Magnetic Material for PM Motors

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FY08 Funding: $400K

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Purpose of Work

- 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 powder processing.
- The fully developed PM material must be suitable for elevated temperature (180-200˚C) operation to minimize motor cooling needs.

Response Reviewers' Comments:

- *"Good results in PM itself in terms of temperature range and manufacturing but should have results tied to actual machine performance." "…seems to be a need for more work with a motor manufacturer to evaluate the impact of (this) work on the actual motor performance."*
  - Produced net shape magnets from new alloy for ORNL prototype motor (FY06), but tests were not able to be performed.
  - Participated in successful CRADA proposal with GM and Arnold Magnetics. Work will commence in FY08.
- *"Cost needs to be addressed."*
  - Alloy modifications targeted reductions in two most costly components, Cobalt and (very recently) Dysprosium.
  - Cost analysis study being performed (FY08) by industry expert.
- *"…like to see this project reach commercialization stage."*
  - Active discussions under NDA with industry partners.

Barriers

VTP Related Challenges

- High operating temperature magnets (180-200ºC) are needed for high torque drive motors
  - *Reduce need for coolant through magnet material design*
- Highly reactive powders require protection during bonded magnet manufacturing processes and in operation
  - *Improve reliability with magnet material coating process*

Technology Related Challenges

- Magnetic strength penalty (4-6X) for using bonded isotropic magnets rather than sintered/aligned
  - *Will achieve motor volume/weight targets through higher material loading, bonded aligned magnets, and development of fully dense aligned materials*
- Highly reactive powders require protection during bonded magnet manufacturing processes and in operation
  - *Improve reliability with magnet material coating process*

Technical Approach

- Develop *isotropic* permanent magnet particulate material with high-temperature (HT) properties
  - Design HT (200°C) magnet alloy by rapid solidification of flake particulate
  - Translate alloy design to fine spherical gas atomized powders for low-cost in-place molding production process
  - Develop thin coating to protect permanent magnet particulate during processing

- Develop new *anisotropic* permanent magnet particulate with HT properties to boost cooperative magnetic strength
  - Develop nanocrystalline anisotropic particles from HT magnet alloy for bonded aligned magnets (2-4X isotropic bonded magnet strength)
  - Develop molding of polymer bonded aligned magnets to retain low cost molding and test environmental stability
  - Develop single grain particles from HT magnet alloy and sintering concept for fully-dense aligned magnets (6X isotropic bonded magnet strength)

Technical Approach for FY08

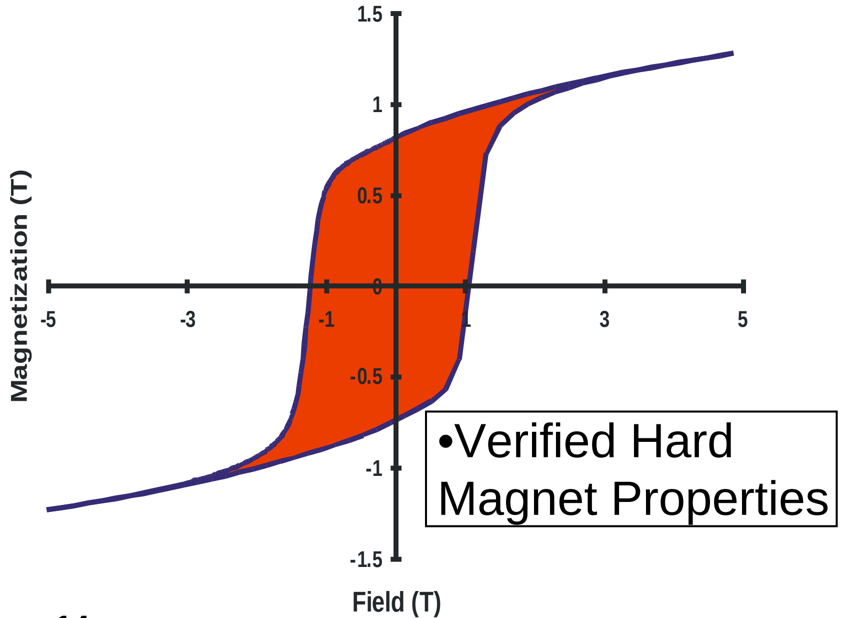
- Complete translation of high temperature magnet alloy to fine spherical isotropic powder (gas atomized/in situ coating).
- Verify manufacturing advantage for drive motors from isotropic bonded magnets, compared to sintered aligned magnets
  - Perform alloy cost and bonded magnet technology analysis
- Continue development of anisotropic nanocrystalline particulate and start on single grain particles and sintering concept from HT magnet alloy.

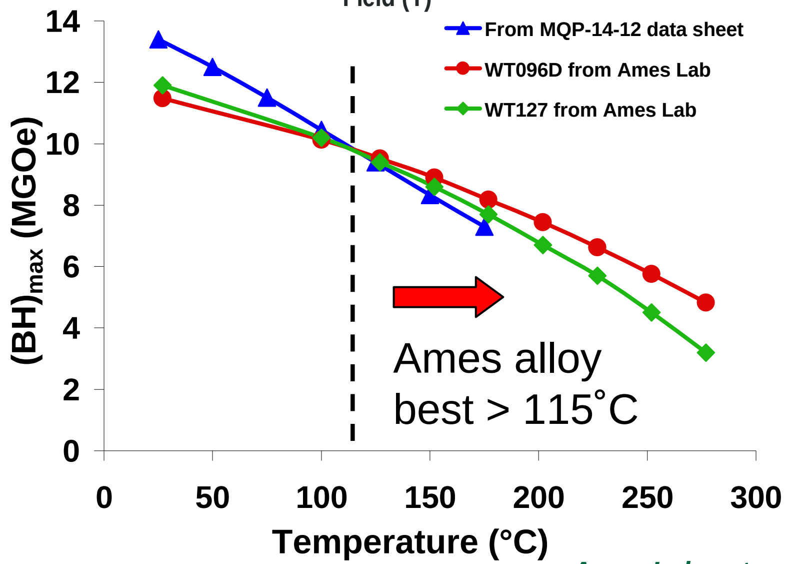
Technical Approach - Uniqueness

- Conventional high strength Nd-Fe-B magnets exhibit rapid drop in magnetic strength above about 125ºC, while new HT magnet alloy retains useful properties to 200ºC.
- Typical bonded magnets of Nd-Fe-B are loaded with flake particulate, but bonded magnets from new fine spherical powders of HT alloy can be loaded heavier (higher magnet strength) and molded at lower pressures.
- Protective coating applied DURING fine spherical powder production or to flake particulate can improve yield of process and safe handling of product, compared to current practices.
- If anisotropic nanocrystalline particulate of HT magnet alloy can be developed for polymer bonded magnet production, magnet strength can be doubled (at least) while retaining low cost of bonded magnet molding.

Technical Accomplishments through FY07

Development of novel high temperature magnet alloy for nano-crystalline particulate.





- **Melt spun ribbon alloy optimized and tested at high temperatures.**
- **Alloy patent application filed and commercial scale batch produced (Magnequench Int.).**
- **Recent improvements to the melt spun ribbon alloy (lower Co) have reduced cost.**

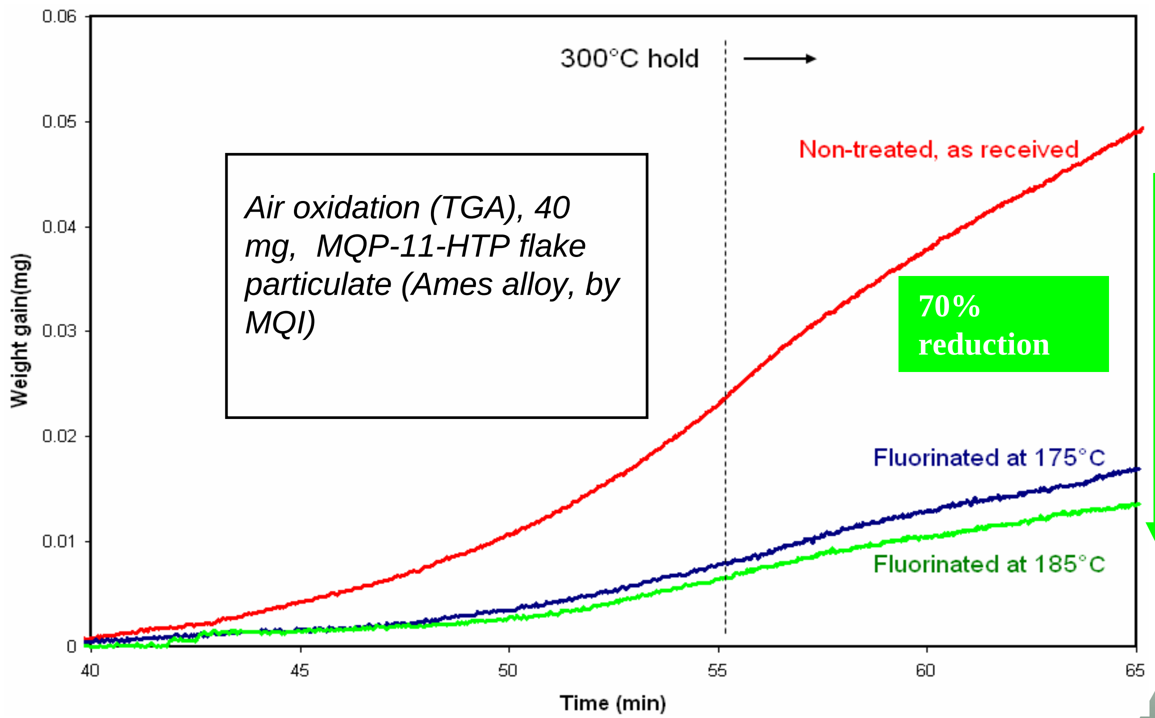
Technical Accomplishments through FY07

Innovative coating methods developed for magnet alloy powders

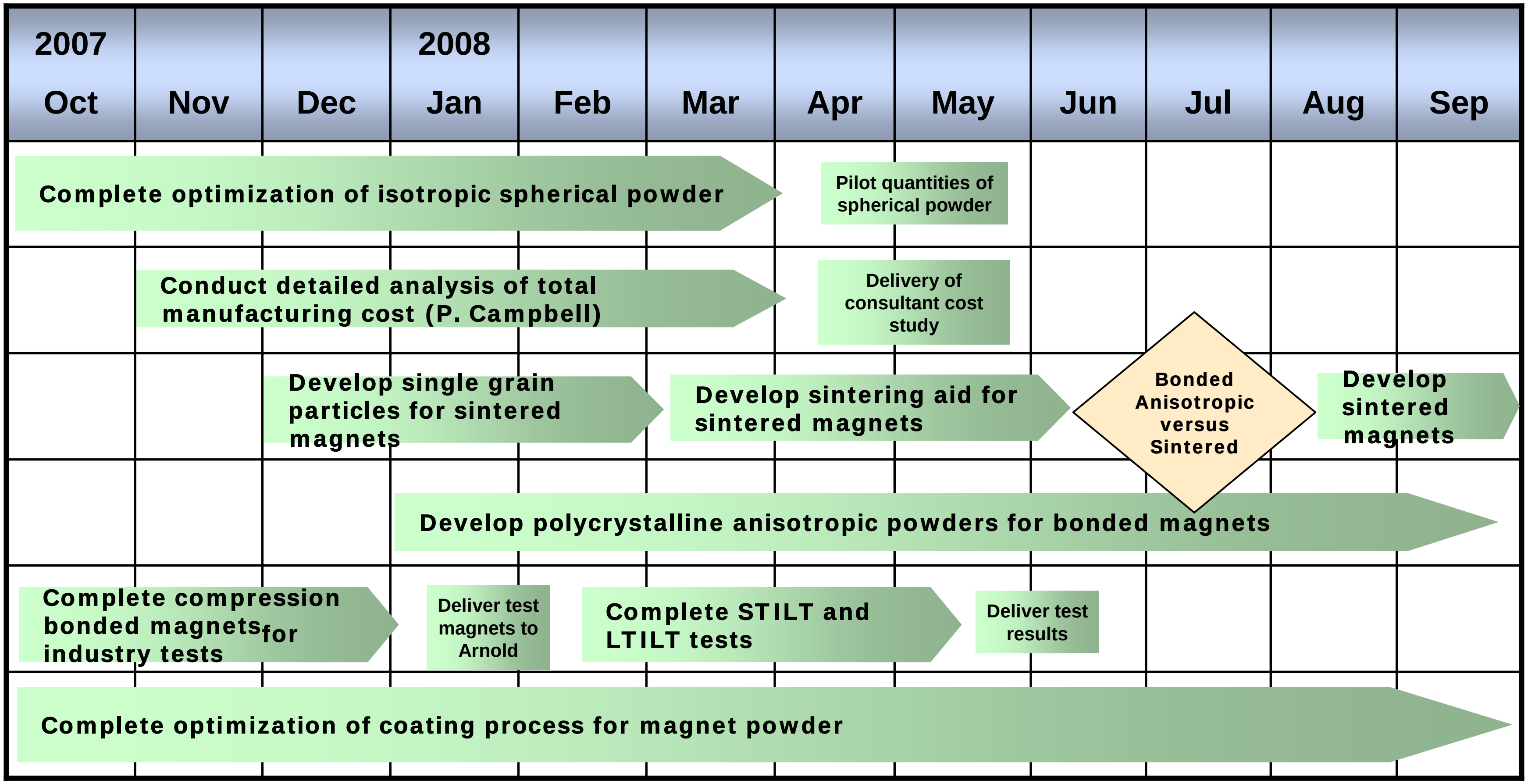
<u>BENEFITS:</u> Protect reactive MRE-Fe-B magnet particulate from oxidation for improved bonded magnet processing and reliability.

<u>STATUS:</u> Significant recent progress in protection of particulate.

- In situ surface passivation approach reduced oxygen content by 60%
- High level of control for up-scaled batch fluorination process reduced air oxidation rate by 70% over commercial particulate
- Bonded magnet samples to be submitted to AMT for high temperature exposure testing.



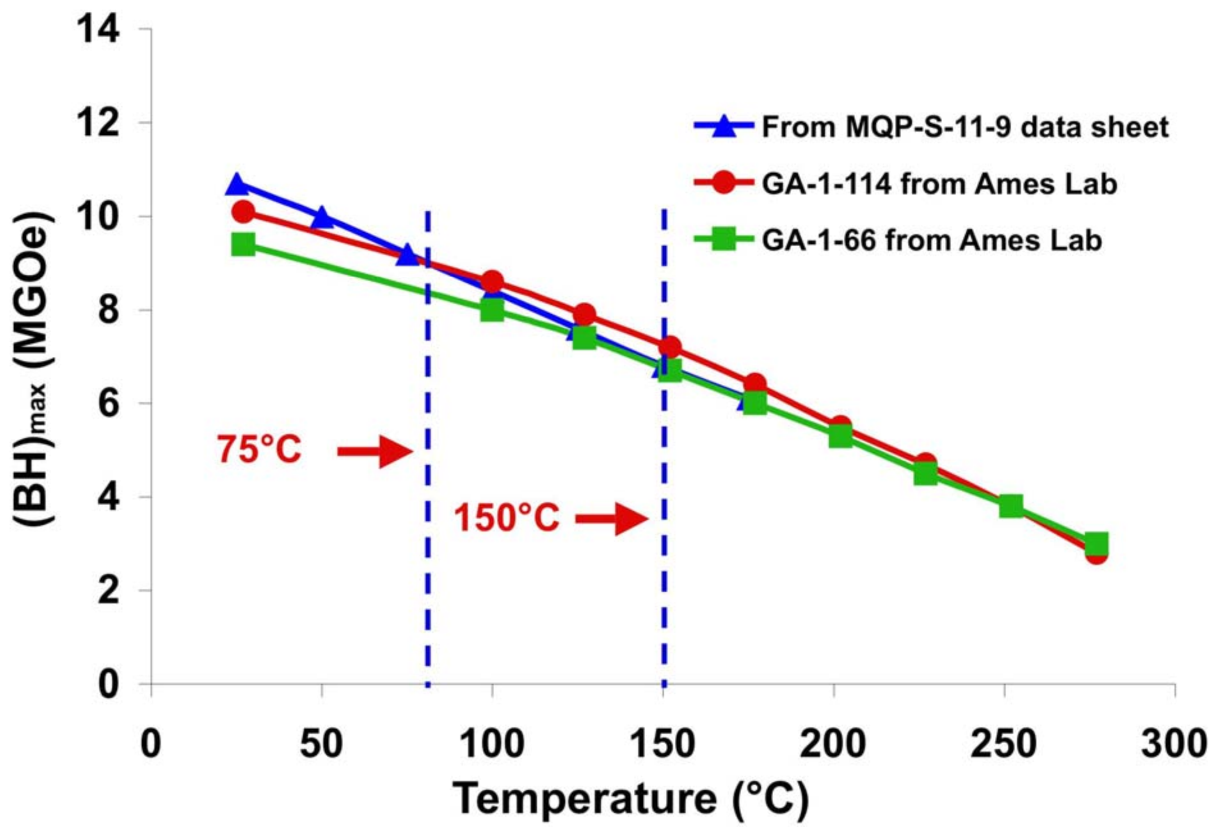
Timeline for FY08

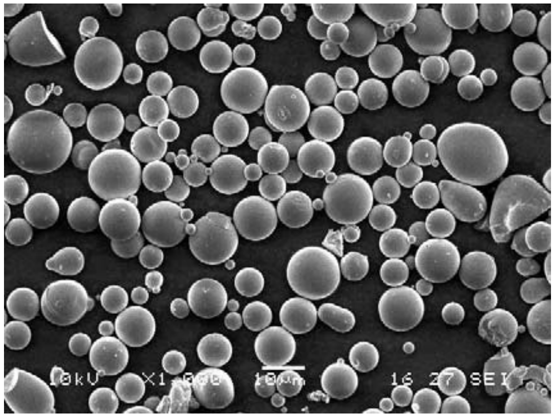


Decision point discussion: Based on the cost analysis study and the progress in anisotropic powders, one of the two types of anisotropic magnets will be chosen as the major project focus

Technical Accomplishments FY08

Improvements in fine spherical powder processing





- •Improved magnetic property "cross-over" temperature, Ames powder superior above 75ºC (FY2008).
- •Low cost Ar gas for atomization, replaced He gas, improved technology transfer

MQP-S-11-9 spherical powder, Magnequench International (d_{50}≈45µm) -unsuitable (too coarse) for heavily loaded injection molding
GA-1-114 fine spherical powder, Ames Lab (d_{50}≈23µm) -preferred size for heavily loaded injection molding

Technology Transfer

- Continuing active collaboration with Arnold Magnetic Technologies (AMT)
  - ✓ industrial environmental (oxidation) testing of Ames bonded magnets
- New project entitled “Integrated Traction Drive System” (motor/magnet trial)
  - ✓ CRADA partnership with GM and AMT (FY08 start)--10 month project
  - ✓ other partners on overall project represent full supplier chain
- Further strengthen Magnequench International cooperation
  - ✓ supplied custom melt spun particulate (100 kg batch)
  - ✓ additional melt spun batches anticipated
  - ✓ cooperation planned with secondary powder making partners

Future Work

- **FY09**
  - **Pursue most promising approach for producing aligned nanocrystalline particulate using melt spinning and gas atomization to boost magnet energy product possible with anisotropic polymer bonded magnets.**
  - **Initiate development of magneto-crystalline alignment procedures during molding of magnetic particulate/polymer compound to maximize magnetic strength of finished bonded magnets.**
- **FY10**
  - **Explore modification of high temperature magnet alloy to micro-crystalline state and design of sintering aid for aligned/sintered magnets.**
  - **Refine magneto-crystalline alignment procedures during molding of magnetic particulate/polymer compound and verify improved magnetic strength of finished bonded magnets.**

Summary

- As (petroleum fueled) IC engines are phased out, PM electric motors are the preferred option to power the drive trains of hybrid, plug-in hybrid, and EV (fuel cell/battery) vehicles.
- Magnet alloy design, processing, and manufacturing improvements are needed to enable cost reduction, improve reliability, and realize market acceptance.
- Successful series of technology advancements have been critical to maintaining progress toward commercialization.
  - HT magnet alloy design discovered (patent applied, FY05)
  - Protective coating for magnet particulate verified (FY07)
  - Low cost atomization gas proven promising (FY07-08)
  - Alloy component cost reduction in progress (FY08)
- Consistent plan for technology transfer followed.
- FY08 plans include next logical advancements for further gains in magnet properties and decreased cost.

Publications and Presentations (FY07)

Presentations

- **W. Tang, K.W. Dennis, Y. Q. Wu, M. J. Kramer, I. E. Anderson and R. W. McCallum, "Comparison of Microstructure and Magnetic Properties of Gas-Atomized and Melt-Spun MRE-Fe-Co-M-B (MRE=Y+Dy+Nd, M=Zr+TiC)" , Presented in the 10th Joint MMM/Intermag Conference, Baltimore, Maryland, January 7-11, 2007**
- **P.K. Sokolowski, I.E. Anderson, W. Tang, Y.Q. Wu, K.W. Dennis, M.J. Kramer, and R.W. McCallum, "Processing of Improved MRE2Fe14B for High Performance Permanent Magnet Applications," Presented in MS&T (Materials Science & Technology) Conference, Cincinnati, Ohio, October 15-19, 2006.**
- **P.K. Sokolowski, I.E. Anderson, W. Tang, Y.Q. Wu, K.W. Dennis, M.J. Kramer, and R.W. McCallum, "In situ Passivation during High Pressure Gas Atomization of Improved MRE2Fe14B for High Performance Permanent Magnet Applications," Presented in TMS (The Minerals, Metals, & Materials Society), Orlando, Florida, February 25-28, 2007.**

Publications

- **Tang, W.; Wu, Y. Q.; Dennis, K. W.; Kramer, M. J.; Anderson, I. E.; McCallum, R. W.. "Comparison of microstructure and magnetic properties of gas-atomized and melt-spun MRE-Fe-Co-M-B (MRE=Y+Dy+Nd,M=Zr+TiC)." Journal of Applied Physics (2007), 101(9, Pt. 2), 09K510/1-09K510/3.**
- **P.K. Sokolowski, I.E. Anderson, W. Tang, Y.Q. Wu, K.W. Dennis, M.J. Kramer, and R.W. McCallum, "In situ Passivation during High Pressure Gas Atomization of Improved MRE2Fe14B for High Performance Permanent Magnet Applications," in *8th Global Innovations Symposium: Trends in Materials and Manufacturing Technologies for Energy Production*, TMS (The Minerals, Metals, & Materials Society, Warrendale, PA), ISBN: 978-0-87339-677-6 (2007) pp. 7-17.**
- **P.K. Sokolowski, I.E. Anderson, W. Tang, Y.Q. Wu, K.W. Dennis, M.J. Kramer, and R.W. McCallum, "Gas Atomized $MRE_2Fe_{14}B$ Permanent Magnet Particulate with Enhanced High Temperature Performance," in *Advances in Powder Metallurgy and Particulate Materials-2007*, compiled by J. Engquist and T.F. Murphy, (Metal Powder Industries Federation, Princeton, NJ, 2007), part 9, pp. 119-132.**

Questions