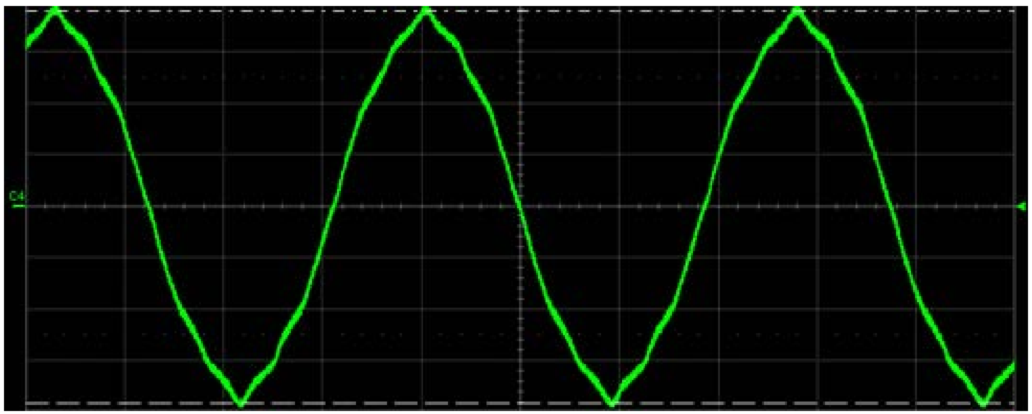
✓Power Profile (POC2)

✓Maximum Speed test (POC1) – **Achieved 10krpm**

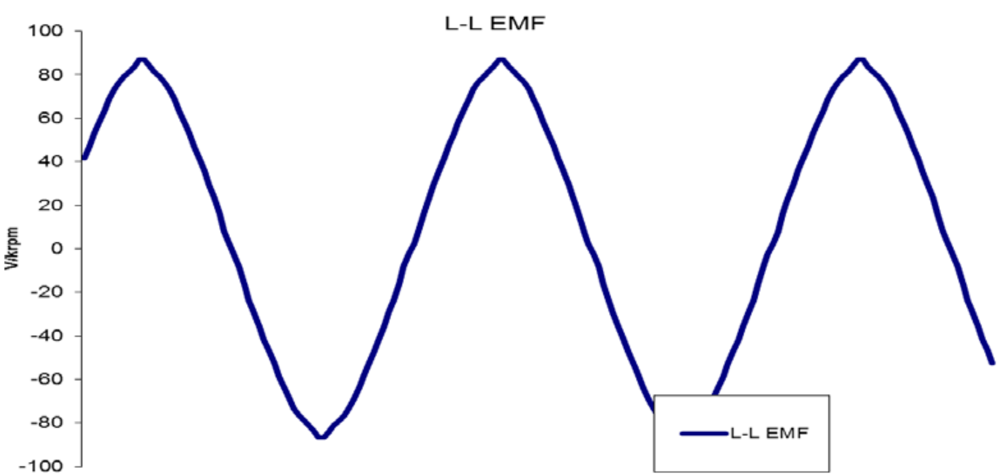
- 3rd party testing to be performed at ORNL

Accomplishments & Progress

- Back-EMF measurement on low side of tolerance range, but within tolerance of magnet properties



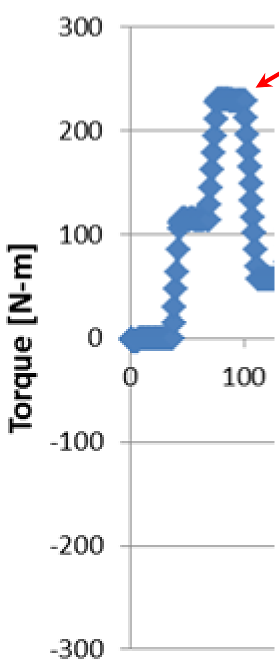
✓Measured EMF Amplitude = 84.5 V/krpm L-L



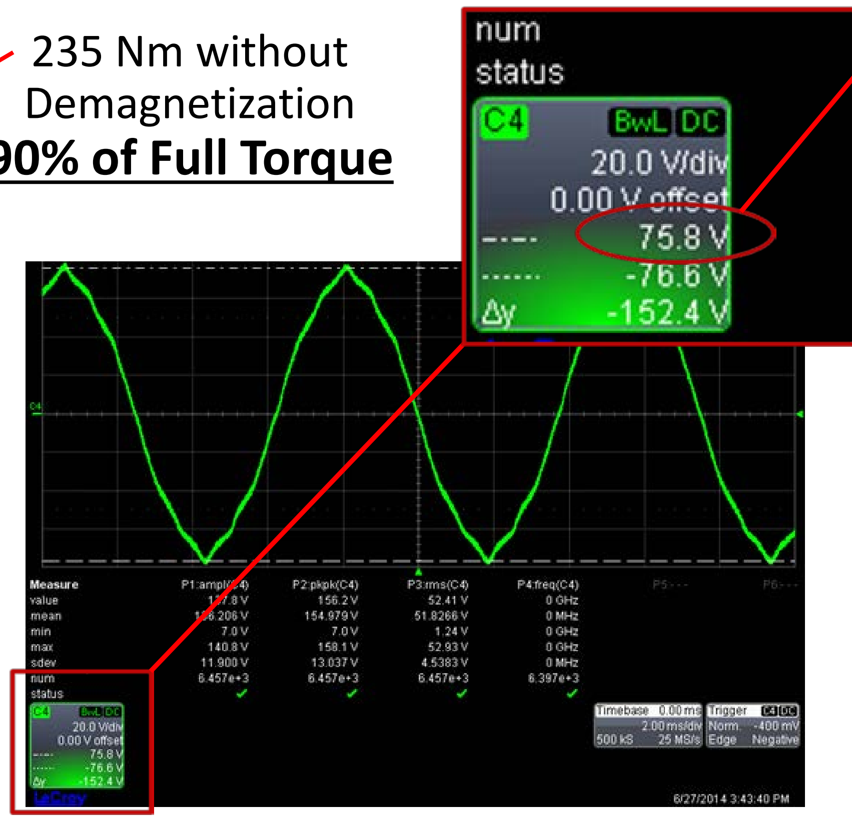
✓EMF prediction 89.7 V/krpm L-L

Accomplishments & Progress

- Maximum Torque Test POC1
  - Torque was incremented at low speed in 10% steps
  - EMF was measured after each torque step

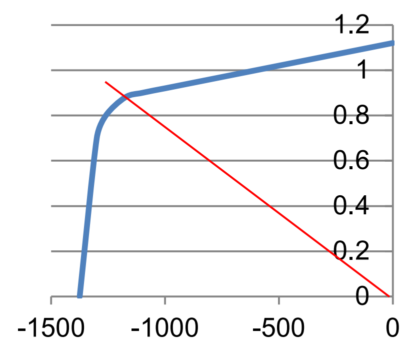


235 Nm without Demagnetization
<u>90% of Full Torque</u>



✓ Measured 8% Lower EMF at 100% torque requested

✓ Validates predicted load line at full torque

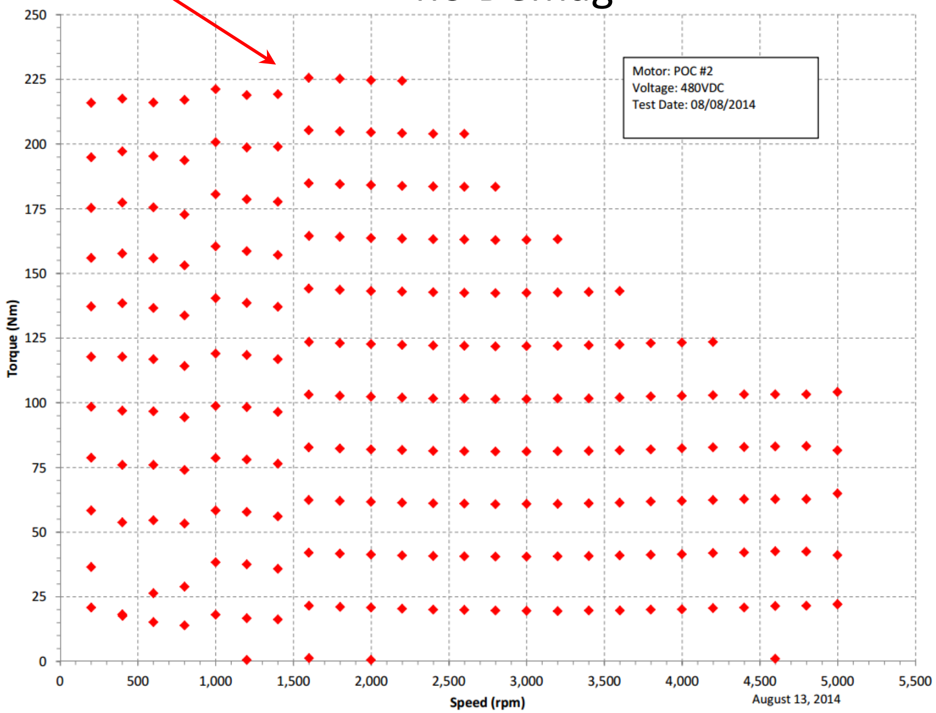


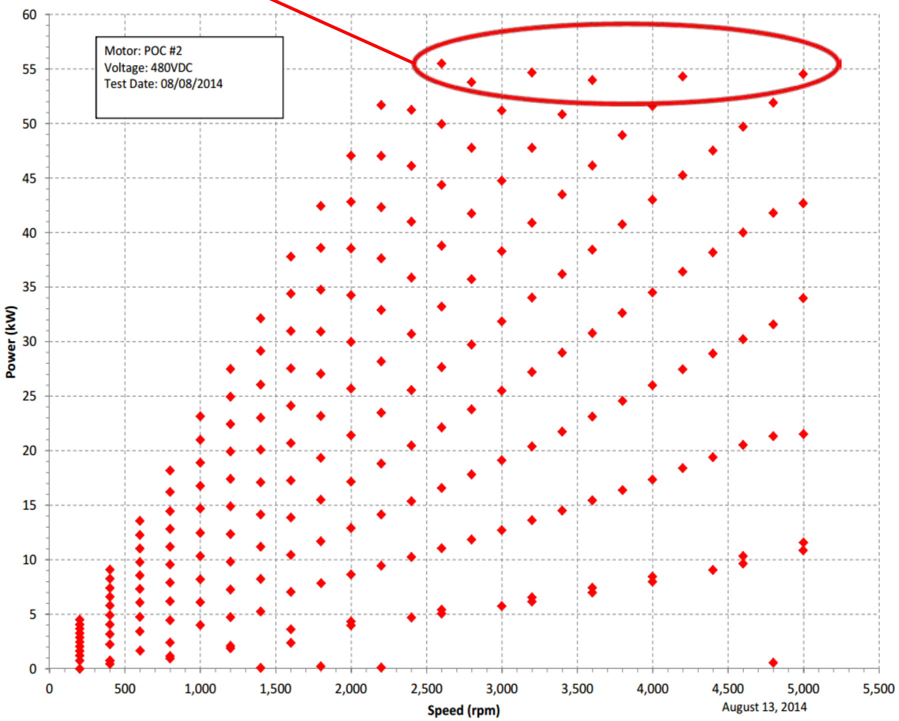
Accomplishments & Progress

- Maximum Power Provide POC2
  - Measure torque and power vs. speed
    - Limit speed to 5000 rpm b/c of durability concerns

Limit torque to 225 Nm to ensure no Demag

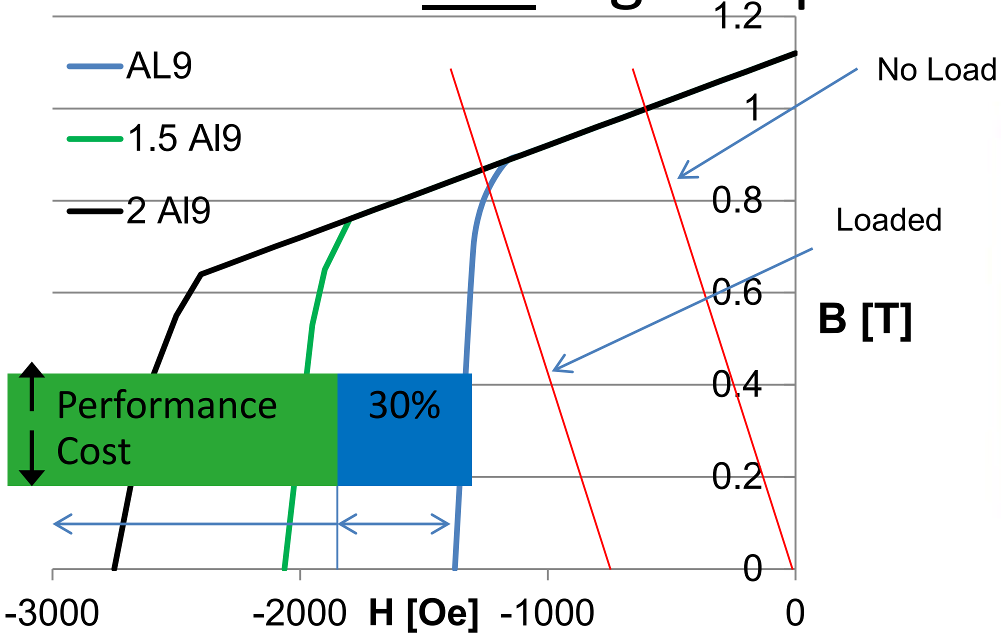
Achieved 55 kW, 2000 rpm to 5000 rpm



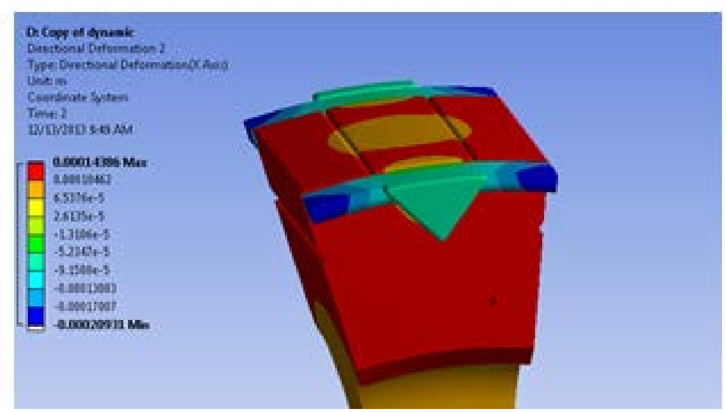


Accomplishments & Progress

- Refine for Proof of Design (POD motor)
- 30% higher coercivity needed to achieve full torque with 20% design margin
- >30% increase in coercivity = reduced magnet content = reduced cost and higher speed capability

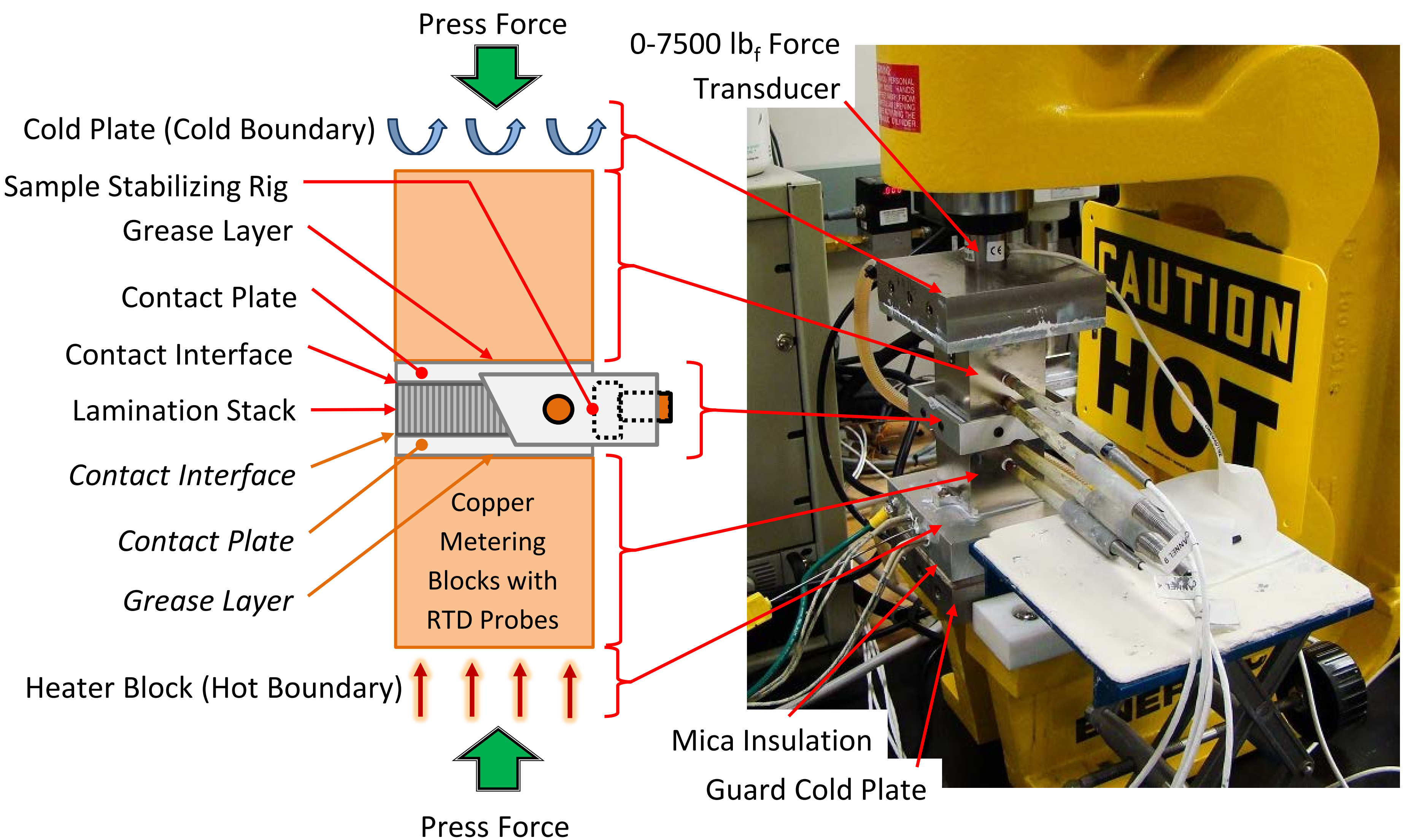


Refine magnet retention



NREL: Stator-to-Case Thermal Resistance

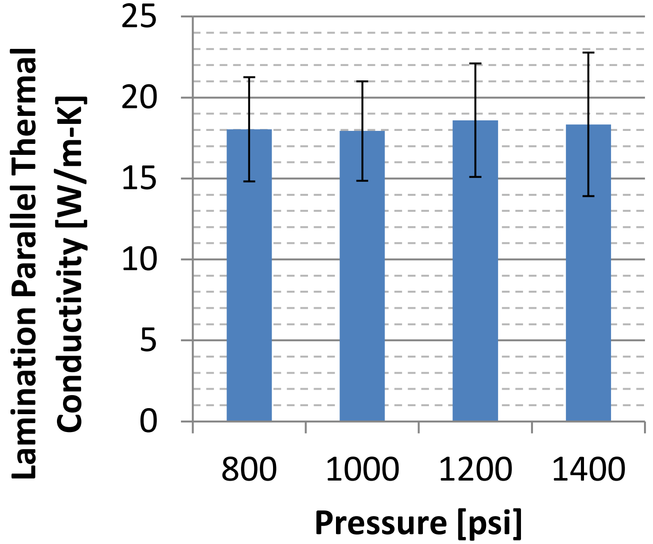
Objective: Measure thermal resistance of contact between stator and housing

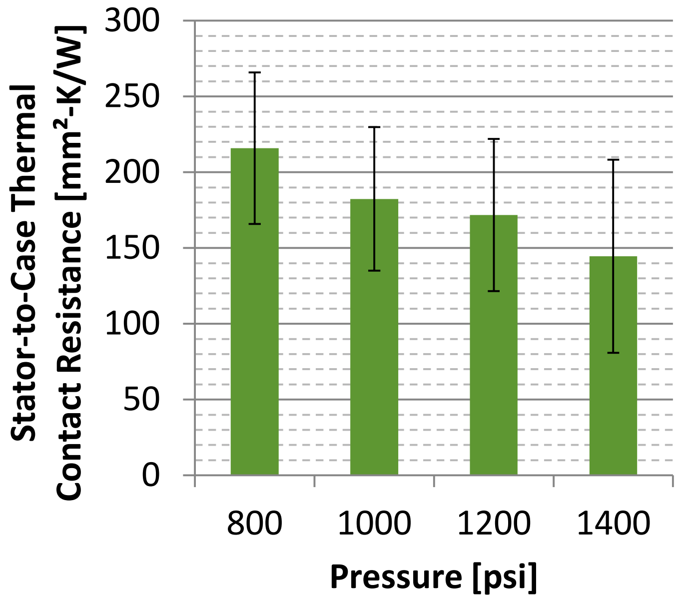


NREL: Stator-to-Case Thermal Resistance

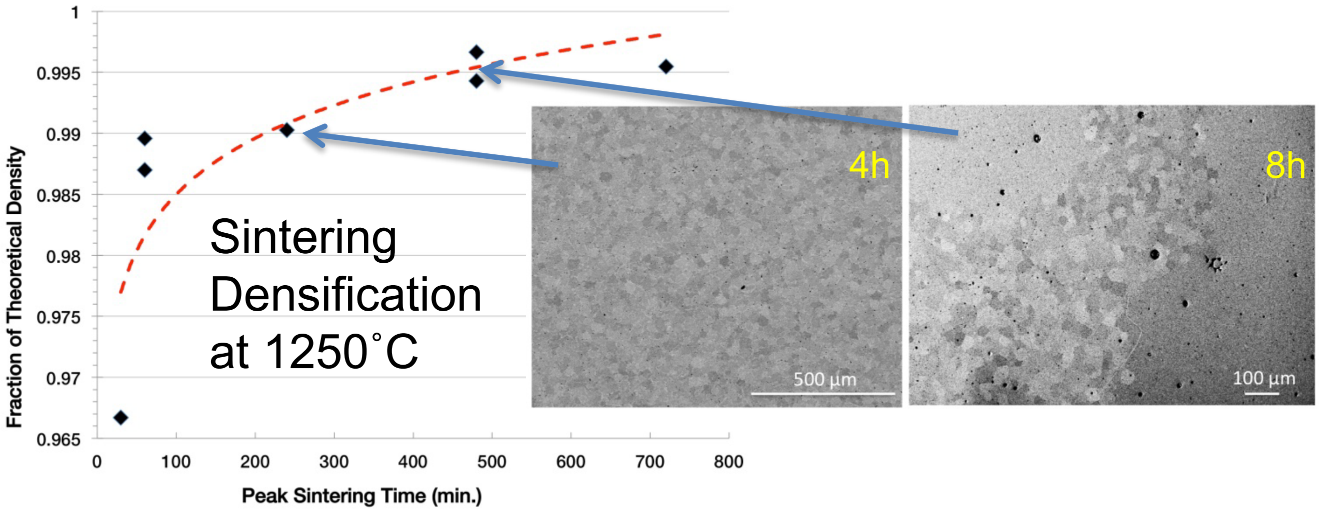
Results

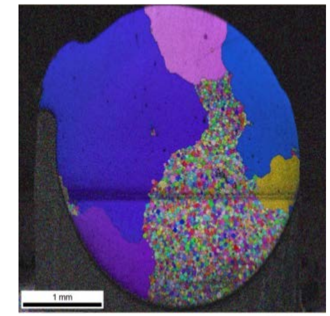
- Completed measurement of M19, 29 gauge material
- Measured 3 coupon thicknesses
- Analysis of results provides:
  - Thermal conductivity of laminations parallel to the orientation of the laminations
  - Thermal contact resistance between case and laminations
- Performed 3 repetitions per data point
- Error bars represent 95% confidence interval including random and systematic uncertainties
- Error bars may be reduced with additional repetitions
- Additional materials are being tested

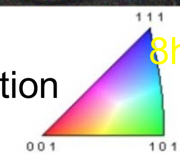




AMES: Compression Molding: Bulk Magnets from Pre-alloyed Powder







Grain Orientation Image

Sample	Br (G)	Hc (Oe)	Hci (Oe)	(BH)max (MGOe)	Hk (Oe)	Hk/Hci
AGK-2-3 (1h)	8,523	1,521	1,632	4.87	459	0.28
AGK-2-5 (4h)	8,789	1,569	1,685	5.04	483	0.29
AGK-2-1 (8h)	10,052	1,608	1,688	6.5	601	0.36

- Sintering dwell time induces abnormal grain growth in resulting magnet after 8h.
- 50 vol.% of sample aligned near 111 axis: **explains Br rise**

- Results on 8h sinter show improved remanence, energy product, and squareness, due to partial alignment of grains in sample.
- Since this grain growth was "happy accident," experiments are in-progress to develop aligned grain growth control.
- Magnet still needs better coercivity (significantly above 2,000 Oe).
- Theory indicated that refined spinodal spacing (nano-structure) can double coercivity and experiments are in-progress.

Future Work

- Complete Design of POD Motors
  - Incorporate enhanced AlNiCo magnets from Ames
  - Incorporate learning from POC motors and 3rd party testing at ORNL
  - Build 2 POD magnets
- Motor Characterization POD motors –
  - Verify fundamental parameters (Bemf, cogging torque no load losses ..)
  - Show improvements over POC motors, full torque, speed, viability
  - Verify performance (peak and continuous torque/power and efficiency)
- Demonstrate Proof-of-Design testing at UQM
- ORNL (3rd party) Testing for POD motors
- Design 120 kW version to demonstrate scaleability

Summary

- POC motor demonstrates performance very close to requirements with OTS magnet material
- Motor ⇔ Inverter analysis indicates that the design is not field weakening compatible and will require a voltage boost inverter
  - Field weakening may be achievable with 50% improvement in magnet properties
- NREL models and data to optimize cooling and heat transfer are being incorporated into POD motors.
- Ames' work for increasing magnet properties will also be incorporated into POD motors
- Motor build will demonstrate the feasibility of the approach and appears it will meet or exceed DOE requirements with Ames magnets and optimize cooling methods from NREL