Permeability Engineered Co-Based Magnetic Core Technology for Inductive Components
Emerging Trends → Need for New Technology!

- Electrification of Aerospace, Aviation, Automotive, and Military Sectors
- Electrical Grid Modernization Including Integration of High Penetration of “Distributed Energy Resources” (PV, Wind, Energy Storage, Fuel Cells, etc.)

New Power Electronics and Sensor Technologies are Required!

Predictive Global Electric Vehicle Sales

[Graph showing electric vehicle sales by region (EU, US, China, Rest of the World) from 2013 to 2025]

[Image of a map of the USA]
Wide Bandgap Semiconductor Technologies Have Enabled a Step Change in Power Electronics Conversion Opportunities

“Opportunities” = Challenges for Inductive Components (Inductors, Current Transformers, Transformers, etc.)

→ Higher Operational Temperatures
→ Higher Switching Frequencies
→ Higher Power Ratings
Current State of the Art: Inductive Components

- Current Transformers / Sensors
  - Gapped Magnetic Steel Cores
  - Rogowski Coils (No Core Material)

- Filter and Power Inductors
  - Ferrite Cores
  - Powder Cores
  - Fe-Based Amorphous or Nanocrystalline Gapped Cores

Limitations Include: Temperature, DC Bias, Linearity, High Frequency Losses, Mechanical Properties, Manufacturability of Large Components
The Team: NETL and CMU Technology

Paul Ohodnicki, Materials Scientist, NETL
~15 Years Experience in Magnetic Materials Research
PhD, Carnegie Mellon University 2008

Kevin Byerly, Staff Scientist, NETL
10+ Years Industrial Experience in Soft Magnetic Materials, Cores, and Applications

Carnegie Mellon University

Michael McHenry, Faculty, Carnegie Mellon University
Pioneer in the Field of Soft Magnetic Nanocomposites

Alex Leary, Materials Scientist, NASA GRC
~10 Years Experience in Magnetic Materials Research
PhD, Carnegie Mellon University 2016

Vladimir Keylin, Staff Scientist, NASA GRC
30+ Years Industrial Experience in Soft Magnetic Materials, Cores, and Applications
New Concept: NETL and CMU Technology

Co-Based Nanocomposite Alloy Cores with “Tuned” Permeability

Planar Flow Casting for Co-Based Amorphous Alloy Synthesis

Strain Annealing to Optimize Properties and “Tune” Permeability

Pilot Scale Caster Up to 1-2” Ribbon Widths

In-Line Processing

Co-Based Nanocomposite

Nanocrystals

Intergranular Phase

D~10nm

Full-Scale Prototype Core

Carnegie Mellon University

U.S. DEPARTMENT OF ENERGY
New Concept: NETL and CMU Technology

Co-Based Nanocomposite Alloy Cores with “Tuned” Permeability

Alloy Chemistry + Applied Tension Optimizes and Tunes Permeability

Permeability Control From ~10-10,000 Spans the Entire Range of Inductive Applications!

Permeability Dictates Inductive Component Performance!

Composition Dependence at 200MPa

Applied Tension Dependence at Fixed Composition
New Concept: NETL and CMU Technology

Co-Based Nanocomposite Alloy Cores with “Tuned” Permeability

Local Permeability Control Has Been Demonstrated for the First Time By the Project Team!

System Level Advantages of Local Permeability Control → Thermal Management, Power Density, and Efficiency
Unique Advantages of the Technology

Co-Based Nanocomposite Alloy Cores with “Tuned” Permeability

Temperature Stability of Magnetic Properties Up to Temperatures Approaching ~400-500°C!

Unparalleled Linearity of B-H Loops with DC Bias as Compared to Powder Cores and Ferrites!

Robust Mechanical Properties Improve Manufacturability and Service Performance.
Key Applications and Value Proposition

**Target:**
High Temperature Inductors and Current Sensors

**Value:**
No Existing Commercial Solutions Identified for T>~200-250°C

**Target:**
Current Sensors for High Current Breakers, Transmission Lines, etc.

**Value:**
Reduced Size, Complexity, and Cost of Existing CTs for Equivalent Performance

**Target:**
Filter Inductors for Motor Drives and Grid-Tied Inverter Applications

**Value:**
Reduced Size, Improved Linearity, and Improved Temperature Performance of Existing Inductors
Emerging Market Opportunities

Electric Vehicles is projected to be a rapidly growing market with ~10-40% through 2020 CAGR depending on segment.

Current Transformer Market:
CAGR of 7.8% through 2021 to $277M

Inductor Market:
CAGR of ~4% through 2022 to $4B

North America is expected to see substantial growth in demand for inductors in automotive applications!

This technology line falls directly into a number of emerging growth markets in the application areas identified.

Figure 1: Annual global light duty vehicle sales

Source: Bloomberg New Energy Finance
Technology Current Status/Accomplishments

• Timeline of Concept (Key Publications)
  • Field Annealed Co-Based Alloys (Ohodnicki, 2008)
  • Strain Annealed Co-Based Alloys (Kernion, 2012)
  • “Virtual Bound State” Alloys (Leary, 2015)
  • “Graded Permeability” Prototype (Byerly, 2017)

• Intellectual Property
  • Co-Based Strain Annealing Patent Application Submitted, 2014 (Joint CMU / NETL)
  • Local Permeability Tuning Patent Application Submitted, 2016 (Joint CMU / NETL)

• Strategic Partnerships for Prototyping
  • Partnership with a Major Vendor and Leading University
  • Demonstrations of Inductor Technology Expected in 2018
Next Steps To Maturation / Commercialization

• Detailed Performance Characterization
  • Currently Underway But Always Seeking New Opportunities
  • All Pilot-Scale Facilities are in Place, Need “End User” Partners

• Current Alloy and Processing Technology Transfer
  • On-Going Dialogue with Major Alloy Manufacturers
  • Also a Potential “Start-Up” Opportunity

• Alloy and Process Optimization For New Applications
  • Optimize Losses for Power Inductor Applications
  • Develop Manufacturing Processes for Motor Applications

We are Interested in Discussing Partnering on Technology Development, Licensing, and Start-Up Venture Opportunities to Transition the Technology.
Summary - Technology Recap

- Emerging Trends Create Demand for Novel Inductive Components
- Strain Annealed Co-Based Nanocomposites are a New Magnetic Core Technology with Unique Value at Component Scale

  **Now:**
  - Current Transformers
  - Filter Inductors

  **Future:**
  - Power Inductors
  - Rotating Electrical Machinery

- Advantages Include Temperature Stability, Linearity, DC Bias, Tunable Permeability
- Prototyping, Alloy / Process Licensing, and Additional Process Development is Required to Move the Technology Forward

- Collaborations and Partnerships are Actively Being Sought to Transition this Technology to Commercialization!
Thank You

• Dr. Paul R. Ohodnicki, Jr.
• NETL Partnership Options
  • Licenses
  • Cooperative Research and Development Agreements
  • Contributed Funds Agreements
• Contact the NETL Tech Transfer Office with Any Further Questions