ELECTRON ENERGY CORPORATION

EXPERTS IN
- RARE EARTH MAGNETS
- MAGNET DESIGN
- MAGNET SYSTEMS

High Performance Permanent Magnets for Advanced Motors

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Electron Energy Corporation

06-10-2010

Project ID # **APE031**

Overview

Timeline

- **Project start date**: 08/15/2008
- **Project end date**: 08/14/2010
- **Percent complete**: 83%

Budget

- **Total project funding**
  - DOE share: $750,000.00
  - Contractor share: 0
- **Funding received in FY09**
  - $375,000.00
- **Funding for FY10**
  - $375,000.00

Barriers

- **Barriers addressed**

  D. Manufacturability

  G. Performance

Partners

- Univ. of Delaware
- Electron Energy Corporation (Project lead)

Objectives

- **Develop new composite magnets with superior magnetic properties** and *high electrical resistivity to reduce eddy current losses*;
- *Improve the performance* **of permanent magnets**: **maximum energy product of 35-38 MGOe maximum operating temperature of 240 ^{o}C;**
- *Reduce the manufacturing costs* **of permanent magnets for advanced motor applications.**

Milestones

Month/Year	Milestone or Go/No-Go Decision
Nov-09	❖ Development of compositionally modified Sm_2Co_{17}-type magnets with a maximum energy product of 35-38 MGOe able to operate at 240°C ❖ Development of new hybrid magnets via hot-consolidation and die-upsetting with higher thermal stability than that of Neo magnets
May-10	❖ Increase by ten times the electrical resistivity of permanent magnets with $(BH)_{max}$ > 35 MGOe able to operate at temperatures of 200-240°C ❖ Development of short thermal cycles to reduce the cost of sintered Sm-Co 2:17 magnets
Aug-10	❖Testing of mechanical properties and corrosion resistance of the new composite magnets with enhance electrical resistivity ❖Develop a magnetic subsystem to test at Rolls-Royce

Technical Approach

- ***Optimize the composition and process*** *to* ***increase the maximum energy product*** *of Sm(Co,Fe,Cu,Zr)$_z$ type magnets.*

- ***Apply die-upsetting techniques*** *to develop hybrid magnets with better temperature stability than Neo magnets.*

- *Use calcium- and rare earth fluorides as* ***dielectric constituents*** *of permanent magnets to* ***increase the electrical resistivity****.*

- ***Optimize processes parameters*** *(such as thermal cycle length and others) to* ***reduce manufacturing cost****.*

FY08 & FY09 Accomplishments

Task 1: Sm_2Co_{17}-type magnets with a maximum energy product of 35-38 MGOe able to operate at 240°C

❖ **Developed $Sm(Co,Fe,Cu,Zr)_z$ magnets with increased magnetic remanence and maximum energy product, $(BH)_{max}$ = 33 MGOe (10% increase) by compositional tuning, better compositional uniformity and process optimization (e.g. solution temperature).**

Task 2: New hybrid magnets via hot-consolidation and die-upsetting with higher thermal stability than that of Neo magnets

❖ **Demonstrated that hybrid magnets consisting of Nd-based 2:14:1 and Sm-based 1:5 phases, produced by hot pressing and die upsetting can develop a good texture and has a better thermal stability than the single phase Nd-based 2:14:1 magnets.**

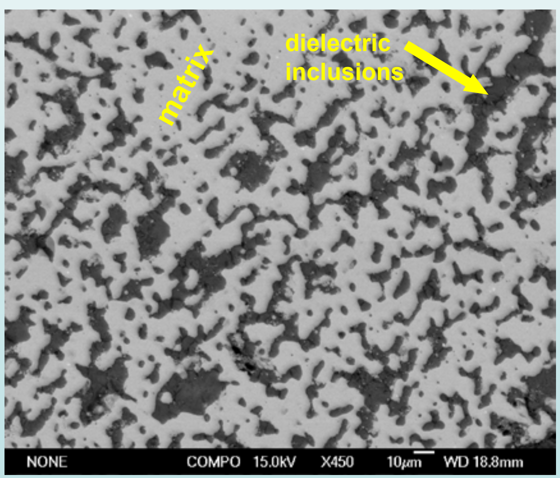
❖ $SmCo_5$ / Co hybrids produced by hot pressing and die upsetting showed a unique three-phase 1:5 / 2:17 / Co layered morphology at submicron level which may play a critical role in developing good permanent magnet properties.

❖ Fabricated hot-deformed Co / Sm-Co-Fe-Mn composite magnets with increased maximum energy product compared to the Sm-Co-Fe-Mn magnets.

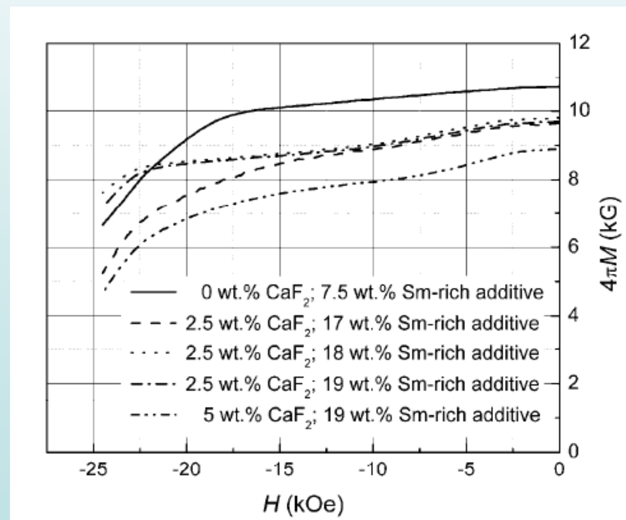
FY09 Accomplishments

Task 3: Increase by ten times the electrical resistivity of permanent magnets with $(BH)_{max}$ > 35 MGOe able to operate at temperatures of 200-240°C.

❖ **Composite** (homogeneous) **$Sm(Co,Fe,Cu,Zr)_z$ / CaF_2 magnets with 30 – 700% higher electrical resistivity were produced by conventional sintering.** A remanence of 9 kG and intrinsic coercivity greater than 25 kOe were obtained for samples with 30 % increase in resistivity (see Figs. below). A remanence of 7.3 kG and intrinsic coercivity greater than 25 kOe were obtained for samples with 50 % increase in resistivity. All these magnets can operate at 240 °C.



Morphology of composite $Sm(Co,Fe,Cu,Zr)_z$ / CaF_2 permanent magnets.

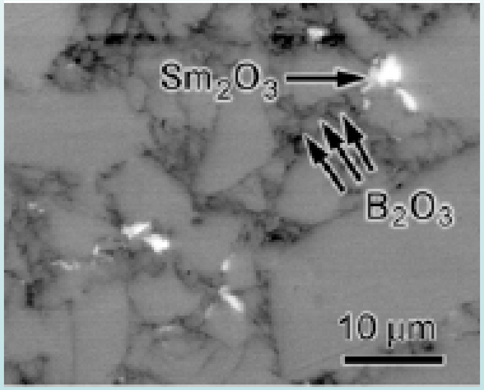


Demagnetization curves of composite $Sm(Co,Fe,Cu,Zr)_z$ / CaF_2 permanent magnets with 30 % increase in resistivity. The composition was adjusted with a Sm-rich additive.

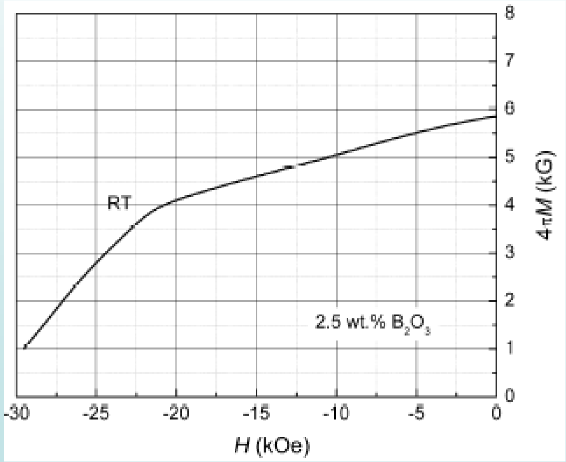
FY09 Accomplishments

Task 3: Increase by ten times the electrical resistivity of permanent magnets with $(BH)_{max}$ > 35 MGOe able to operate at temperatures of 200-240°C. *(Cont'd)*

❖ **"Glass-Bonded" $Sm(Co,Fe,Cu,Zr)_z$ / B_2O_3 magnets with electrical resistivity above 1000 μ·Ωcm (a more than 10 times increase) and high coercivity were produced by thermal consolidation. The magnets are able to operate at 240 °C.**



Morphology of "Glass-Bonded" $Sm(Co,Fe,Cu,Zr)_z$ / B_2O_3 magnets.

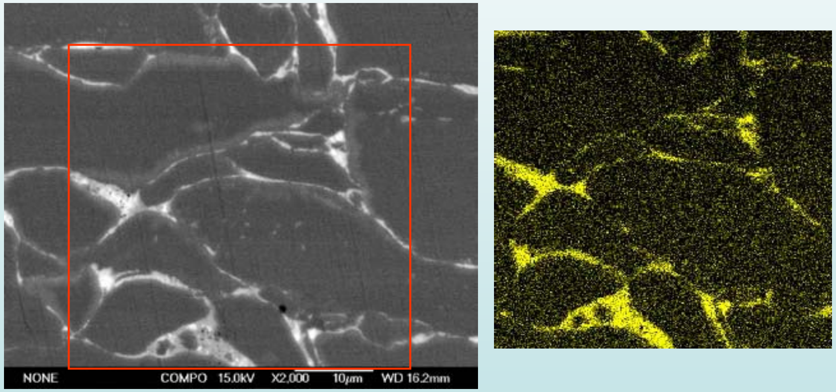


Demagnetization curve for "Glass-Bonded" $Sm(Co,Fe,Cu,Zr)_z$ / B_2O_3 magnets.

FY09 Accomplishments

Task 3: Increase by ten times the electrical resistivity of permanent magnets with $(BH)_{max}$ > 35 MGOe able to operate at temperatures of 200-240°C. *(Cont'd)*

❖ **Composite Nd-Fe-B / fluorides and Pr-Fe-B / fluorides magnets with the electrical resistivity increased by up to 6 times compared to the value for the conventional metallic counterparts, were synthesized by hot pressing and die upsetting.** In some cases, the addition of fluorides was found to improve the magnetic properties.

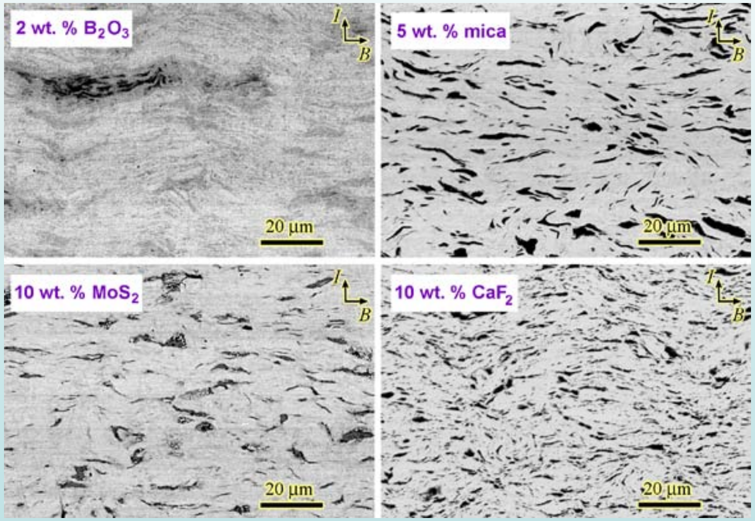


Distribution of dielectric fluoride within a $Nd_{14.5}Fe_{79.5}B_6$ / 5 wt.% DyF_3 hot-pressed magnet.

FY10 Accomplishments

Task 3: Increase by ten times the electrical resistivity of permanent magnets with $(BH)_{max}$ > 35 MGOe able to operate at temperatures of 200-240°C. *(Cont'd)*

❖ **Micro-laminated isotropic magnets with electrical resistivity increased by up to 4.8 times, were fabricated from the recently developed $SmCo_5$ nanoflake precursors, by hot pressing with or without a dielectric addition** (such as boron oxide, muscovite (mica), molybdenum disulfide and calcium fluoride).



Morphology of laminated permanent magnets produced from $SmCo_5$ nanoflake precursors and dielectric inclusions.

Dielectric addition	Electrical resistivity (μ Ω*cm)		Remanent induction (kG)	Intrinsic coercivity (kOe)
	Perpendicularly to predominant flake orientation	Parallel to predominant flake orientation		
no addition	133	92	6.45	17.6
2 wt. % CaF_2	125	97	5.92	16.0
5 wt. % CaF_2	141	117	5.55	15.4
10 wt. % CaF_2	328	110	4.98	16.4
1 wt. % mica	159	68	6.42	16.7
5 wt. % mica	196	55	4.49	11.4
2 wt. % B_2O_3	644	197	5.09	13.6
10 wt. % MoS_2	236	130	5.13	12.3

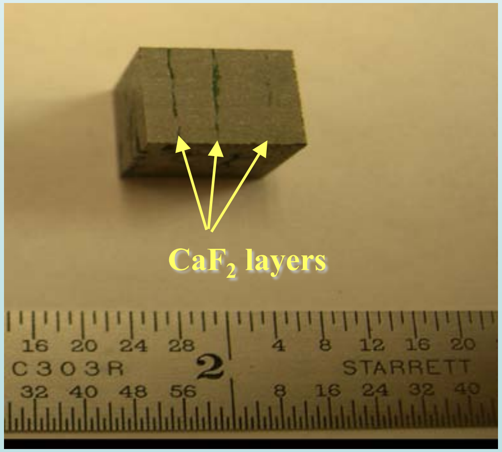
Magnetic properties of laminated permanent magnets produced from $SmCo_5$ nanoflake precursors and dielectric inclusions.

FY10 Accomplishments

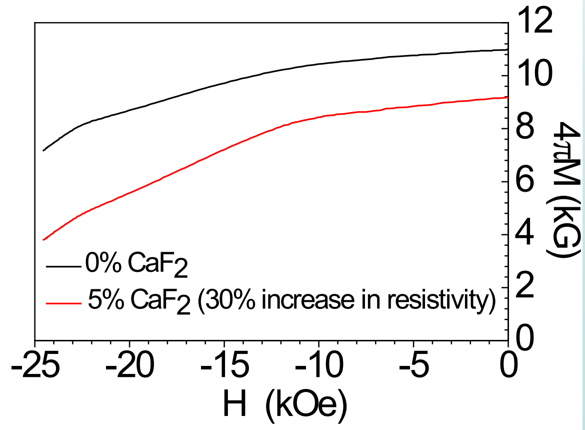
Task 3: Increase by ten times the electrical resistivity of permanent magnets with $(BH)_{max}$ > 35 MGOe able to operate at temperatures of 200-240°C. *(Cont'd)*

❖ Continued to produce magnets with good magnetic performance and electrical resistivity increased by 30% able to operate at 240°C.

❖ **Laminated anisotropic magnets consisting of $Sm(Co,Fe,Cu,Zr)_z$ and CaF_2 layers that can electrically insulate the magnet layers, were produced by a one-step sintering. The magnetic layers have the same properties as a bulk magnet with $(BH)_{max}$ of up to 33 MGOe.** A magnet specimen with 3 dielectric layers (equivalent to 5 wt%) has a *total* magnetic remanence of 9 kG, intrinsic coercivity exceeding 25 kOe.



Morphology of laminated $Sm(Co,Fe,Cu,Zr)z$ / CaF_2 magnet.



Demagnetization curve for laminated $Sm(Co,Fe,Cu,Zr)_z$ / CaF_2 magnet.

FY10 Accomplishments

Task 4: Development of short thermal cycles to reduce cost of the sintered Sm-Co 2:17 magnets.

❖ Fine modifications in the solution temperature and quenching allowed for the fabrication of larger magnet blocks (without cracking) and more uniform magnetic properties.

Task 5: Testing of mechanical properties and corrosion resistance of the new composite magnets with enhance electrical resistivity.

❖The mechanical strength in composite $Sm(Co,Fe,Cu,Zr)_z$ / CaF_2 magnets with increased electrical resistivity is similar to that of the regular $Sm(Co,Fe,Cu,Zr)_z$ magnets.

Collaboration and Coordination with other Institutions

Academia

Univ. of Delaware

Industry

General Electric

Curtiss-Wright

Proposed Future Work

- Develop a production process that will allow the magnet and dielectric powder layering with a control of the layer thickness down to hundreds of microns.
- Continue the efforts to improve the maximum energy product $(BH)_{max}$ of the permanent magnets to at least 35 MGOe.
- Continue to test the mechanical properties of the composite magnets with higher electrical resistivity.
- Test the corrosion resistance of the composite magnets with higher electrical resistivity.
- Continue to develop magnets with high electrical resistivity for our customers and receive the feedback on their performance.

Summary

- **Permanent magnets with increased maximum energy product were produced by compositional and process optimizations.**
- **Composite Sm-Co based** (homogeneous) **magnets containing dielectric inclusions, with 30 – 700% higher electrical resistivity than conventional magnets, were produced by sintering.**
- **Layered magnets with resistivity increased up to the level of electrical insulation, were produced by one-step sintering.**
- **A new type of magnets with a layered microstructure and up to 4.8 times increase in electrical resistivity, were produced from nanoflake magnet precursors and dielectric powder.**
- **Composite Nd-Fe-B and Pr-Fe-B based magnets with dielectric dispersions and electrical resistivity increased by 6 times, compared to the value for the conventional metallic counterparts, were synthesized by hot pressing and die upsetting.**
- **The new composite magnets with dielectric inclusions and high electrical resistivity have similar mechanical strength as compared to conventional magnets.**
- **Optimizations and automations lead to the cost reduction of the magnet processing.**