Creating Materials and Energy Solutions

AMES LABORATORY
United States Department of Energy
Creating Materials and Energy Solutions

Magnetic Material for PM Motors

2009 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review

Iver E. Anderson
Ames Laboratory (USDOE)
May 21, 2009

IOWA STATE UNIVERSITY

FreedomCAR & Fuel Partnership

Project ID # pmp_23_anderson

Project Overview:

Timeline

- Start - August 2001
- Finish - September 2012
- 75% Complete

Budget

- Total project funding
  - DOE share $3,490K (since FY01)
- FY08 Funding - $500K
- FY09 Funding - $400K
- FY10 Funding - $400K (planned)

Barriers/2015 Targets

- Higher operating temperature (150-200C) and long life (15 yrs.) needed for magnets in PM motors.
- Permanent magnet energy density increase needed in PM motor (Specific power >1.2kW/kg) to reduce cost (<$12/kW).
- Highly efficient interior PM motors (>93%)require sintered or bonded magnets with complex shape and simplified manufacturing.

Partners

- Arnold Magnetic Technologies
- GM, Magnequench, ORNL
- Consultant: Peter Campbell
- Project lead: Ames Lab

Overall Objectives:

- To meet enhanced performance and reduced cost goals for high volume manufacturing of advanced electric drive motors, it is essential to improve the alloy design and processing of permanent magnets (PM), particularly by solidification and powder processing.

- The fully developed PM material must be suitable for elevated temperature (150-200˚C) operation with superior magnetic performance to minimize motor cooling needs and must have competitive room temperature magnetic properties with high magnetic energy density to conserve valuable materials.

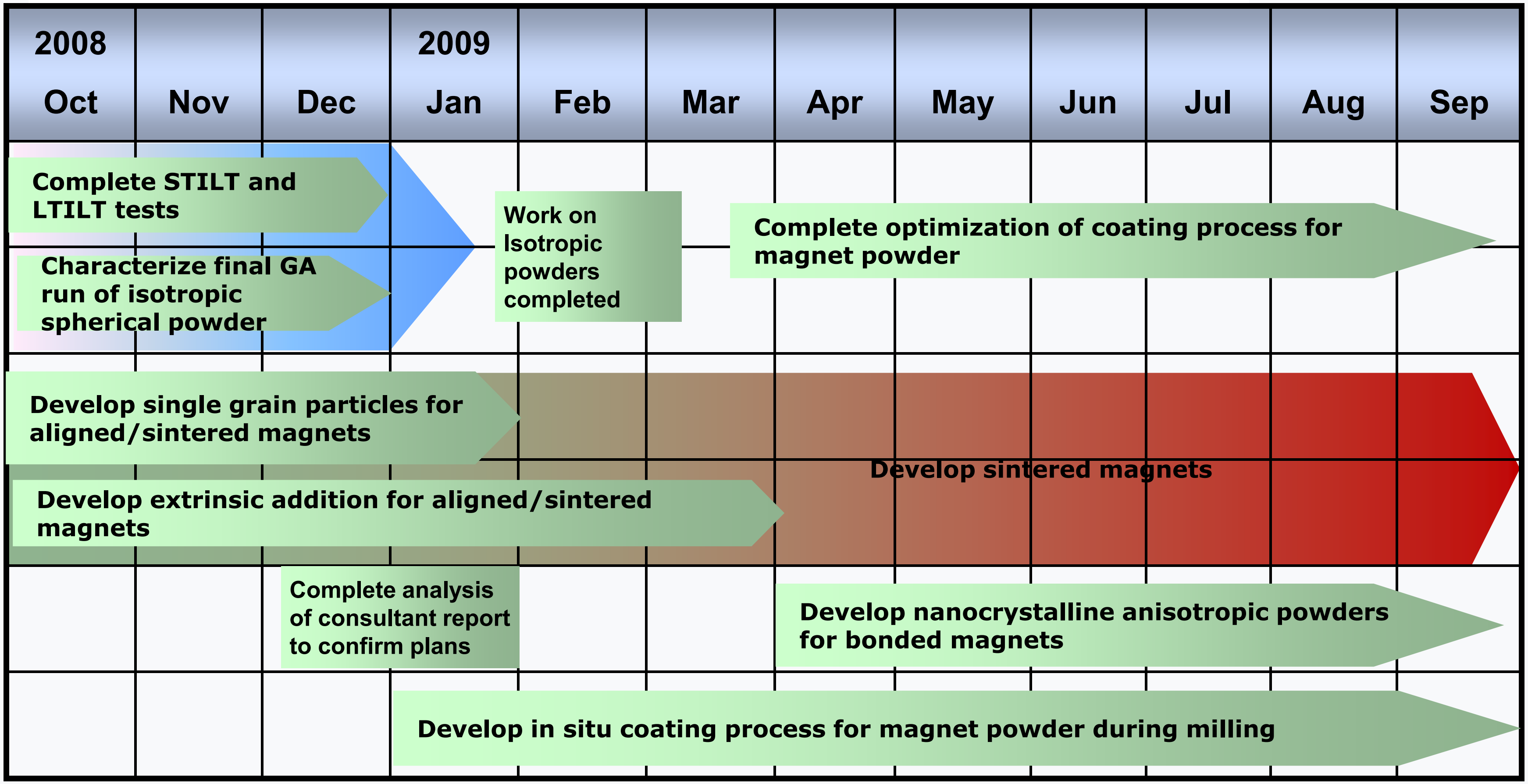
Objectives for FY09

Increase energy density & retain high temp. tolerance

- Further develop anisotropic sintered magnets to achieve highest energy product (4-6X isotropic bonded) with high temperature stability from single crystal/single domain micron-sized particles.
  - Modify alloy to promote grain growth, mill to 1-3 μm particles
  - Aligned/consolidated with or without sintering aid (5 vol.% max.)
- Pursue development of anisotropic nano-crystalline particulate to enable compression molding of aligned net-shape bonded magnets for 2-3X greater magnetic strength than isotropic bonded magnets.
  - PPS bonded at high (75-80%) loading of coated particulate.
  - Align particulate in curved pattern during insert molding in rotor.

DOE 2015 targets: Enhance energy density (Specific power >1.2kW/kg) and reduce cost (<$12/kW)

Milestones



•**Transition in project direction to highest energy (anisotropic) magnets, building on prior accomplishments.**

Industry Expert Assessment of Magnet Needs Delivered

Report Title: System Cost Analysis for an Interior Permanent Magnet Motor, (Ames Laboratory Report No. IS-5191, August 2008)

Author: Dr. Peter Campbell

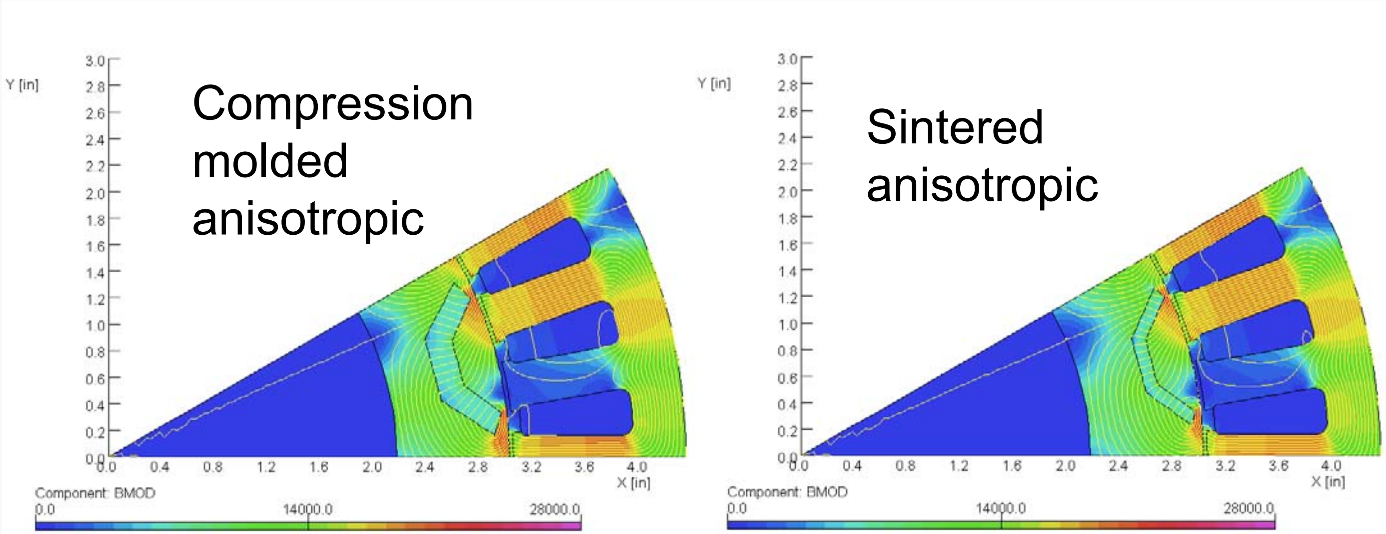
1999-2005 V.P. Technology and Sales, Magnequench Int.

1981-1999 Univ. S. California, E.E. Dept. (electrical machines)

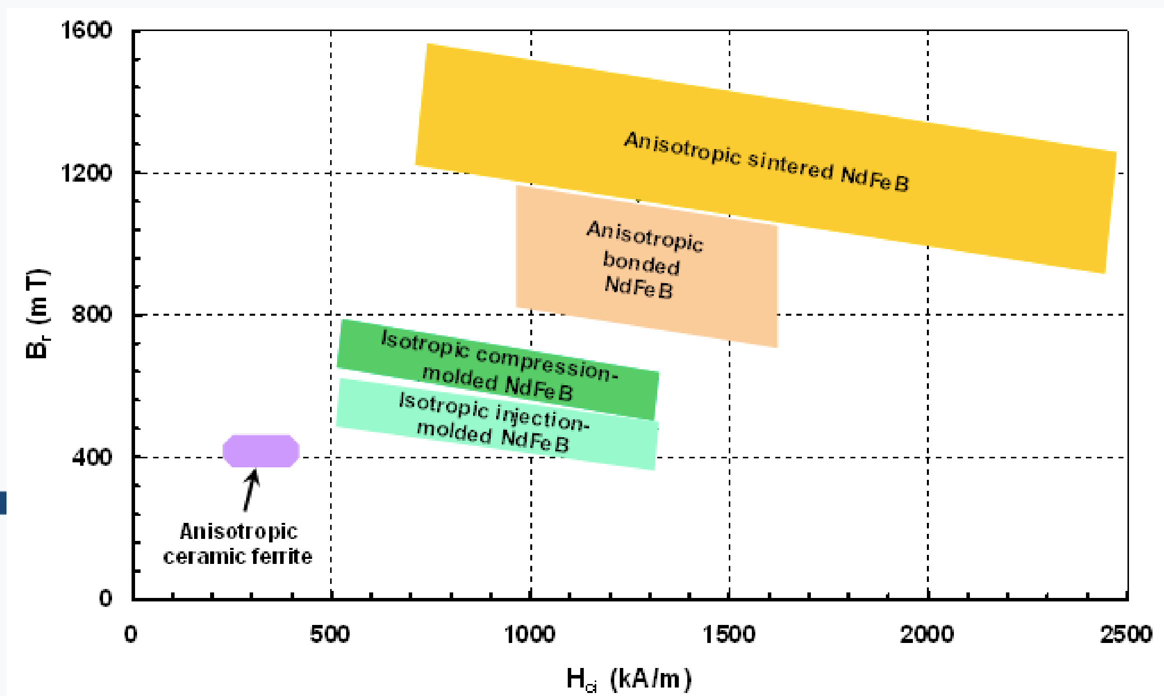
Objective: Provide an assessment of the cost structure for an interior permanent magnet (IPM) motor, which is designed to meet the 2010 FreedomCAR specification, including evaluation of sintered and bonded grades of rare earth magnets. Must consider key processing steps, alternative magnet shapes, rotor assembly and magnetization, mechanical stresses, temperature limits, and alternative motor/rotor cavity designs.

Summary: *"We have noted that Ames Laboratory has developed an alloy with improved temperature stability for use in bonded (2-14-1)magnets, and if it were possible to moderate its dysprosium content while developing (nano-crystalline) grain alignment to turn this into an* ***anisotropic*** *powder, it would be certainly be preferable to HDDR powder as a compression molded magnet for the IPM motor."*

Anisotropic Magnet Types for IPM Motor Designs

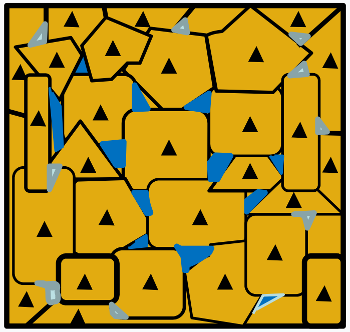


- FEM magnetic field analysis comparison from consultant report.



- Trade-off between magnetic energy density and manufacturing simplicity.
- Develop anisotropic sintered form of HT magnet alloy.
- Compression molding of bonded anisotropic particulate may have IPM motor cost advantage.

Technical Approach for FY09



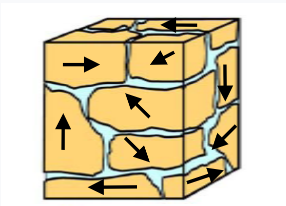
- Task 1: Pursue aligned/sintered (full density) permanent magnets in high temperature MRE-Fe-B alloys.
  - Enhanced maximum energy product at HT from ideal structure.
  - Choice of intrinsic LP sinter (high T) or extrinsic SS sinter (low T)
- Task 2: Explore anisotropic, nanocrystalline magnetic microstructure in MRE-Fe-B particulate for bonded magnets.
  - Boost energy product (2-3X) of isotropic bonded magnets.
  - Retain high temperature performance and net-shape molding
- Task 3: Complete development of the post-anneal fluidized bed coating process for the rotating kiln vessel.
  - Enhance protective coating for spherical and flake particulate
- Task 4: Additional reduction in the cost of the magnet alloy components will also be pursued, e.g., by substitution of less expensive RE (i.e., Y for Dy, La for Y, etc.) and by minimizing the Co.
  - Maintain acceptable energy product and temperature coefficients.

•Approach supports anisotropic (aligned) magnet emphasis.

Aligned/Sintered $MRE_2Fe_{14}B$ Magnets

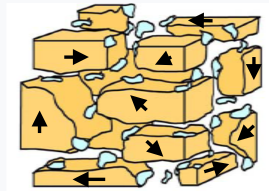
❑ Intrinsic Sintering Approach

Cast Ingot

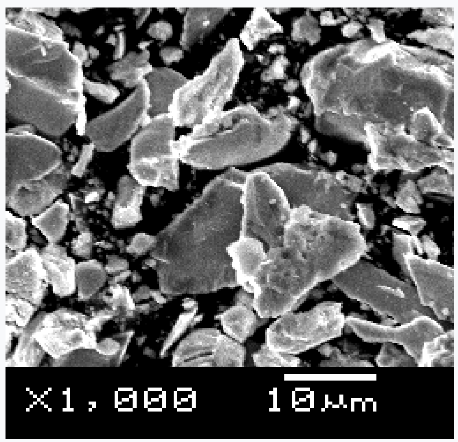


- $MRE_2Fe_{14}B$
- MRE-Rich

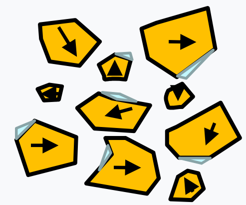
H_2 Decrepitation



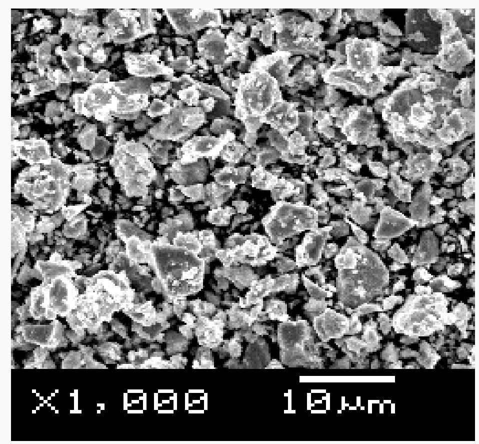
After 3-5 bar H_2 for 3hrs at room temperature, average D<20µm



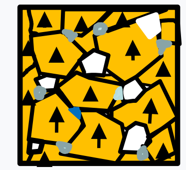
Milling



After 15hr ball milling, average D=3-5µm



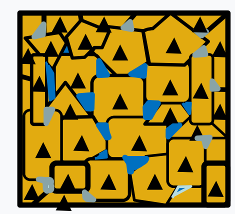
Align & Press



☐ **Porosity**

Aligned at 1.5 T
Die-press & CIP
d is 58% of d_T

Sinter & HT



1100-1130°C for 1-2hrs
600-700°C for 2hrs
d is 98% of d_T

Processed under controlled atmosphere to the maximum extent possible

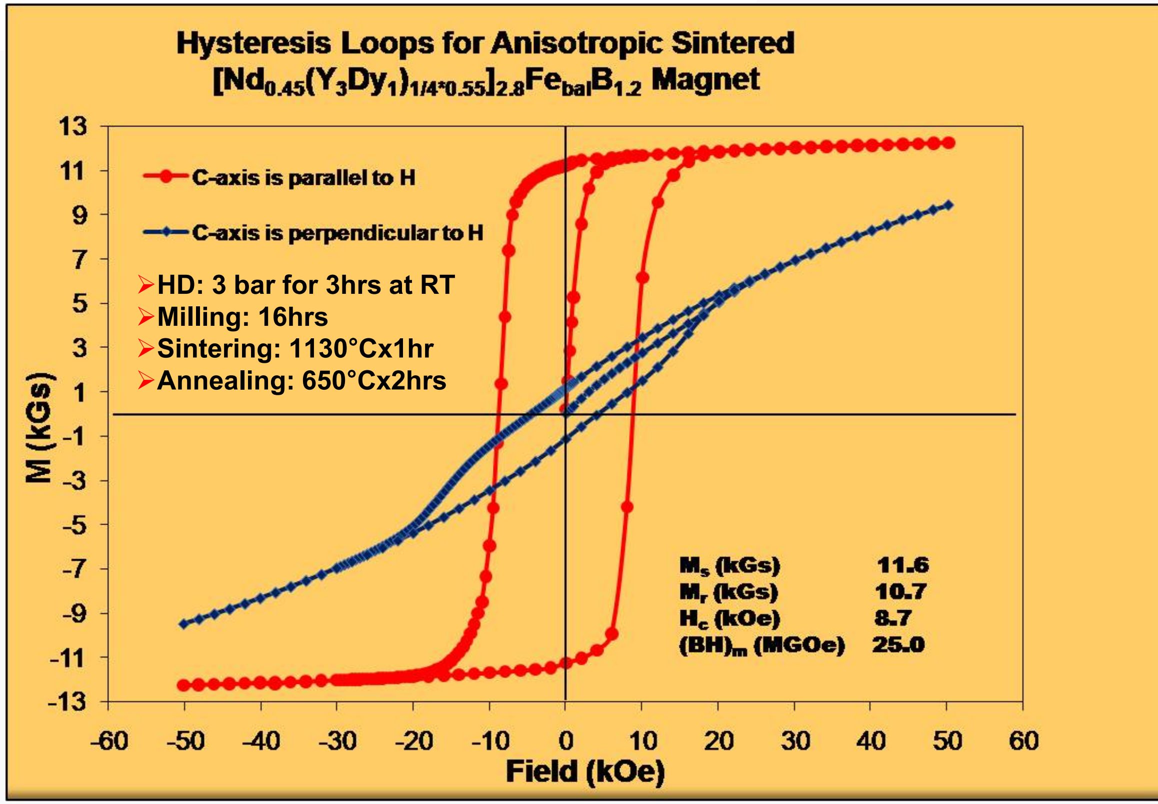
•Adding hydrogen decrepitation helps milling effectiveness.

Anisotropic Magnets

Sintered from Cast Alloy

- **two stage approach to develop anisotropic magnets**
  - **cast and crushed aligned and sintered**
    - **Significant differences in phase diagram than traditional $Nd_2Fe_{14}B$**
      - **Significant modification of process**
      - **Approaching desired magnet structure (25 MGOe achieved)**
  - **Individual grains (particles) must be magnetically isolated**

❑ **Current Status**



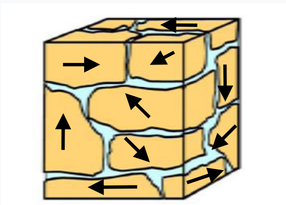
- **Studying**
  - **Reduction in RE alloy content**
  - **Grain boundary smoothing**

•Improved from 6 MGOe to 25 MGOe since FY2008 report

Aligned/Sintered $MRE_2Fe_{14}B$ Magnets

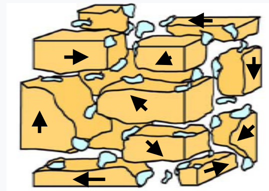
- **Planned Approach with Extrinsic Sintering Addition**

Cast Ingot



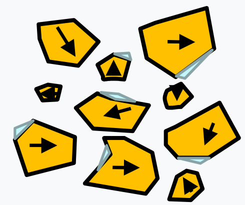
- $MRE_2Fe_{14}B$
- MRE-Rich

H_2 Decrepitation



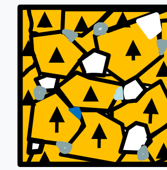
After 3-5 bar H_2 for 3hrs at room temperature, average D<20µm

Milling



After 15hr ball milling, average D=3-5µm

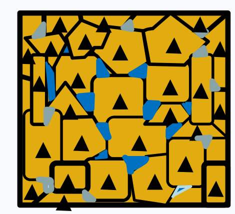
Align & Press



Aluminum powder added

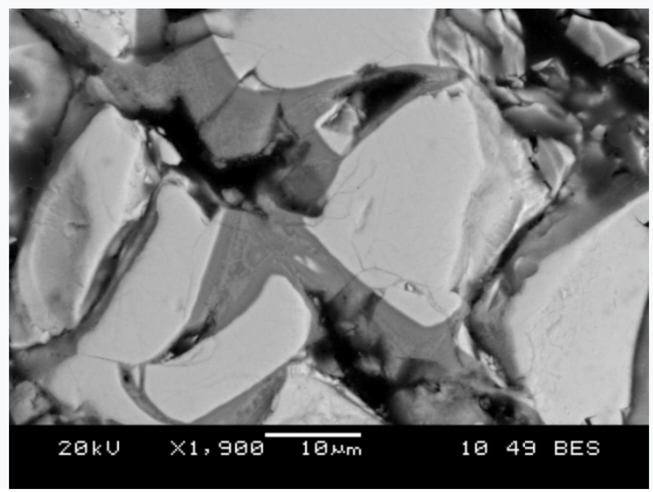
Aligned at 1.5 T
Die-press & CIP
May see 90% d_T

Low T Sinter



570-598°C for 10 min.
No additional HT
May see 98% of d_T

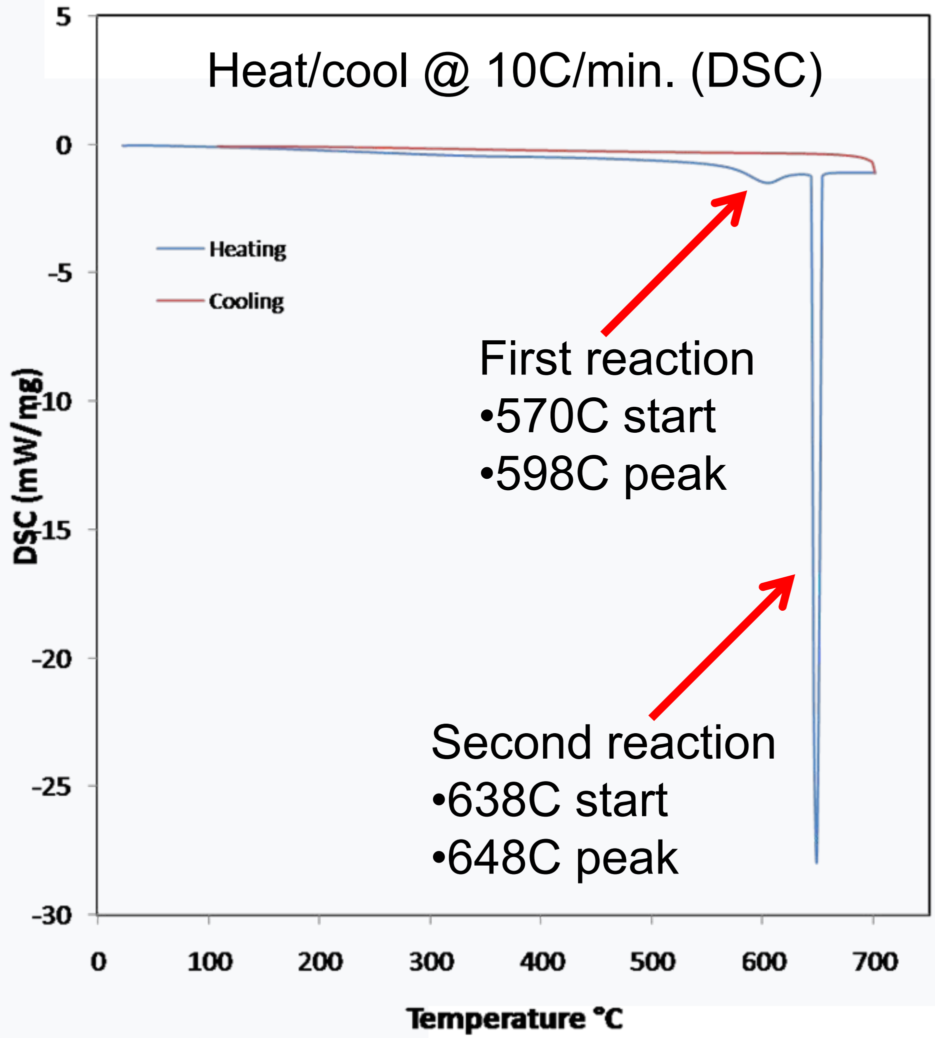
Concept tested with 90% magnet flake/10% Al powder, **solid state sintered** at 598C for 6 minutes in high vacuum.

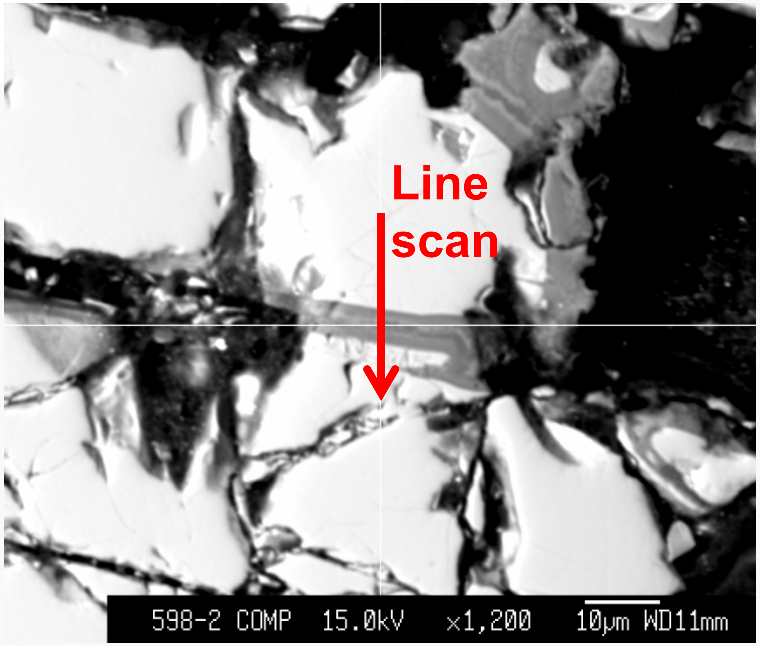


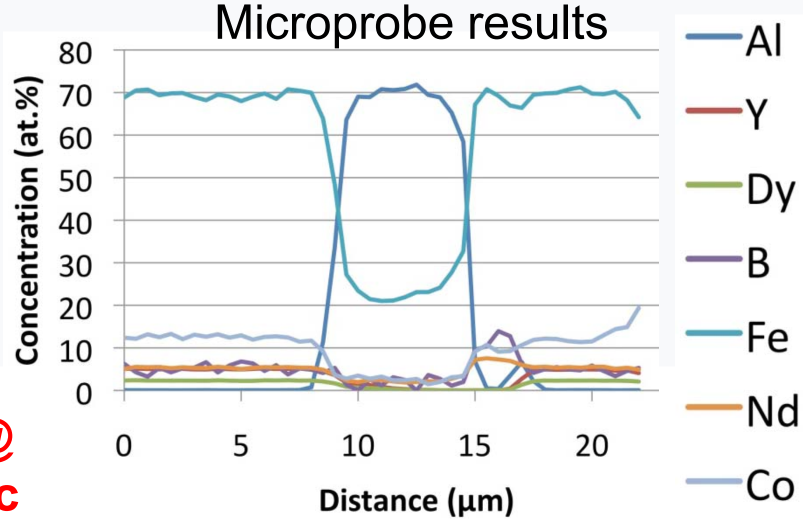
Minimum processing temperature under inert atmosphere---least possible surface oxidation

- **Must demonstrate consolidation and magnetic strength.**

Promise for Extrinsic Sintering Addition



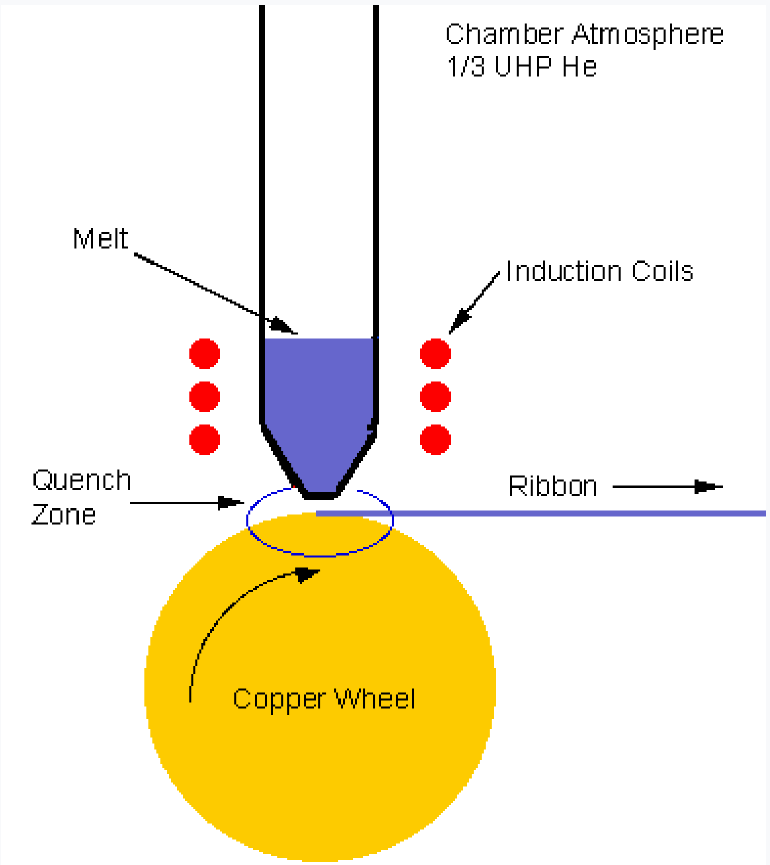




•Solid state reaction @ 598C bonded magnetic particles with layer of Al_3Fe

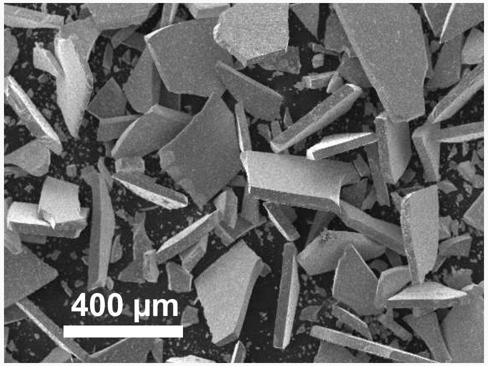
Anisotropic/Bonded $MRE_2Fe_{14}B$ Magnets

❑Planned Approach for Anisotropic Nanocrystalline Particulate



Anneal & Crush

Anneal @ > 600 C
Crush, Sieve to < 32 µm



Align & Press

❑ **PPS polymer added**

Align at 1.5 T
Compression mold
May see 98% d_T

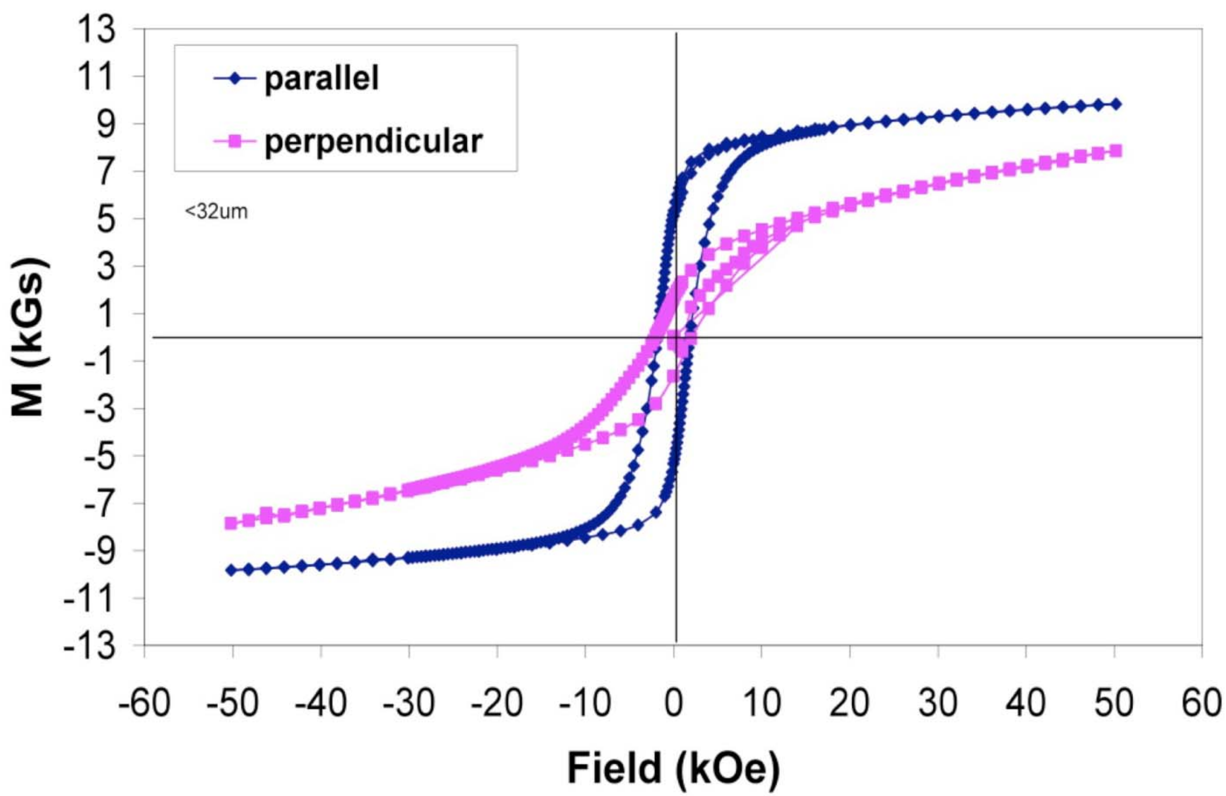
•Potential for direct compression molding of anisotropic bonded magnets in rotor cavities.

•Can be magnetized in-place with shaped pattern to maximize flux use efficiency.

•Critical need to generate uniform nano-metric cellular pattern on solidification for max. magnetic strength.

Preliminary Results for Bonded Anisotropic Magnets

WT201, $[Nd_{0.45}(Y_2Dy_1)_{0.55}]_2Fe_{14}B$



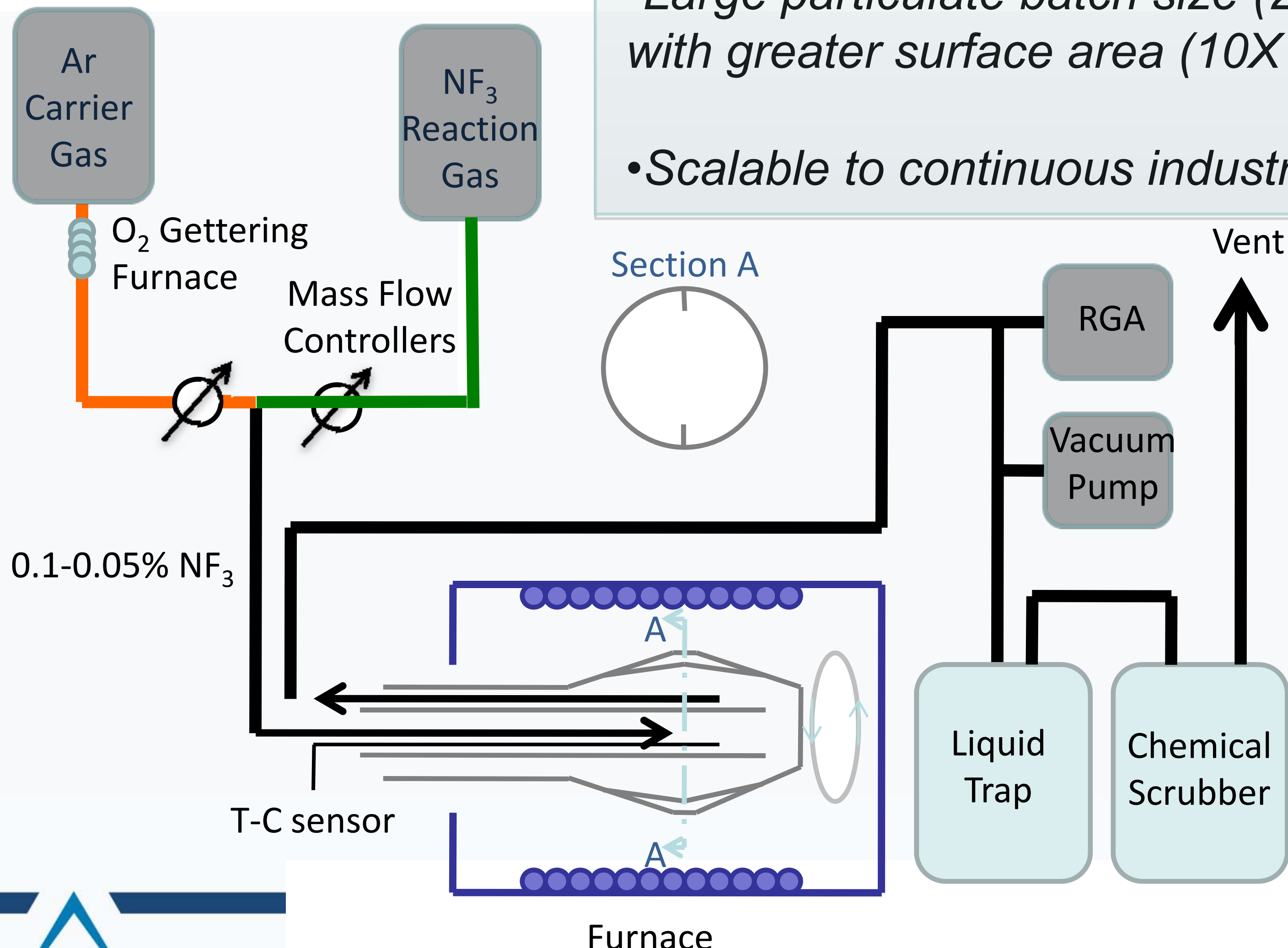
Melt spun @ 5 m/s in 1/3 atm. He, Annealed @1000C for 4 days, Crushed and sieved to < 32µm, Aligned and epoxy bonded.

- Good potential for increased energy product (approaching 20MGOe) in aligned bonded magnet.
- Need further control of nano-cellular solidification pattern to achieve fully uniform crystalline alignment.
- To try reduced thermal conductivity on wheel surface to supress chill zone grains.

•Microstructure analysis needed to correlate with magnetic properties, but lack of uniform grain alignment is apparent.

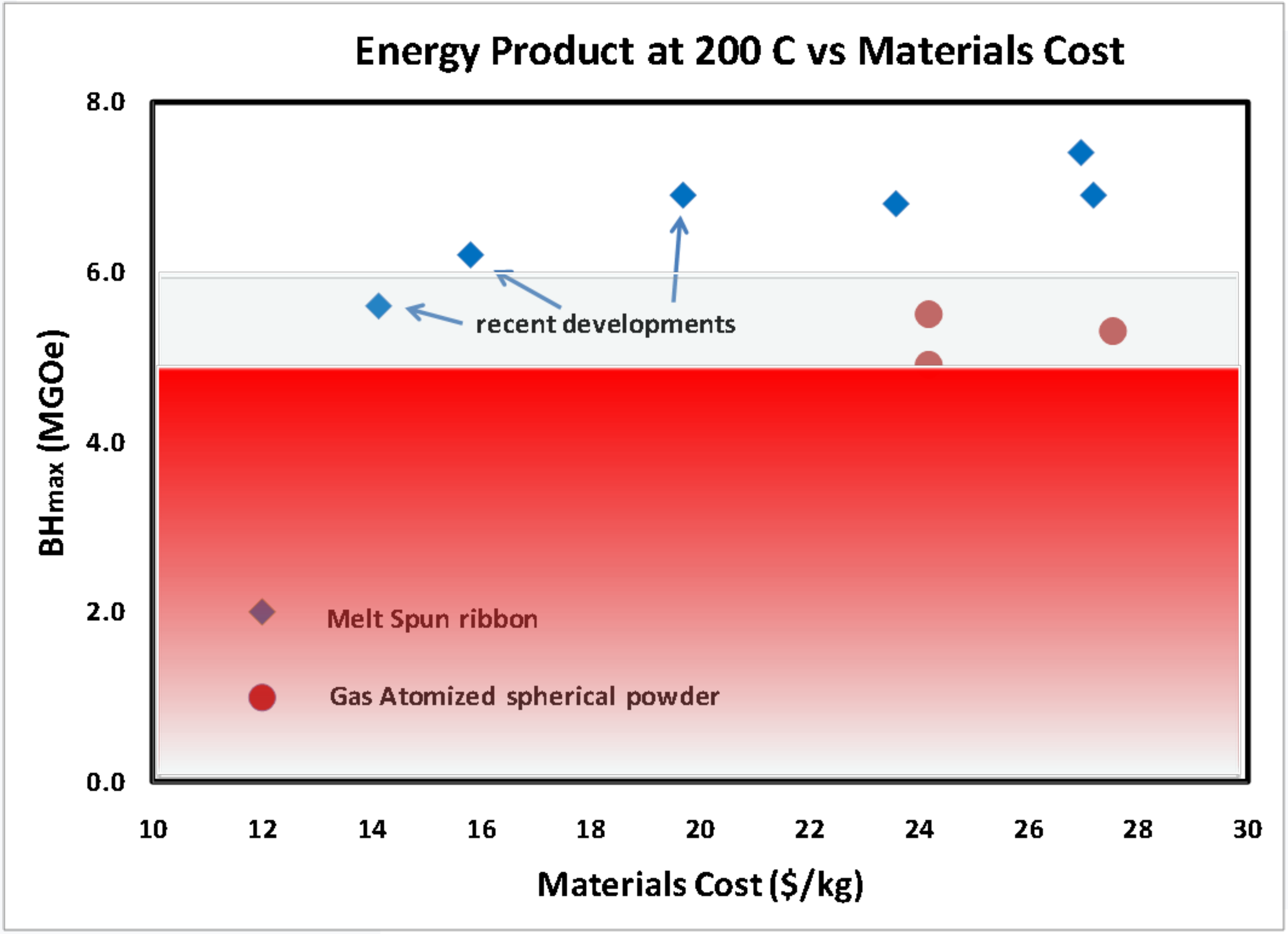
Fluorination Coating Approach – Rotating Kiln

- *Large particulate batch size (200g, max.) with greater surface area (10X previous).*
- *Scalable to continuous industrial process*



•Enhanced concentration needed to coat greater surface area.

Cost reduction of HT magnet alloy



- High temperature (200C) energy product shows benefits of Ames alloy.
- Should maintain high temperature performance with increased energy density of aligned magnets.

•Favorable comparison to the best available commercial isotropic magnet alloy particulate.

Future Work

<u>Aligned/Sintered Magnets</u>

- Improve composition and heat treatment.
- Enhance particulate milling.
- Try CIP consolidation.
- Choose sintering approach.
- Test corrosion resistance.

<u>Anisotropic Bonded magnets</u>

- Form fully textured ribbons.
- Smooth grain/cell boundaries.
- Try grain/cell boundary phase formation for decoupling.
- Explore thermo-mechanical routes for grain alignment.

- **FY2010**
  - Improve processing to promote grain growth by rapid annealing of HT magnet alloy and further enhance particulate milling procedures to generate optimum size micro-crystalline powders with protective coating for aligned/sintered magnets.
  - Refine most promising approach for producing aligned nano-crystalline particulate using either melt spinning or gas atomization and develop suitable alloy additions and crystallization anneals for improved anisotropic bonded magnets.

Summary

•Project Accomplishments as Springboard

- ✧ New 2-14-1 alloy phase developed for high temperatures based on mixed rare earth (MRE) for high performance permanent magnets.--US Patent Application
- ✧ New alloy developed as flake particulate and fine spherical powder that can be heavily loaded in net-shape **isotropic** bonded magnets for PM electric motors.
- ✧ Novel gas reaction coating process developed to protect fine powder against oxidation/corrosion during powder production, molding, and extended magnet service.--Industrial activity (Magnequench)

•Project Advances in New Direction

- ✧ Analysis of industry expert viewpoint confirmed next project direction: "System Cost Analysis for an Interior Permanent Magnet Motor." AL Report No. IS-5191
- ✧ Major step up in magnetic energy density for patented MRE magnet alloy being realized in new **anisotropic** magnet studies.
- ✧ Aligned/sintered **anisotropic** magnet processing from new MRE alloy can take similar path to conventional Nd-based high performance magnets.
- ✧ Extrinsic sintering addition shows promise for improved magnet consolidation.
- ✧ Synthesis of fully aligned nanocrystalline particulate with coating for **anisotropic** polymer bonded magnets is still in early stages.

•Outlook is encouraging for high energy permanent magnets to enable efficient and powerful electric drive vehicles.