2016 DOE Vehicle Technologies Office Review
Unique Lanthanide-Free Motor Construction

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4/11/16

EDT044

Overview

Timeline

Project start date: 10/1/2011

Project end date: 9/30/2016

Percent complete: 90%

Budget

Total project funding

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

Funding received in FY15: $311K

Funding for FY16: $950K

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.
- Information to include:
  - Objectives: Proving out Proof of Concept design motors and confirmed near compliance with set specifications
  - Motors under development are applicable to a number of vehicle architectures for which the VTO is developing technology, including pure Evs, Plug-in Evs 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

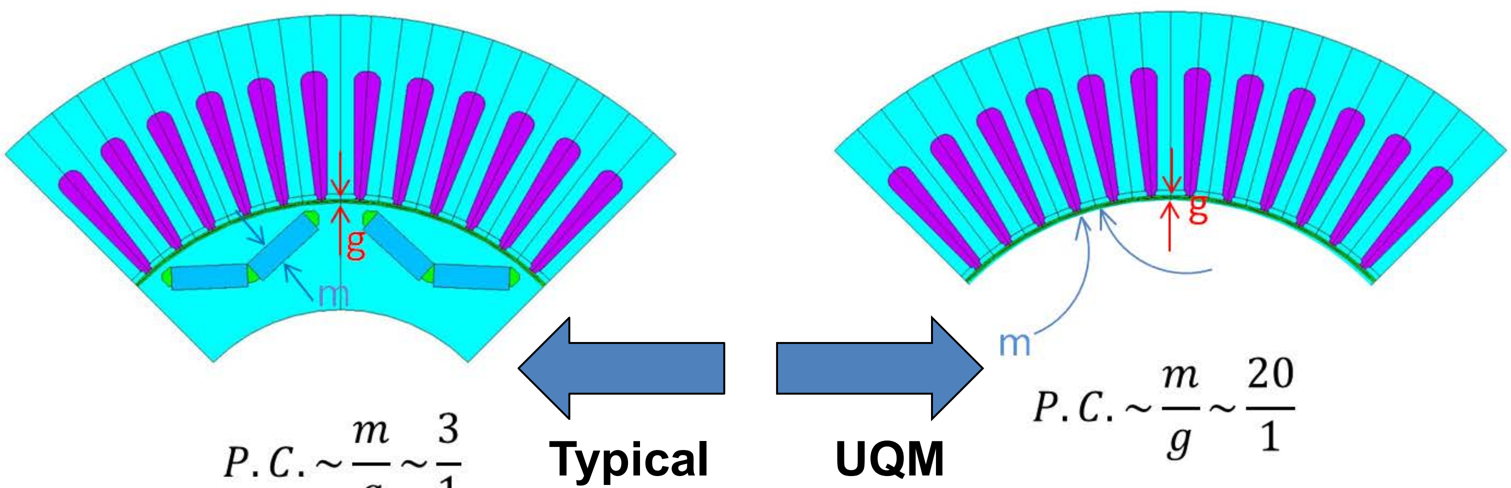
Approach - Milestones

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
02/2016 ✓	Milestone: Incorporate enhanced magnets into POD motor design (AlNiCo 8HE incorporated)
06/2016	Milestone: Build two (2) POD motors
08/2016	Milestone: Dynamometer test at UQM POD motors to validate improvements
09/2016	Milestone: Complete higher power (120kW) motor design
09/2016	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

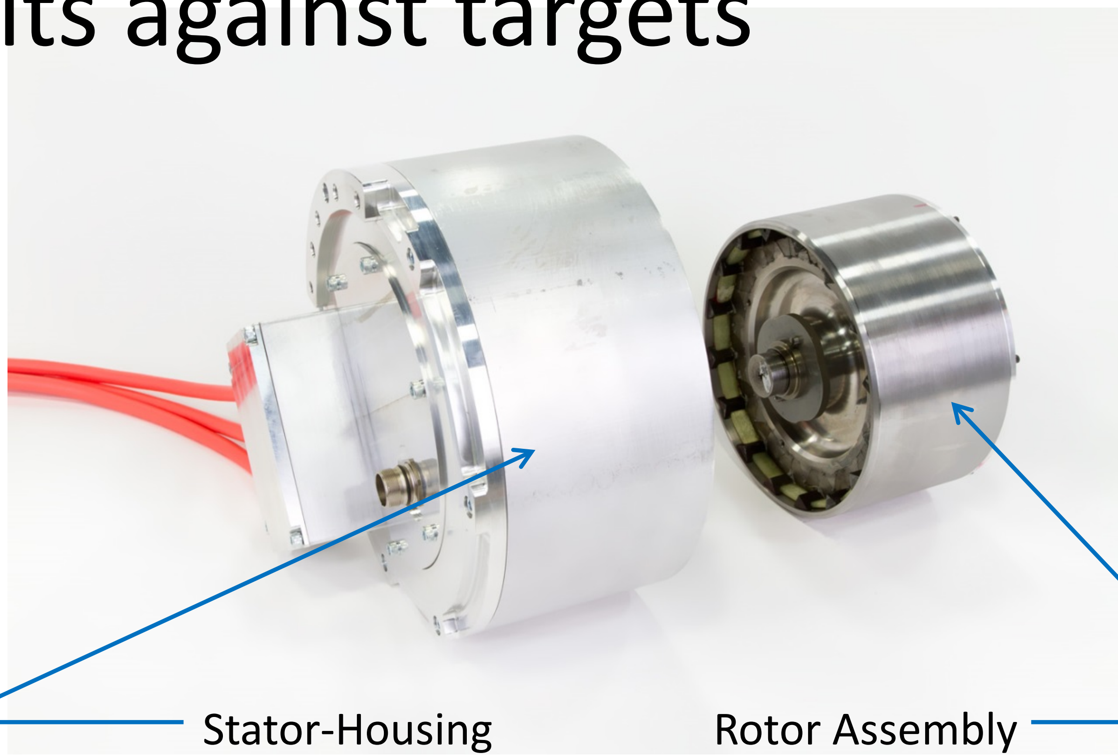


$$P.C. \sim \frac{m}{g} \sim \frac{3}{1}$$

$$P.C. \sim \frac{m}{g} \sim \frac{20}{1}$$

Accomplishments & Progress
Previous Periods

- POC 1 and 2 Motor Build very good results against targets



Stator-Housing Assembly

Rotor Assembly (With Keeper)

Accomplishments & Progress FY15

- Worked with Ames and DOE to utilize AMES magnets
  - Procured no cost extension
  - Ames magnets not ready, triggered contingency plan for 8HE
- ORNL testing POC motor
- Design refinement for Proof of Design (POD motor)
  - Improved Rotor and magnet retention system for mechanical Integrity and manufacturability
  - redesigned and analyzed for 8HE grade AlNiCo
- Worked with NREL to improve thermal performance
  - Measure and optimize Stator-housing resistance
  - Improved thermal conductivity of materials
- Performance predicted to be maintained with 8HE magnets!
  - Better feasibility and Manufacturability than AlNiCo9
  - Drawback some efficiency decrease, thermal performance

Progress - Key Specifications

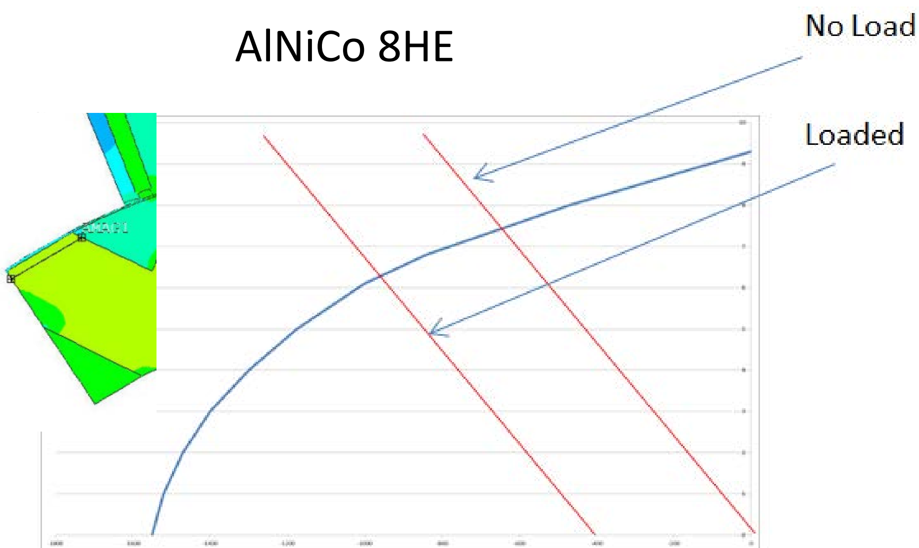
Requirement		Value	Model Prediction	POC #1 &2	Prediction POD
DOE Requirements	Efficiency	>90%	Comply	>93%	Comply
	Peak Power	55 kW	55 kW	55 kW verified	55 kW
	Maximum Speed	10,000 rpm	10,000 rpm	10krpm(durabilit y concerns)	10,000 rpm
	Operating Voltage Range	200-450 VDC 325 VDC Nom	Analyzed, Comply [1]	Comply [1]	Comply [1]
	Maximum phase current	400 Arms	280 Arms	8% Demagnetization	~350 Arms
	Torque	262 N-m	Analyzed, minimal demagnetization	235 Nm	235 Nm
	Total Volume	≤ 9.7 L	9.59 L	9.59 L (actual)	9.59 L
UQM Internal Requirements	Max Stator Diameter	254 mm	250.8 mm	250.8 mm (actual)	250.8 mm
	Magnet Weight Limit (cst)	4.5 kg	4.5 kg	4.5 kg (actual)	4.5 kg
	EMF Voltage	83.6-92.4 V/krpm	88 V/krpm L-L	84.3 V/krpm L-L	70 V/krpm L-L
	EMF THD	< 10%	Comply	Comply	Comply
	EMF Harmonics	< 5% of Fundamental	Comply	Comply	Comply
	Cogging Torque	< 4 N-m	3.85 N-m	Comply	Comply
	Specific Power	1.57 kW/kg	1.57 kW/kg	1.44 kW/kg	1.57 kW/kg
	Power Density	5.74 kW/Liter	5.74 kW/Liter	5.74 kW/Liter	5.74 kW/Liter

Notes:
1. Complies using voltage boost topology inverter

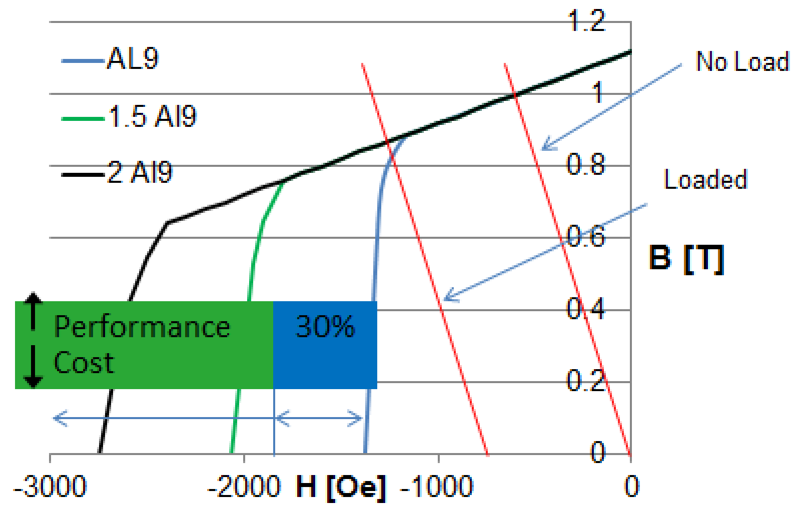
Accomplishments & Progress FY15

- Increased current to maintain performance of AlNiCo 9 with 8HE, increase copper, heat rejection to mitigate loss
- Even with less squareness of 8HE, design utilizes linear portion enabled by very high Permeance coefficient
- Future improvements to AlNiCo materials will improve cost: Coercivity, Induction, or Squareness

AlNiCo 8HE



AlNiCo 9



Responses to Reviewer Comments

Comment #1: The reviewer stated, further project progress is dependent on Ames Laboratory (AMES) delivering improved AlNiCo 8 magnets to improve the motor's top speed and torque capability. If the magnetic material is challenged for arrival, the project will suffer significantly.
UQM Response: Yes, the peak torque goal will suffer if the AlNiCo 8 material from AMES is not used, however, UQM has chosen a contingency plan to use, commercially available AlNiCo 8HE material for the second iteration, proof-of-design (POD) motors. Although, the AlNiCo 8HE will not have the full advancements of the material that AMES has developed, significant improvements and design feasibility can be demonstrated. We are also perusing follow on work to accommodate Ames magnets.

Comment #2: This reviewer found that the challenge to address this market is to get the coolant temperature requirement closer to the 105°C capability, and suggested that a next phase for the project to work on increasing the temperature rating.
UQM Response: The role of NREL throughout the project has been to investigate the opportunities to improve the thermal characteristics within the motor. The POD motors will incorporate several of these improvements identified by UQM and NREL. In addition, UQM is also perusing follow on work to further improve the thermal characteristics of electric motors, leveraging the advances made within this project.

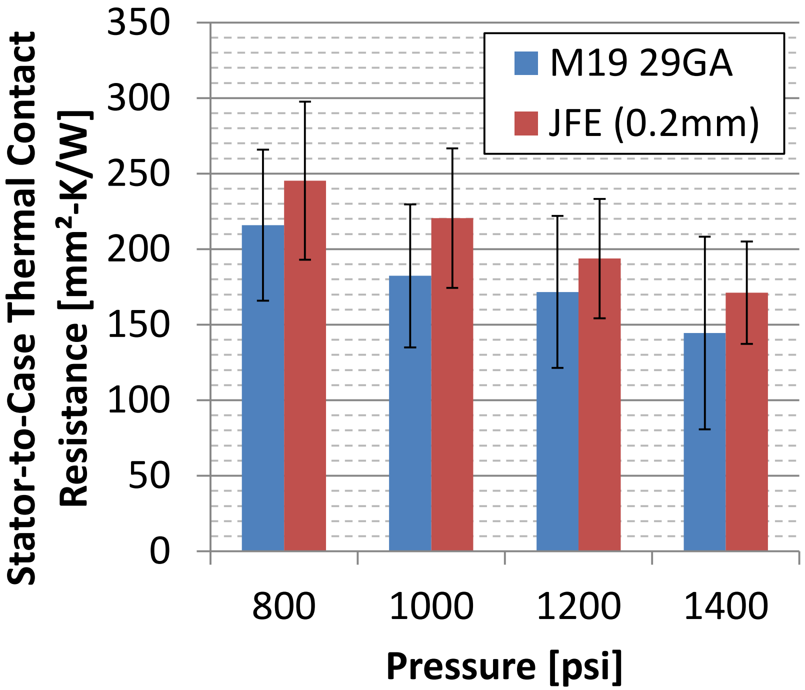
Comment #3: The reviewer stated that the summary statement by the team that the POC motor demonstrates performance very close to requirements and feels the motor is just barely able to operate at steady state conditions, and it was not clear it can survive fault conditions without significant demagnetization.
UQM Response: The POD motors will incorporate AlNiCo 8HE level magnets that have improved properties consistent with improving the reviewers noted performance limitations. Motor would need to be derated by some percentage (Controller/inverter dependent) to ensure demag is not induced by fault conditions. Although torque is shy of target, motor is still quite capable.

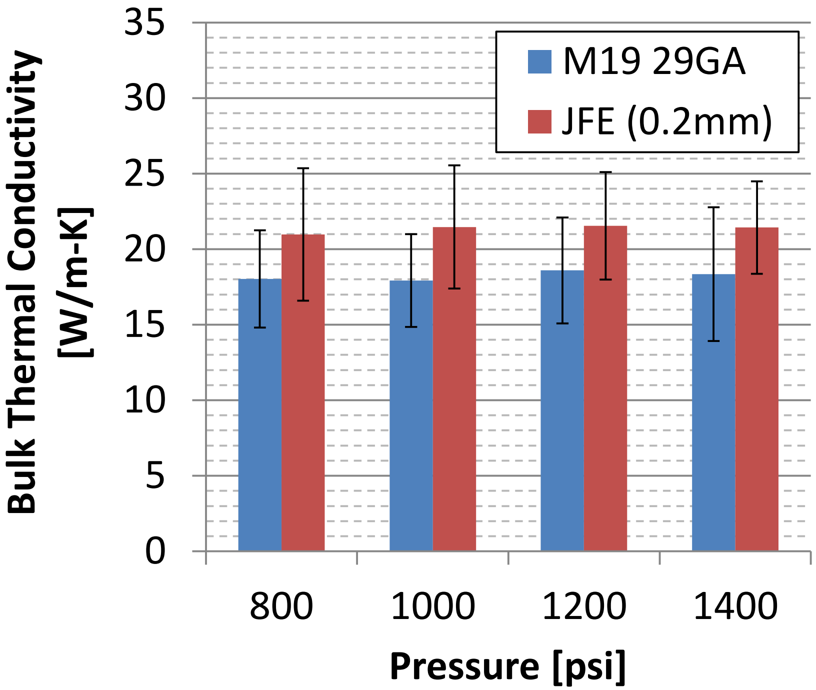
Coordination and Collaboration with Other Institutions

- 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

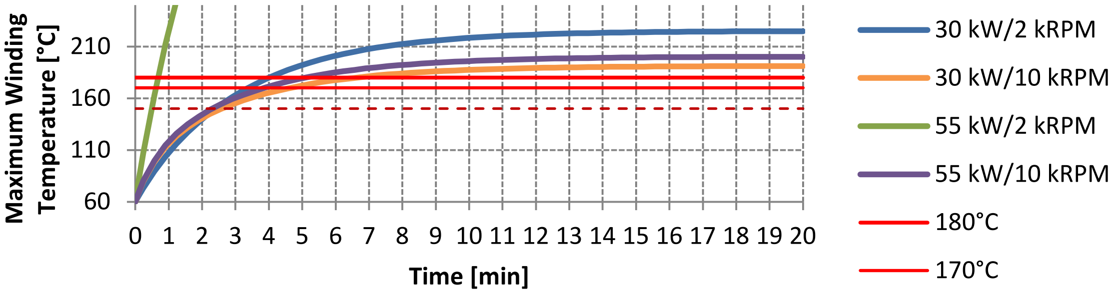
NREL: Stator-to-Case Thermal Resistance (FY15)

- Completed measurements with selected lamination materials
- Analysis of results provides:
  - Thermal conductivity of laminations parallel to the orientation of the laminations
  - Thermal contact resistance between case and laminations
- Error bars represent 95% confidence interval including random and systematic uncertainties





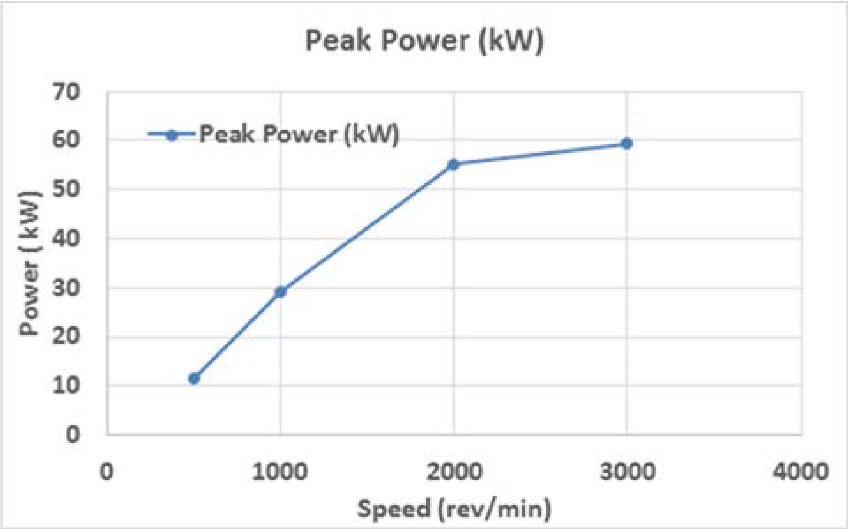
NREL: AlNiCo8HE Thermal Results

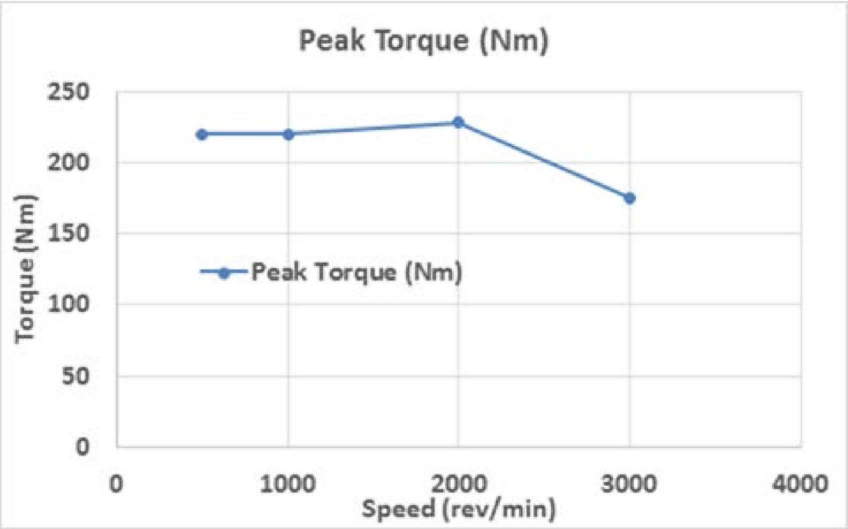


			Outputs – With Improved Materials		Outputs - No Material Change		Temperature Reduction	
	Power	Speed	Temperature Cu Maximum	Temperature Fe Maximum	Temperature Cu Maximum	Temperature Fe Maximum	Temperature Cu Maximum	Temperature Fe Maximum
	[kW]	[rpm]	[C]	[C]	[C]	[C]	[C]	[C]
AlNiCo 9	30	2000	150.91	137.51	192.17	154.72	41.26	17.21
	30	10000	175.62	181.3	191.04	193	15.42	11.7
	55	2000	362.29	311.06	503.78	367.52	141.49	56.46
	55	100000	181.01	185.89	197.57	199.51	16.56	13.62
AlNiCo 8HE	30	2000	173.24	155.7	225.27	177.09	52.03	21.39
	30	10000	175.83	181.48	191.3	193.23	15.47	11.75
	55	2000	443.76	377.96	623.89	449.54	180.13	71.58
	55	100000	183.25	187.8	200.36	202.66	17.11	14.86

- Thermal results with AlNiCo8HE above are above temperature limits
- UQM/NREL to implement improved materials to address thermal performance
- Reduces slot temp by 50 C and allows acceptable temperature at 30 kW

ORNL: Progress

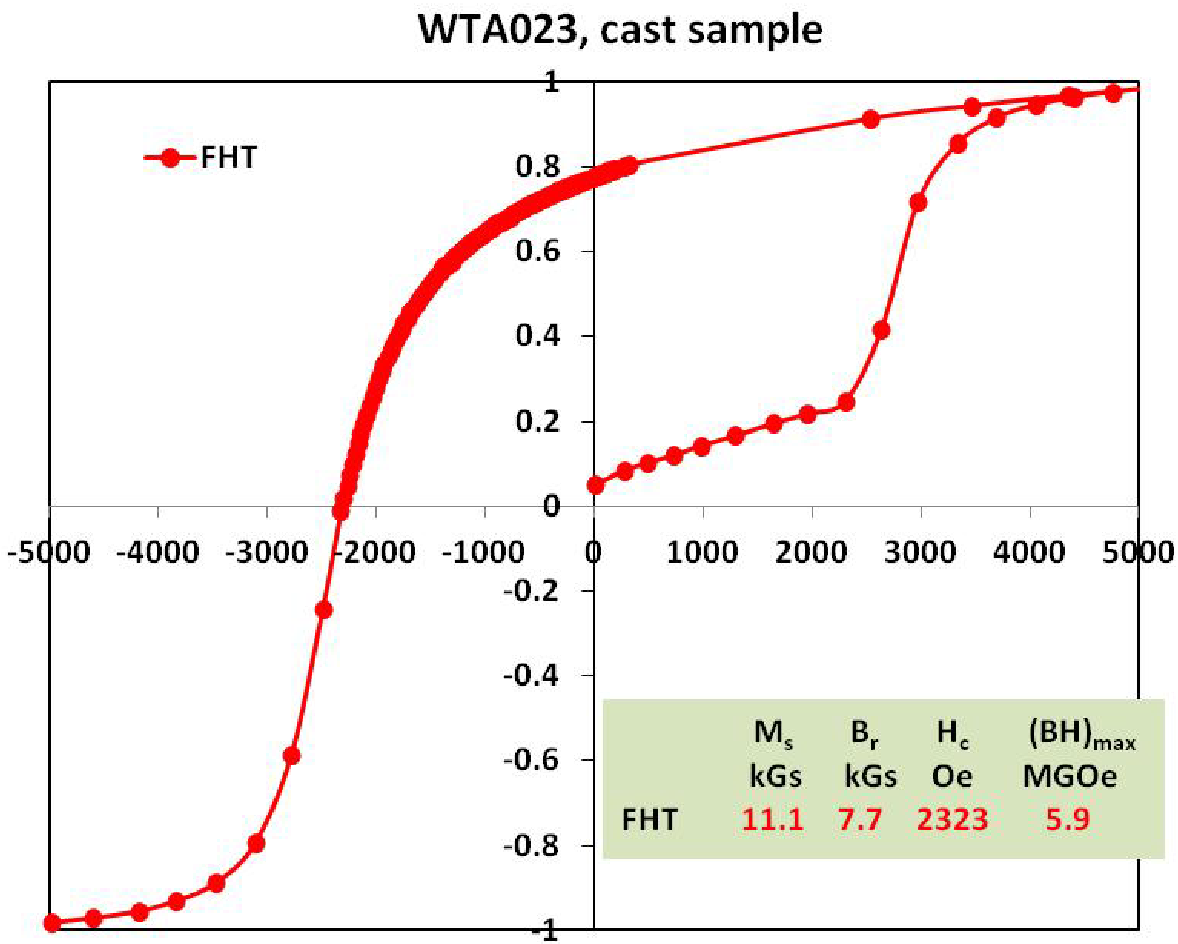




Note:

- Efficiency > 93%, Continuous torque 115 Nm ~24 kW at 2000 rpm
- Torque Confirmed 235 Nm, Peak Power confirmed 60 kW
- Speed limited to ensure mechanical integrity with AlNiCo 9 magnets.

AMES: Progress



Note:

- This sample is a cast one, without grain orientation.
- The target composition of GA 262 (equal to alnico 8H) is the same with this sample.
- Br and (BH)max of sintered GA262 sample will be further increased by our aligned grain growth technique.

Remaining Challenges and Barriers

Challenges for POD motor and future commercialization

- Need better heat rejection to sink additional heat due to higher current needed for 8HE magnets
  - Working with NREL to continue to refine thermal mgt. strategies.
- Cost analysis looks close to NdFeB motors at todays magnet prices; UQM AlNiCo motor becomes more economical at material cost ratio >3 for $/kg NdFeB vs. $/kg AlNiCo
  - Currently the cost ratio is slightly below 3 and therefore slightly more costly than NdFeB machines.
  - Cost ratio must also cover cost of additional magnet retention materials.
- Only small incremental improvements in AlNiCo needed
  - Ames making progress

Future Work

- Complete Design of POD Motors
  - Incorporate 8HE grade AlNiCo magnets replacing AlNiCo9
  - Incorporate learning from POC motors
  - Build 2 POD motors
  - AlNiCo magnets from Ames to be implemented in future work
- 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, efficiency)
- Demonstrate Proof-of-Design testing at UQM
- Finalize Volume Cost Analysis
- Design 120 kW version to demonstrate scaleability

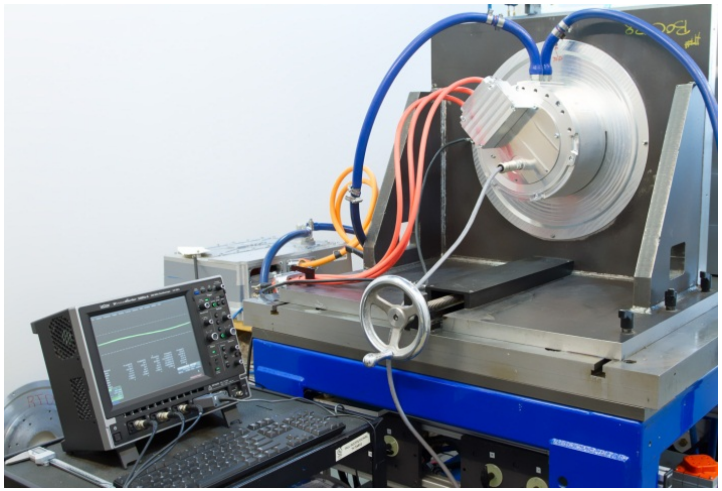
Summary

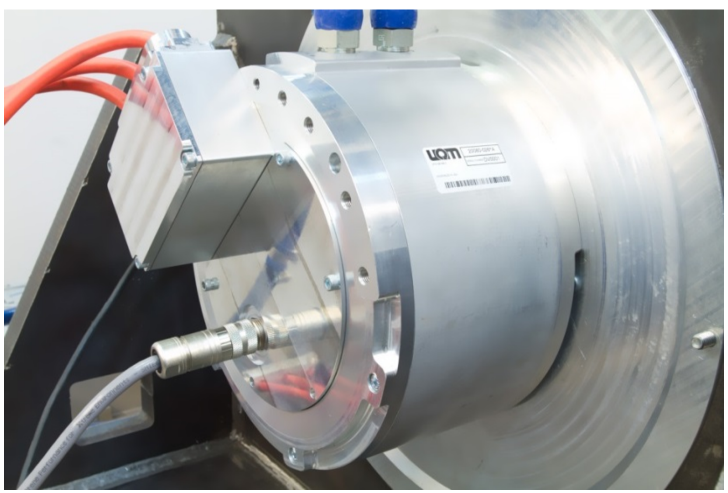
- The program has demonstrated a feasible architecture to enable the use of off-the-shelf AlNiCo Magnets
- Proof-of-Concept motor with AlNiCo 9, shows compliance with DOE and UQM-internal specifications
- Proof-of-Design motor with AlNiCo 8HE will maintain all performance previously achieved, better manufacturing and mechanical durability
- Thermal improvements developed with NREL will enable the necessary heat rejection
- Preliminary cost analysis indicates path to DOE cost targets in Volume
- The resulting motor demonstrates feasibility, competitive in Performance and cost with state of the art motors
- Ames' work shows promising progress toward increase in magnet coercivity, which will ultimately reduce magnet content required for the motor and reduce the 3:1 cost ratio threshold.

Technical Back-up Slides

Accomplishments & Progress FY14

- Motor performance characterization on the UQM dynamometer





✓Back EMF measurements

✓Maximum Torque tests (POC1)

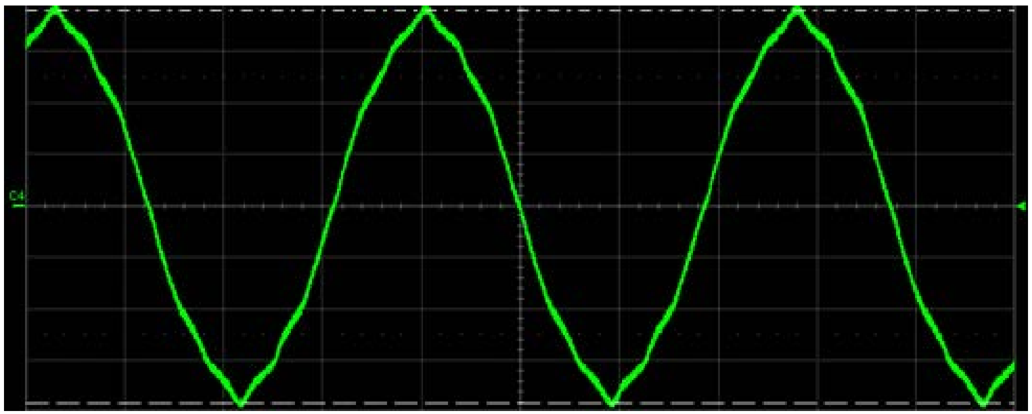
✓Power Profile (POC2)

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

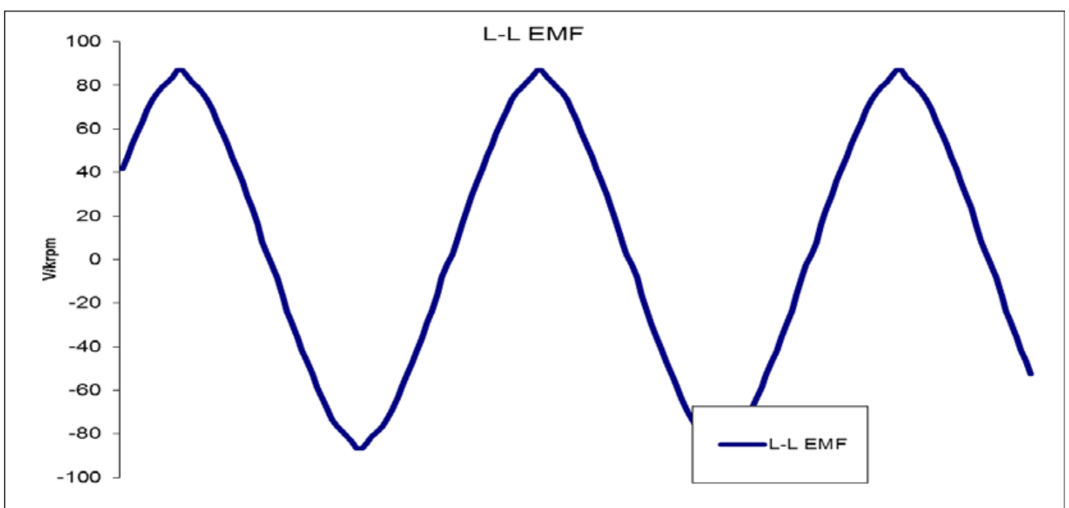
- 3rd party testing to be performed at ORNL

Accomplishments & Progress FY14

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



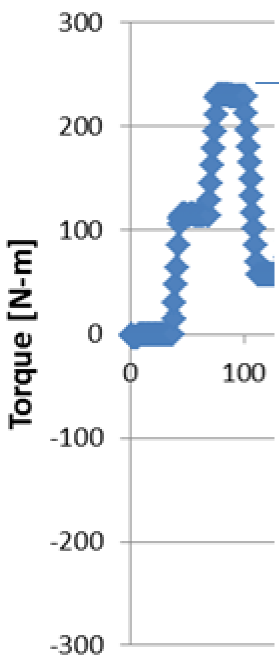
✓Measured EMF Amplitude = 84.5 V/krpm L-L



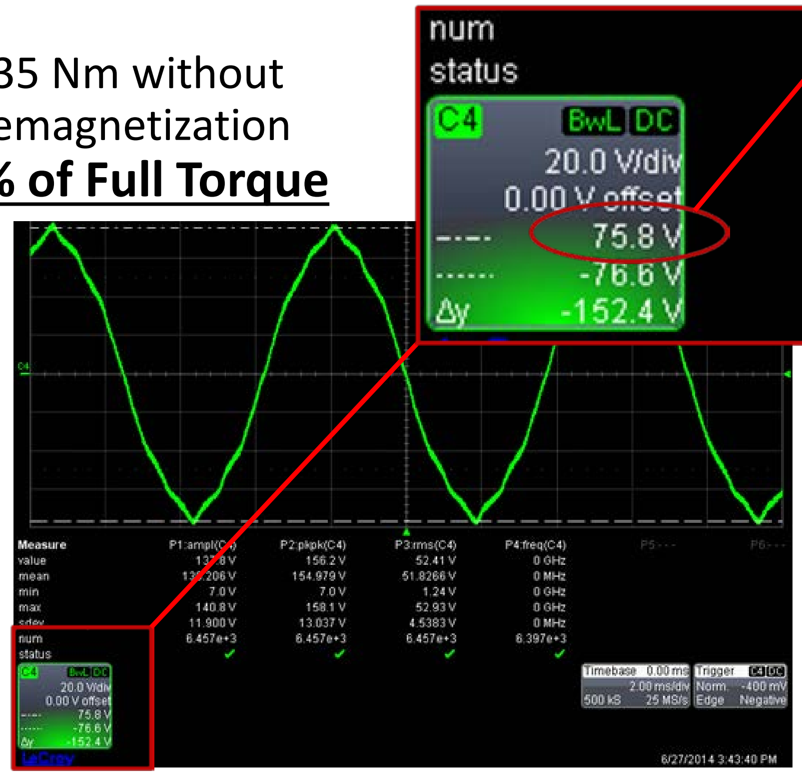
✓EMF prediction 89.7 V/krpm L-L

Accomplishments & Progress FY14

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

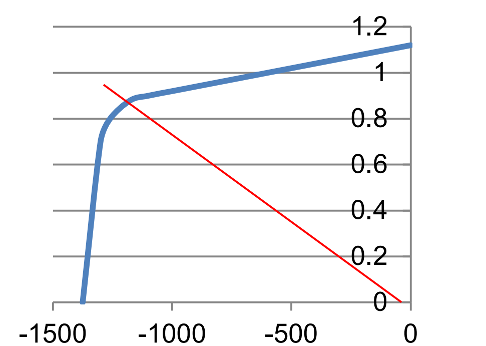


235 Nm without Demagnetization
90% of Full Torque



✓Measured 8% Lower EMF at 100% torque requested

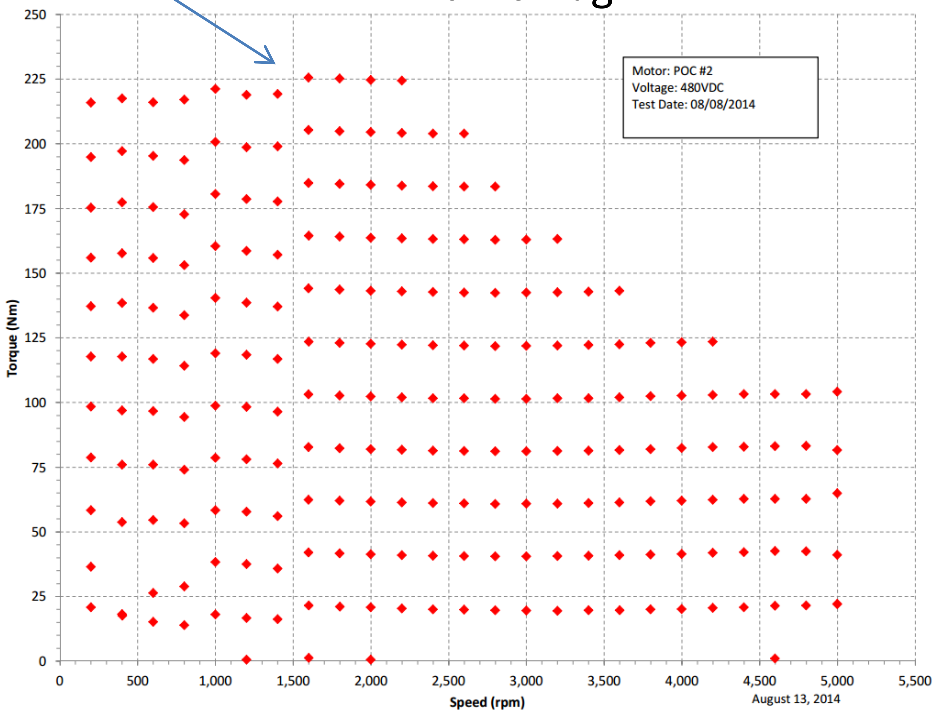
✓Validates predicted load line at full torque



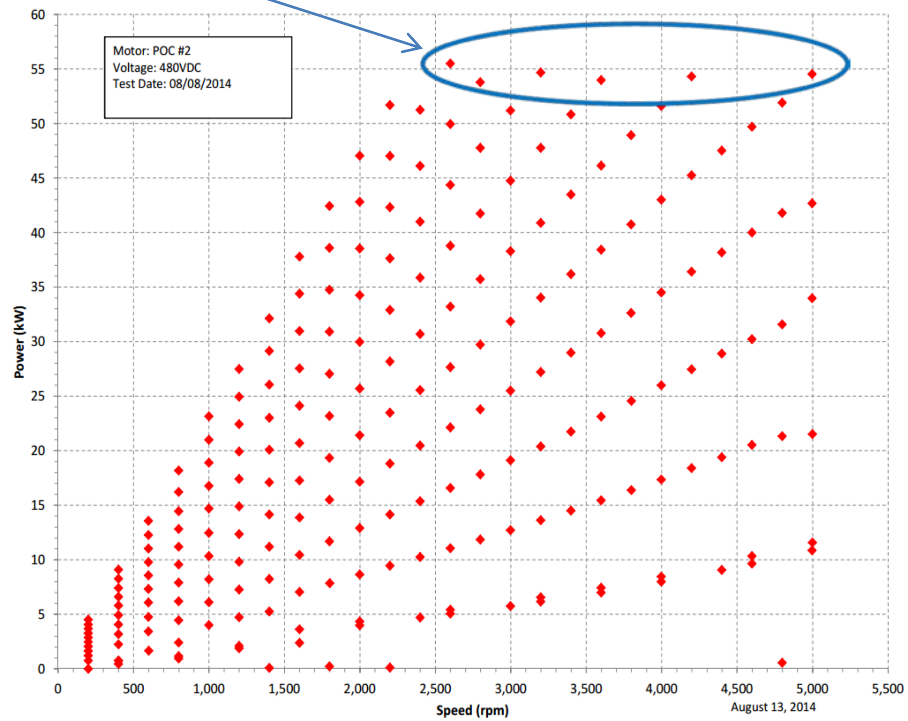
Accomplishments & Progress FY14

- 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

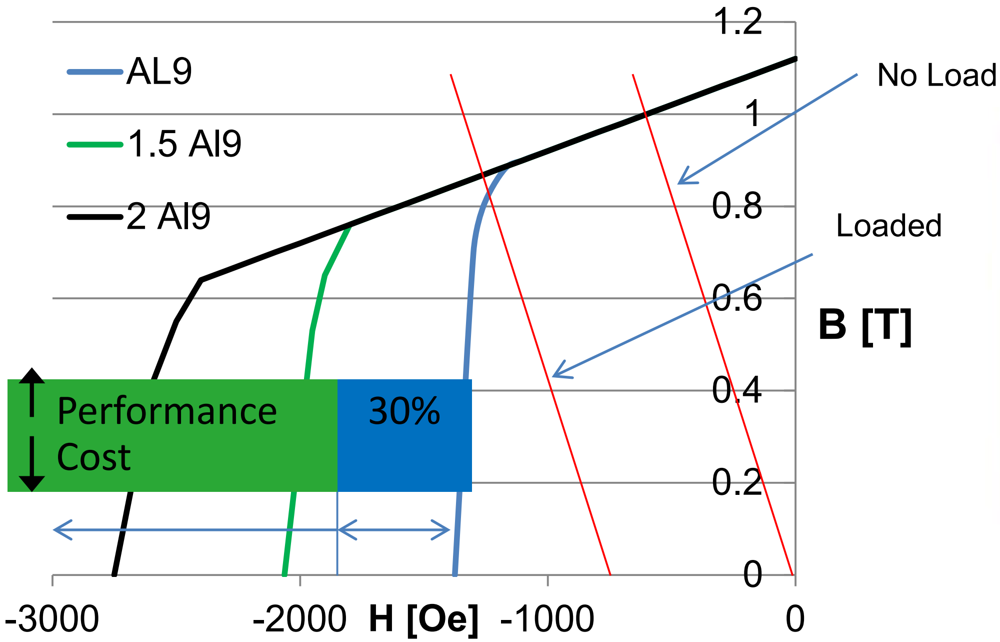


Achieved 55 kW, 2000 rpm to 5000 rpm



Accomplishments & Progress FY14

- 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 <u>and</u> higher speed capability



Refine magnet retention