Unique Lanthanide-Free Motor Construction

Josh Ley, Principal Investigator

Jon Lutz, Presenter

Alan Gilbert, Program Manager

UQM Technologies, Inc.

March 16, 2012

APE044

Overview

Timeline

Project start date: 10/01/2011

Project end date: 04/30/2015

Percent complete: 40%

Budget

Total project funding

- **$3,025K DOE Share**
- **$1,008K UQM Share**

Funding received in FY12: $309K

Funding for FY13: $1,084K

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 – Objectives

Focus Area: Motors with Reduced or Eliminated use of Rare Earth Permanent Magnets for Advanced EDV Electric Traction Drives

Overall Objectives

- This project pursues unique motor construction that:
  - Eliminates rare earth elements
  - Meets DOE size, weight and efficiency targets
  - Performs comparably to rare-earth motors
- Compliance with the DOE motor specifications
  - Use of low cost magnet (AlNiCo) to meet cost targets
  - High air-gap flux to meet size, weight and efficiency targets
  - 55 kW baseline design
  - Scalable to 120 kW or higher

Relevance – Addressing Barriers

- **Electric motor cost**
  - Rare-earth magnet prices have been fluctuating wildly (roughly $80/kg to $750/kg to $220/kg)
  - AlNiCo has been far more stable at ~ $40/kg
  - UQM approach requires roughly 3X the magnet material for a given power rating, leading to cost reductions and stability
- **Elimination of rare-earth elements**
- **Efficiency**
  - Permanent magnet motors offer efficiency advantages
  - Proposed technology offers PM motor flux levels to maintain efficiency advantages

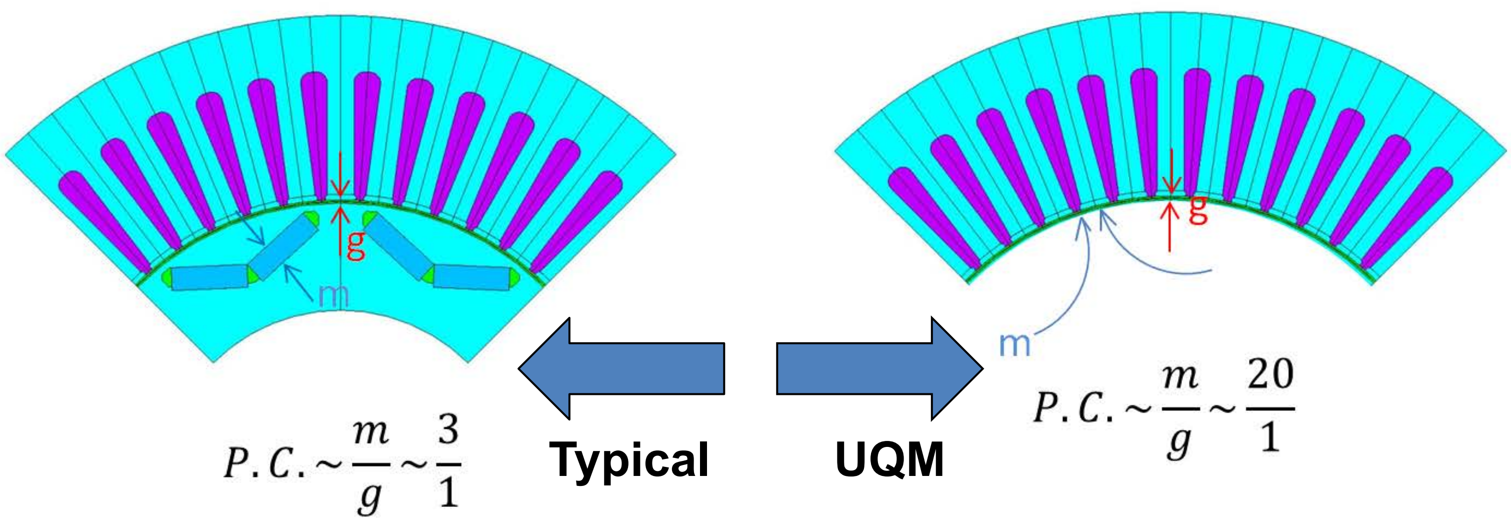
Approach - Milestones

Month/Year	Milestone or Go/No-Go Decision
FY12 ✓	Go/No-Go: electromagnetic modeling confirmed that non-RE magnets are usable w/o demagnetization
12/2012 ✓	Milestone: complete analysis of motor-to-controller interaction (commutation) and refine electromagnetic design accordingly
02/2013 ✓	Milestone: complete motor assembly concept
06/2013	Milestone: motor drawing package complete
10/2013	Milestone: motor build complete and ready for dynamometer testing
12/2013 (Period 2)	Go/No-Go: UQM dynamometer testing demonstrates technology feasibility
02/2014 (Period 2)	Milestone: delivery of proof of concept motor to ORNL for independent testing

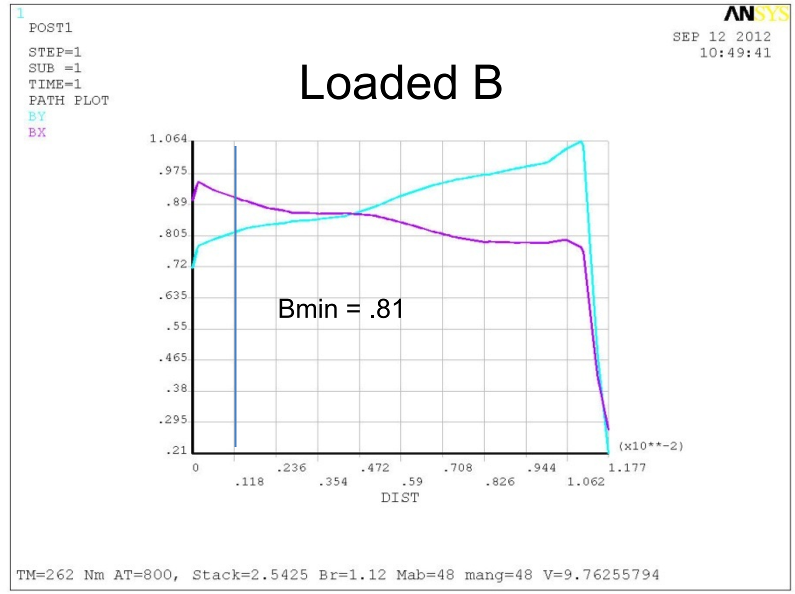
Approach - Project Strategy

- **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

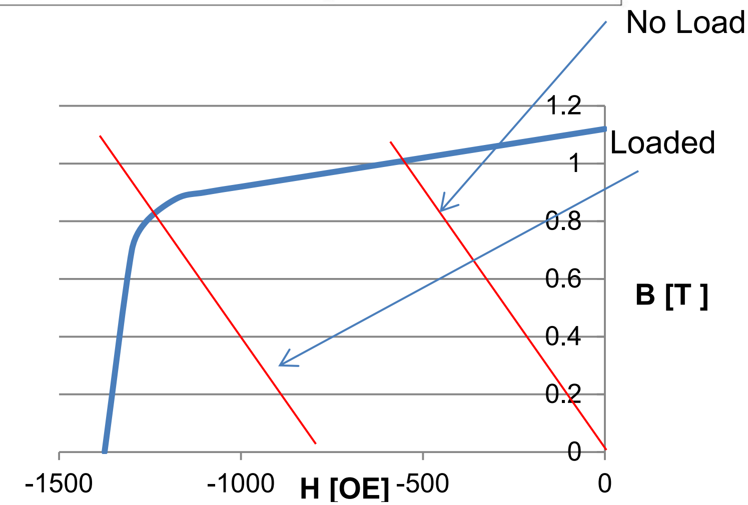


Accomplishments - Magnetics



The electromagnetic design simulation indicates that maximum torque and power is achieved within volume limits

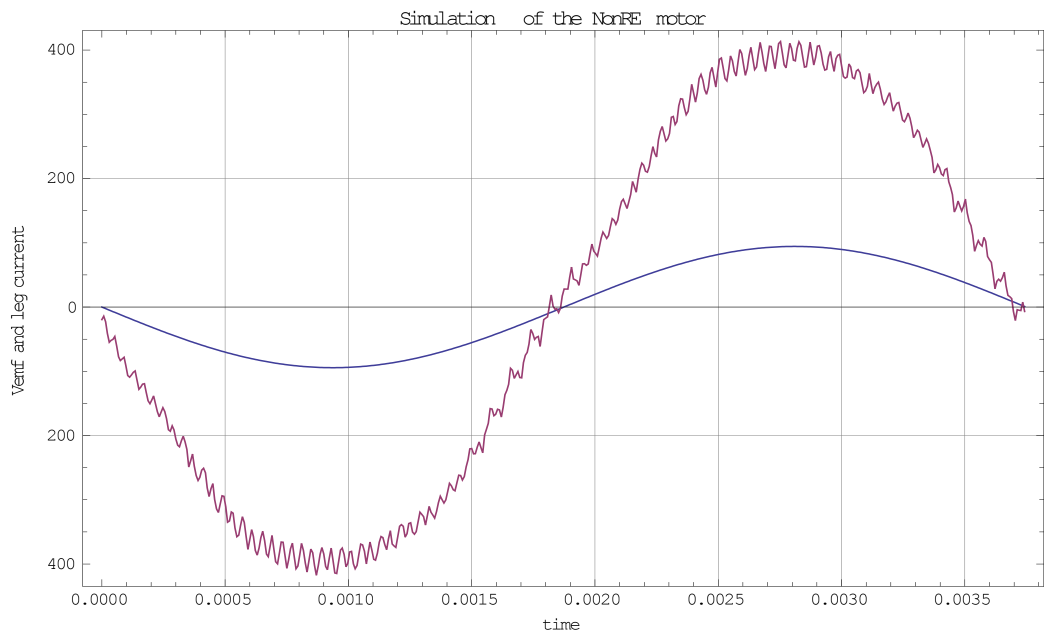
The design incorporates a unique magnetic path to address the low coercivity of AlNiCo magnets (rotor concept is patent pending)



Accomplishments – Inverter (controls) Simulation

Mathematica simulation is a program that UQM uses to model motor ↔ controller interaction

- Commutation (switching) strategies
- Models compared and refined to match test data for over 17 years



Inputs

Motor parameters, controller topology, IGBT switching, speed, voltage, coolant temp

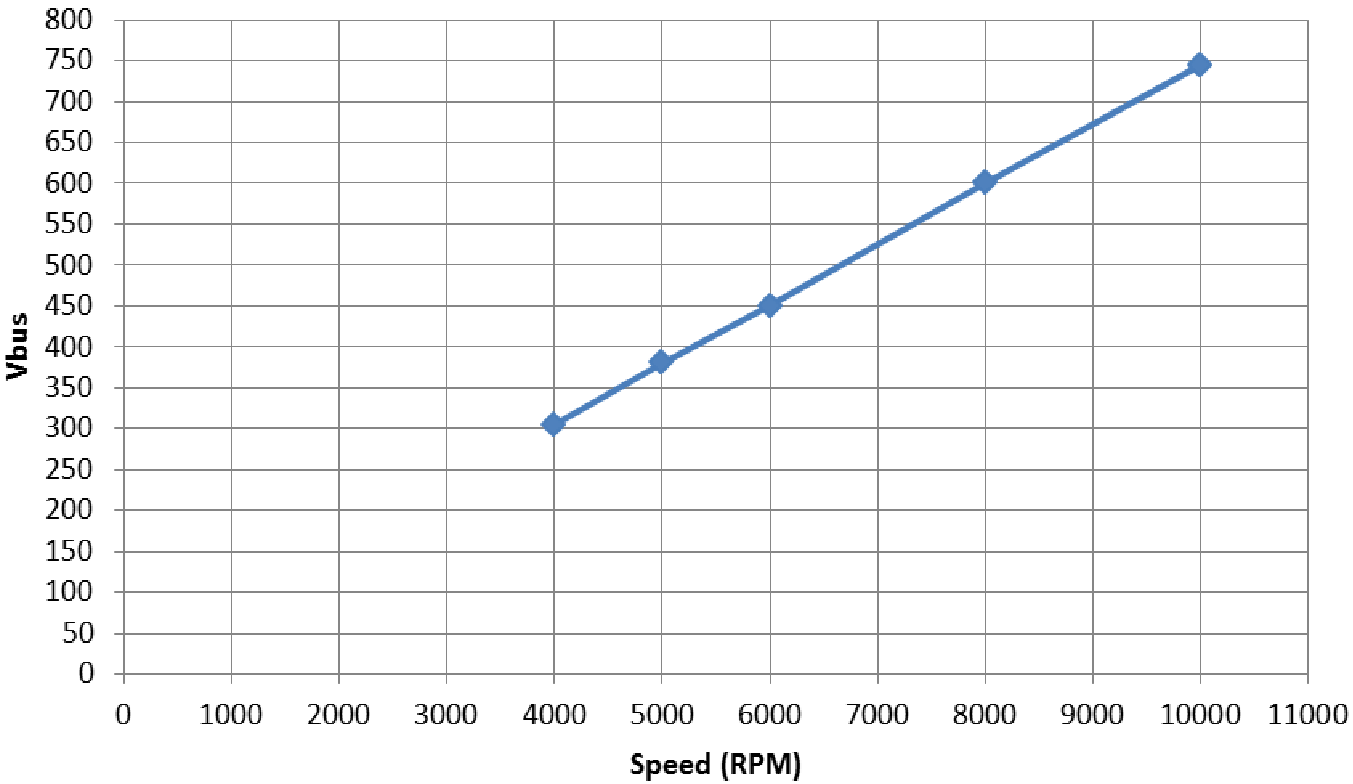
Outputs

Torque, output power, current waveform, efficiency (losses), temperature rise

Accomplishments – Inverter (controls) Simulation

Battery voltage required as a function of speed

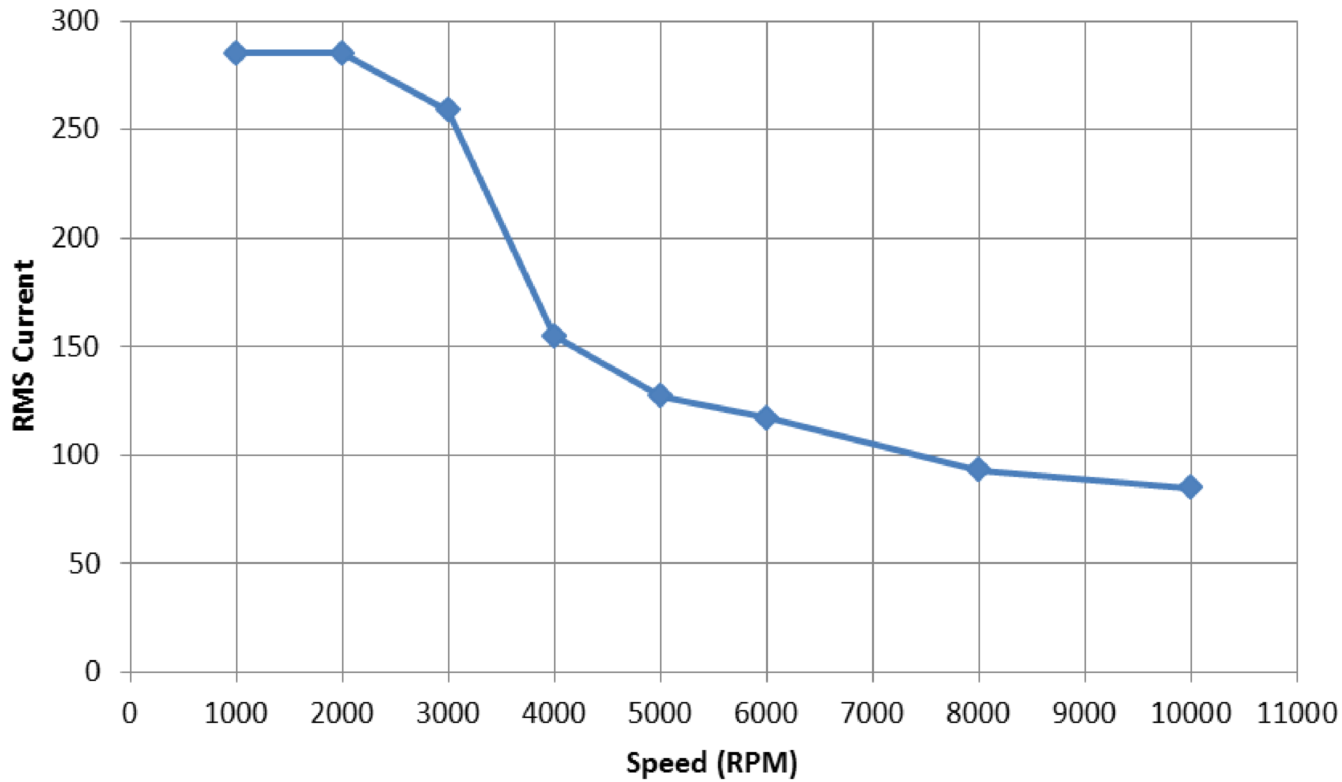
- **300 VDC for speeds lower than 4,000 RPM**
- **Linear increase to 750 VDC from 4,000 to 10,000 RPM (boost)**



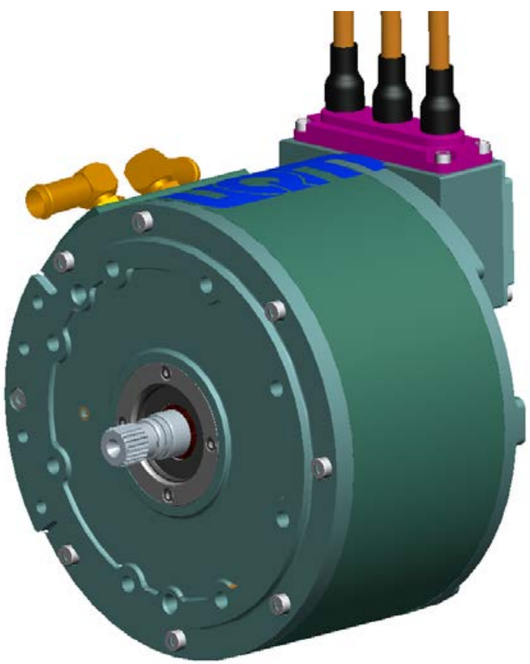
Accomplishments – Inverter (controls) Simulation

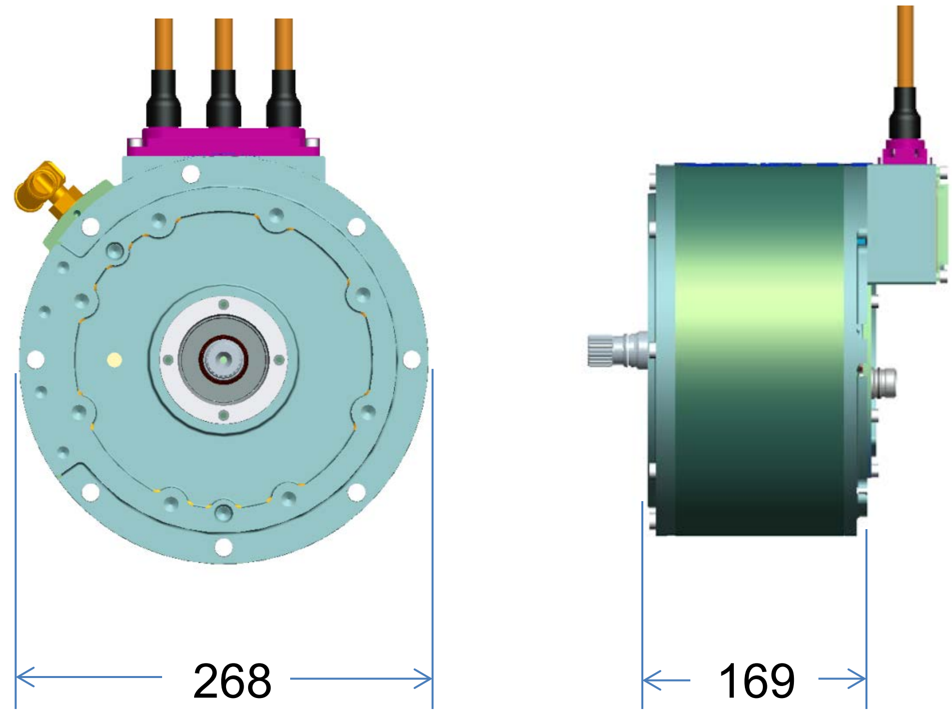
RMS current required as a function of speed

- **At full power of 55 kW**
- **Maximum of 280 amps RMS (400 amps peak)**



Accomplishments – Motor Packaging

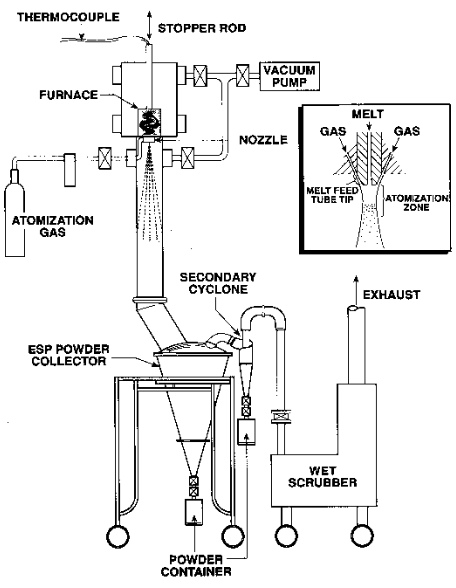




Total volume is 9.5 liters, meeting 9.7 liter volume requirement

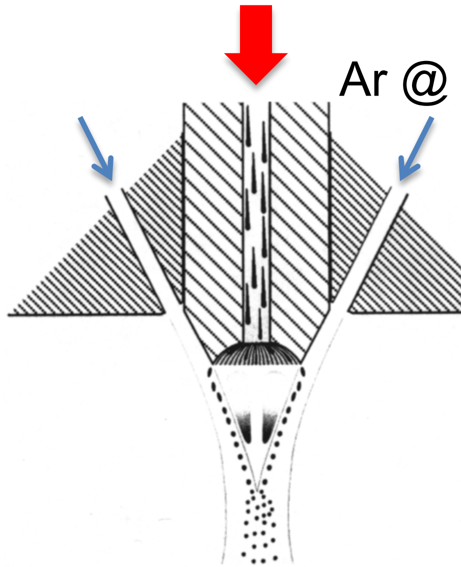
Accomplishments – Higher Coercivity through Process Innovation

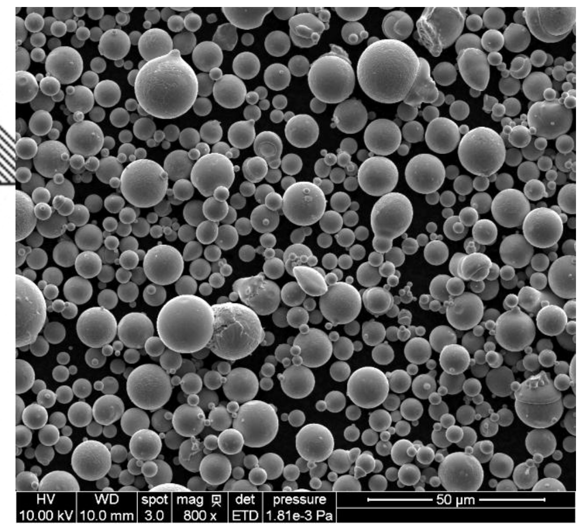
First Gas Atomized Pre-Alloyed Alnico 8



Melt @ 1625˚C

Ar @ 425 psi





Dia.<20µm screened powder

Melt stream before spray onset.

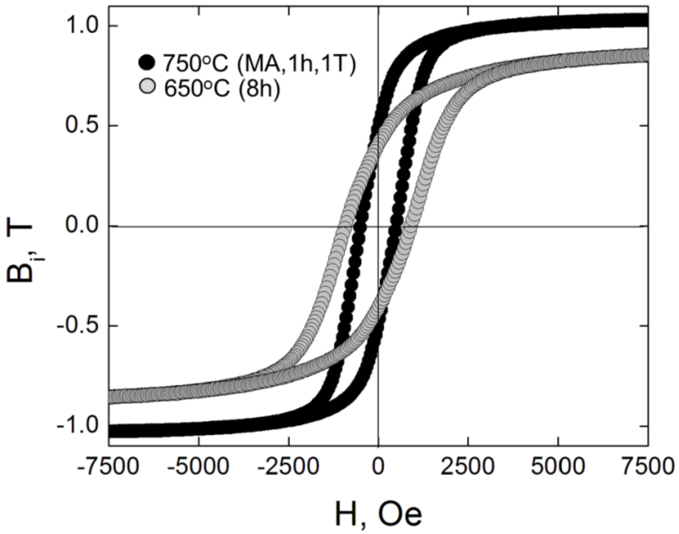
Powder Yield: Avg. particle dia.= 30 µm

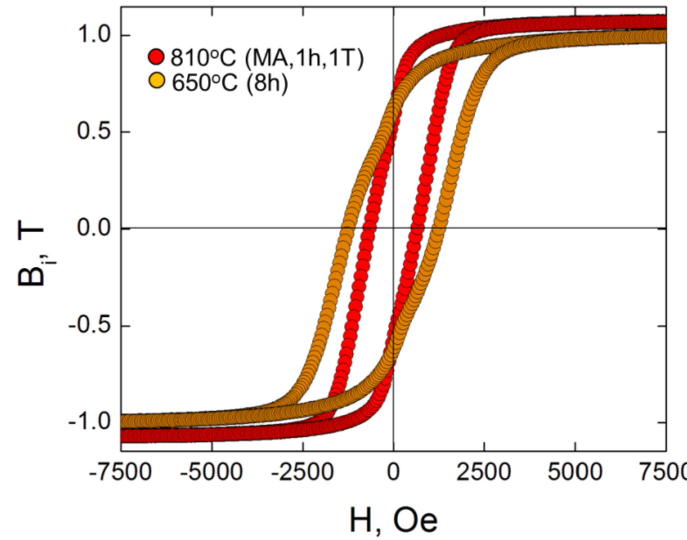
Aim alloy: 32.3Fe-38.0Co-13.0Ni-7.3Al-6.4Ti-3.0Cu (wt.%) ≈ alnico 8H
Analyzed: 32.4Fe-38.1Co-12.9Ni-7.3Al-6.4Ti-3.0Cu (45-75µm powder sample)

Interstitial impurities (ppmw): C=66, N=<10, O=420, S=30
(<20µm powder sample)

Accomplishments – Higher Coercivity through Process Innovation

Summary of Hysteresisgraph Results for Powder Processed Alnico 8H





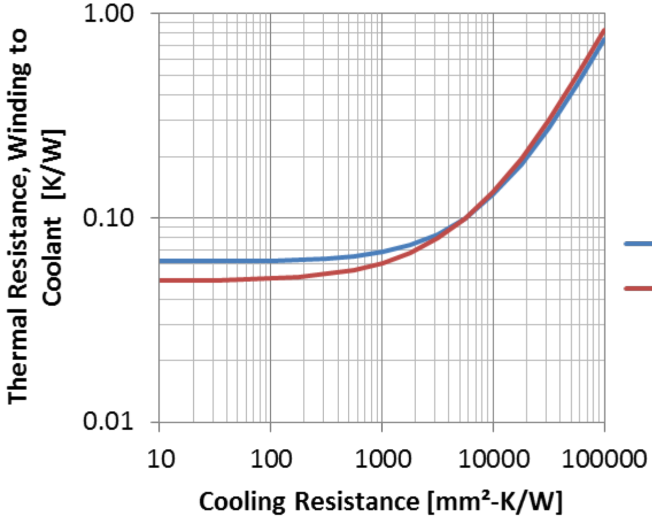
First attempt shows promise for new approach.

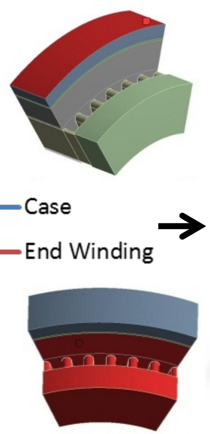
	● 750°C (MA)	○ 650°C (8h)	● 810°C (MA)	● 650°C (8h)
Hci	494 Oe	914 Oe	657Oe	1250 Oe
Bs	1.03 T	0.87 T	1.07 T	1.00 T
Br	0.49 T	0.41 T	0.57 T	0.62 T

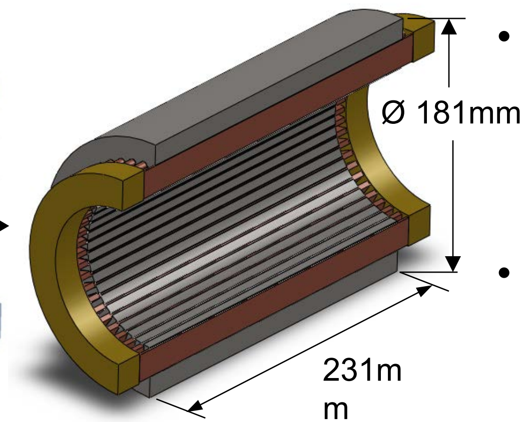
IEC Code	Class	Al wt%	Ni wt%	Co wt%	Cu wt%	Ti wt%	BHmax MGOe	Br Gauss	Hc Oersted	Hci Oersted
R1-1-13	Sintered Alnico 8H	7	14	38	3	8	4.50	6700	1800	2020
GA-194	**HIP Alnico 8H**	**7.3**	**13**	**38**	**3**	**6.4**		**6200**		**1250**

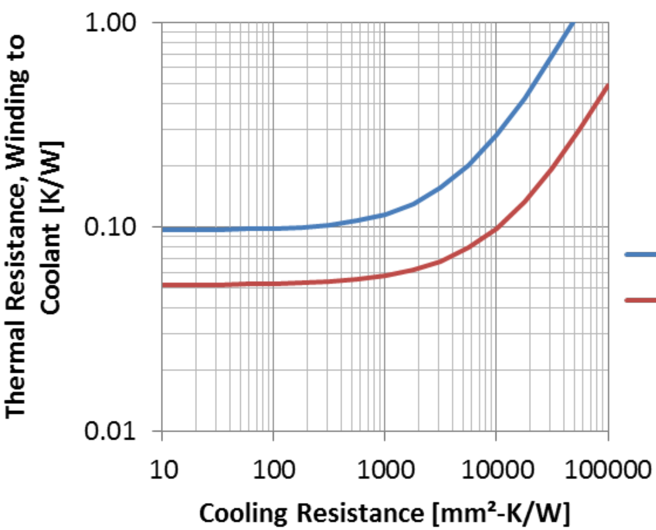
Accomplishments – Thermal Analysis

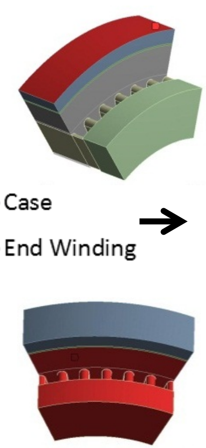
Comparison of Motor Geometry and Cooling Method
(Case or Ending Winding, Water Ethylene Glycol or Transmission Oil)

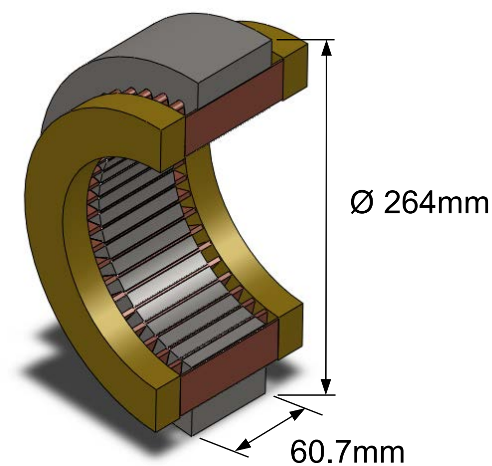












- Geometry and total thermal resistance target affects cooling selection
- Shorter stack length shows benefit from cooling end windings
- Cooling resistance estimated from effective heat transfer coefficient (U)

$$NTU = \frac{UA}{\dot{m}c_p}$$

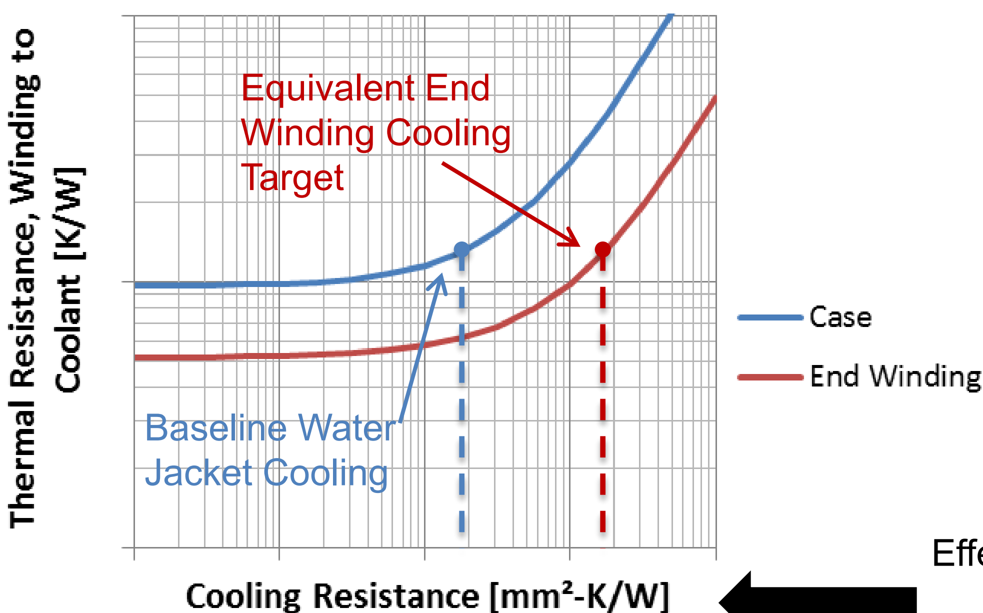
$$\varepsilon = 1 - e^{-NTU}$$

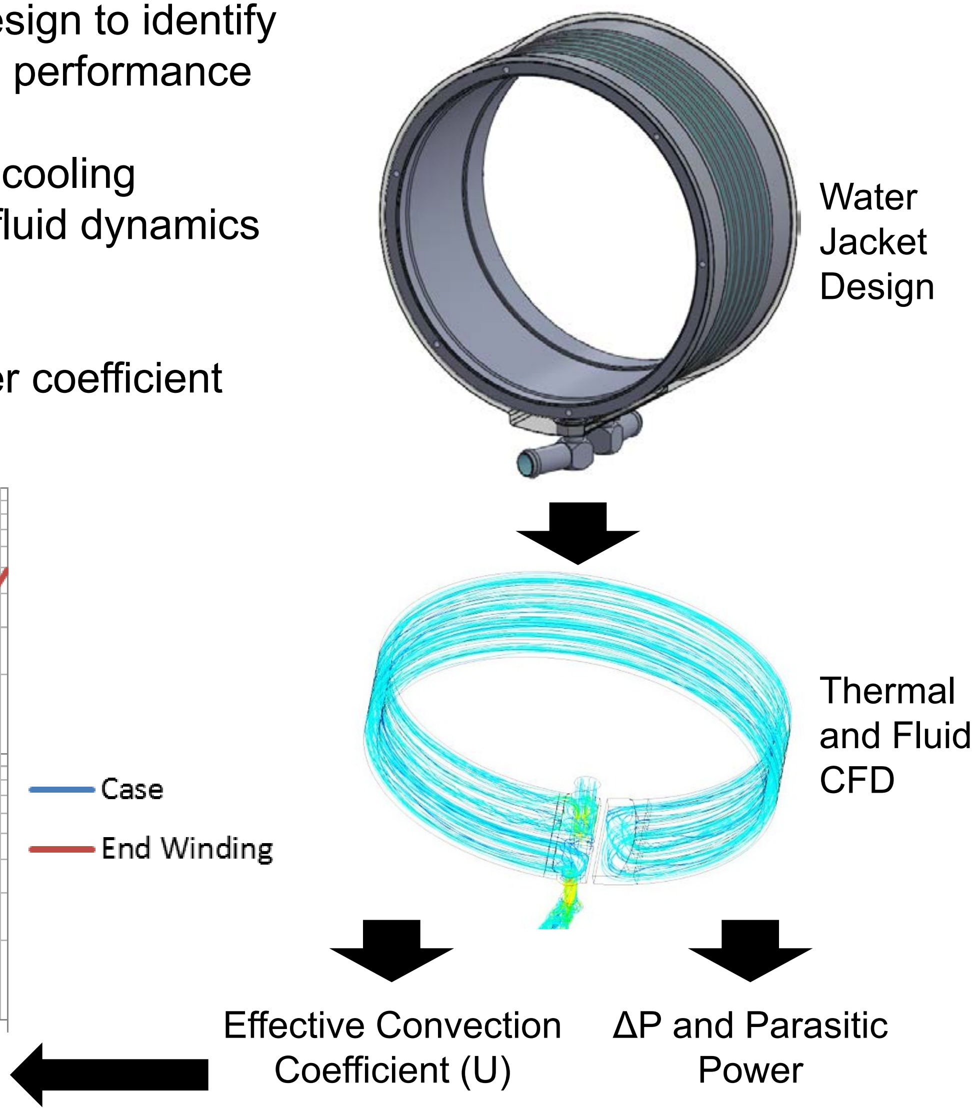
Cooling Resistance

$$R''_{th,ha} = \frac{A}{\varepsilon \dot{m} c_p}$$

Accomplishments – Thermal Analysis

- Applying technique to UQM motor design to identify appropriate cooling technologies and performance targets
- Characterizing baseline water jacket cooling performance through computational fluid dynamics (CFD) models
  - Establish key pressure drops
  - Determine effective heat transfer coefficient
  - Identify temperature gradients





Accomplishments – Requirements Compliance

DOE Requirements: Efficiency through Total Volume

UQM Internal Requirements: Max Stator Diameter through Cogging Torque

Requirement	Value	Status
Efficiency	>90%	Analyzed, Comply
Peak Power	55 kW	55 kW
Maximum Speed	10,000 rpm	TBD, Pending Magnet Retention Analysis
Operating Voltage Range	200-450 VDC 325 VDC Nominal	Analyzed, Comply
Maximum phase current	400 A	Analyzed, small amount of Demag.
Torque	262 N-m	Analyzed, small amount of Demag.
Total Volume	<=9.7 L	9.59 L, based on preliminary design
Max Stator Diameter	10 inches	Analyzed, Comply
Pole Coverage	50%-90%	55 %
Magnet Weight Limit (For Cost)	4.5 kg	4.5 kg
EMF THD	<10%	2.86%
EMF Harmonics	<5% of Fundamental	2.27%
Cogging Torque	< 4 N-m	3.85 N-m

Collaboration and Coordination 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

Future Work

- Complete motor drawing package (detailed part drawings) in June 2013
- Motor build complete in October 2013
  - Uses standard off-the-shelf magnets
  - Optimized water/glycol cooling (NREL analysis)
  - Unique tooling to handle magnet properties
  - Unique method of magnet retention
- UQM testing by the end of the calendar year, using UQM controller that operates to 750 VDC
- ORNL testing early next year
- Vision for Year 3 work (second motor build)
  - Oil cooled variant if analysis shows significant thermal improvement
  - Improved magnet properties from Ames' process work

Summary

- Magnetic finite element analysis demonstrates a feasible architecture to enable the use of non-RE magnets
- Motor ⇔ Inverter analysis indicates that the design is not field weakening compatible and will require a voltage boost inverter
- NREL models to optimize water cooling channel are being finalized for first motor; analysis to establish direction for second motor
- Ames' work is demonstrating methods to increase magnet coercivity, which will ultimately reduce magnet content required for the motor
- Proof-of-concept motor, through analysis, shows compliance with DOE and UQM-internal specifications
- Motor build late this year will demonstrate the feasibility of the approach