U.S. DEPARTMENT OF ENERGY
Office of Electricity

Soft Magnetic Alloy Advanced Manufacturing Through In-Line Processing (Concept #1)

Metal / Oxide Nanocomposite Materials for High Frequency and High Power Magnetics (Concept #2)

TRAC Program Review

US Department of Energy, Office of Electricity

Presented at Oak Ridge National Laboratory

Oak Ridge, TN

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August 14, 2019

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Project Overview

Project summary :

- *Concept #1*: Application of in-line processing in amorphous and metal / amorphous nanocrystalline alloy systems.
- *Concept #2*: Development of advanced oxide / metallic-based nanocomposite core materials for high frequency switching.
- *Goal*: Develop new materials and advanced manufacturing methods for soft magnetic applications spanning kHz – MHz and kW – MW range.

Total value of award : $1M ($500k per project) over 2 execution years

Period of performance : 10/1/2019 – 3/31/2021

Project lead and partners : NETL (lead), Carnegie Mellon Univ., U. Pitt.

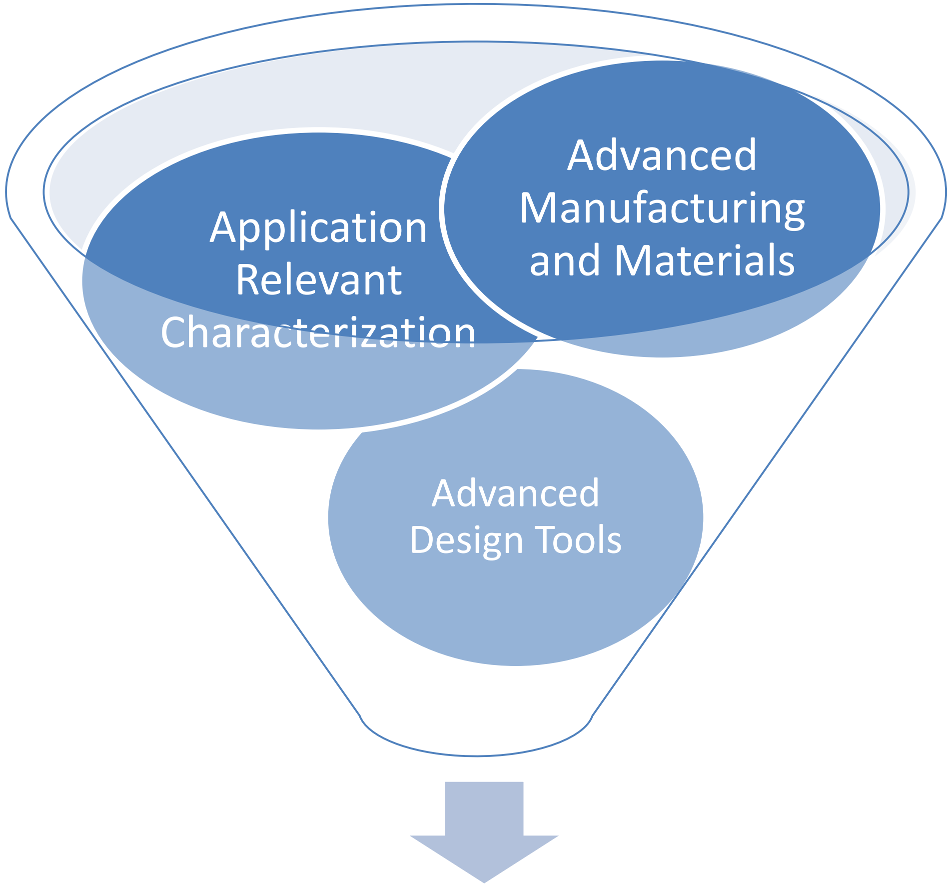
The Problem Being Addressed : Research Motivation

What tools are needed to design high frequency magnetic components?

1. Advanced Manufacturing Processes and Materials

2. Application Relevant Core / Component Characterization
   – Publication of Data Sheets

3. Advanced Design Tools
   – Multi-Objective Optimization
   – Co-Simulation Methods

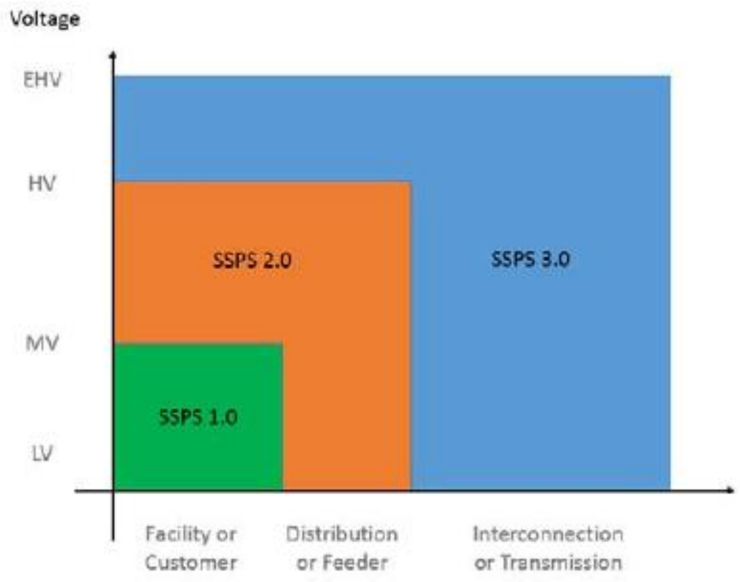


Optimal HF magnetic components

Context concerning the problem : Drivers for MV-HV Power Electronics

Solid State Power Substation Vision

Near-Term → Intermediate-Term → Long-Term



LV - MV Power Electronics

(Grid Integration, SSTs)

MV-HV+ Power Electronics

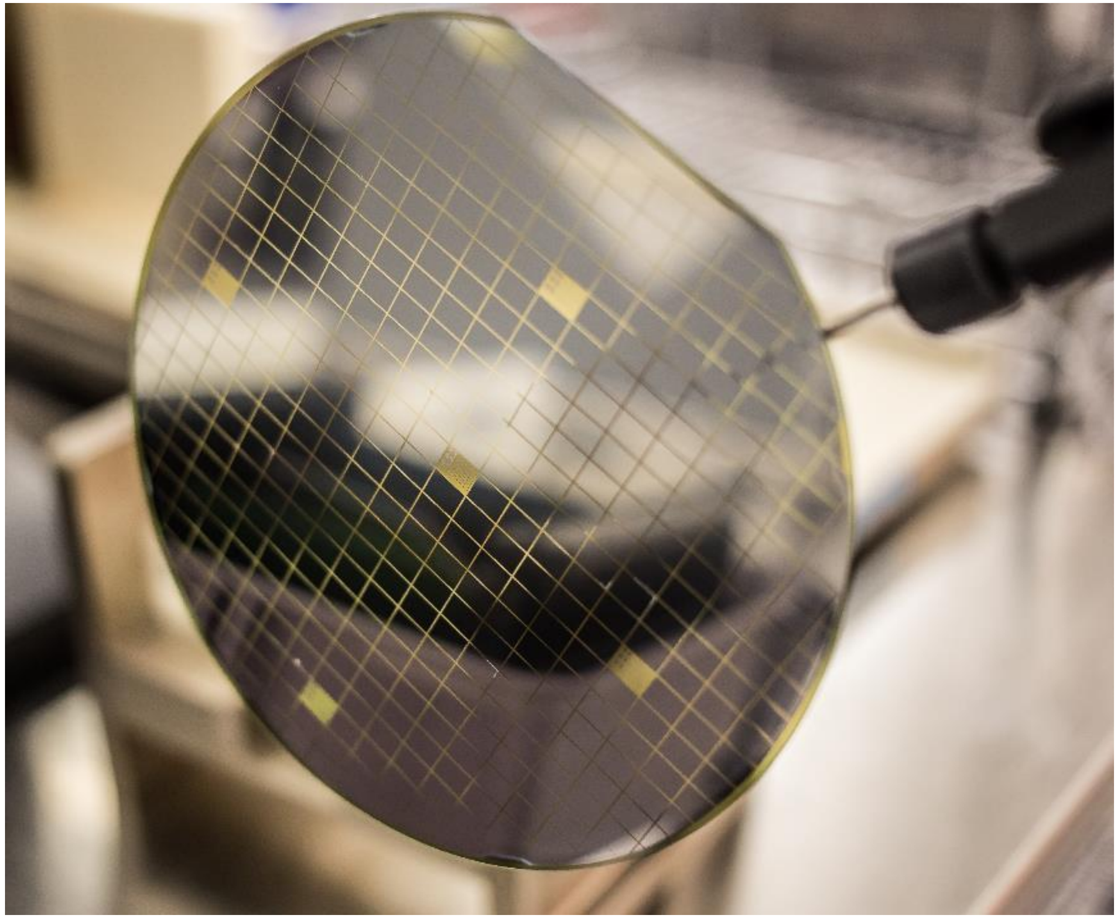
(Power Flow Control, Substation Level)

US DOE, Solid State Power Substation Workshop Summary Report, September 2017

A Vision for Medium and High Voltage Power Electronics Has Been Put Forward by the OE TRAC Program through the Solid State Power Substation Road-mapping Effort.

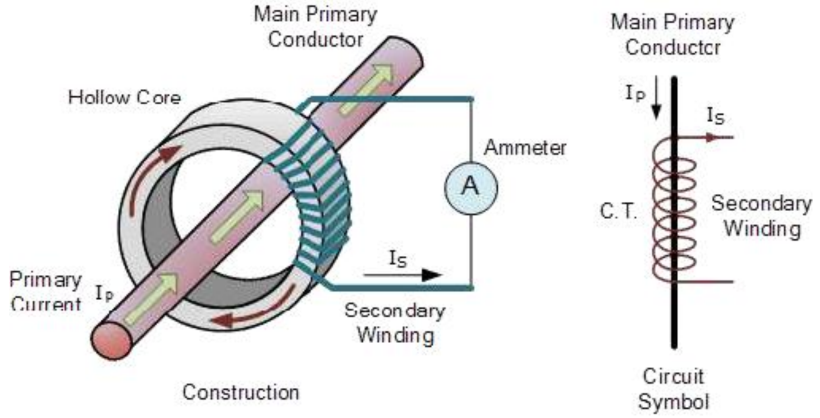
Context concerning the problem: Drivers for Soft Magnetic Components

- **<u>Wide Bandgap Devices</u> are a Reality and Creating New Challenges and Opportunities for Passives, Including Magnetics …**
- **<u>Ultra-Wide Bandgap Devices</u> are Being Discussed for Next Generation Switching Devices to Push to Even Higher Voltage / Frequencies and Will Be Needed for MV-HV+ Power Electronics**
- **Breakthroughs in Passives Require Sustained and Focused R&D Efforts to Maintain Pace**
- **Desired Attributes of New Magnetic Components:**
  - → Improved Thermal Performance
  - → Lower Loss at Higher Switching Frequencies
  - → Higher Power Ratings
  - → Linearity at High DC Bias Fields
  - → Minimize Requirements for Insulation Materials

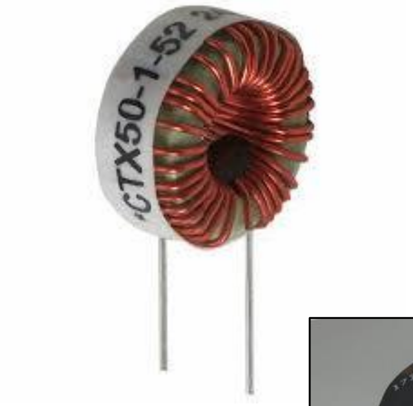


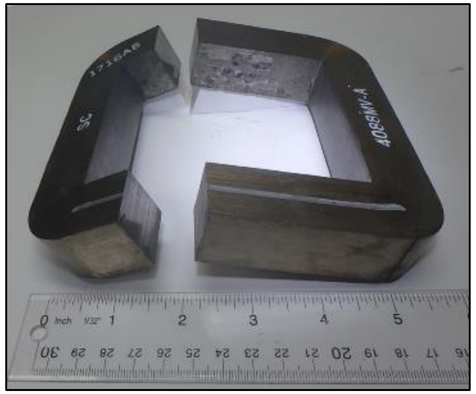
Current State of the Art : Inductive Components

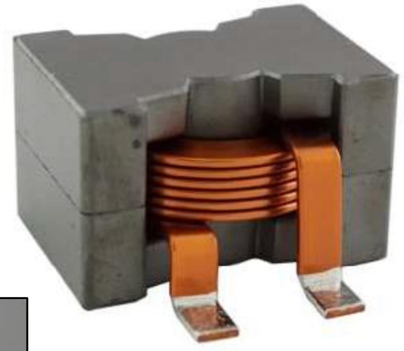
- **Current Transformers / Sensors**
  - → Gapped Electrical Steel Cores
  - → Rogowski Coils (No Core Material)
  - → Limitations: Bandwidth, Linearity, Saturation



- **Filter and Power Inductors**
  - → Ferrite Cores
  - → Powder Cores
  - → Fe-Based Amorphous or Nanocrystalline Gapped Cores
  - → Limitations: Temperature, DC bias, Linearity, High Frequency Losses (e.g. Proximity Losses Near Gaps), Mechanical Properties, Large Component Manufacturability

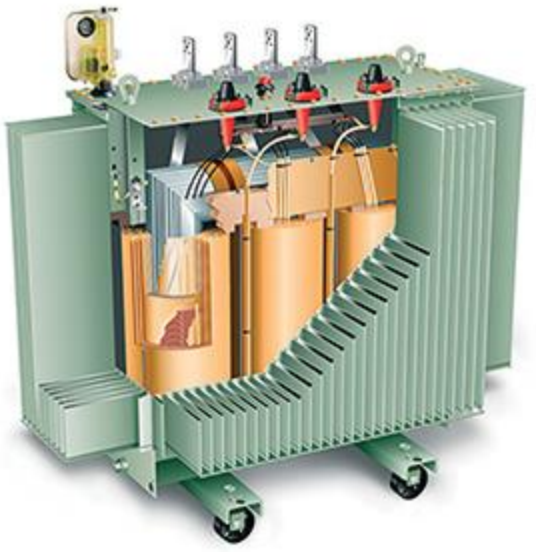




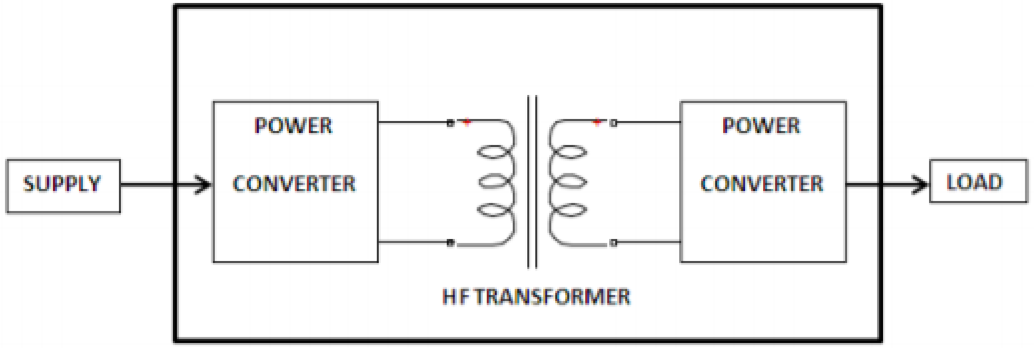


Transformers : Current State of the Art / New Technologies

- **Conventional Transformer (CT)**
  - → Laminated core (E-I shape), Toroidal, or Electrical steel strip
  - → Advantages: Cheap, Efficient, Reliable, Mature technology
  - → Disadvantages: Bulky size / Heavy weight, No control mechanism from system disruptions / overloads.



- **Solid State Transformer (SST)**
  - → Power electronic converter with semiconductor switch
  - → High frequency (HF) transformer (e.g. amorphous / nanocomposite core material)
  - → Advantages: Reduced size / weight, Fast fault detection / protection, Controllability
  - → Disadvantages: Cost, Design requirements for HF transformer, Not a 1:1 replacement for CT



SOLID STATE TRANSFORMER

Current State of the Art : Magnetic Core Materials

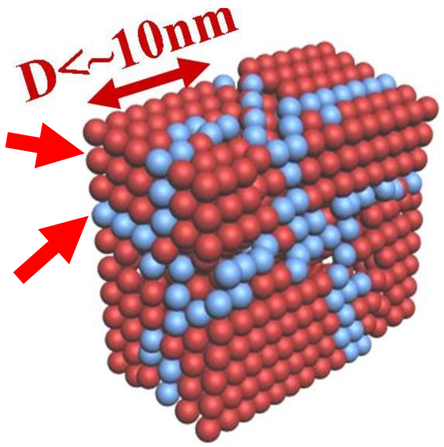
Material Classes	Saturation Magnetization (T)	Resistivity (μΩ-cm)	Upper Temp. Limit (C)	Upper Freq. Limit (Hz)	Mechanical Properties	Manufacturing Scalability
Ferrites (NiZn, MnZn)	0.2-0.4	$>10^3$	100-300	10^6-10^9	Brittle But Machinable	Limited (Powder Process)
Bulk Crystalline Alloys	1-2.5	~10	400-1000	10^2	Excellent	Excellent
Amorphous Alloys	1-1.6	~100	150	10^5	Good	Good
Commercial Metal / Amorphous Nanocomposites (MANCs)	1.3	~100	150	10^5	Brittle	Limited (Brittle Properties)
Emerging MANCs for WBG	1-1.9	~150	150-500	10^5	Good	Good
Ideal for UWBG	1-2	$>10^3$	300-500	10^6-10^7	Excellent	Excellent

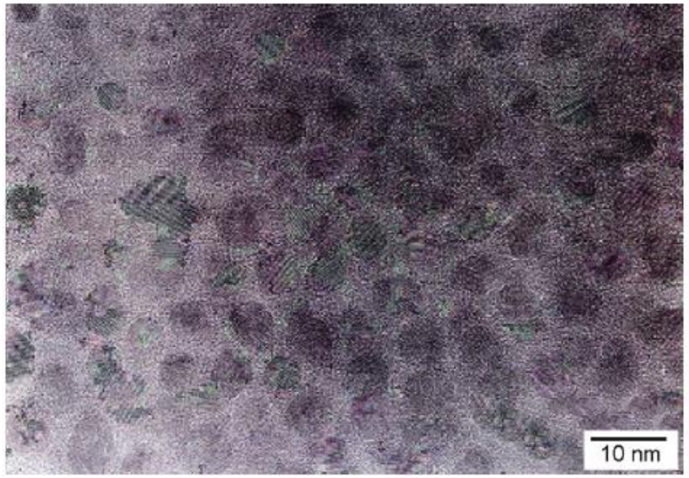
New MANC Alloy Compositions and Manufacturing (Concept #1)

Completely New Materials Systems (Concept #2)

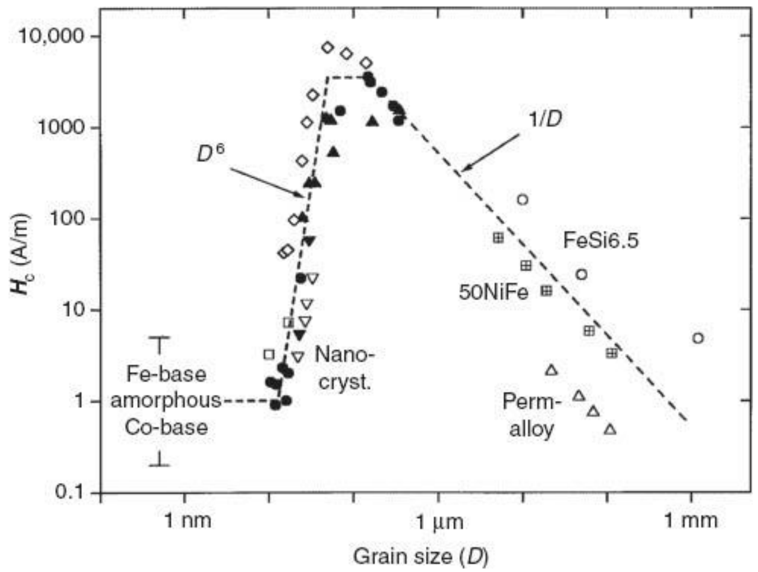
Uniqueness of the Proposed Solution : Nanocomposite Magnetics

- ❑ **Role of Intergranular Phase:**
  - → Refined Microstructure
  - → Source of Induced Anisotropy
  - → Intergranular Exchange Coupling
  - → Increased Effective Resistivity
  - → High Temperature Stable Microstructure





Nanoscale Microstructure Yields Soft Magnetic Properties



Grid-Scale Applications Require Manufacturing Scalability

Metal Nanocrystal and Metallic Glass Intergranular Phase Nanocomposites (MANCs) are the Only Commercial Nanocomposites Available at Scale

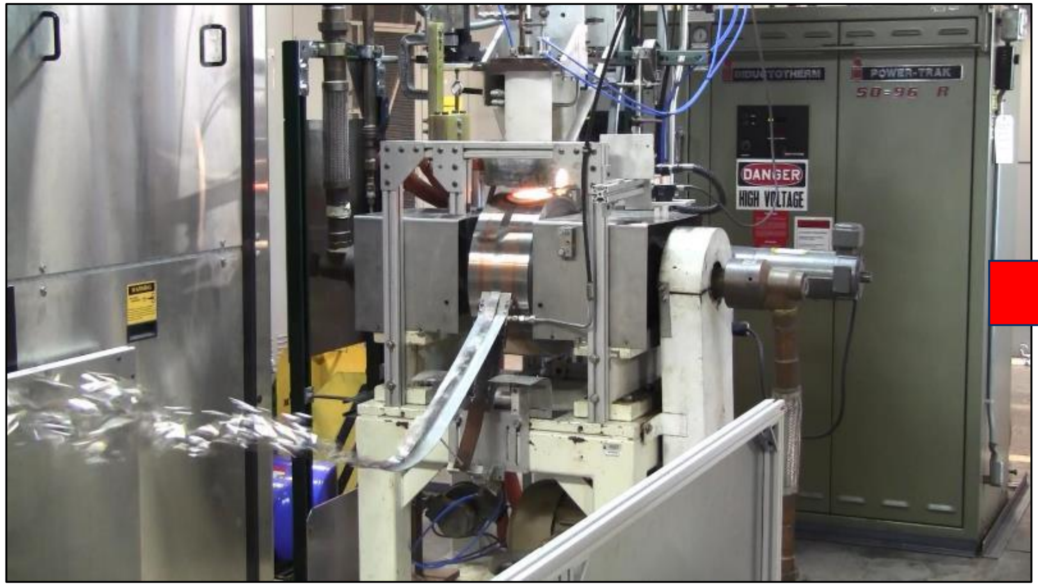
AM Leary, PR Ohodnicki, ME McHenry, JOM 64 (7), 772-781 (2012). M. E. McHenry, M. A. Willard, D. E. Laughlin, Prog. in Materials Science 44 (4) 291-434 (1999).

Uniqueness of the Proposed Solution : Concept #1 Advanced MANCs

- **Metal Amorphous Nanocomposite (MANC) Cores with "Tunable" Permeability**

Planar Flow Casting for Cobalt-Based Amorphous Alloy Synthesis

Field and / or Strain Annealing to Optimize Properties and "Tune" Permeability in Full-Scale Cores



Pilot-Scale Caster Up to 2" Widths

In-Line Processing

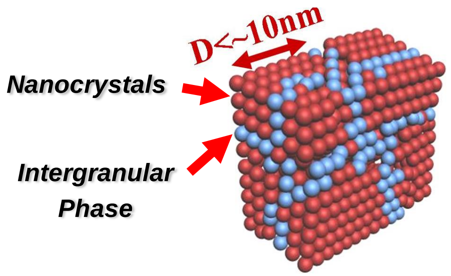
Full-scale Prototype Core w/ Nanocomposite Microstructure

Recent Efforts Have Targeted Application of Advanced Manufacturing Processes to Newly Developed MANC Alloy Compositions For Optimized Properties at Component Scale

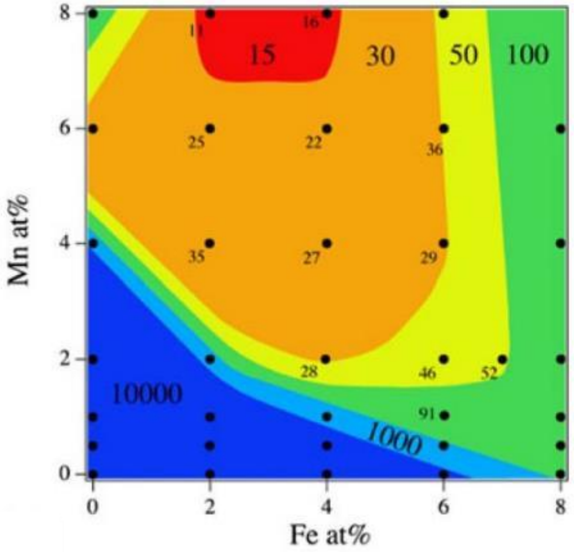
Uniqueness of the Proposed Solution : Concept #1 Advanced MANCs

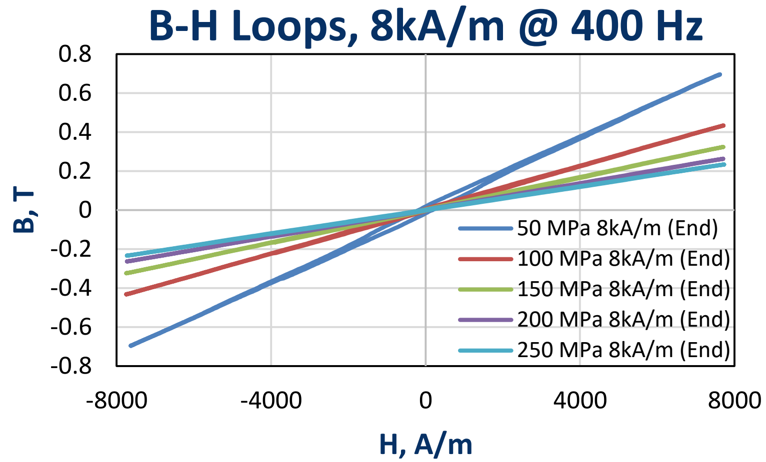
❑ Cobalt-Based Nanocomposite Alloy Cores with "Tunable" Permeability

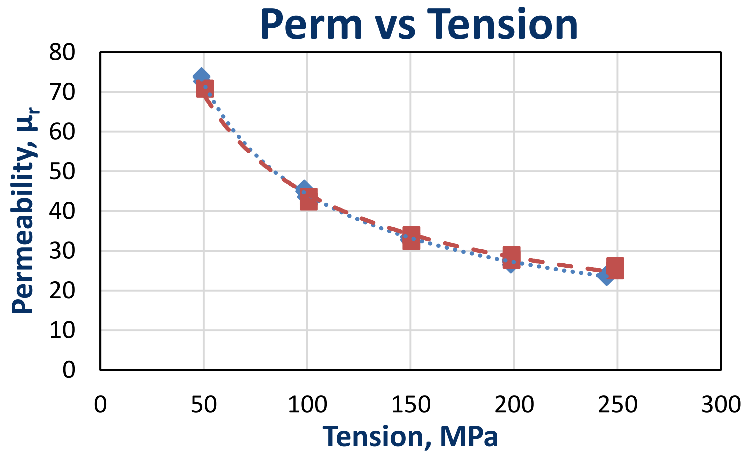
- → Alloy Chemistry + Applied Tension Optimizes and "Tunes" Permeability
- → Permeability Control From ~10-10,000 Spans the Entire Range of Inductive Applications
- → Permeability Dictates Inductive Component Performance



$Co_{80-x-y}Fe_xMn_yNb_4Si_2B_{14}$







Composition Dependence at 200MPa

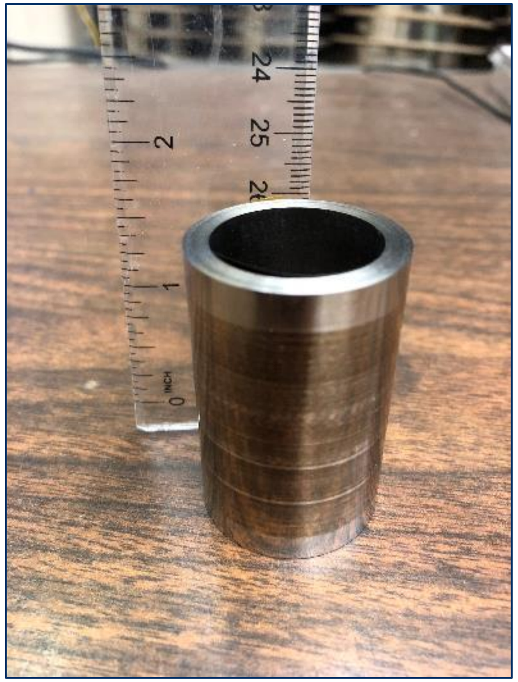
Applied Tension Dependence at Fixed Composition

A. Leary, V. Keylin, A. Devaraj, V. DeGeorge, P. Ohodnicki, and M. E. McHenry, Journal of Materials Research 31 (20), 3089-3107 (2016).

Uniqueness of the Proposed Solution : Concept #1 Advanced MANCs

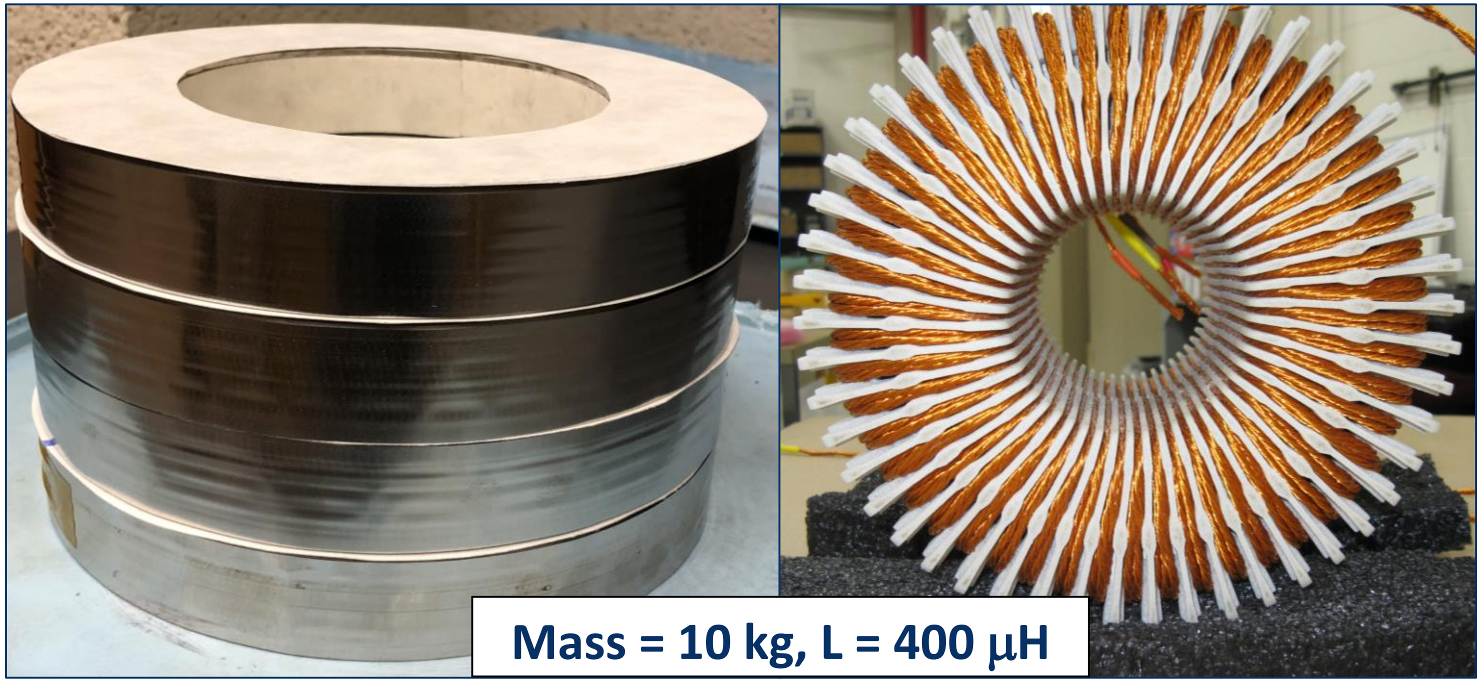
Key to Manufacturability = Mechanical Properties of Alloys + Thermal Stage

2" Wide Strain Anneal



Cast Length Strain Anneal

Fabrication of Large-Scale Power Inductor Cores

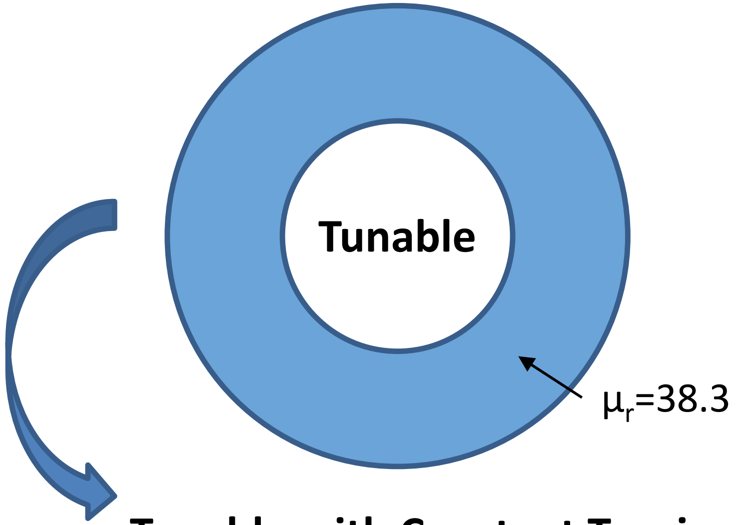


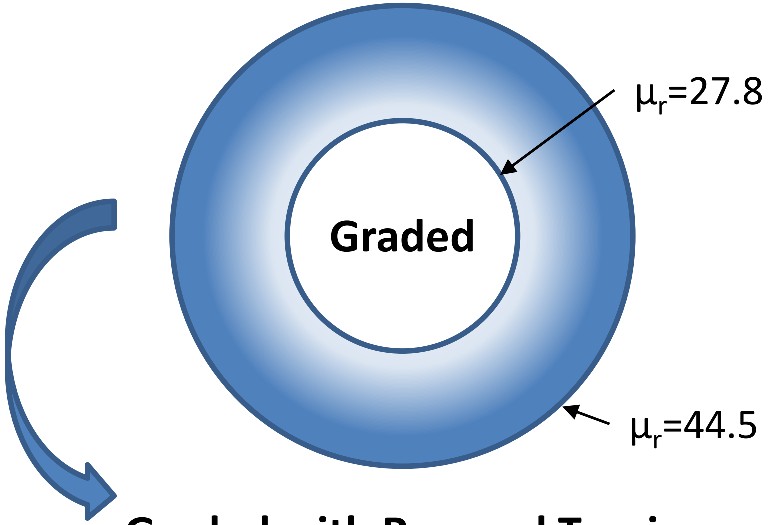
Mass = 10 kg, L = 400 μH

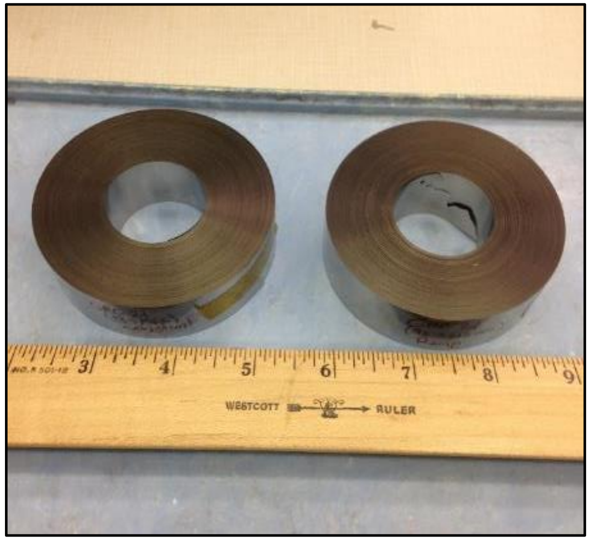
Successful Demonstrations of Strain Annealing Wide Width / Long Lengths Co-Based Ribbon for Large-Scale Core Fabrication Have Been Demonstrated with Conventional Strain Annealing

Uniqueness of the Proposed Solution : Concept #1 Advanced MANCs

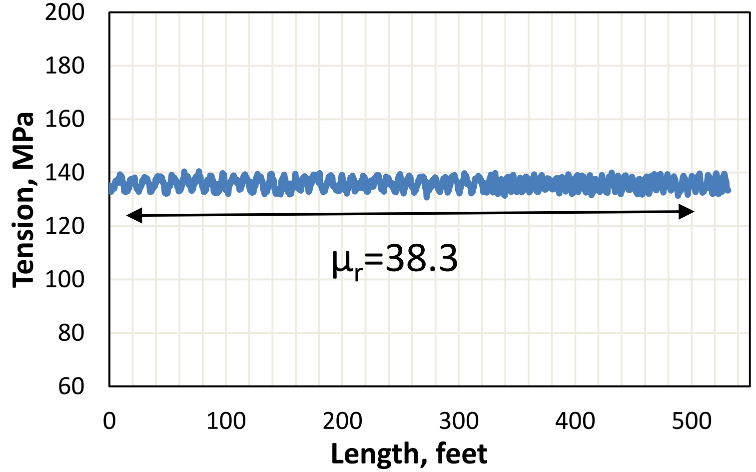
Locally Engineered Permeabilities for Optimized Thermal and Efficiency Performance



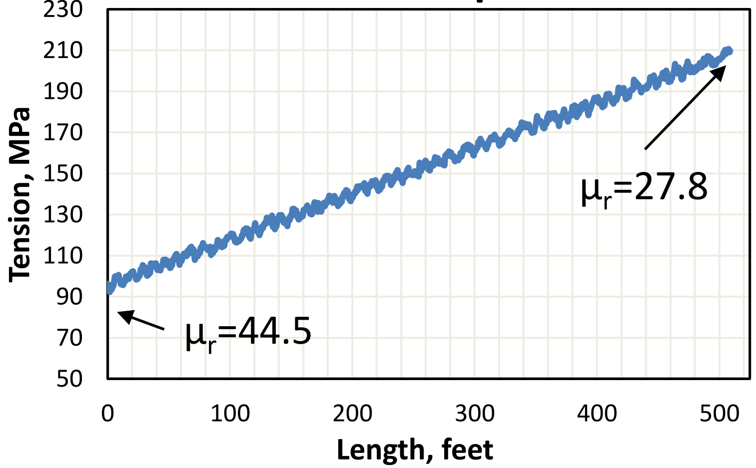




Tunable with Constant Tension



Graded with Ramped Tension



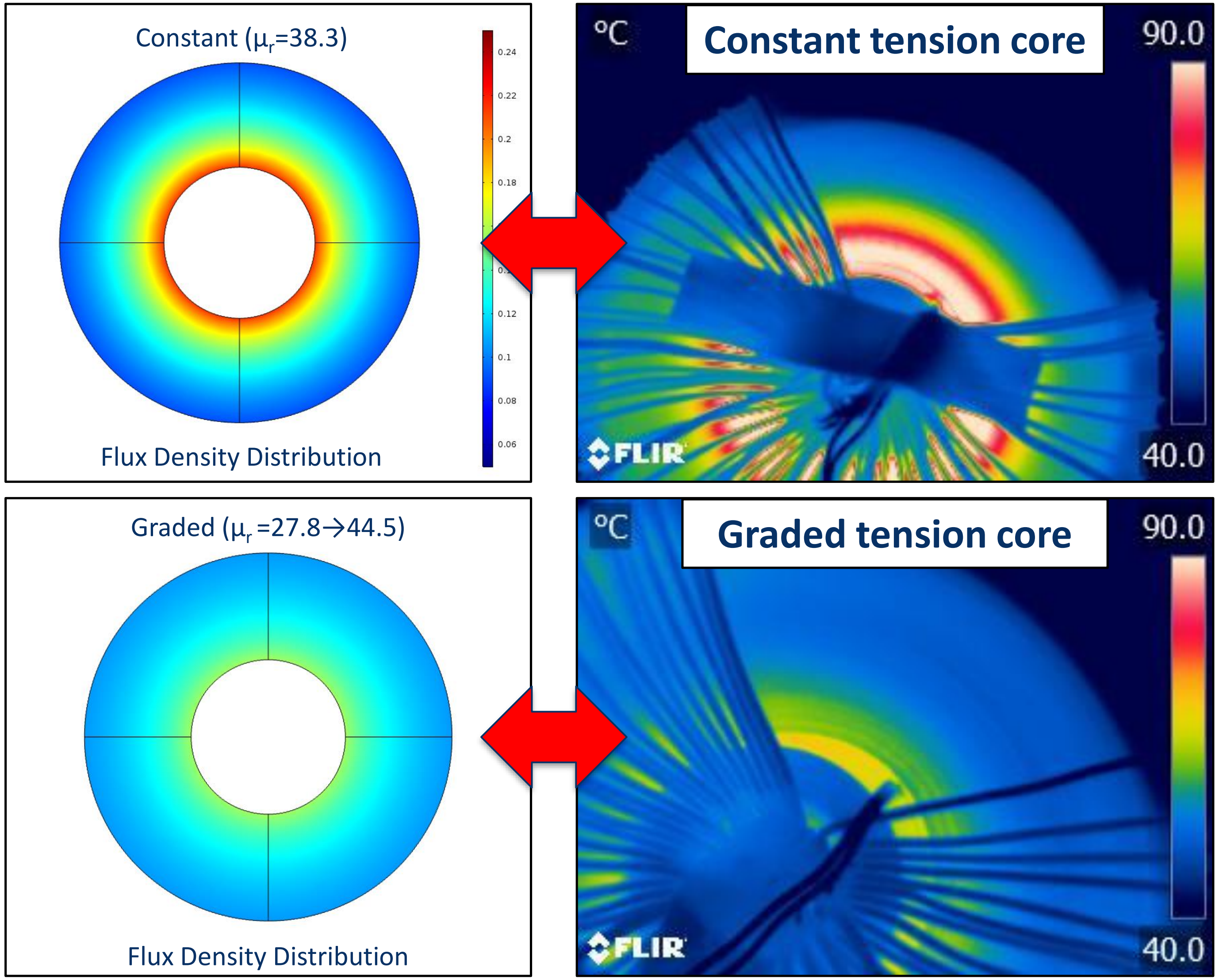
Fabricated Strain Annealed Cores

Mass	OD	ID	HT
600 g	79 mm	33 mm	25 mm

Real-Time Process Controls Allow for Spatially Varying Permeability : Inductor Core Example

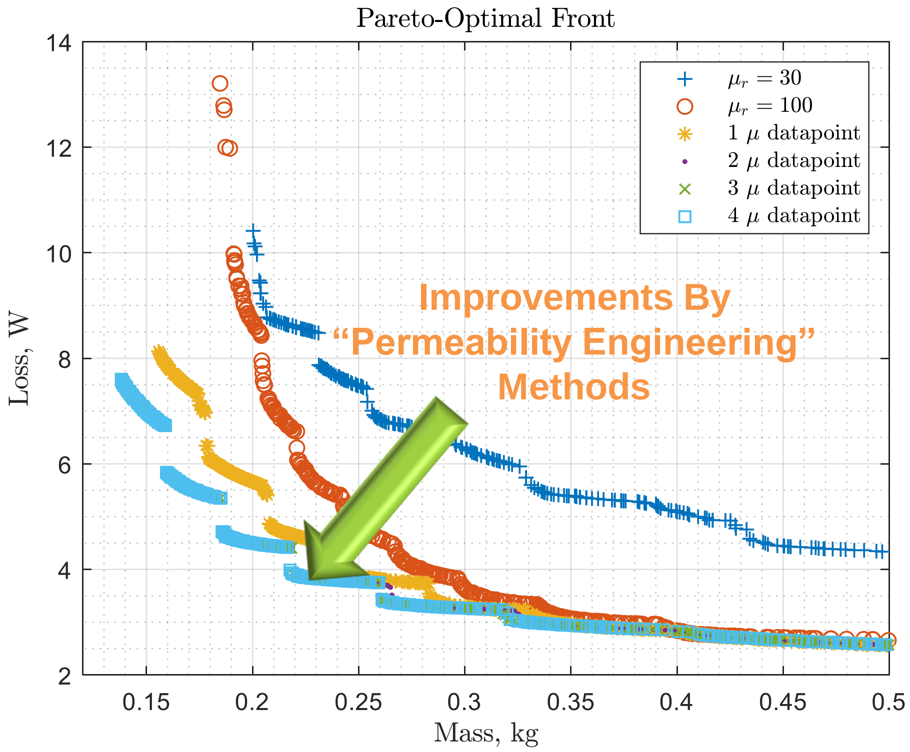
K. Byerly, P. R. Ohodnicki, S. R. Moon, A. M. Leary, V. Keylin, M. E. McHenry, S. Simizu, R. Beddingfield, Y. Yu, G. Feichter, R. Noebe, R. Bowman, S. Bhattacharya, JOM, Volume 70, Issue 6, pp 879–891 (2018).

Uniqueness of the Proposed Solution : Concept #1 Advanced MANCs



Multi-Objective Optimization

Leveraging "Permeability Engineering"



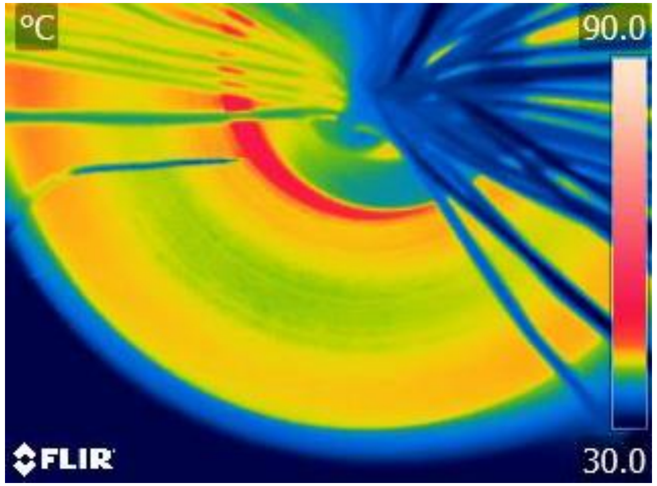
New Design Spaces with Improved Thermal, Mass, and Loss Performance are Made Possible

K. Byerly, P. R. Ohodnicki, S. R. Moon, A. M. Leary, V. Keylin, M. E. McHenry, S. Simizu, R. Beddingfield, Y. Yu, G. Feichter, R. Noebe, R. Bowman, S. Bhattacharya, JOM, Volume 70, Issue 6, pp 879–891 (2018).

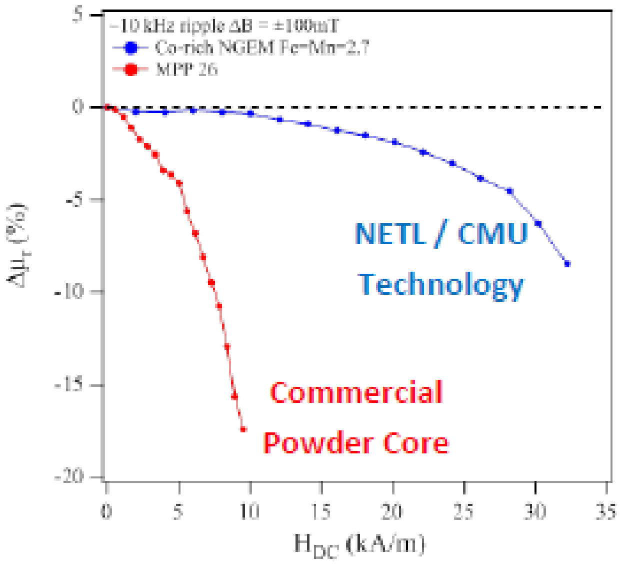
Significance of the Results : Concept #1 Advanced MANCs

❑ Application Perspective

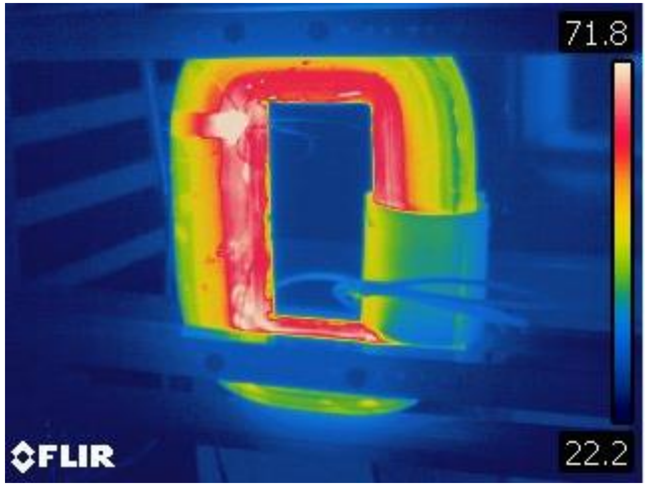
1. Inductors: Flux smoothing = Core temperature smoothing
2. Current Transformers: Low permeability / Linear *B-H* characteristic
3. HF Transformers (Rectangular-shaped): Elimination of hot spots on inner radii / corners



Graded Perm Inductor Core Exhibits 'Smoothed' Temperature



Linearity with DC Bias



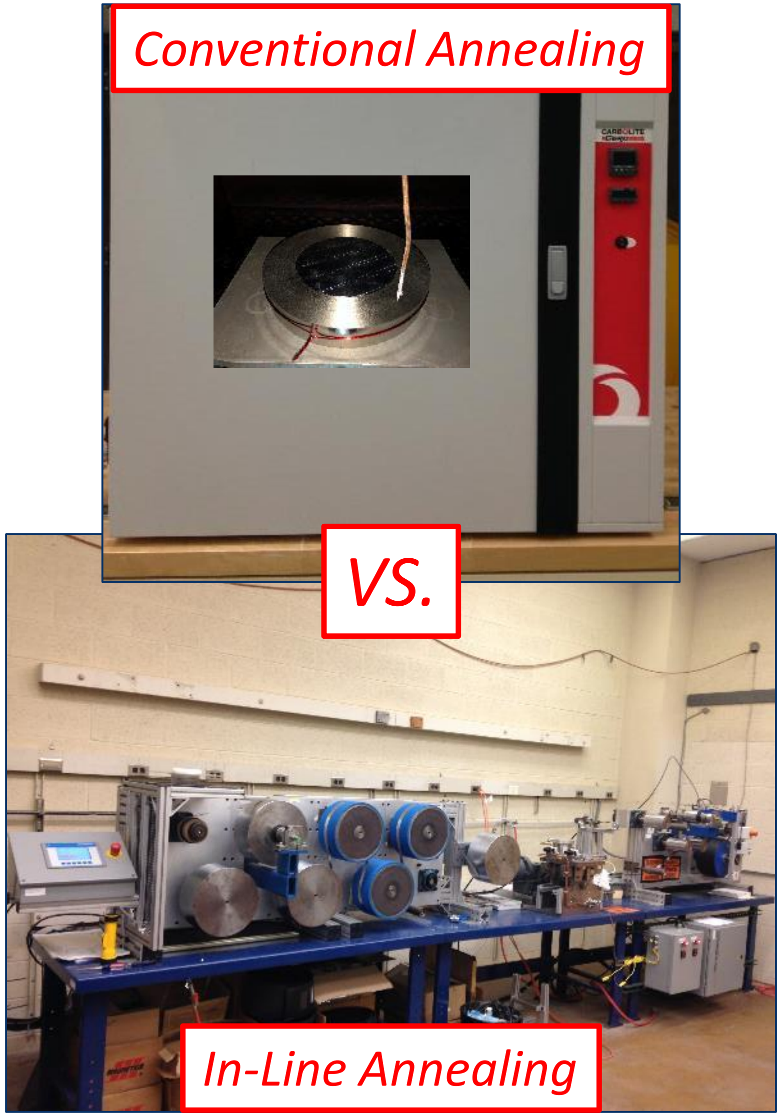
Spatial Trend in Temperature for an Energized Transformer

P. Lu, M. Buric, K. Byerly, S.R. Moon, M. Nazu, S. Simizu, A.M. Leary, R. Beddingfield, C. Sun, P. Zandhuis, M.E. McHenry, P.R. Ohodnicki, IEEE Trans. On Power Delivery, Volume 34, Issue 4, pp 1588-1598 (2019).

Significance of the Results : Concept #1 Advanced MANCs

❑ Technology Perspective

1. Finer control of magnetic properties
2. More repeatable / reproducible properties (along the ribbon length)
3. Reel-to-reel process → Manufacturability of large parts is now independent of the furnace size
4. Reduction in number of processing steps → Possible to eliminate processing steps like impregnation / gapping
5. Compact heating zone → Cost and energy intensity savings



Project Schedule, Deliverables, and Current Status : Concept #1

- **Milestones:**
  - Commission a new small-scale annealing system (3/31/2020)
  - Perform literature review of various mechanisms of heating and annealing (9/30/2020)
  - Perform advanced annealing treatments for commercial Fe-based alloys (9/30/2020)
  - Perform advanced annealing treatments for newly developed alloys (3/31/2021)
  - Fabricate / characterize a toroidal core w/ one or more processed alloys (3/31/2021)
- **Deliverables:**
  - Literature review of advanced annealing mechanisms for nanocomposite alloy systems (9/30/2020)
  - Technical report outlining results of new annealing system / materials research (3/31/2021)

Total Budget = $500k
Funding Received = $250k
Project to Initiate 10/1/2019

Uniqueness of Proposed Solution : Concept #2 Metal / Oxide Based

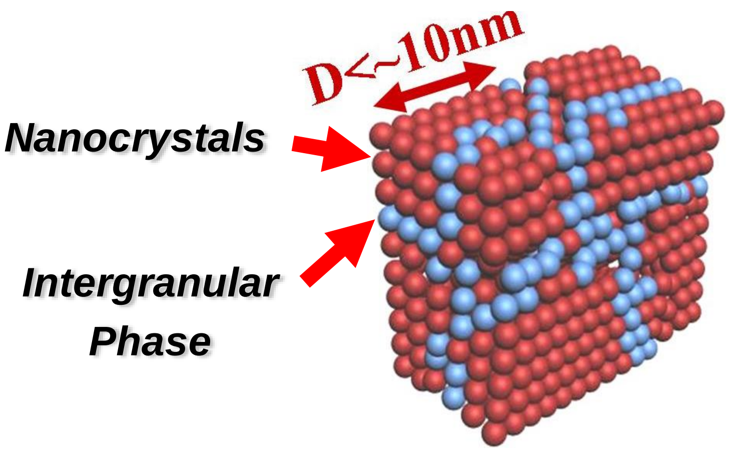
- ❑ **Insulating Oxide Phases Can Improve High Frequency Performance**
- ❑ **Metallic Phase Can Retain High Saturation Induction For High Power Applications**

Examples of Processing Strategies:

→ Thin Film Deposition

→ Thick Film Deposition

→ Powder Based Processing



Role of Intergranular Phase:

→ Refined Microstructure

→ Source of Induced Anisotropy

→ Intergranular Exchange Coupling

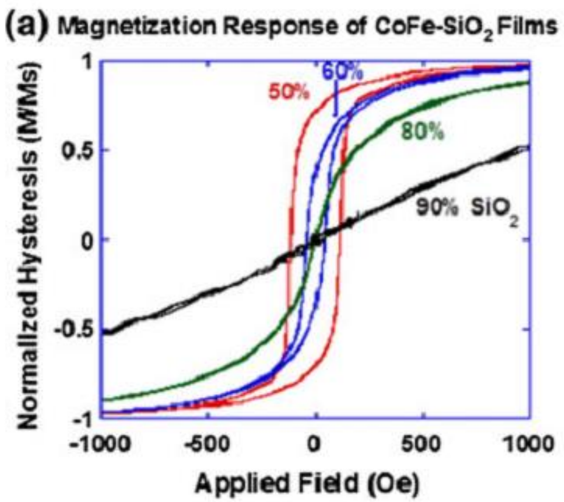
→ Increased Effective Resistivity

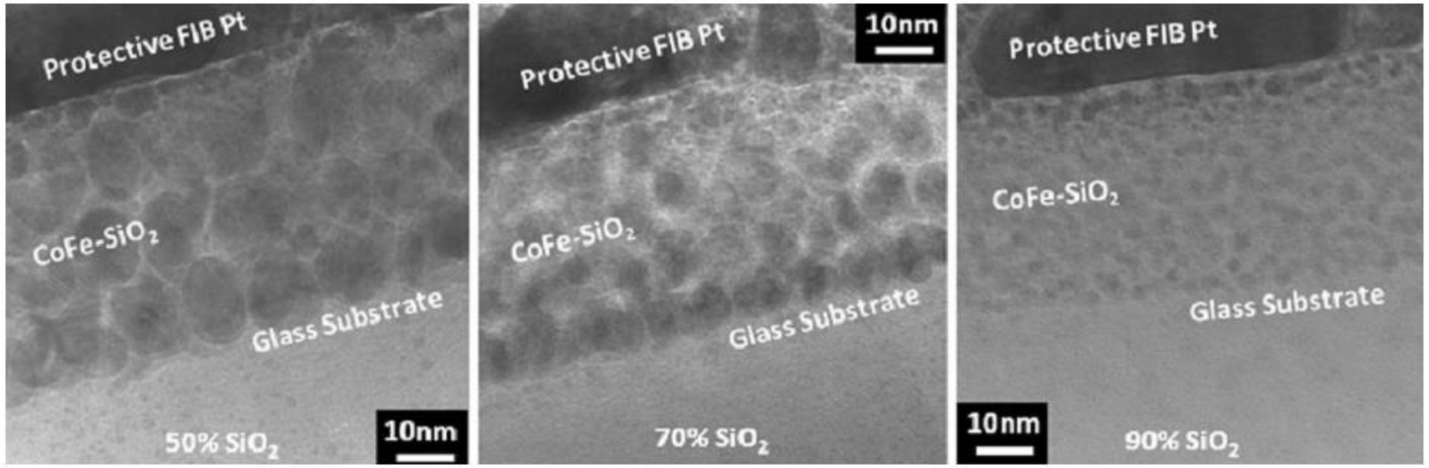
→ High Temperature Stable Microstructure

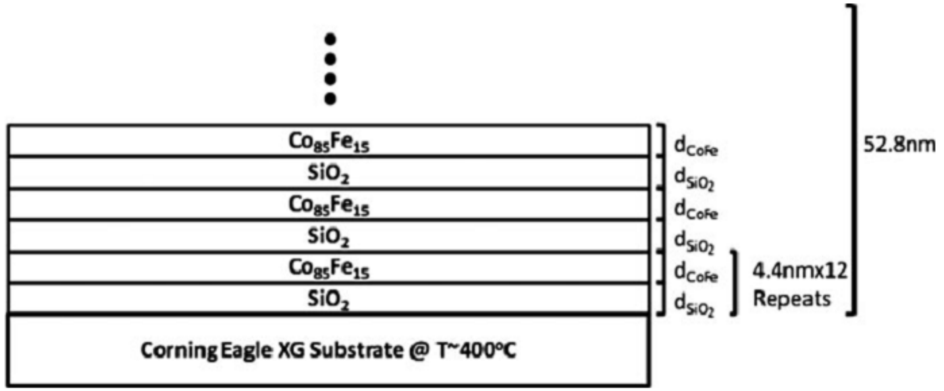
New Nanocomposite Materials Comprised of Metal and Oxide Nanocomposite Based Systems Will Be Pursued in Terms of Scalable Manufacturing for Emerging Applications

Uniqueness of Proposed Solution : Concept #2 Metal / Oxide Based

- **Examples of Processing Strategies:**
  1) Thin Film Deposition
  2) Thick Film Deposition
  3) Powder Based Processing





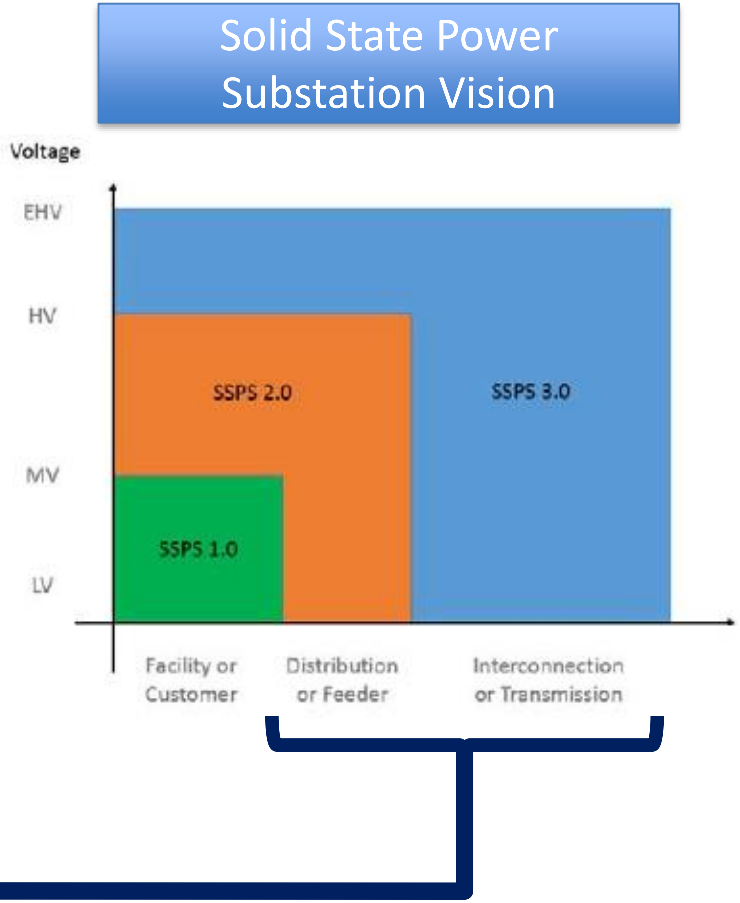


Careful Control of Microstructure in Such Systems Has Historically Involved Carefully Controlled Synthesis Procedures Such as Thin Film Deposition Techniques, Not Scalable for High Power

Significance of the Results : Concept #2 Metal / Oxide Systems

Material Classes	Saturation Magnetization (T)	Resistivity (μΩ-cm)	Upper Temp. Limit (C)	Upper Freq. Limit (Hz)	Mechanical Properties	Manufacturing Scalability
Ferrites (NiZn, MnZn)	0.2-0.4	$>10^3$	100-300	10^6-10^9	Brittle But Machinable	Limited (Powder Process)
Bulk Crystalline Alloys	1-2.5	~10	400-1000	10^2	Excellent	Excellent
Amorphous Alloys	1-1.6	~100	150	10^5	Good	Good
Commercial Metal / Amorphous Nanocomposites (MANCs)	1.3	~100	150	10^5	Brittle	Limited (Brittle Properties)
Emerging MANCs for WBG	1-1.9	~150	150-500	10^5	Good	Good
Ideal for UWBG	1-2	$>10^3$	300-500	10^6-10^7	Excellent	Excellent

Completely New Materials Systems (Concept #2)

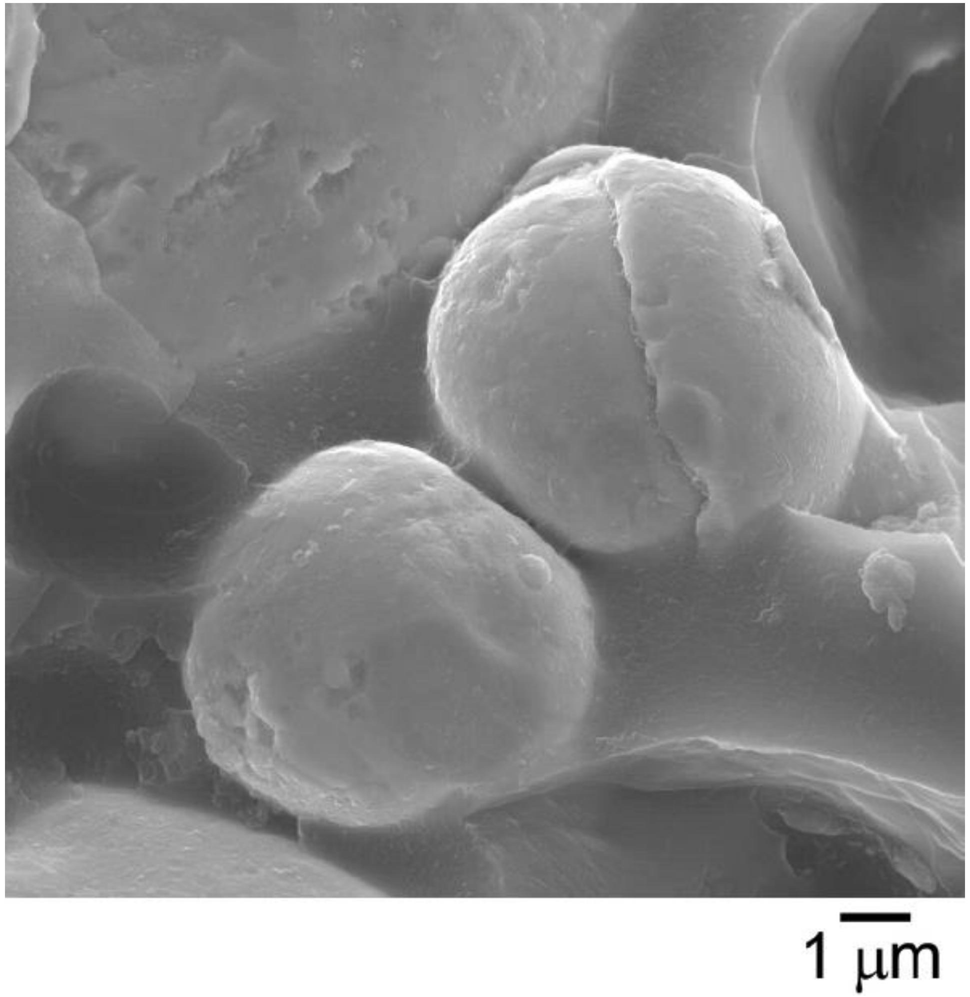


- **New Core Materials Would Be Relevant for Emerging Ultra-Wide Bandgap Semiconductors and Applications**
- **New Switches and Enabling Magnetics Will Be Critical for Realizing the Vision of MV-HV+ Power Electronics of SSPSs**

Specific Research Questions Being Addressed : Concept #2

- Thermodynamic and Kinetic Factors Dictating Microstructure Evolution
- Inter-Relationships Between Magnetic Properties and Microstructure in Metal and Oxide Nanocomposites
- Phase Transformations and Microstructural Evolution for Various Compositions and Processing Conditions
- Underlying Physics of Intergranular Magnetic Coupling and Impacts on Core Material Performance

Example: Iron powder with resin coating layer



Advanced Grid Research
OFFICE OF ELECTRICITY
US DEPARTMENT OF ENERGY

Project Schedule, Deliverables, and Current Status : Concept #2

Milestones:

- Perform literature review of existing oxide-based nanocomposite research (6/30/2020)
- Establish laboratory facilities for synthesizing candidate materials (9/30/2019)
- Synthesize new materials and perform structural / magnetic characterization (12/31/2020)
- Fabricate / characterize at least one toroidal core based on the new material (3/31/2021)

Deliverables:

- Technical report outlining results of literature review (6/30/2020)

Total Budget = $500k
Funding Received = $250k
Project to Initiate 10/1/2019

Anticipated Challenges and Risk Mitigation Strategies : Concept #1

Challenges/Risks	Severity	Probability	Mitigation Strategy
Advanced Annealing Techniques Cannot Be Controlled Accurately	High	Medium	Optical thermometry can be used to monitor temperature in real-time. Initial studies will also be pursued on well-known commercial alloys to understand impacts of advanced annealing methods.
Difficulty Controlling Microstructure with Powder Based Processing Techniques	Medium	High	Literature reviews will be pursued to explore a number of parallel potential processing strategies to be pursued. Known processing methods for ferrites and powders will be leveraged where possible with minimal modifications.
Limited Scalability of Manufacturing Techniques Selected	High	Low	Scalability will be a key factor during early screening of synthesis techniques selected for further investigation.
Magnetic Properties of New Materials Can Be Difficult to Benchmark with Existing Materials	Medium	Low	Well established capabilities in magnetic property measurements will be leveraged to compare and benchmark performance of new materials.

Broader Impact

Patents

- "Advanced Annealing Techniques for Amorphous Metal Ribbons" (Converted to US Non-Provisional Patent Application, Filed by Carnegie Mellon University)
- "In-Line Annealing of Amorphous and Nanocomposite Alloys for Inductive Applications" (Converted to US Non-Provisional Patent Application, Filed by Penn State University)

Presentations

- MS&T 2019 Technical Meeting and Exhibition, Sept. 29 – Oct. 3, 2019, Portland OR, "Advanced In-Line Nanocrystallization of Amorphous Metal Ribbon Through Mechanical and Electromagnetic Fields"
- TMS Annual Meeting and Exhibition, Feb. 23 – 27, 2020, San Diego, CA, "Continuous Strain Anneal Processing of Amorphous Metal Ribbons for Inductor Applications"

Carnegie Mellon University

PennState

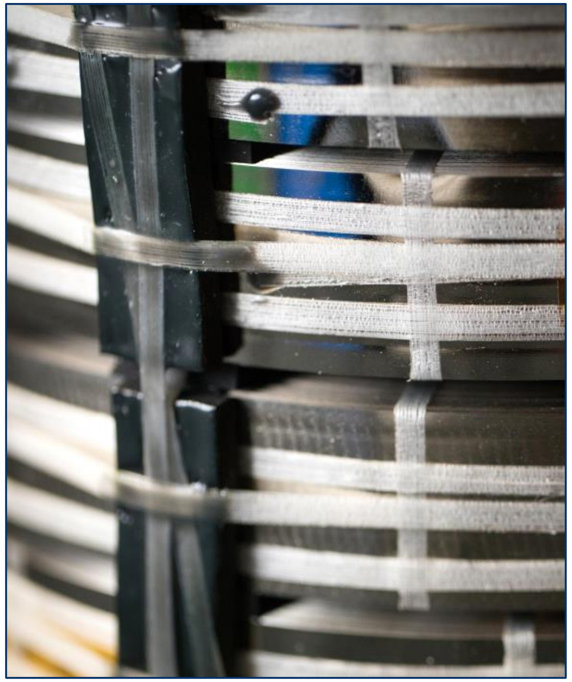
MS&T
MATERIALS SCIENCE & TECHNOLOGY

TMS

A Suite of Intellectual Property was Developed Around the Thermal Annealing Stage to be Leveraged in Upcoming Research Efforts Proposed Under The Project

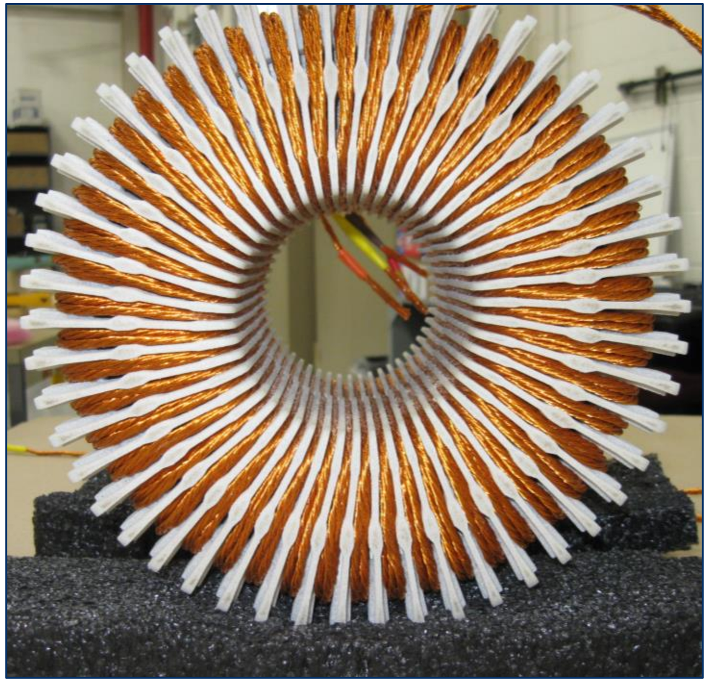
Broader Impact

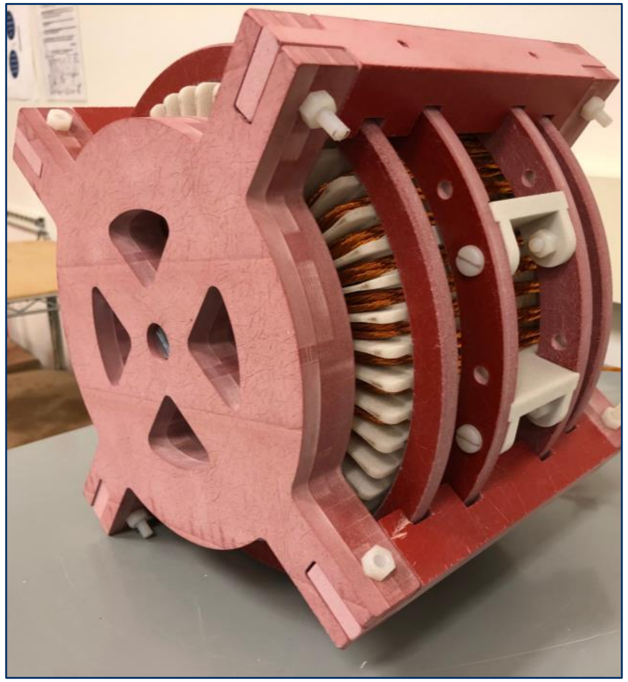
- 3-Phase, 440µH Filter Inductor Fabricated with Strain Annealed Cobalt-Based Nanocrystalline Ribbon



12kg Metal Mass

Multi-Strand Wire





20kg Total Mass

Power Inductors for 1 MW-Scale Next Generation Electrical Machinery (NGEM)

Broader Impact

- Strain Annealed Core Technology VS. State of the Art:

Strain Annealed

- Gapless Design
- Oil Immersion
- **12 kg** Metal Mass
- **20 kg** Total Mass
- **2 – 2.5X** Smaller Volume

Kool Mμ powder

- Distributed Gap
- Glued Arc/Bar Segments
- Edge-Wound Coil
- Liquid Cooling with Pump
- **60 kg** Total Mass

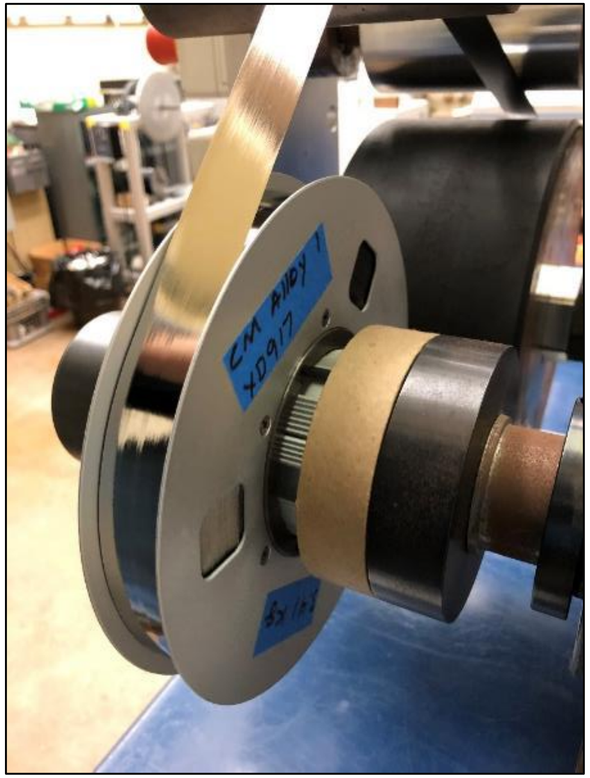
Iron-alloy powder

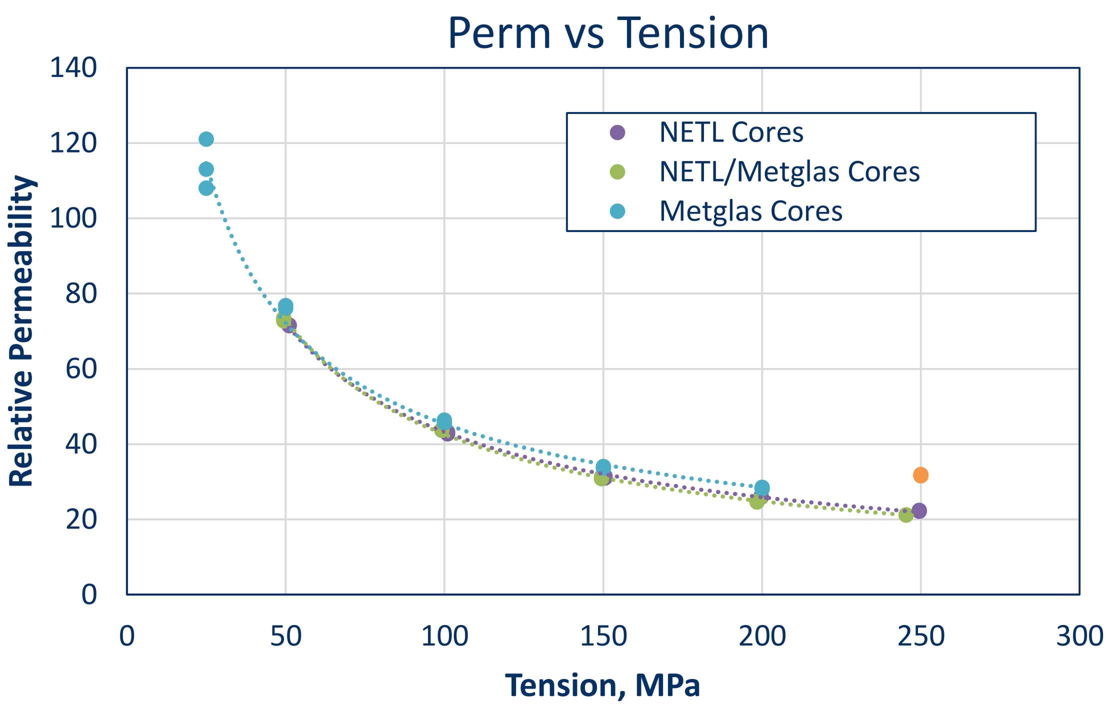
- Distributed Gap
- Potted Assembly
- Liquid Cooling with Pump
- **100 kg** Total mass

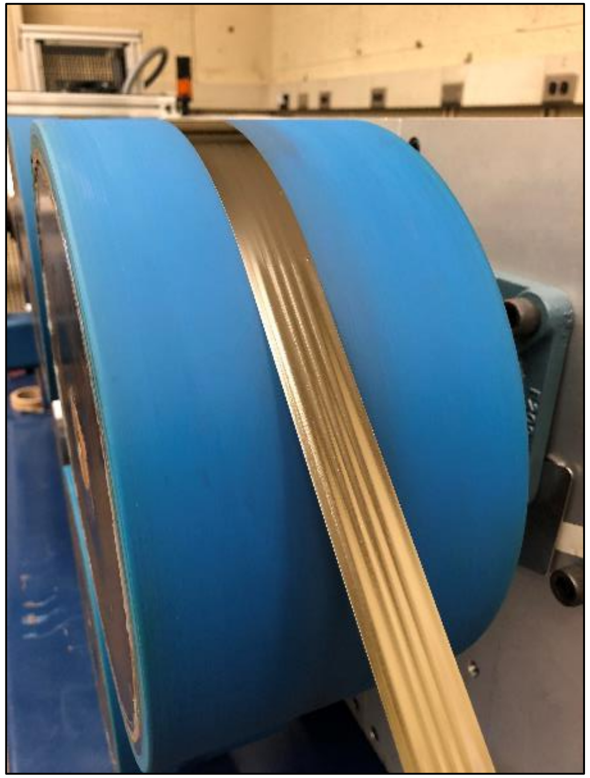
Broader Impact

Metglas®, Inc. Carnegie Mellon University

❑ Metglas, Inc. / NETL / CMU Research License Agreement







Successful Cast of Cobalt-Based Alloy and Reproduction of Strain Annealing Results

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