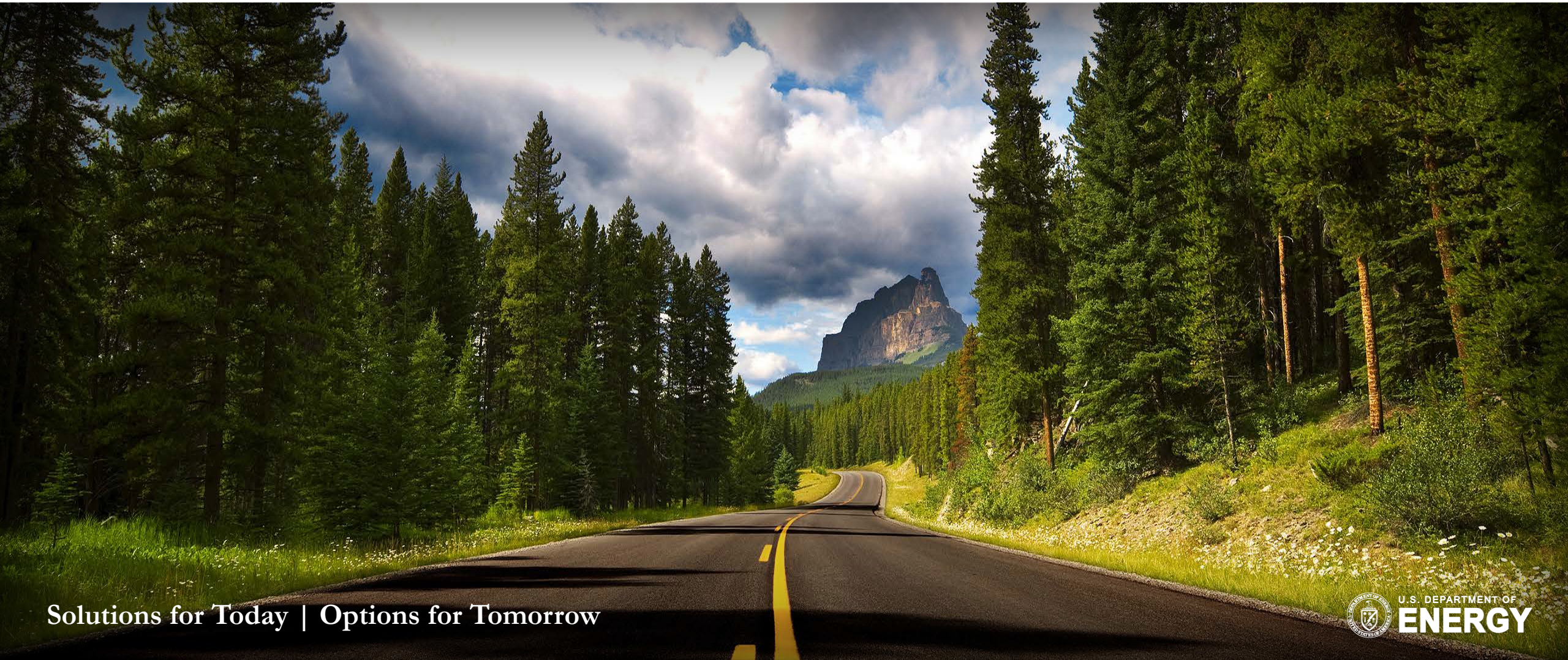
Permeability Engineered Co-Based Magnetic Core Technology for Inductive Components

NATIONAL ENERGY TECHNOLOGY LABORATORY

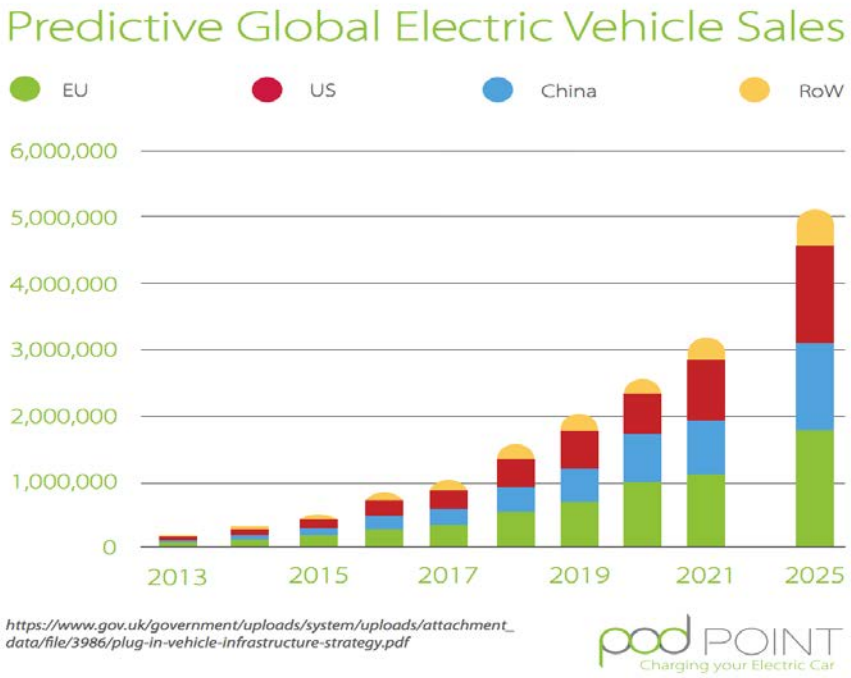


Solutions for Today | Options for Tomorrow

U.S. DEPARTMENT OF ENERGY

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!

Advances in New Switches Driving the Passives

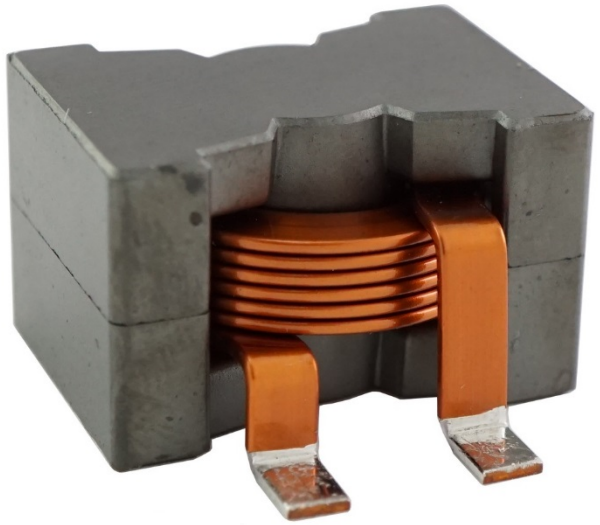
- Wide Bandgap Semiconductor Technologies Have Enabled a Step Change in Power Electronics Conversion Opportunities

- "Opportunities" = Challenges for Inductive Components (Inductors, Current Transformers, Transformers, etc.)

  →Higher Operational Temperatures

  →Higher Switching Frequencies

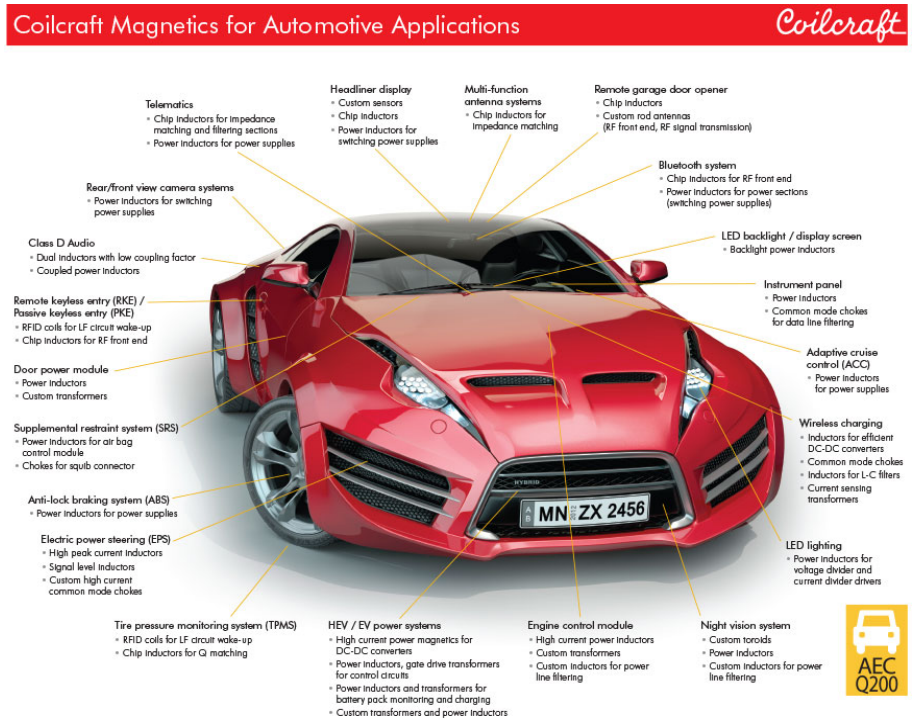
  →Higher Power Ratings



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



Inductive Components: Automotive Applications

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

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

Kevin Byerly, Staff Scientist, NETL

10+ Years Industrial Experience in Soft Magnetic Materials, Cores, and Applications

Vladimir Keylin, Staff Scientist, NASA GRC

30+ Years Industrial Experience in Soft Magnetic Materials, Cores, and Applications

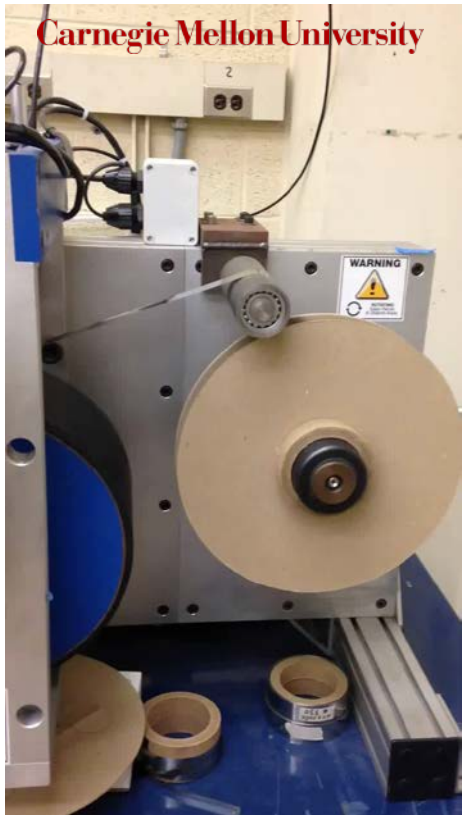
New Concept : NETL and CMU Technology

Co-Based Nanocomposite Alloy Cores with "Tuned" Permeability

Planar Flow Casting for Co-Based Amorphous Alloy Synthesis

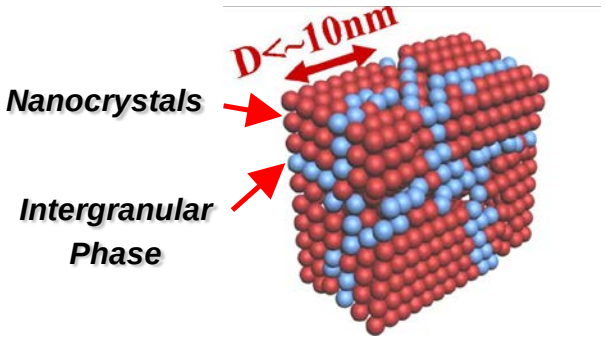
Pilot Scale Caster Up to 1-2" Ribbon Widths

Strain Annealing to Optimize Properties and "Tune" Permeability



In-Line Processing

Co-Based Nanocomposite



Full-Scale Prototype Core

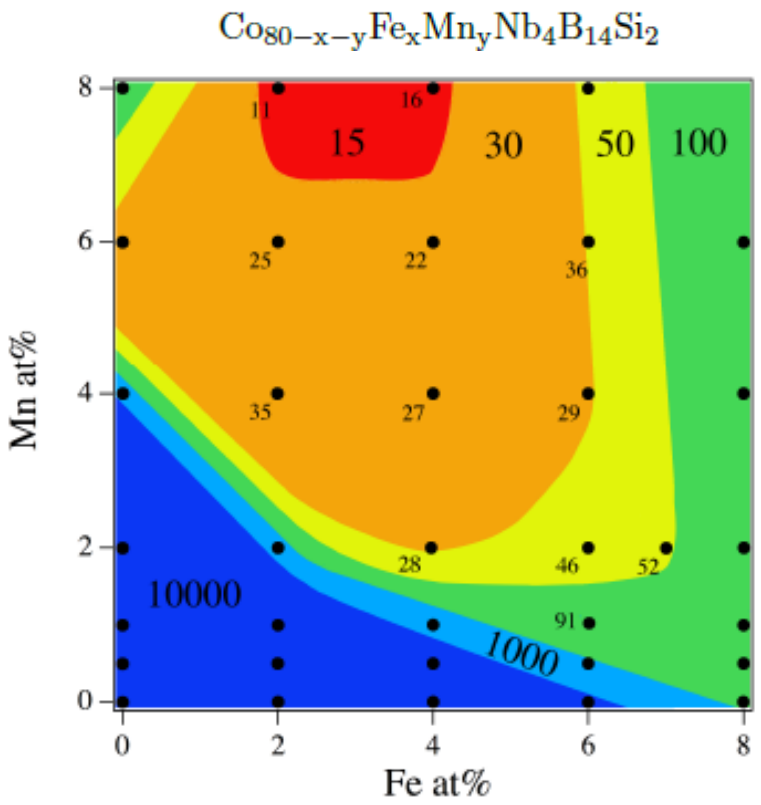
New Concept : NETL and CMU Technology

Co-Based Nanocomposite Alloy Cores with "Tuned" Permeability

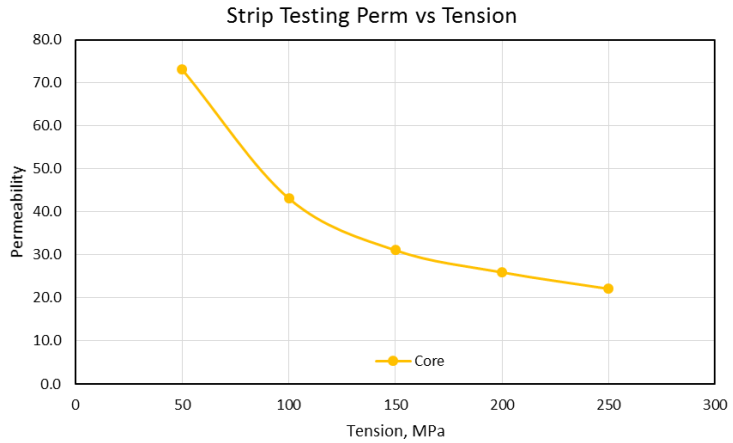
Alloy Chemistry + Applied Tension Optimizes and Tunes Permeability

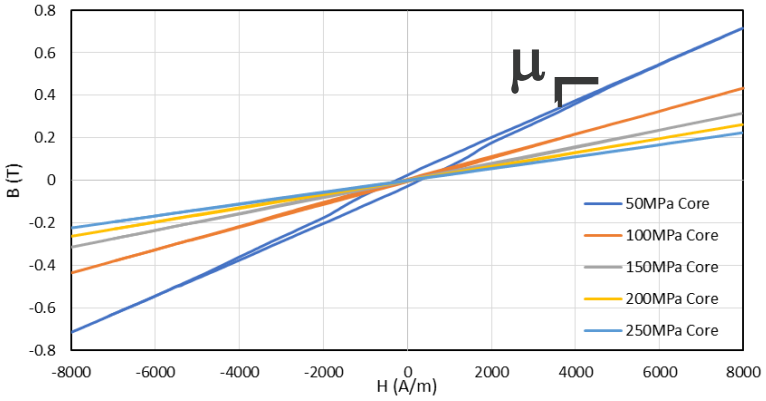
Permeability Control From ~10-10,000 Spans the Entire Range of Inductive Applications!

Permeability Dictates Inductive Component Performance!



Composition Dependence at 200MPa



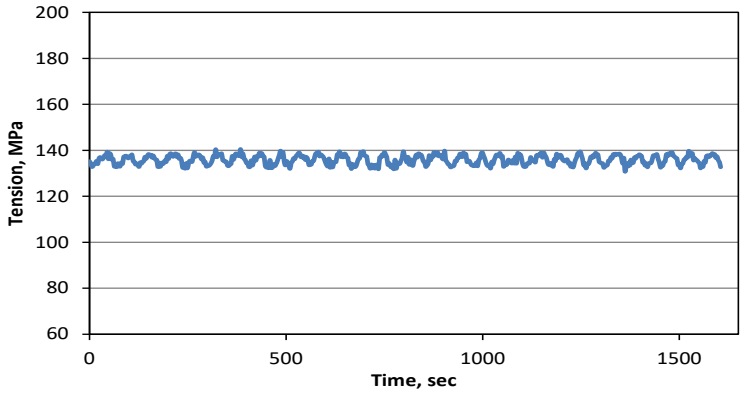


Applied Tension Dependence at Fixed Composition

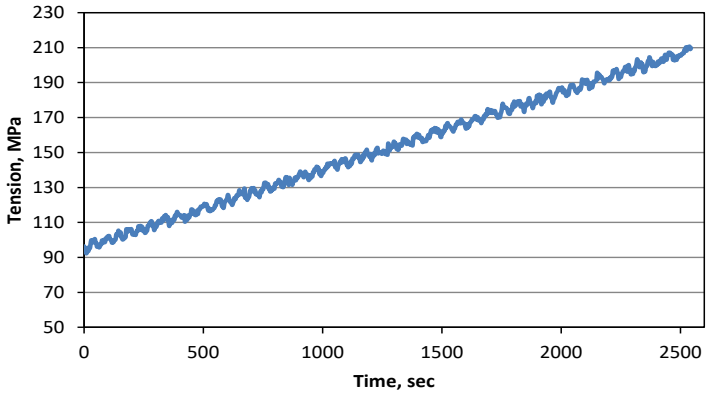
New Concept : NETL and CMU Technology

Co-Based Nanocomposite Alloy Cores with "Tuned" Permeability

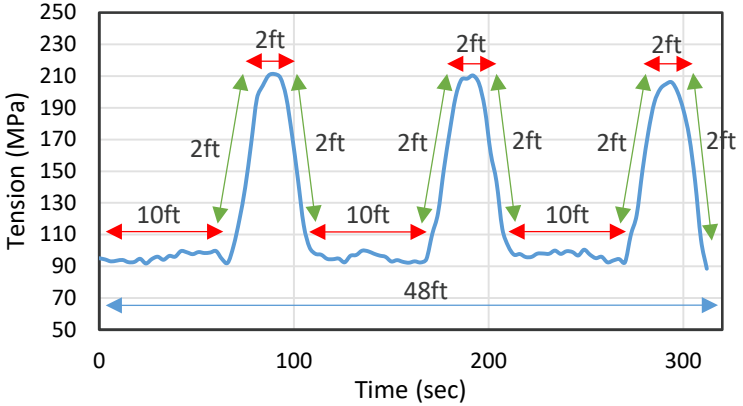
"Tuned Permeability"



"Graded Permeability"



"Heterogeneous Permeability"



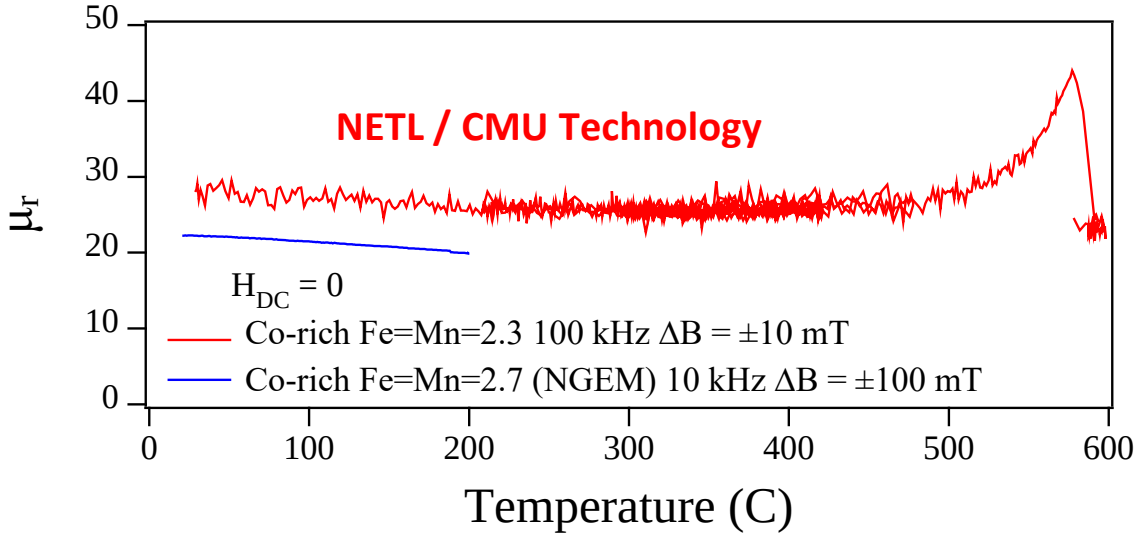
Local Permeability Control Has Been Demonstrated for the First Time By the Project Team!

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

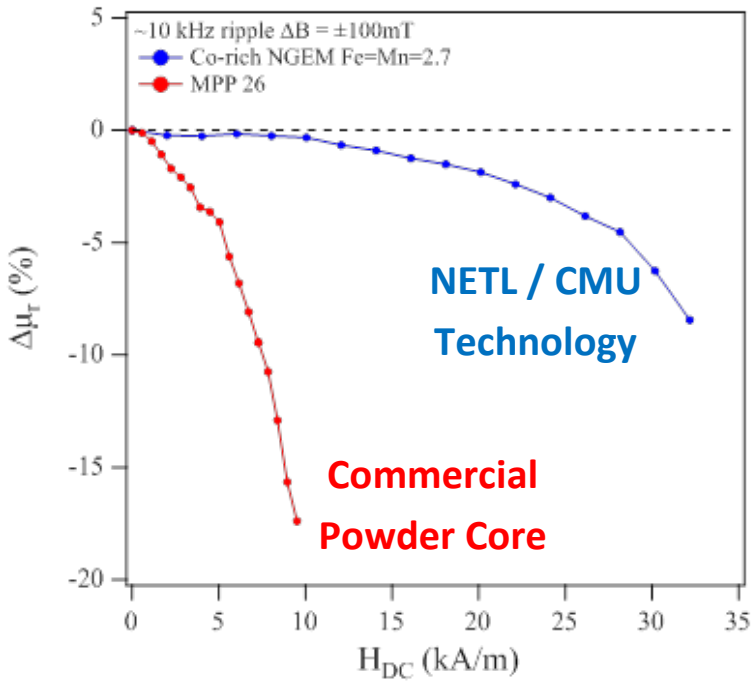
Unique Advantages of the Technology

Co-Based Nanocomposite Alloy Cores with "Tuned" Permeability

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

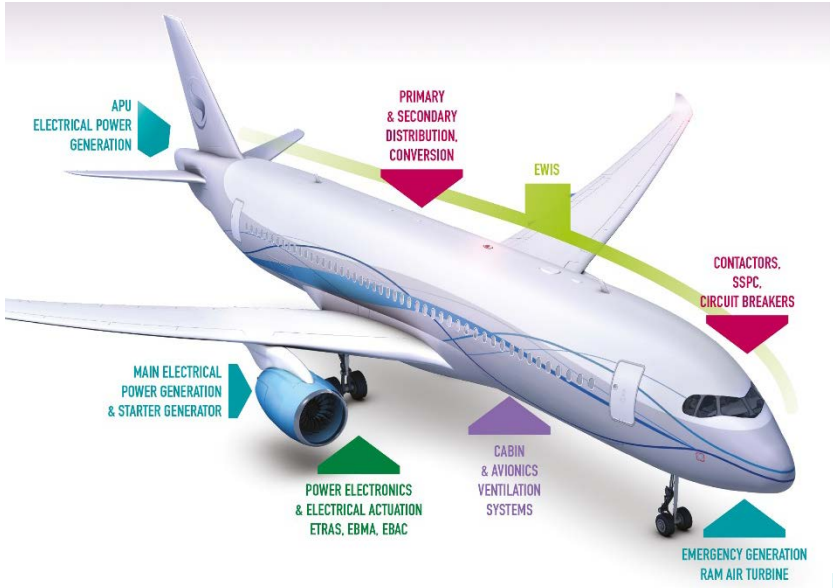


Unparalleled Linearity of B-H Loops with DC Bias as Compared to Powder Cores and Ferrites!



Robust Mechanical Properties Improve Manufacturability and Service Performance.

Key Applications and Value Proposition



Target:

High Temperature Inductors and Current Sensors

Value:

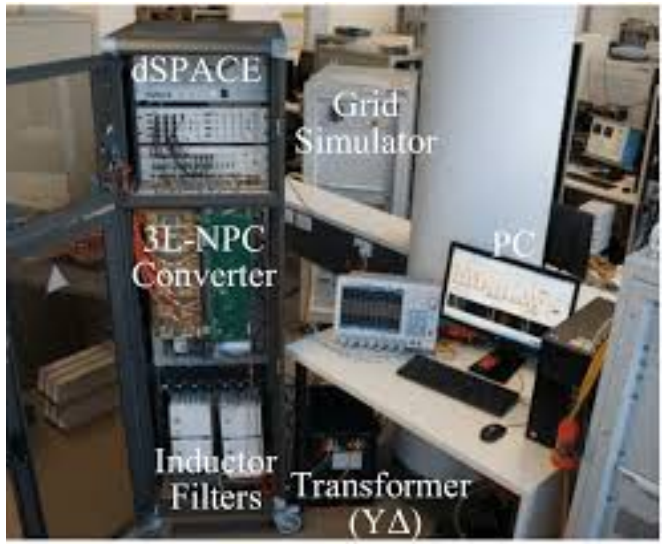
No Existing Commercial Solutions Identified for T>~200-250°C

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

Current Transformer Market :

CAGR of 7.8% Through 2021 to $277M

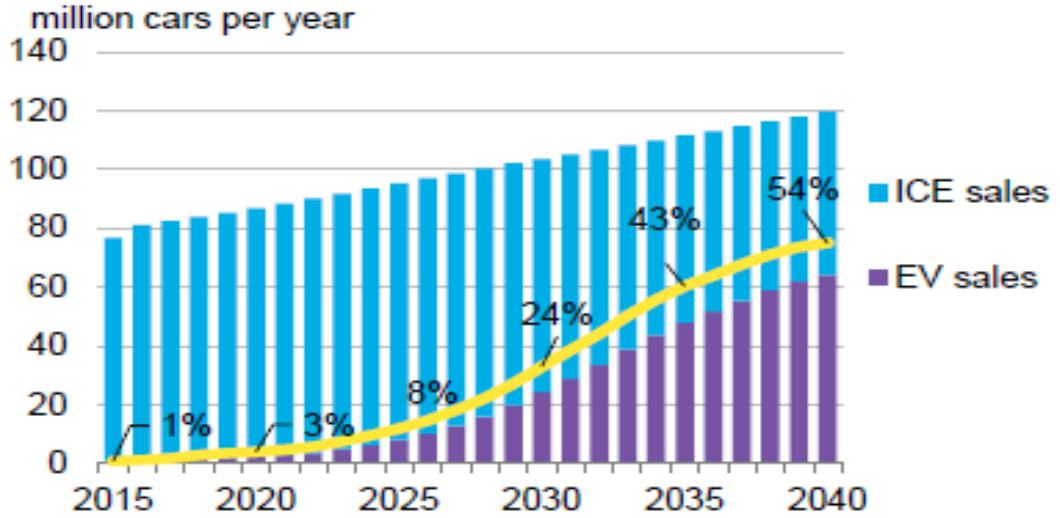
Inductor Market :

CAGR of ~4% Through 2022 to $4B

North America is Expected to See Substantial Growth in Demand for Inductors in Automotive Applications!

Electric Vehicles is Projected to Be a Rapidly Growing Market with ~10-40% Through 2020 CAGR Depending on Segment

Figure 1: Annual global light duty vehicle sales



Source: Bloomberg New Energy Finance

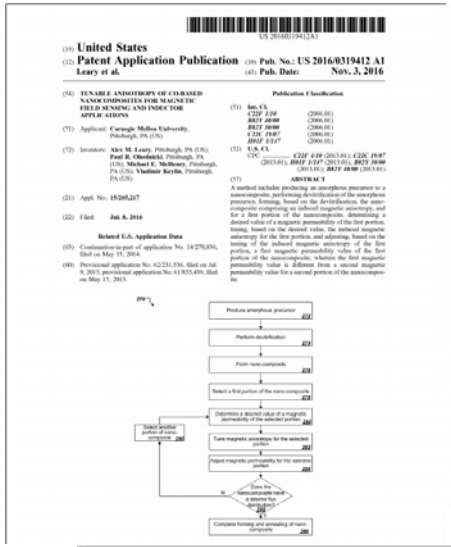
This Technology Line Falls Directly into a Number of Emerging Growth Markets in the Application Areas Identified.

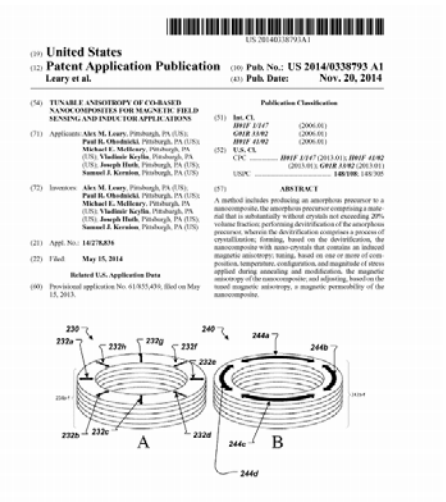
Technology Current Status/Accomplishments

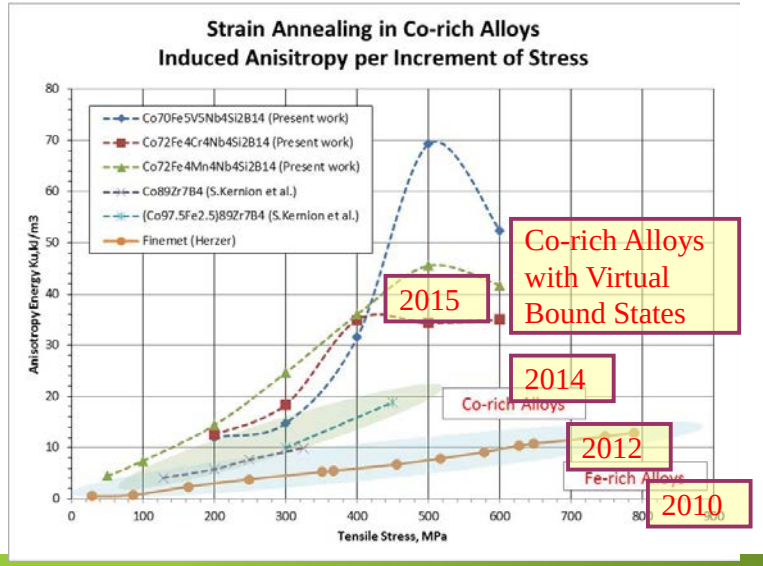
- **Timeline of Concept (Key Publications)**
  - Field Annealed Co-Based Alloys (Ohodnicki, 2008)
  - Strain Annealed Co-Based Alloys (Kernion, 2012)
  - “Virtual Bound State” Alloys (Leary, 2015)
  - “Graded Permeability” Prototype (Byerly, 2017)

- **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



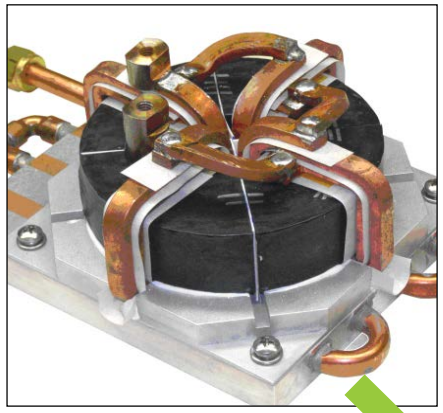




Next Steps To Maturation / Commercialization

- **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

New Magnetic Core Technology for Advanced Inductive Components



Example: Ungapped Inductor Cores

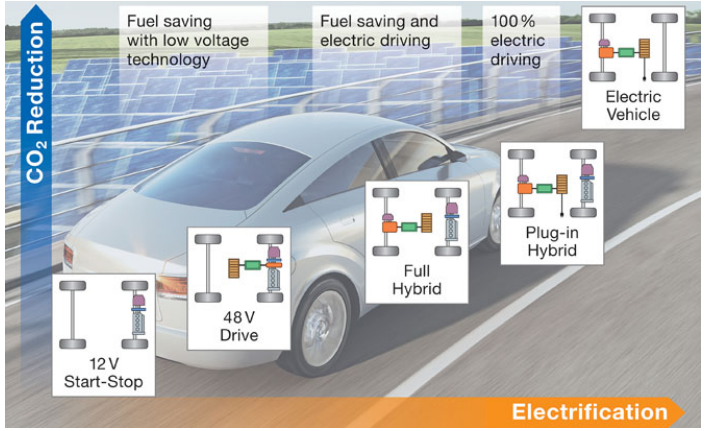
We are Interested in Discussing Partnering on Technology Development, Licensing, and Start-Up Venture Opportunities to Transition the Technology.

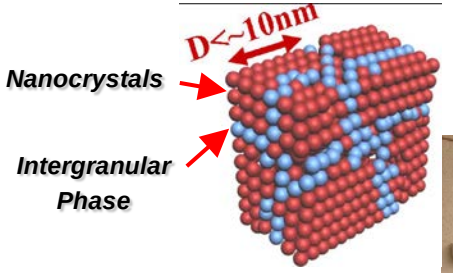
Summary - Technology Recap

- **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