Development of Sustainable High Performance Magnetic Materials for Exceptional Power Density Electric Drive Motors

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Ames Laboratory

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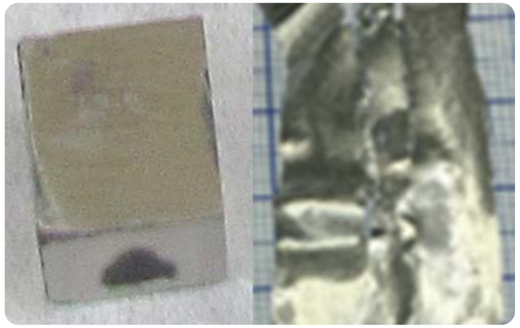


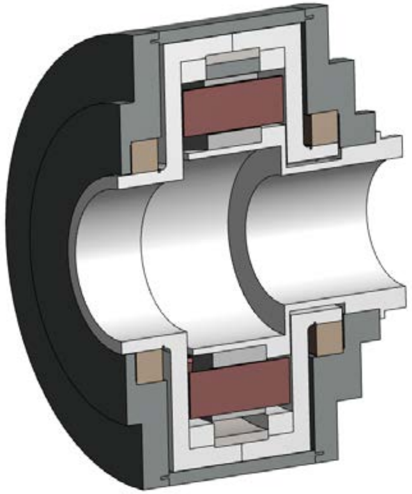


Figure adapted: Jason Preis (ORNL)

Overview

Timeline

- Start: October 1, 2018
- End: September 30, 2023
- Percent complete: 30%

Budget

- Project funding estimate
  - $2,250 K (Federal)
  - $0 K (Cost share)
- Funding for FY 2020: $450K

  (Permanent Magnet portion)

Barriers and targets

- Barriers addressed
  - Permanent magnet (PM) cost and heavy rare earth (HRE) element scarcity and price volatility
  - Non-rare earth PM electric motor has low power density
- Targets
  - Exceptional drive motor power density and reduced cost (50 kW/l at $3.3/kW).

Partners

- Oak Ridge National Laboratory
- National Renewable Energy Laboratory
- Sandia National Laboratory

Consortium Relevance

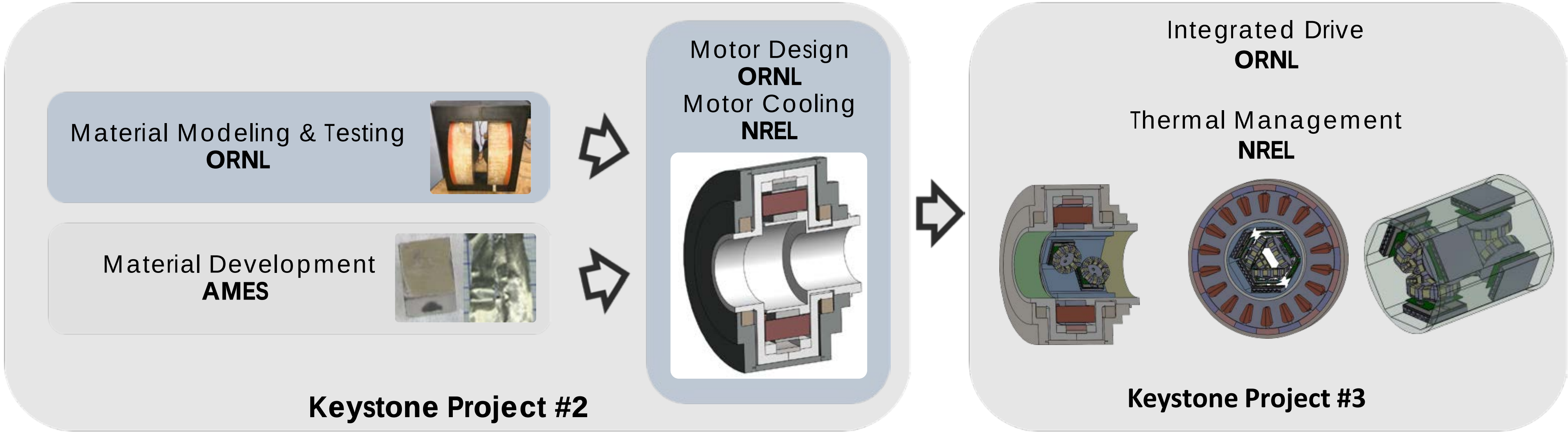
Magnetic Material Development

Electrical steel core losses

- Lower machine inductances lead to worse pulse-width modulation induced core losses
- Lower surface area to volume ratio makes accurate prediction of hot spot temperatures more important for cooling system analysis
- Vector hysteresis and eddy current losses exhibit different flux density magnitude dependency than uniaxial properties

Heavy rare earth free permanent magnets

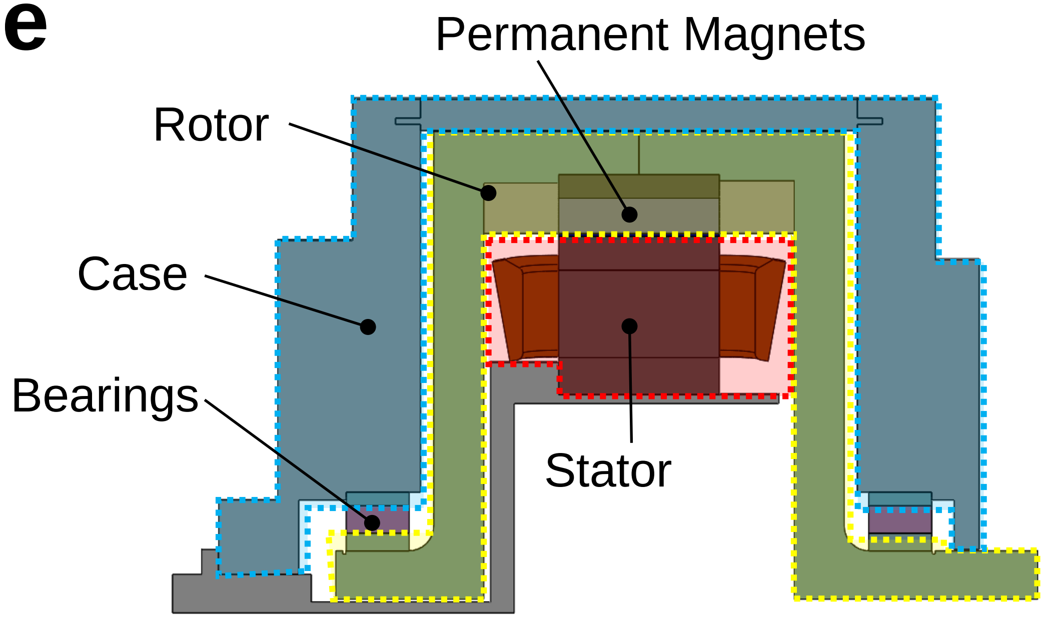
- Low coercivity leads to reliability issues from demagnetization
- Complex magnet arrangements lead to vector demagnetizing fields that are not well modeled with commercial software



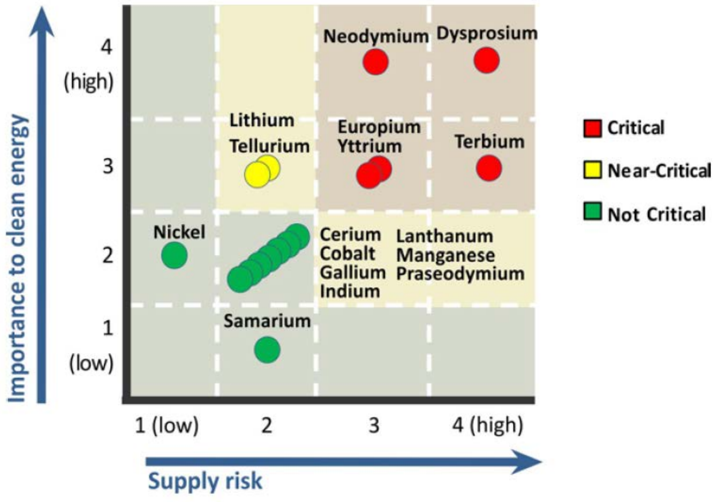
Any proposed future work is subject to change based on funding levels

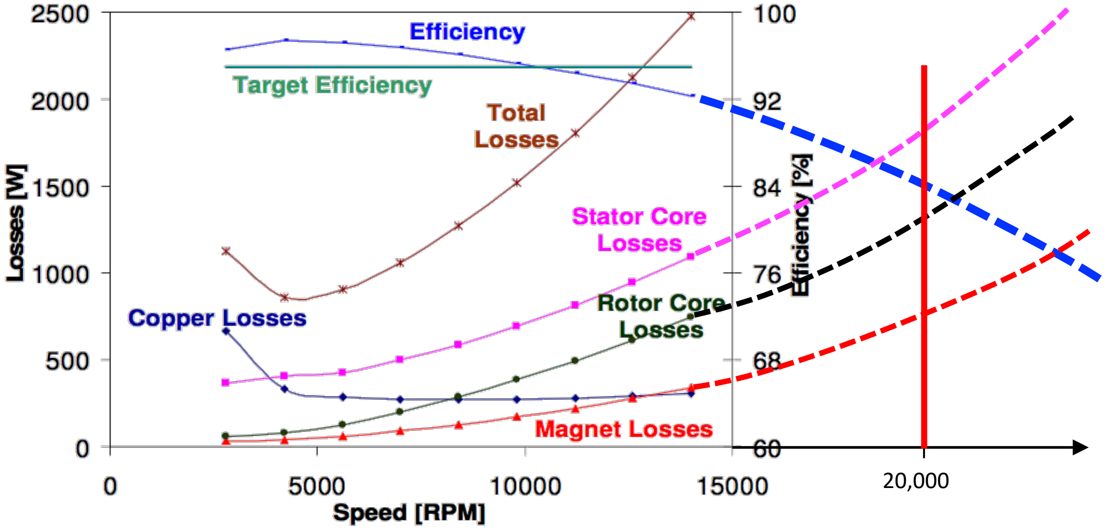
Relevance

- Objective
  - Develop permanent magnetic (PM) materials and processes to avoid scarce/costly heavy rare earth (HRE) metals, but have suitable performance for electric motors with exceptionally high power density.
- Impact
  - Reduces permanent magnet (PM) motor magnet eddy current losses at increased frequency (up to 20,000 RPM)
  - Improve PM motor power density for new outer rotor PM motor designs (ORNL)
  - Maintain drive system cost-effectiveness and high efficiency at elevated temperature to minimize PM cooling needs.



Motor Design (ORNL)
Figure adapted: Kevin Bennion (NREL)





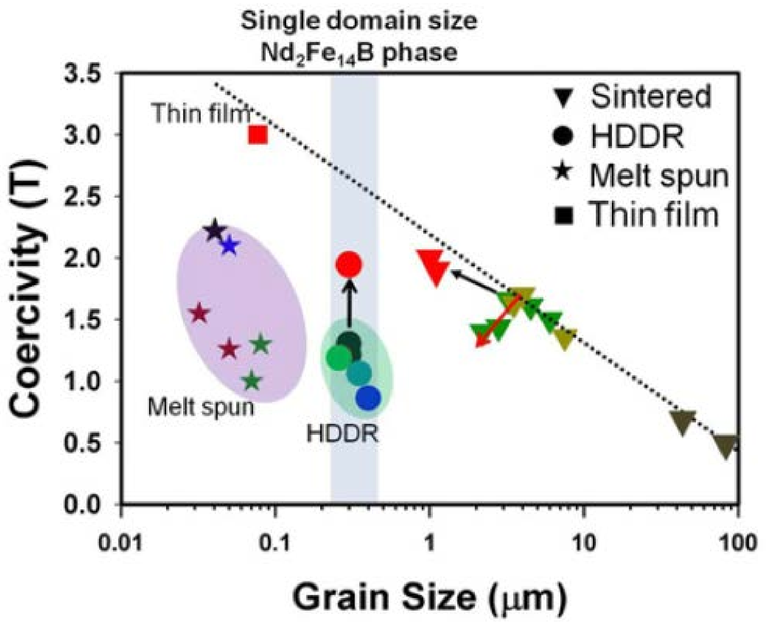
Milestones: Permanent Magnets

Tasks #	Description	FY2019				FY2020				Status
1	Develop fine-grain RE permanent magnet with high coercivity at high temperature	1	2	3	4	1	2	3	4	
Yr1-Q3	Down select and evaluate processes for fine grain magnet production by powder-based approach.									100%
Yr1-Q4	Validate and initial testing of magnets identified through micro-magnetic modeling of bulk RE permanent magnets with heterogeneous and homogenous microstructures.									100%
Yr2-Q1	Evaluate the capability of the dual (opposed) jet mill to produce fine, low oxygen magnet powder suitable for producing fine-grained bulk Nd-Fe-B magnets.									100%
Yr2-Q2										
Yr2-Q3	Demonstrate fine powder production at full size refinement and passivation (1-3 micron, 1 kg).									20%
Yr2-Q4										
2	Develop graded HRE-free magnet with high performance at high temperature	1	2	3	4	1	2	3	4	
Yr1-Q3	Develop methods for achieving spatially varying composition architectures to maximize coercively where needed.									100%
Yr1-Q4	Validate and initial testing of architectures identified through micro-magnetic modeling									100%
Yr2-Q1										
Yr2-Q2	Validate the micromagnetic model by fabricating sample graded magnet and determining the MH loop of the sample using hysteresigraph at ambient temperature.									80%
Yr2-Q3	Magnetic properties of fabricated sample of graded magnet are improved over the MH loop of the “core” magnet sample using hysteresigraph.									
Yr2-Q4										

Task 2.7 Develop ultrafine-grain HRE-free RE-PM with high coercivity at high temp.

Challenge: ***Highly refined grain size in HRE-free RE-PM with improved magnetic & mechanical strength***

Advantages	Challenges



- ➢ Dy in RE-PM for drive motors maintains high coercivity at high operating temperatures.
- ➢ Ultrafine grain non-Dy RE-PM can also raise coercivity and stabilize high temperature properties.
- ➢ New ORNL outer rotor design has less stringent criteria on the permanent magnet's strength.

- Difficult to produce and handle fine powder in manufacturing process
  - – Requires narrow particle size distribution and smooth grains for enhancing coercivity.
  - – High flammability of the fine powder requires better handling/coatings to minimize oxidation.
- Difficult to fabricate into bulk magnet
  - – Full grain alignment is more difficult with finer powders, especially with fragmented shapes.
- Deterioration of bulk mechanical properties
  - – Residual surface oxides embrittle microstructure, which is worse with further size refinement.
  - – Poorly controlled atmosphere can lower overall volume fraction of the magnetic phase.

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Hono et al. Scripta Materialia 67, 2012 (530)

Approach: *Processing Ultrafine Grain Size RE-PM without HRE*

- **Investigate production of ultrafine powder/uniform composition (Dy-free): Down-selected**
  - Feedstock: (commercial) strip cast-HD, (lab capability) melt spun/thin profile chill cast
  - Size Refinement: (commercial) multi-jet milling, (lab capability) ball milling (BM)
- **Surface oxidation protection:**
  - Minimal oxide growth (lab glove box processing)
  - Surface passivation control during milling (concept, scalable?)
- **Investigate processing of aligned, ultrafine grain bulk magnets:**
  - Loose powder aligned by external field: die compact or CIP
  - Full density sintering: vacuum sintering or vacuum hot press
- **Alternative novel processing approaches:**
  - Controlled milling experiments (tests delayed due to COVID-19 foreign travel advisory)
  - Grain stabilizers to inhibit grain growth and maintain flexural strength (in-progress)

	Planned milestones and annual go/no-goes
2019	• Down select fine powder production methods • Validate the mechanism of enhancing coercivity through fine grain approach
2020	• Enable fine grain approach as a replacement for heavy RE stabilization of coercivity at high temperature.

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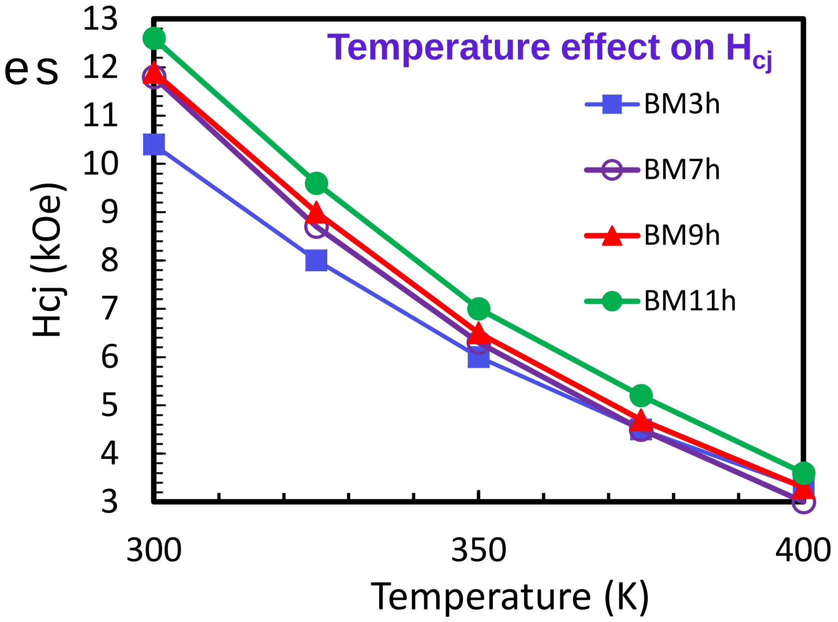
Accomplishments: *Ultrafine Grain Size Effects on RE-PM Revealed*

Improved fabrication techniques compared to the previous ones

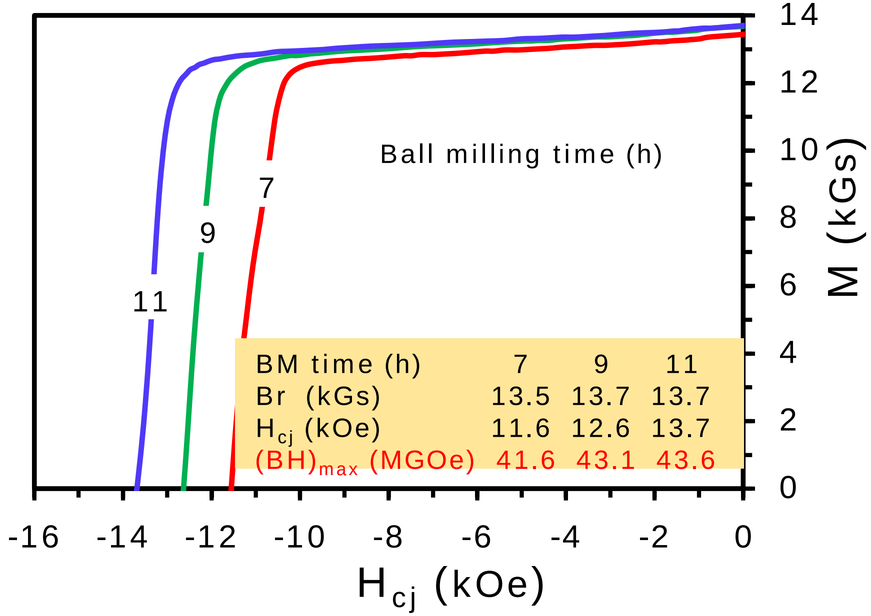
- Optimized ball milling times
- Powder alignment by 9T pulse magnetic field
- Aligned green compaction by 500 MPa CIP
- Demonstrated controlled sample handling: milling to magnet

	BM (h)	7	9	11
Feedstock powder	Average particle size (µm)	**3.6+/-0.15**	**2.2+/-0.15**	**2.1+/-0.15**
Sintered magnet	Average grain size (µm)	**5.0+/-0.15**	**4.6+/-0.15**	**4.0+/-0.15**
	Br (kGs)	**13.5**	**13.7**	**13.7**
	H_{cj} (kOe)	**11.6**	**12.6**	**13.7**
	$(BH)_{max}$ (MGOe)	**41.6**	**43.1**	**43.6**
	$-\alpha_{300-400k}$ (%/K)	**0.15**	**0.14**	**0.14**
	$-\beta_{300-400k}$ (%/K)	**0.74**	**0.72**	**0.71**

- Magnetic properties (FY2020) magnets enhanced by improved techniques: H_{cj} increased from 10.2 to 12.6 kOe; $(BH)_{max}$ increased from 33.0 to 42.7 MGOe
- Optimized Processing to achieve finer grained magnets: H_{cj} increased from 11.6 to 13.7 kOe; $(BH)_{max}$ increased from 41.6 to 43.6 MGOe
- Demonstrated improved temperature performance: Increased H_{cj} over all temperatures.



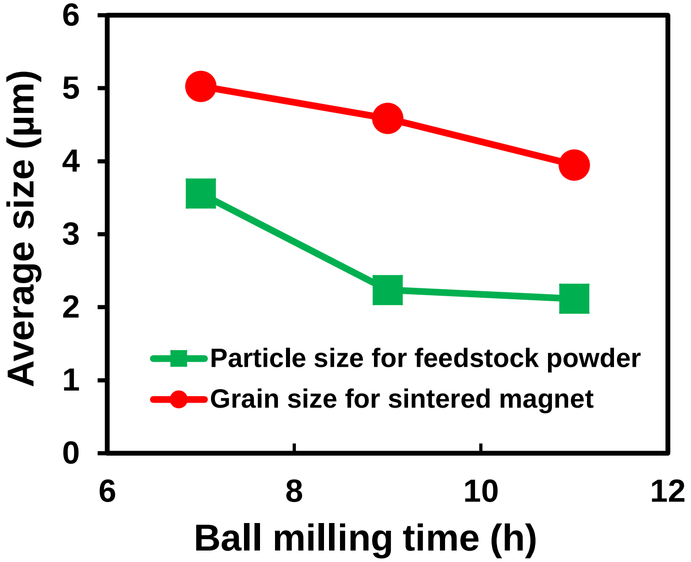
Ball milling time effect on Q2 curves



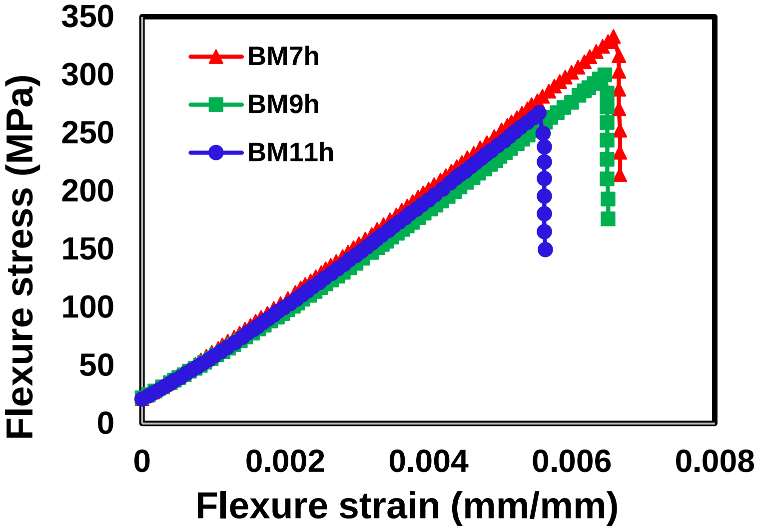
Accomplishments:

Powder particle size vs. grain size and mechanical properties of magnets

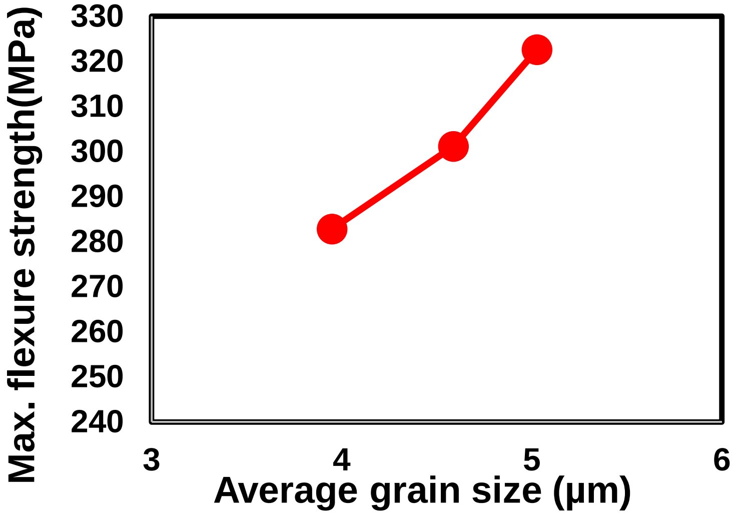
Particle size vs grain size



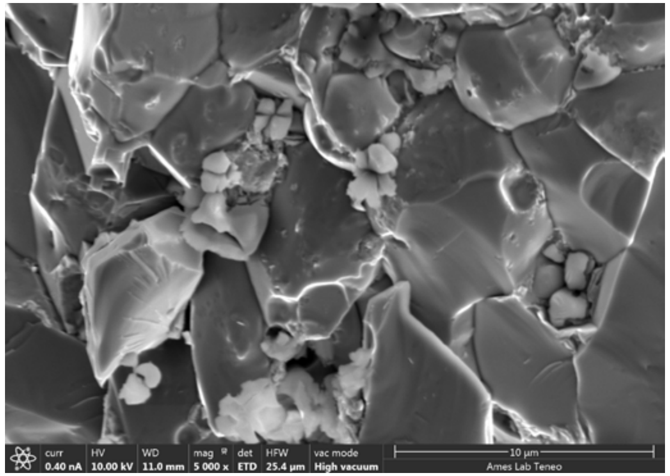
Flexure strain vs stress



Grain size vs Max. strength



Fracture surface morphology



- With increasing ball milling time from 7 to 11 hrs, average particle size reduced from 3.6 to 2.1 μm, while grain size of corresponding sintered magnets reduced from 5 to 4 μm.
- Maximum flexure strength decreases with reduction of grain size of sintered magnets.
- The fracture pattern is typically inter-granular fracture. Cracks mostly propagate along grain boundaries in the fracture path.

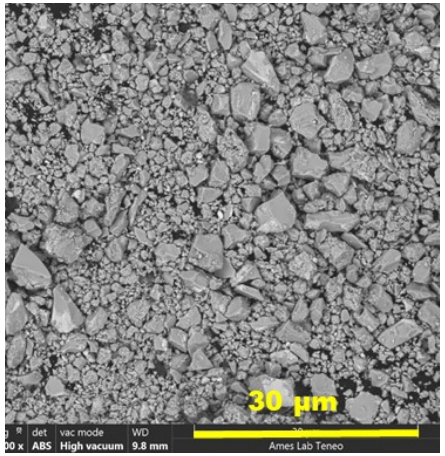
Accomplishments: *Role of Particle Size and Size Distribution*

Used fluid suspension settling to narrow powder distribution from 11h ball milled powder.

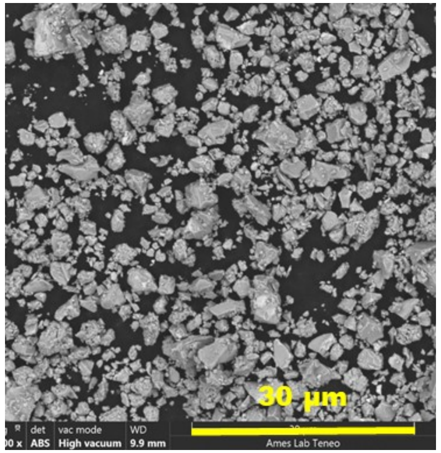
Withdraw suspended finer particles

Fluid/particle suspension separation

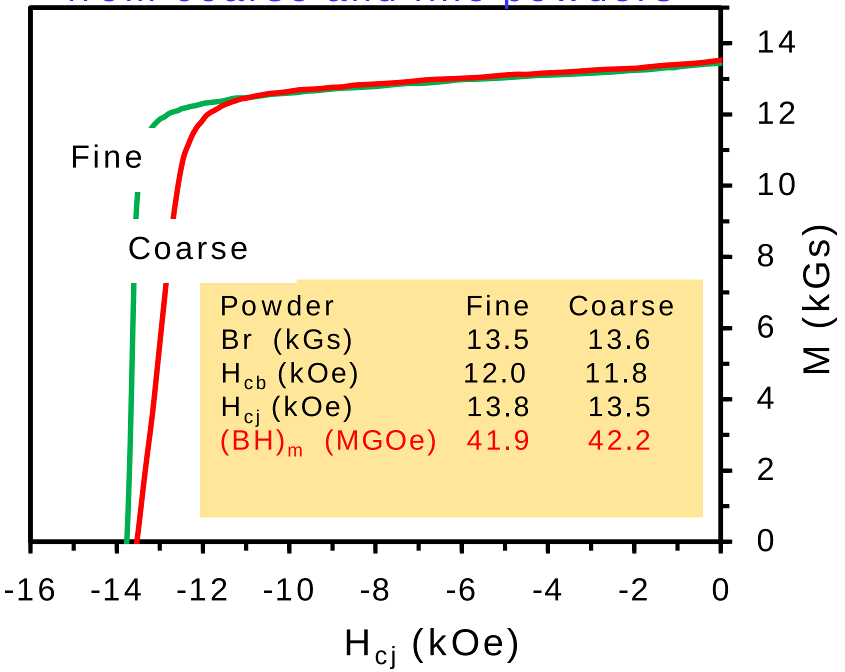
11h ball milled powder



Separated powder (13 min. settling)



Demag. curves of magnets from coarse and fine powders

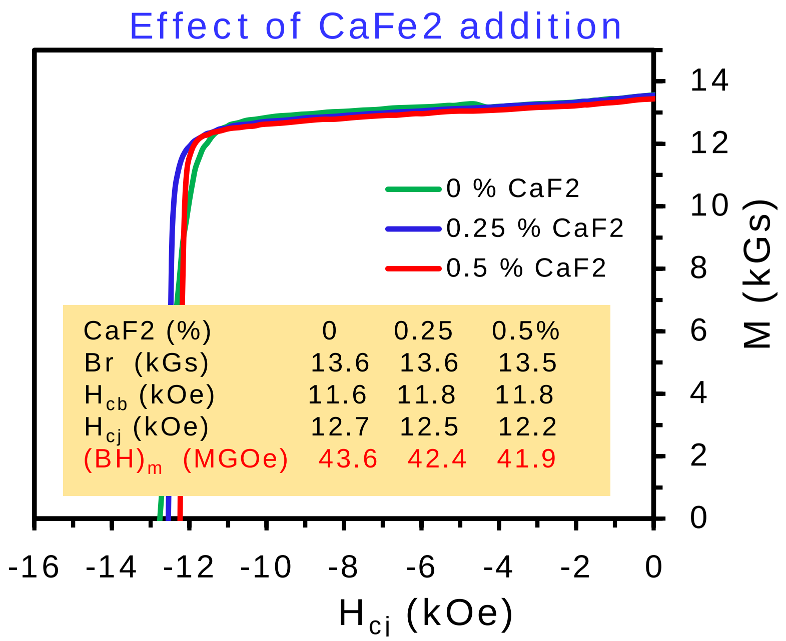


- **Bigger particles removed by settling separation, but lost some ultra-fines to container wall.**
- **Demagnetization curve of magnet made from uniform/ultra-fine powder (dia.<5 µm) exhibits a better squareness from improved alignment.**
- **Improved sintering process for finer powder needs to be developed to maintain ultra-fine grain magnets.**

Accomplishments: Grain growth suppression

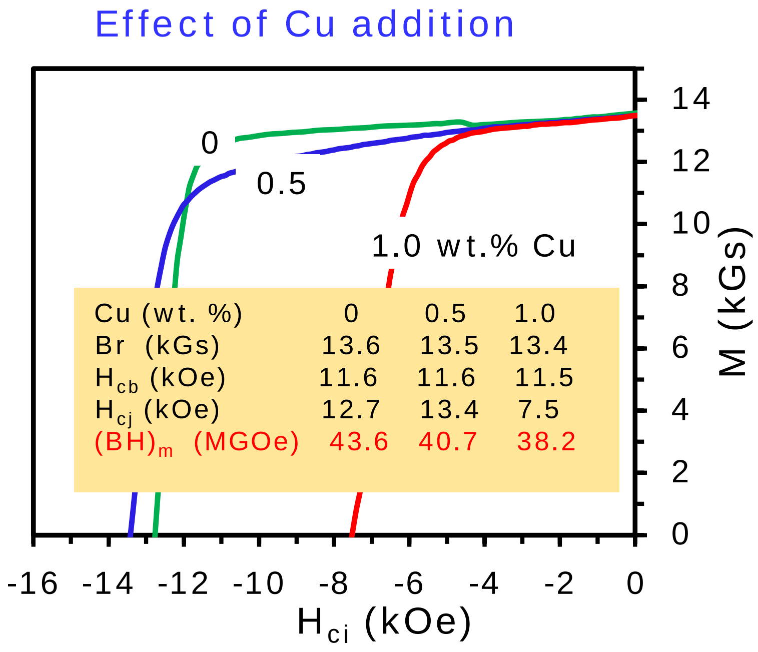
Approach I: Grain growth inhibitors/pinners in feedstock powder

- ❑ Uniformly distributed compounds (MgO, La_2O_3, Nd_2O_3 and CaF_2) at the 2-14-1 grain boundaries, to inhibit grain growth during transient liquid phase (TLP) sintering.
- ❑ Each compound blended with different weight % feedstock powder. Additions of Nd_2O_3 and CaF_2 slightly decreased coercivity, but MgO and La_2O_3 were more harmful to coercivity.
- ❑ Will alternative grain growth pinners that inhibit grain growth to improve coercivity also diminish magnetization and embrittle?

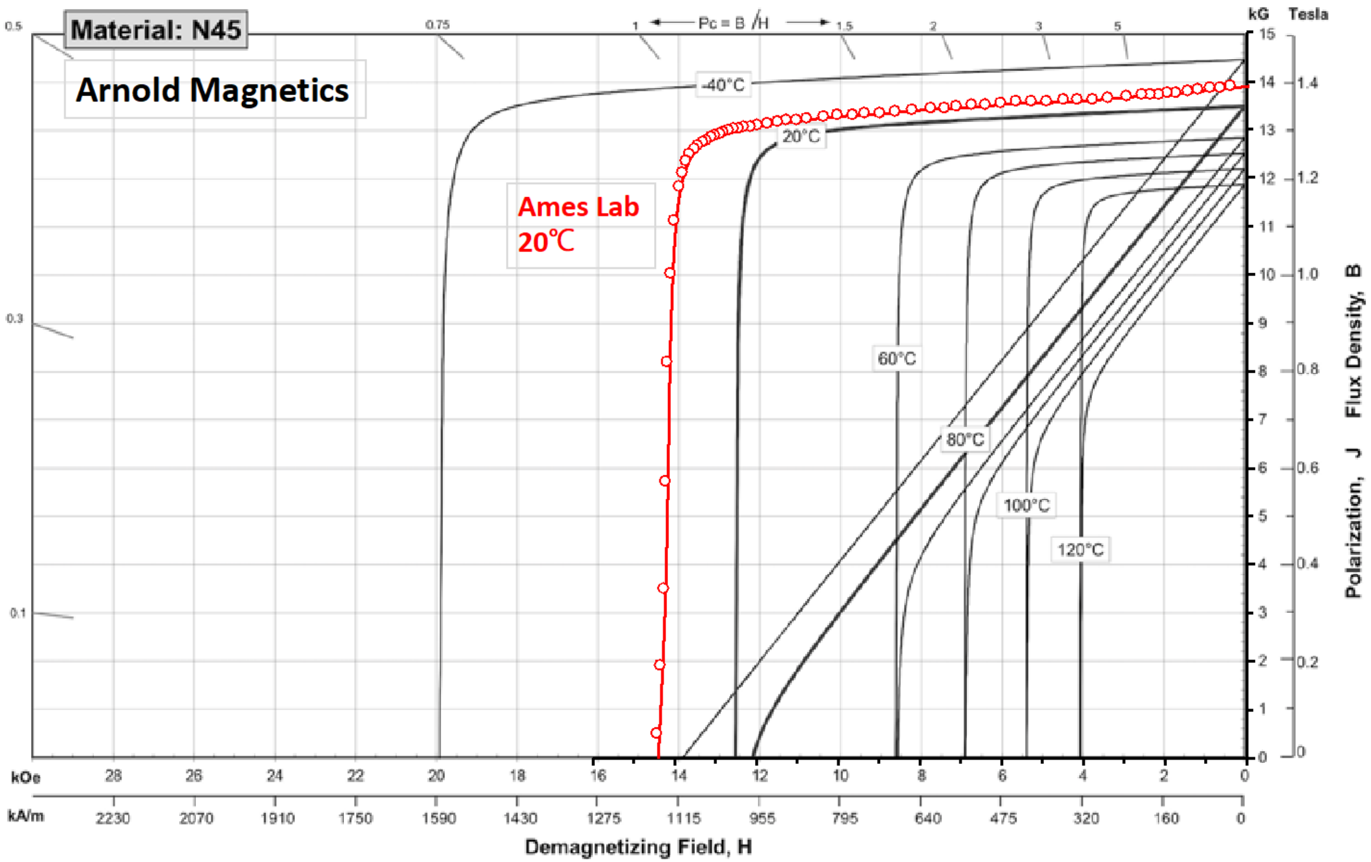


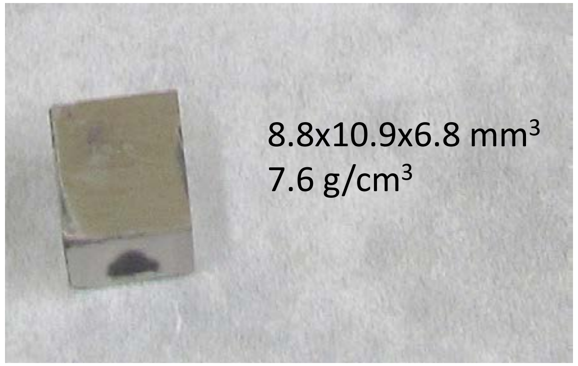
Approach II: Sintering aids with low melting metal/alloy

- ❑ Fine metal powder, e.g., 15 µm Cu, is blended with 2-14-1 powder (Nd-Cu eutectic melting at 520C)) to become TLP agent.
- ❑ Small addition of Cu can improve coercivity, but $(BH)_{max}$ slightly decreases.
- ❑ Plans: Use 0.3 µm ultrafine Cu powder to get better distribution in the feedstock. May also test Pr-Cu powder (Teut. = 450C) addition.
- ❑ Will reduced sintering temperature to exploit TLP sintering aids suppress grain growth/increase coercivity AND maintain magnetization without embrittlement?



Accomplishments:
Current Best Laboratory Ultrafine Grain HRE-free Magnet



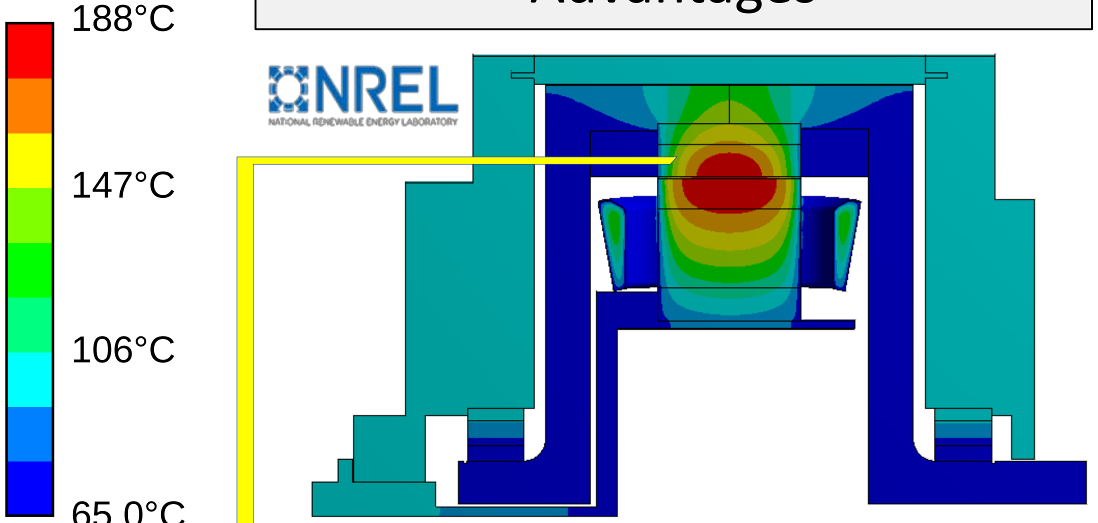


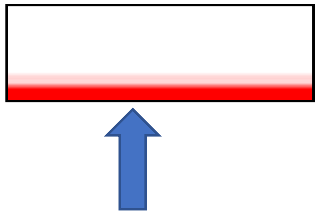
N45 grade	Arnold Magnetics			Ames Lab	
	Min.	Ave.	Max.	Ave.	Max.
Br (kGs)	13.2	13.5	13.8	13.7	13.9
H_{cb} (kOe)	10.8	12.0	13.2	12.3	12.7
H_{cj} (kOe)	12.0	12.6	-	13.7	14.4
$(BH)_{max}$ (MGOe)	42.0	44.0	46.0	43.6	45.3
$-\alpha_{25-100ºC}$ (%/ºC)		0.12		0.12	
$-\beta_{25-100ºC}$ (%/ºC)		0.75		0.78	
Flexural Strength (MPa)		285		283	

2.8 Develop graded HRE-free magnet with high performance at high temp.

***Challenge:* Design/produce graded HRE-free magnet with surface of high coercivity & core of high magnetic saturation.**

Advantages





Needs highest Hc

- During outer rotor PM motor operation a minor portion of the bulk permanent magnets (at rotor gap) feels high demagnetization field.
- Can a portion of the PM outer rotor magnets be “shielded” by high coercivity magnet “cap” with high temperature stability, e.g., $SmCo_5$, if a high saturation magnet with less Hci, e.g. alnico 5-7, is the core and provide sufficient magnetic torque for the motor?

Challenges

- Demagnetization lines are non-linear
  - The de-magnetization field distribution of a non-uniform high coercivity (shielded) magnet in realistic stator field needs to be modeled in appropriate geometry.
- Assembly of two permanent magnets without air-gap requires
  - Compatible thermal-mechanical processing during the bulk graded magnet fabrication process
  - Composite thermal-magnetic treatment adaptable for both magnet types.
  - Compatible CTE during operation to resist thermal fatigue.

Approach: *Modeling and Processing Graded Magnets*

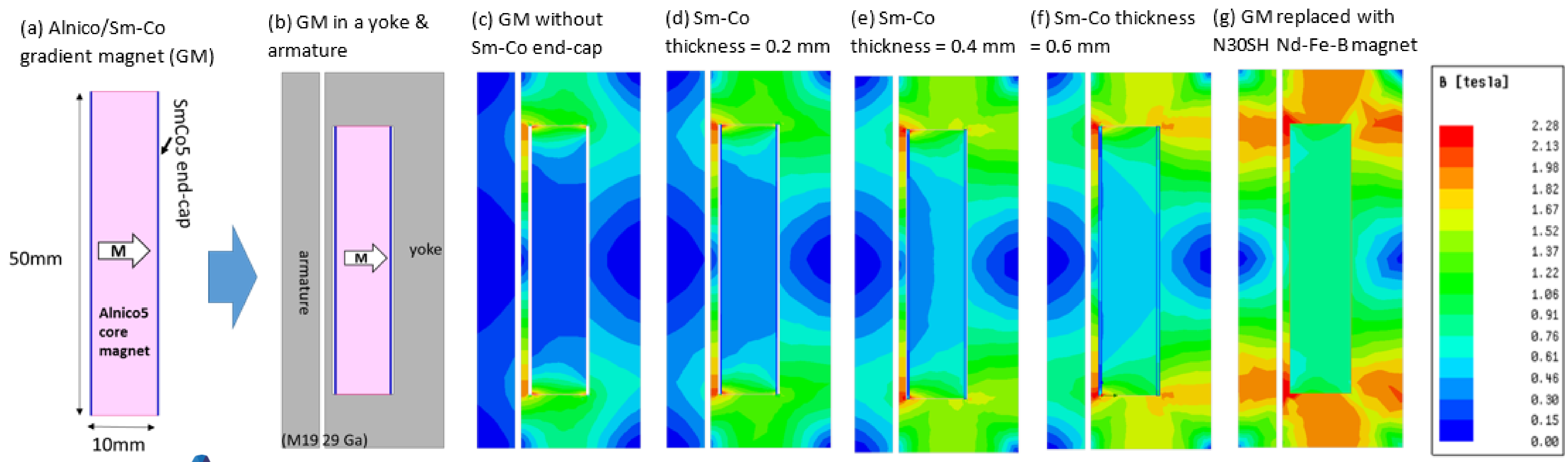
- Conduct preliminary composite magnetic modeling of high H_{ci} magnet shell on high M_{sat} magnet over range of field strength.
- Investigate metallurgical compatibility for consolidation processing and for thermal-magnetic heat treatment of possible magnet pairs.
- Perform geometry-corrected modeling of demagnetization lines with preliminary choice of high H_{ci} /high M_{sat} magnet types ($SmCo_5$ /alnico 5-7)
- Assess technology prospects for graded magnets (alternative approaches for graded magnet processing) and scale-up feasibility.
- Develop physical models and methods for achieving spatially varying composition & alternative architectures to maximize coercivity, as needed.
- Validation and initial tests of graded magnet architectures identified through micro-magnetic modeling.

	Planned milestones and annual go/no-goes
2019	• Determine architecture of the graded-magnets • Investigate process compatibility for a model system (SmCo-AlNiCo)
2020	• Validate graded magnet concept by fabricating and testing a physical model system and then a graded magnet microstructure.

Previous Preliminary Modeling of Graded Magnets: New perspective

Performed preliminary simulation of demagnetization field distribution across gap from electromagnet to adjacent permanent magnet (PM) in outer rotor during normal motor operation.

- Used magnetic FEM to start exploring effect of high coercivity “cap” magnet ($SmCo_5$) on high saturation “core” magnet (alnico 5), similar to geometry of outer rotor PM motor.
- Need to explore fundamental principles for predicting the effects of spatially varying grain size on magnetic and mechanical properties.
- Must gauge trade-off between improved magnetic and physical properties (electrical resistivity and mechanical properties, e.g., fracture toughness).



Accomplishments: Fabricated & Tested Magnetic Properties of Physical Model Composite Magnets

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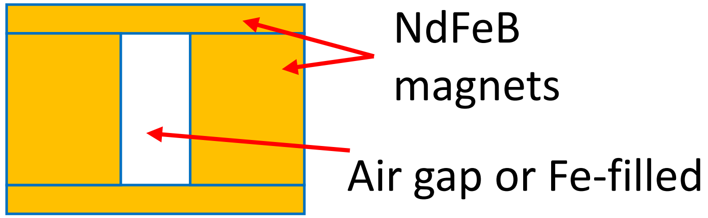
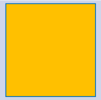
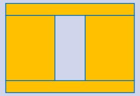
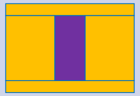
Initial Magnet Physical Models:

Established demagnetization curves for various geometries:

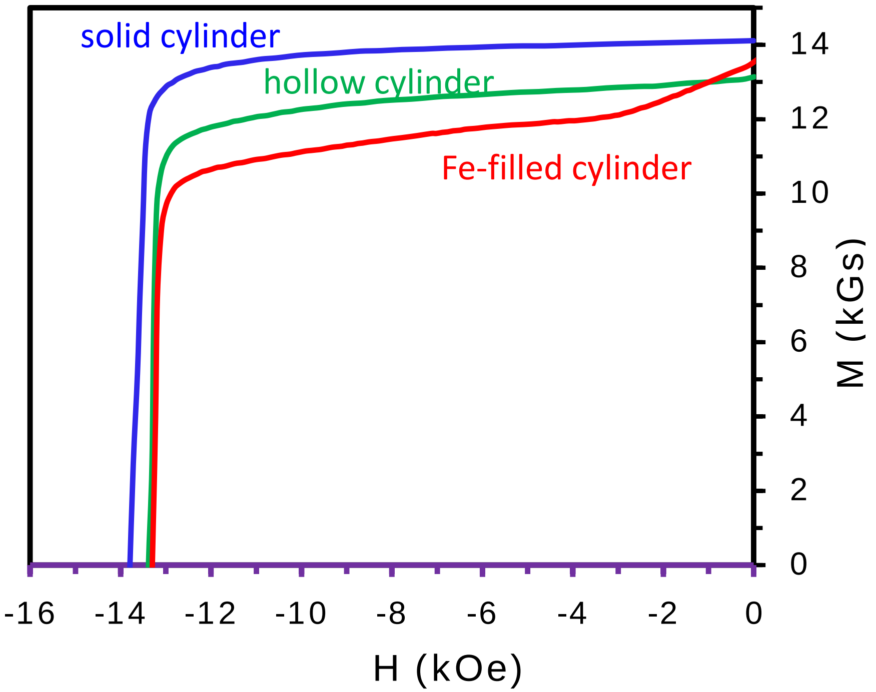
Solid cylinder (blue line), hollow cylinder (green line) and Fe-filled cylinder (red line)



- Air gap (hollow cylinder) shows expected reduction in magnetization with decreased magnetic alloy.
- Slight decrease in coercivity in magnet with air gap.
- Fe-filled magnet shows some exchange coupling at low fields.
- Data will be used to validate micro-magnetic models for complex geometries that need to be developed.

Magnet OD (ID)	12 mm	12 mm (3 mm)	
			
Magnet sample	Solid Cylinder	Air gap: 1.5 mm thick top & bottom	Fe-filled: 1.5 mm thick top & bottom
Br, kGs	14.1	13.1	13.5
H_{cb}, kOe	12.9	11.8	10.9
H_{cj}, kOe	13.8	13.4	13.3
$(BH)_{max}$, MGOe	48.4	40.0	34.8

2[nd] quadrant demagnetization curves



Responses to Previous Year Reviewers' Comments

Question 1: Most reviewers felt the work was timely and relevant. Reviewer 4 asked: This reviewer said it is not clear that what the impact of the HRE(-free) permanent magnet (PM) will have on the motor performance. The reviewer also asked how it compares to commercially available dysprosium (Dy)-free magnets.

Ames response: Without Dy, the coercivity of existing $Nd_2Fe_{14}B$ magnets are reduced from 18 kOe (@22C) to 2.5 kOe (@180C) at peak motor operation temperature. With added Dy and Co, the 2-14-1 magnets can maintain 7 kOe @180C, preventing permanent loss of magnetization from demagnetization field generated by the stator and its coil. Thus, drive motors with existing Dy-free magnets require rigorous temperature control (complex, inefficient and heavy), a significant difficulty for meeting DOE 2025 targets and 8X improvement in power density. However, analysis of our fine-grain $Nd_2Fe_{14}B$ approach predicts the possibility of 25% greater coercivity and we have demonstrated 14% improvement (at 45.2 MGOe). With these enhanced magnetic properties at room temperature in fine-grained $Nd_2Fe_{14}B$, a linear reduction trend predicts that there will be enough coercivity to operate at 180C, similar to the high temperature performance of Dy-added Neo magnets. [Results demanded funding priority.]

Question 2: Most reviewers felt that the project is going well. The graded magnet approach seems very difficult, and physically using blocks of different magnets might be an easier path. [Graded approach truncated by funding limits.]

Ames response: Graded magnets are difficult to develop because optimal architectures (to allow exchange coupling field to pass through) are unknown and metallurgical interactions between "core" and "shell" are unknown, along with the problems with developing mutually compatible heat treatments. Graded fabrication processing is likely to involve additive manufacturing, but also must be developed for these (normally) reactive materials.

Collaboration and Coordination

- Collaboration on motor design advances and sharing expected material magnetic & mechanical properties.
- Guidance on modeling of geometry-corrected demagnetization lines of high M_{sat}/high H_{ci} graded magnet types.
- System level performance modeling.

- Investigation of thermal and mechanical properties of newly developed magnetic materials.

- Coordination of efforts of university partners who are actively engaged in permanent magnet development for associated motor designs.
- Cooperative development of composite permanent magnet processing and designs.

Remaining Challenges and Barriers

- **Multi-jet milling method selected for controlled atmosphere production of ultrafine $Nd_2Fe_{14}B$ powder with uniform size, but not available in US.**
  - Experiments run with common commercial feedstock particulate from strip casting/HD in Dy-free composition.
  - Size refinement by multi-jet milling uses intense energy and controlled atmosphere to produce high purity, rounded ultrafine (< 2 μm) particles preferred for alignment.
  - Capability compatible with plans for minimized oxide growth by development of surface reaction, dry filter box collection, and glove box processing.
  - Co-operation on system purchase is being sought between consortium members.

- **Inert handling, alignment, and consolidation methods need to be extended to retain advantages of new ultrafine jet milled powders.**
  - SEM or automated size analysis needs to verify uniform refinement and rounded shape of as-milled powder.
  - Need to investigate if pulse magnet for loose powder alignment may be incorporated with high pressure CIP densification to suppress any misalignment of powder before sintering.

- **Powder sintering parameters need to be modified to fully exploit reduced temperature of TLP additives activity.**
  - Final composition and wt.% of TLP sintering additive needs to be finally selected.
  - Temperature stability of magnetic properties of resulting ultrafine grain magnets must be tested.

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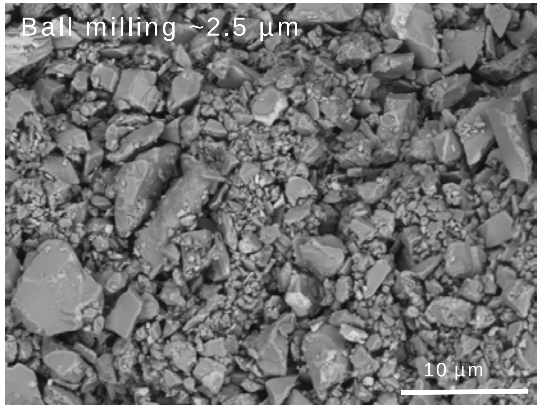
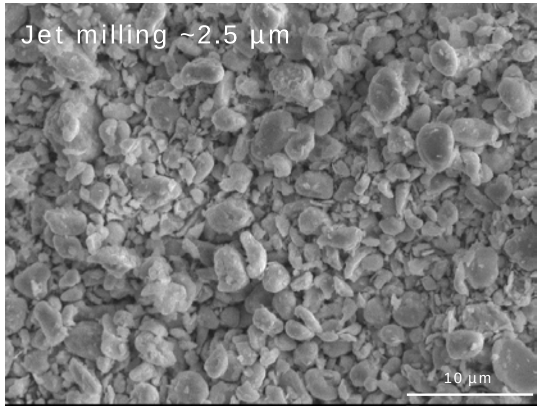
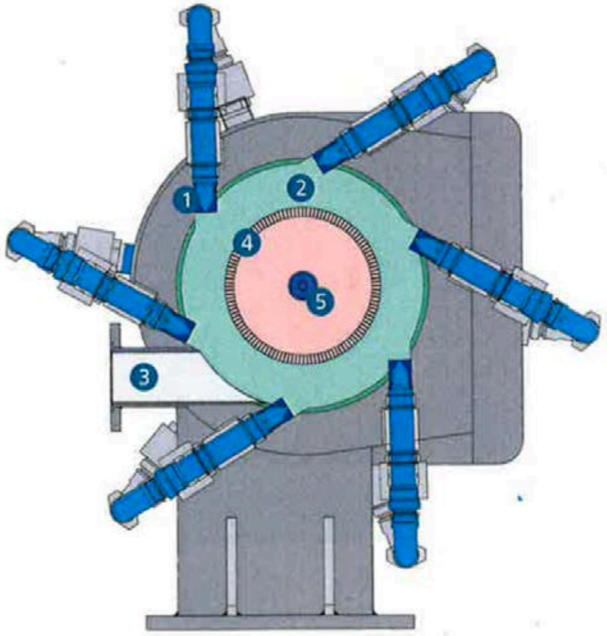
Proposed Future Research

- Must gain access and sufficient expertise with multi-jet milling system to perform critical experiments on alternative methods for passivation of resulting ultrafine (dia.< 2 µm) powder of HRE-free RE-PM alloys.
- Need to develop additive composition and quantity for HRE-free RE-PM alloy powder to maximize retention of ultrafine grain size during full density consolidation without compromising magnetic property gains.
- Validate the hypothesis that mechanical properties improve for ultrafine-grain magnet if surface oxide is thinner and Nd-rich phase on grain boundary suppresses microcrack propagation.
- For ultrafine grain RE-PM magnets, should develop final shape processing to minimize material waste, only needing final grinding to dimensions.







Multi-jet milling system schematic.

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

Summary

- We can make bulk magnets with magnetic properties superior to commercial grade magnets from similar RE-rich (HRE-free) Nd-Fe-B alloy
  - Feedstock powder size refined via extensive ball milling
  - Powder loaded in glove box into alignment capsule for pulsed magnet (9T) alignment.
  - High density green compact made with a new high pressure CIP setup (500 MPa)
  - All powder & green compacts transferred into operations/equipment without air exposure
  - Sintered magnet grain size reduced by 20% from typical 5$\pm$0.2 mm to 4$\pm$0.2 mm via two-step sintering treatment (using feedstock powder with finer particle size) without sintering aids.

- With current ball milling process ultra-fine grained magnets have slightly inferior mechanical properties and strength can become worse if grain size smaller than 1 µm (for highest coercivity and energy product) is achieved. Change to alternative, scalable, high purity process could generate finer powder and experimentally develop new passivation treatment for highly controlled powder surfaces.

- Results indicated that TLP additives are promising for grain growth suppression but sintering parameters were not appropriate for exploiting lower melting behavior.

- Prior graded magnetic modeling of high H_{ci} magnet cap on high M_{sat} magnet core was conducted over range of field strength and encouraged this approach, but recent tests of metallurgical compatibility of a possible magnet pair ($SmCo_5$/alnico 8) and of another physical model ($Nd_2Fe_{14}B$/pure Fe) indicated that the ultrafine grain size approach had more promise and should have higher priority for research funds.