Strain Annealed Metal Amorphous Nanocomposite Soft Magnetic Materials: Manufacturing, applications, optimization, and data sheets

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March 19, 2019

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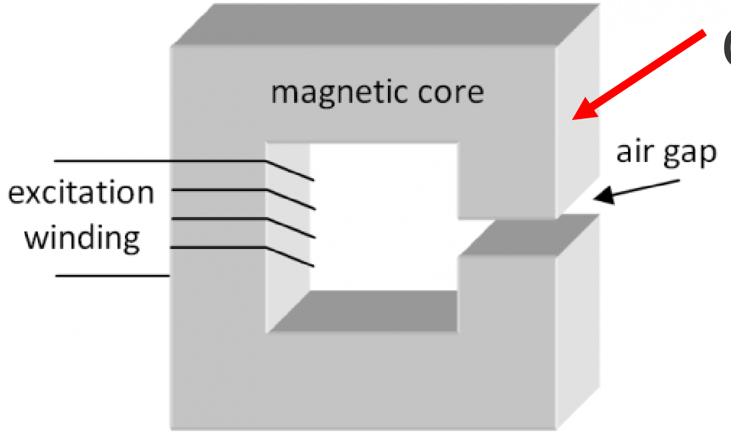
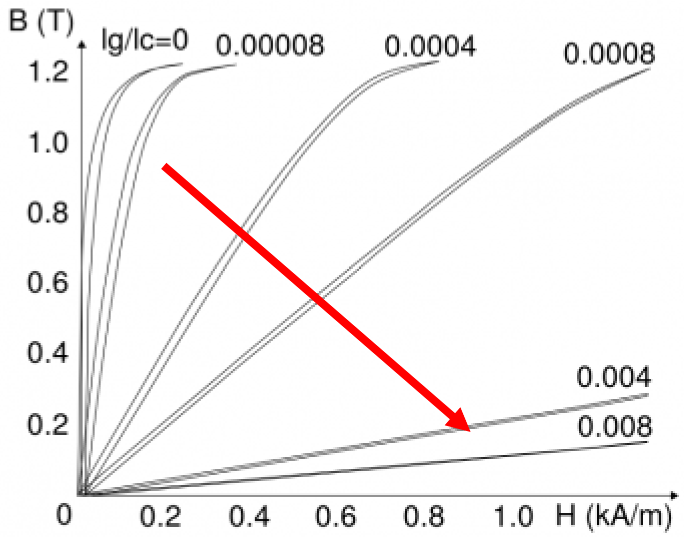
Solutions for Today | Options for Tomorrow

Presentation Overview

- **Conventional Core Design Review**
- **What is Strain-Annealing? & Why use Strain-Annealed cores?**
- **A quick review of Strain-Annealing manufacturing process**
- **Design and Prototyping Activities**
- **DOE’s the Office of Electricity's (OE) Transformer Resilience and Advanced Components (TRAC) program**
  - Advanced Data Sheet for soft magnetics materials and
  - Multi-objective genetic algorithm design optimization
- **Key Take-Away Messages**

Gapped cores: Ferrite and metal ribbon cores





Core has a fixed and high permeability value

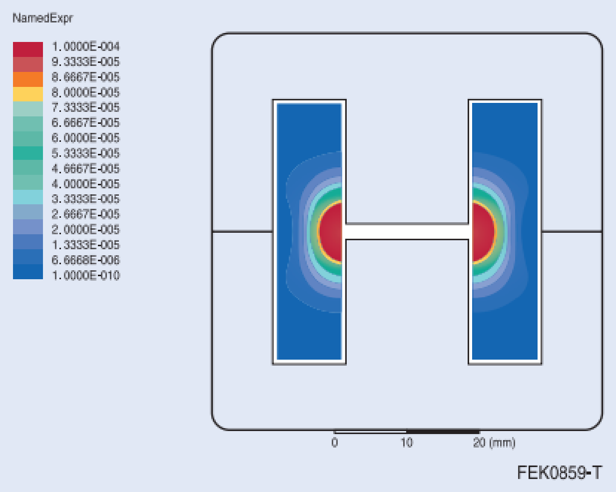
As gap size increases, effective permeability reduces

- **Need to precisely control the gap length, and it can be difficult**
- **Extra losses due to gaps**
  - Fringing flux and winding losses
  - Proximity losses
  - Eddy current losses due to shorted cut surface

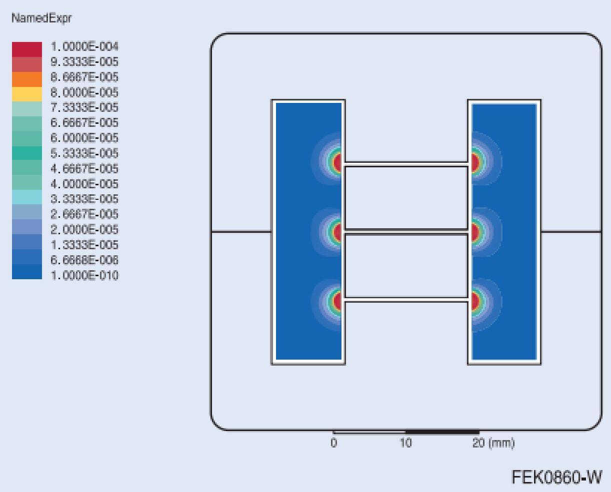
Changes of effective permeability and linearization of the B-H loops caused by increasing air gap. Zurek, Encyclopedia Magnetica, CC-BY-3.0.

Distributed discrete gaps with ferrites

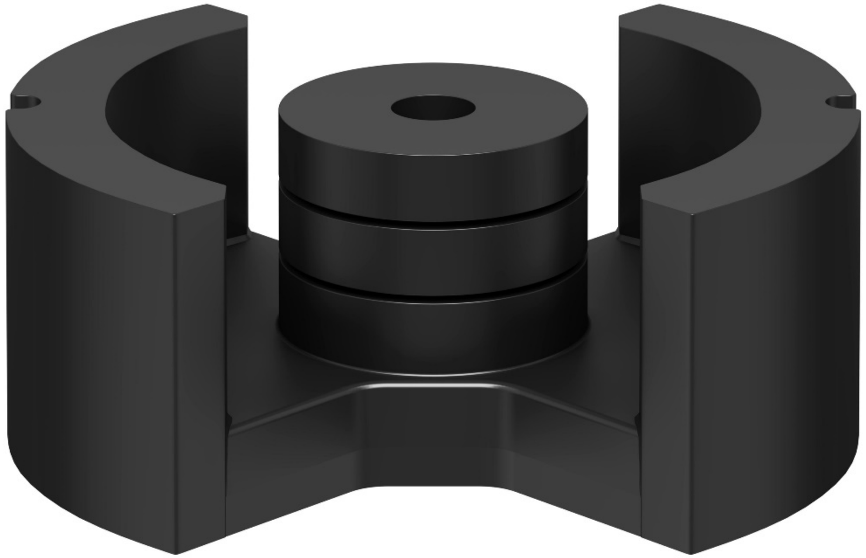
- Increased power density
- Reduce proximity losses
- Enable use of a larger winding area by reducing fringing flux
- Lower winding losses compared to a single large air gap
- Reduction of core size



High fringing flux spreads around a single large air gap.



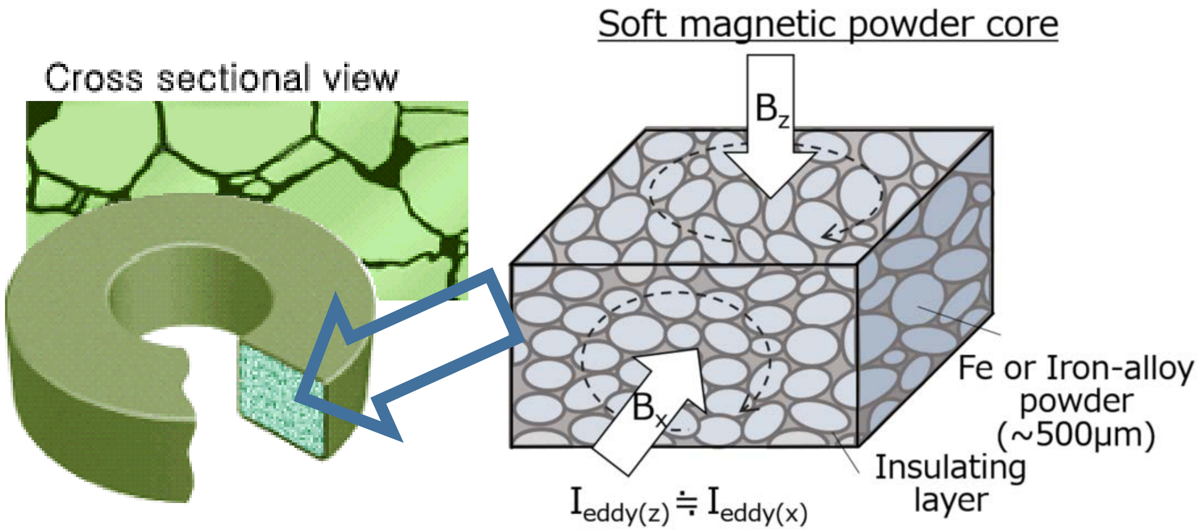
Creating several smaller air gaps improves the situation compared to a single large air gap.

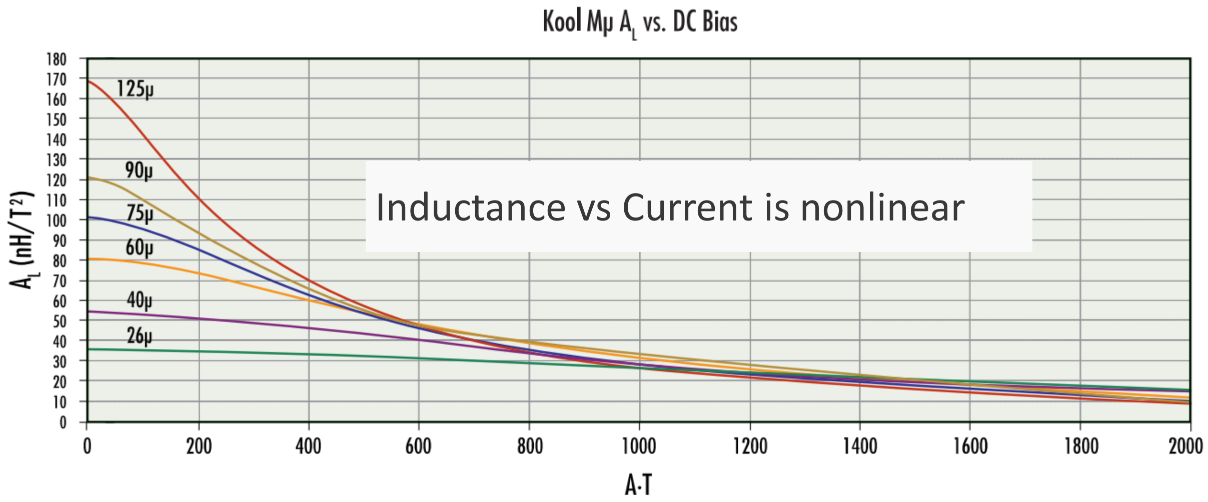


Conventional core design

Distributed gap cores: Powder cores

- Fixed permeability
- Limited size
- Nonlinear saturation characteristic (varying inductance)





1. "Pure-iron/iron-based-alloy hybrid soft magnetic powder cores compacted at ultrahigh pressure" Tatsuya Saito, et al. AIP Advances
2. Kool Mu Core Data "39.9mm OD" www.mag-inc.com

Is there a core that has

- No gaps,
- Linear BH characteristic,
- High saturation,
- No size limitation, and
- **Custom tuned permeability?**

Path Towards New Technologies

NATIONAL ENERGY TECHNOLOGY LABORATORY

What is Strain-Annealing?

- Strain-Annealing is an advanced annealing treatment process used on amorphous metal ribbons (AMRs) to promote nano-crystallization.
- Revolutionary process due to its ability to allow for in-line processing of AMRs prior to final winding.

Why use Strain-Annealed Cores?

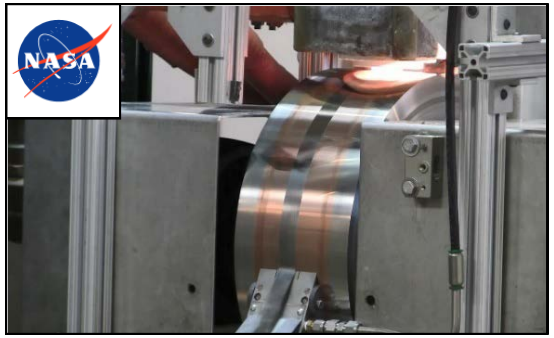
- Allows for customizable magnetic and thermal properties
- Reduces the number of process steps
- There is a need for new core technology!

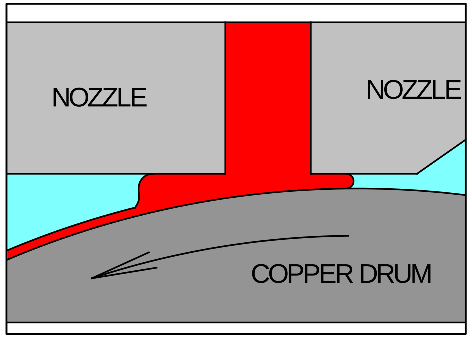
As-Cast Amorphous Metal Ribbon

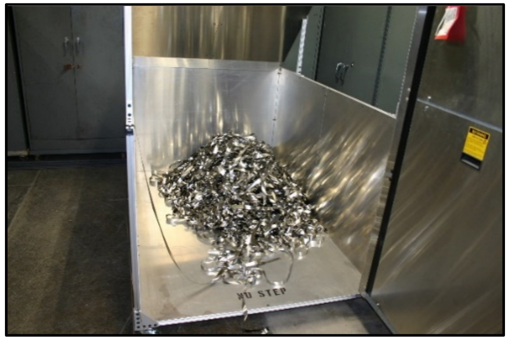
Manufacturing Steps: Metal Ribbon Fabrication

Raw Materials → Planar Flow Casting (PFC) → Spooling → Strain-Annealing & Later Processes

- Amorphous metal alloy ribbons can be casted up to 2" (50.8mm) wide at ~15-25 μm thickness.
- Each planar flow cast makes a spool of ~2000 feet (~600 meters); however, the length can be unlimited.



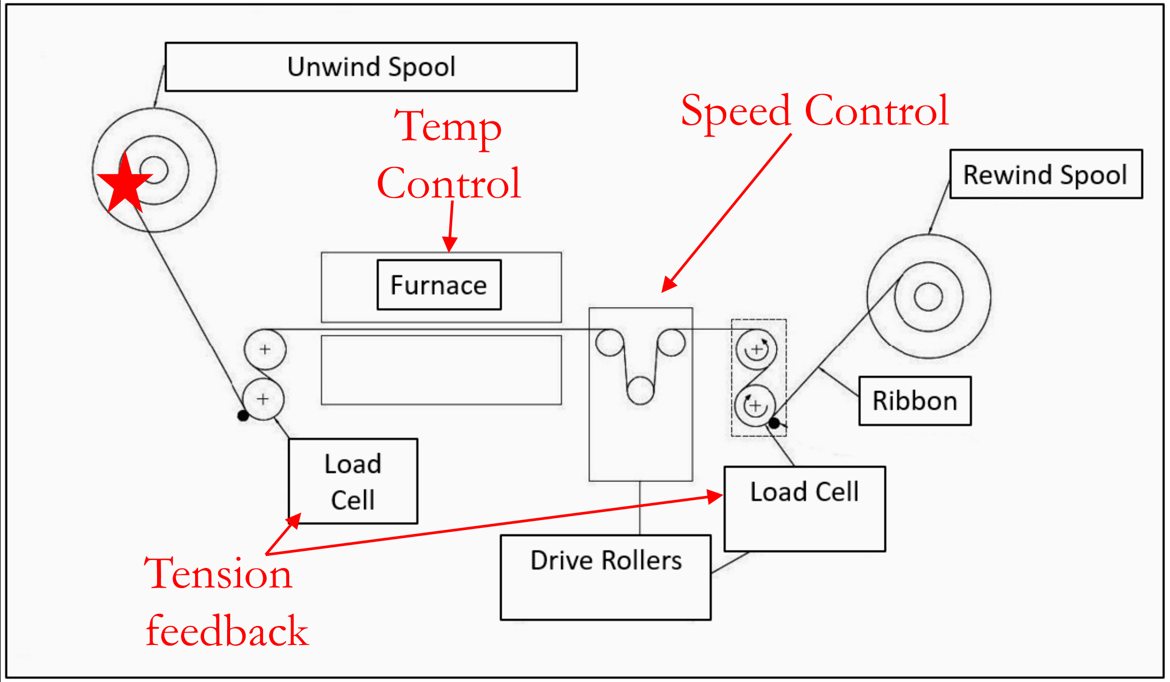




Planar Flow Casting (PFC), 0.25"-2" widths

Video of Strain-Annealing Process

- Strain-Annealing is a key processing technique being leveraged in advanced alloy and core design and optimization.



Strain-Annealing with Cobalt-based Alloys

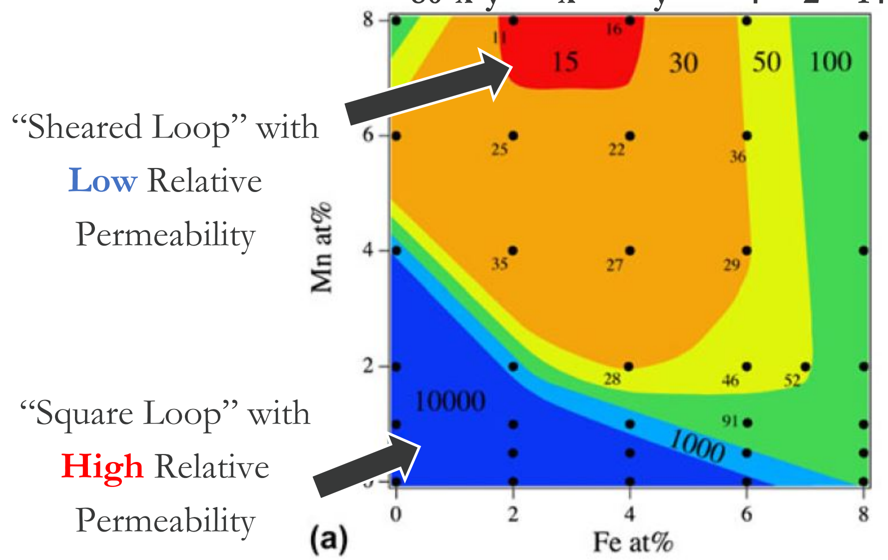
Characteristics:

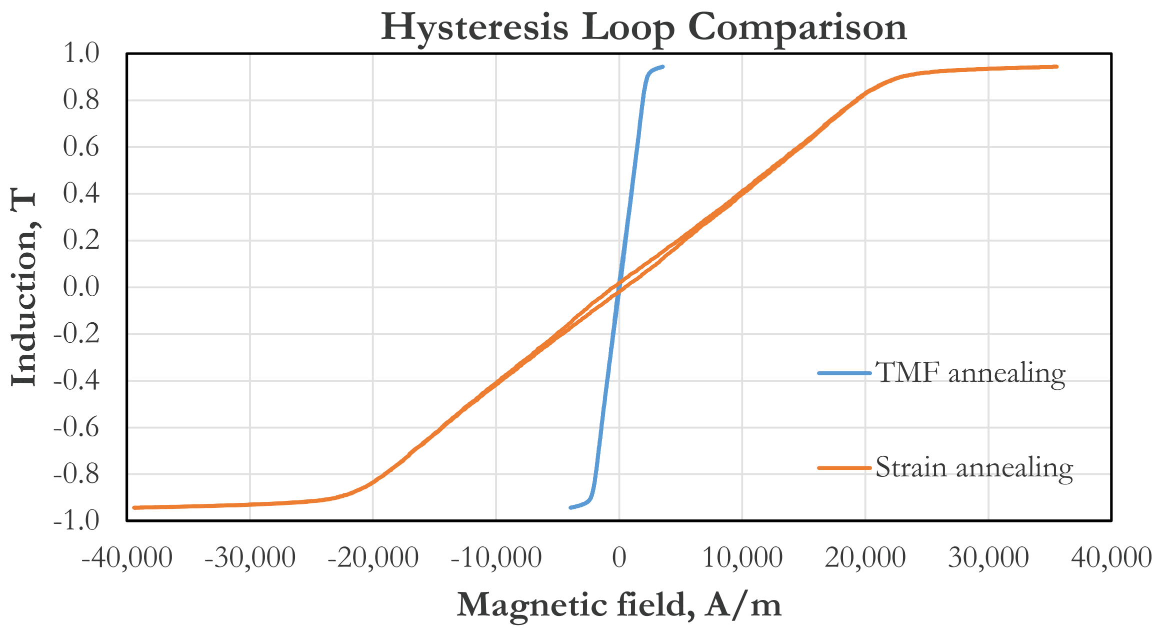
- Improved mechanical properties
- Higher induced anisotropy
- Temperature stable anisotropy
- 'Tunable' permeability (see below)

Control Factors:

- Alloy Chemistry
- Applied Tension
- Anneal Temp/Time

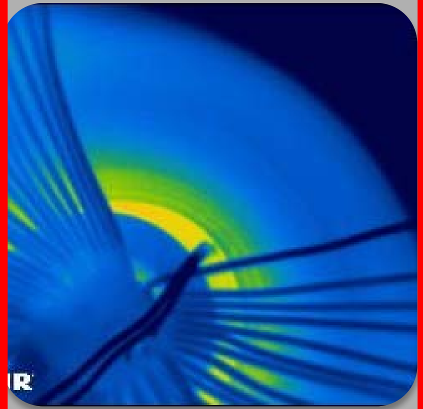
$Co_{80-x-y}Fe_xMn_yNb_4Si_2B_{14}$

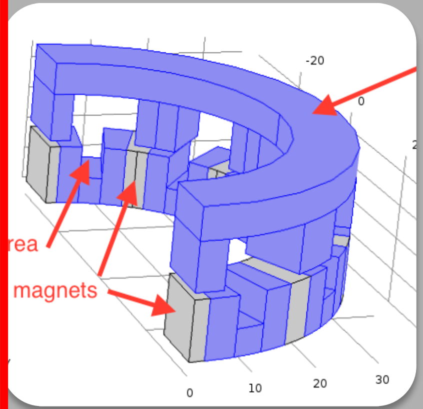




Design and Prototyping Activities:

Partner with





Power Inductors For 1 MW-Scale Next Generation Electrical Machinery

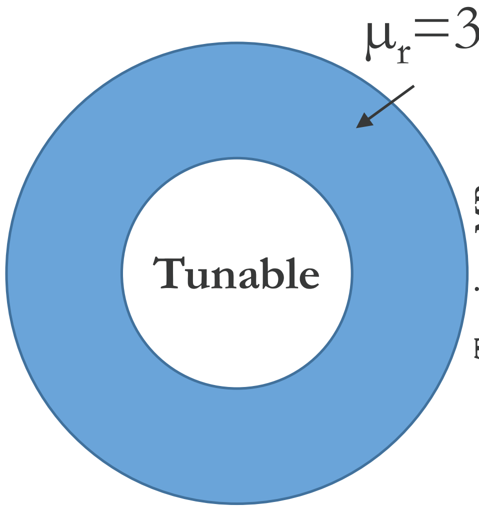
Three-Port High Frequency Transformers For SuNLaMP Program

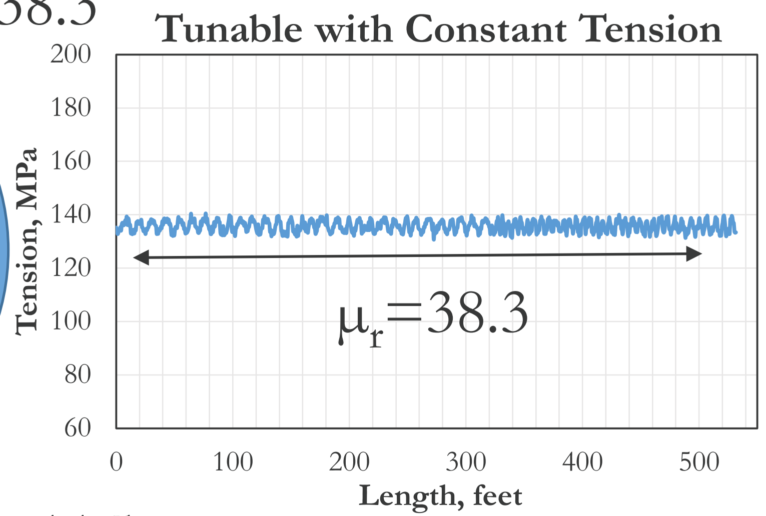
Engineered Permeability Cores Through Advanced Magnetics Manufacturing

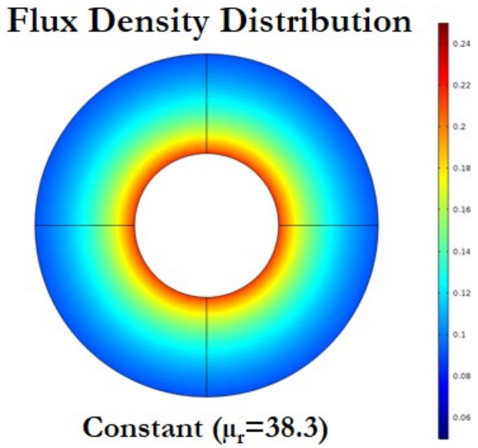
High Speed, High Efficient Motor Project Using High Frequency Design

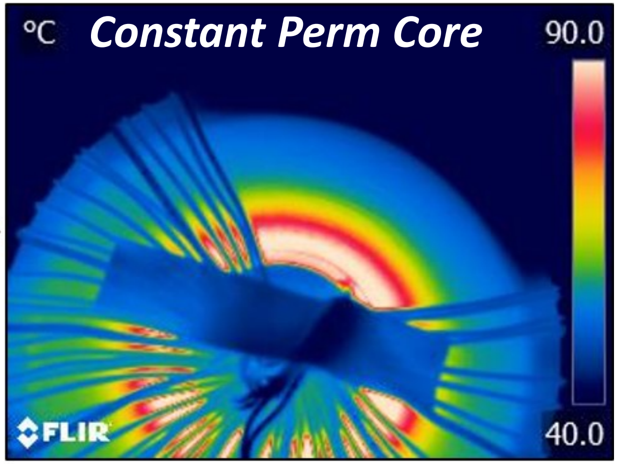
Permeability Engineering: Application Example

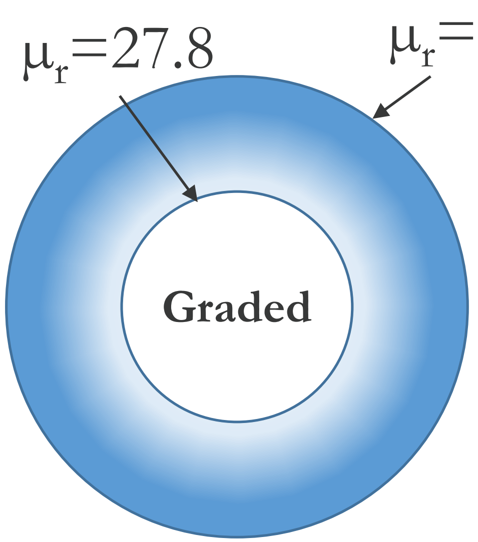
"flux-smoothing" → a more uniform flux distribution → better temperature distribution

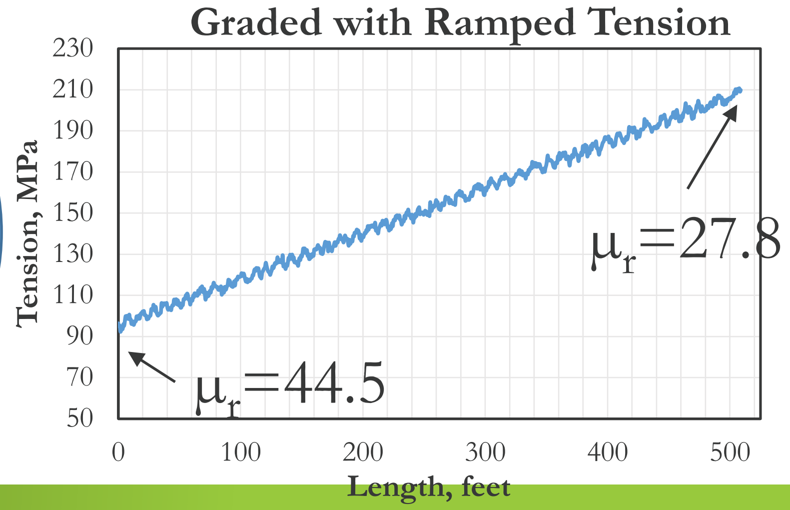


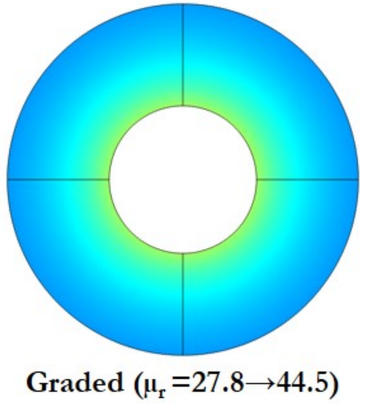


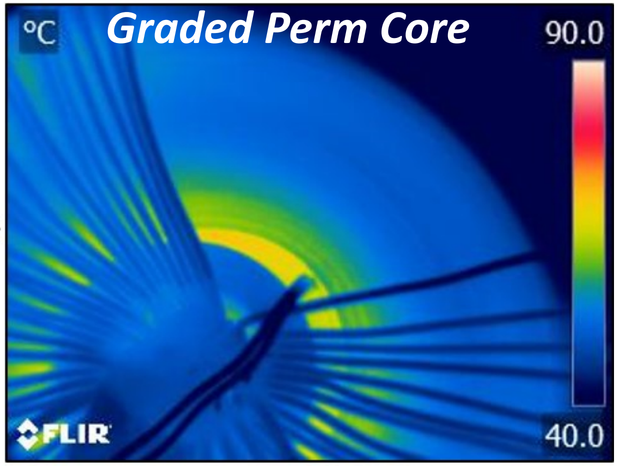








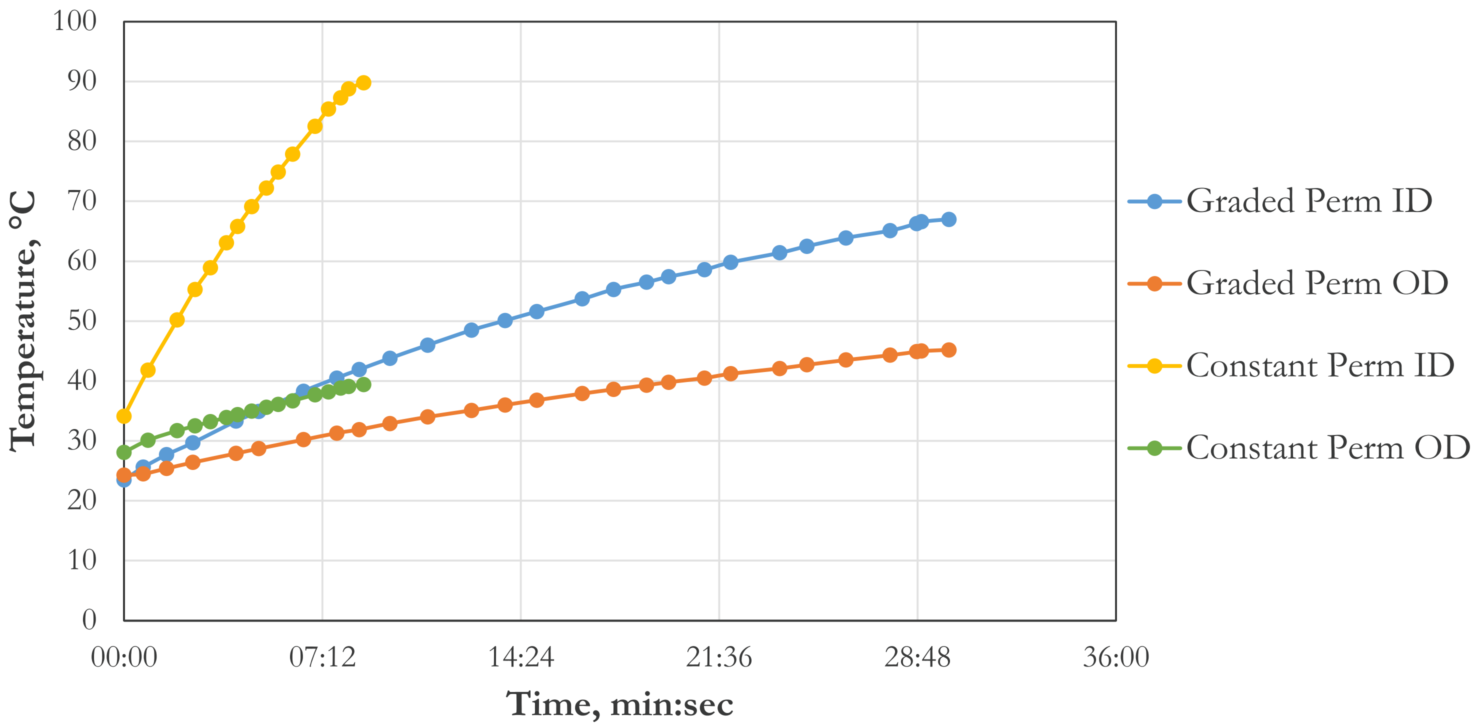


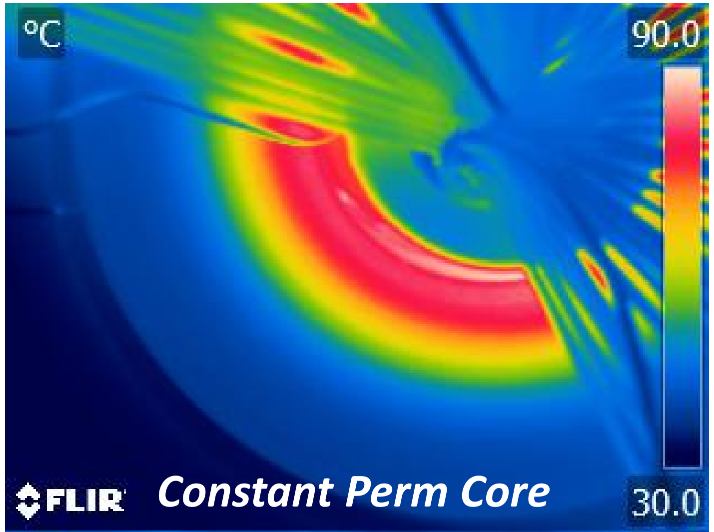


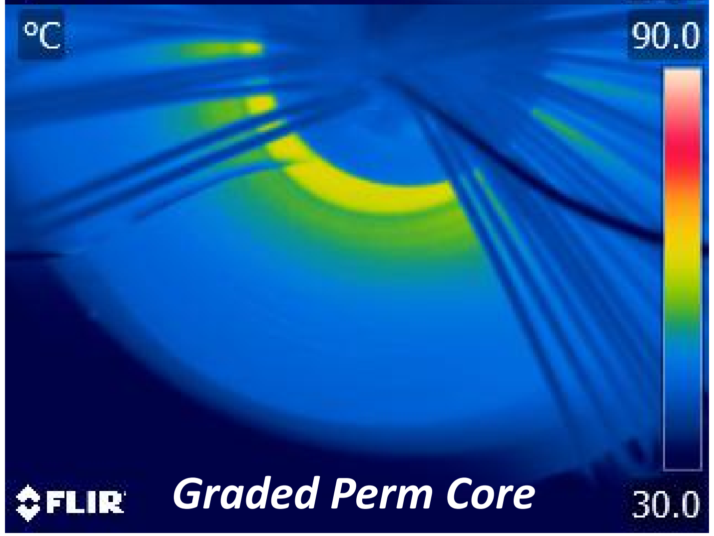
Permeability Engineering: *Application Example*

Constant Permeability vs. Graded Permeability Cores

- 20 kHz square-wave excitation
- Input voltage = 250Vdc
- 50 turns primary, 10 turns secondary
- 30 minute continuous test (B_{peak} = 0.15T)



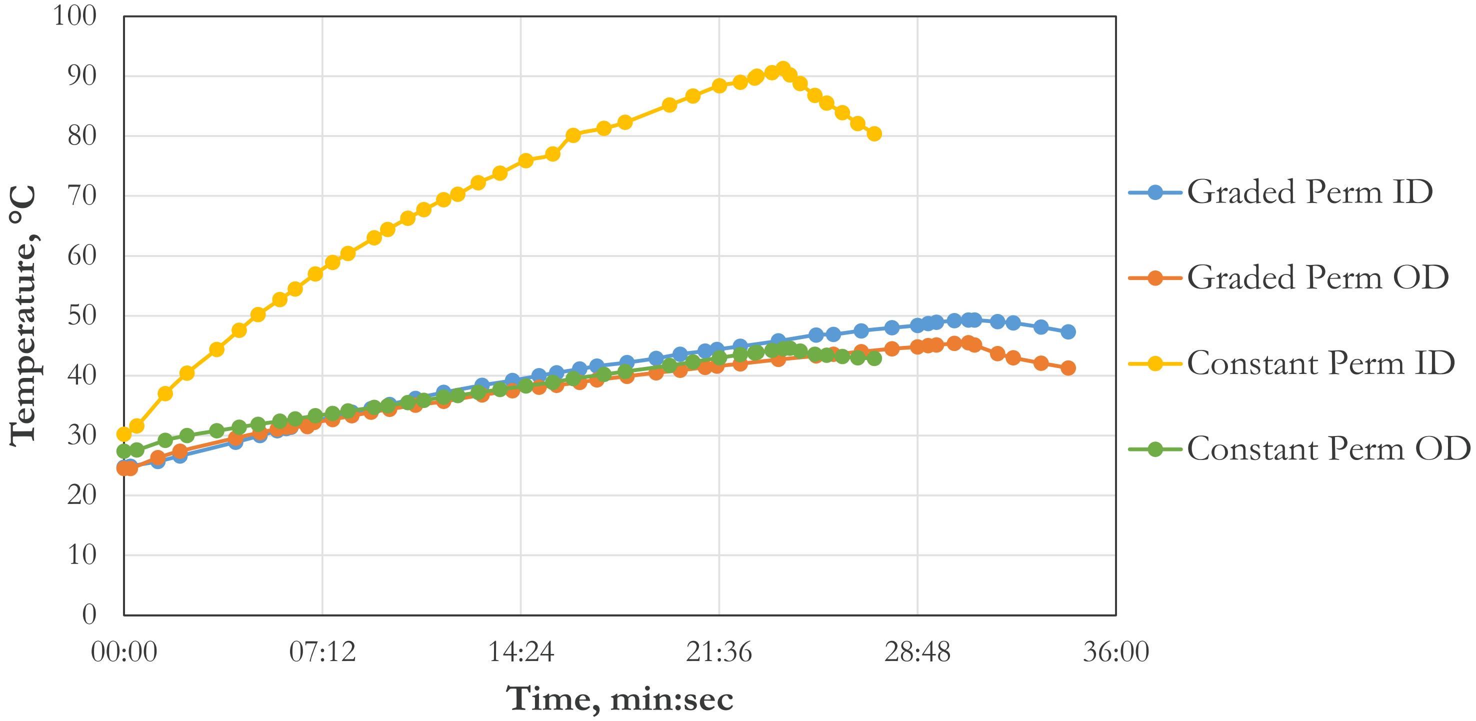


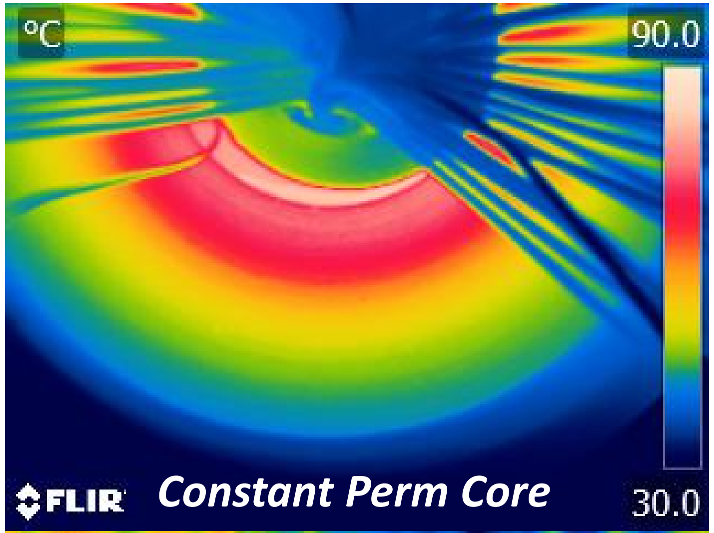


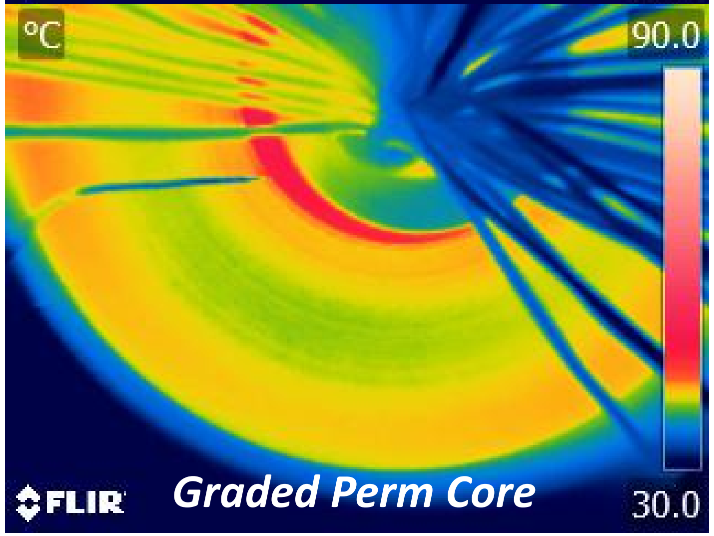
Permeability Engineering: *Application Example*

Constant Permeability vs. Graded Permeability Cores

- 20 kHz <u>square-wave</u> excitation
- Input voltage = 220Vdc
- 50 turns primary, 10 turns secondary
- 30 minute continuous test (B_{peak} = 0.13T)

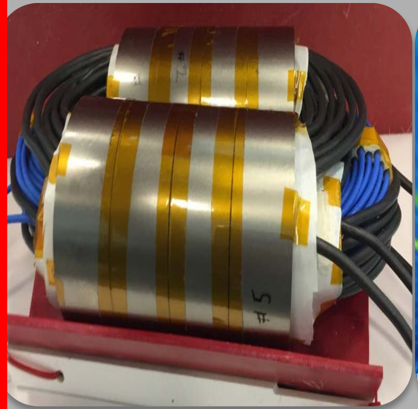


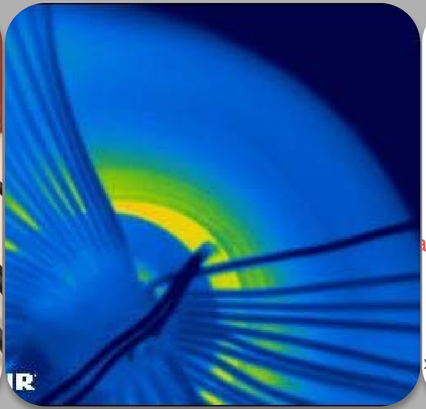


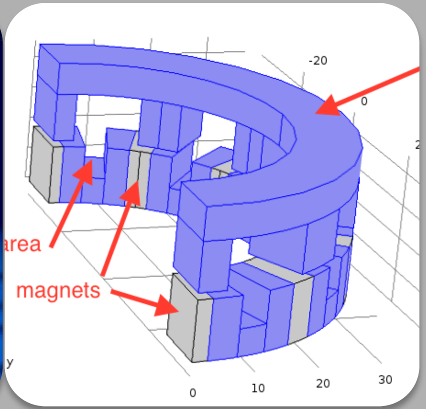


Design and Prototyping Activities:

Partner with NC STATE UNIVERSITY, EATON Powering Business Worldwide, NASA, Carnegie Mellon University







Power Inductors For 1 MW-Scale Next Generation Electrical Machinery

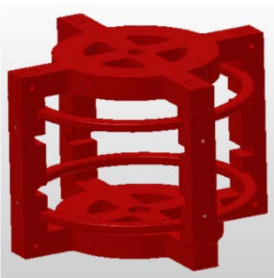
Three-Port High Frequency Transformers For SuNLaMP Program

Engineered Permeability Cores Through Advanced Magnetics Manufacturing

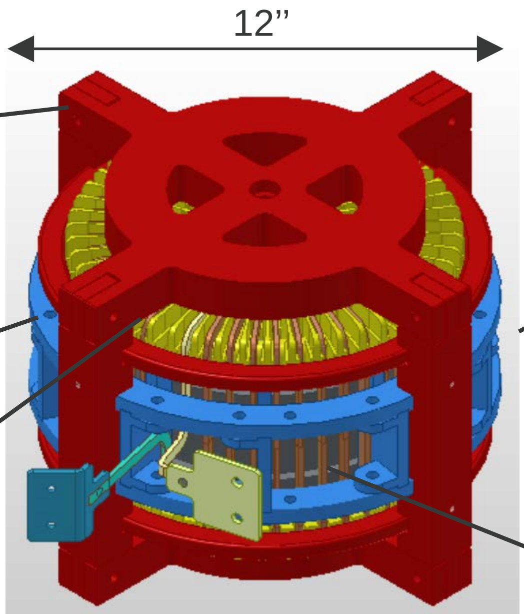
High Speed, High Efficient Motor Project Using High Frequency Design

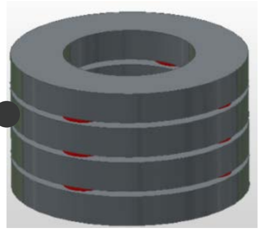
Permeability Engineering: *NGEM Inductor*

Power Inductors for 1 MW-scale Next-Generation Electrical Machinery

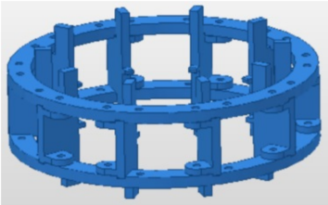


Strong non-conductive fixture

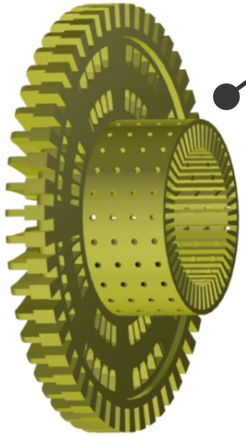




Gapless low loss <u>nanocrystalline</u> strain-annealed core



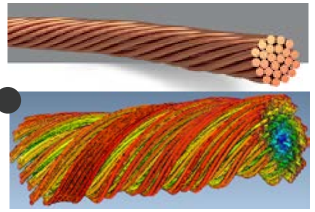
3D printed core holder with rubber interface



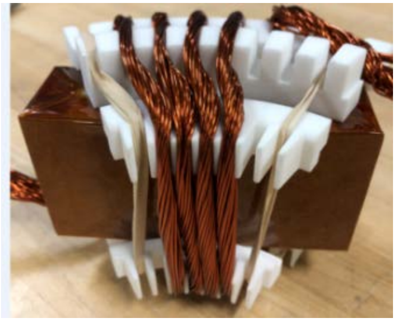
3D printed <u>ceramic</u> bobbin with oil flow passage

Liquid immersion cooling of a MW power, 4160V, high frequency inductor for medium voltage drive:

- Medium voltage isolation
- Low loss fragile core
- Super high power density
- Low loss low capacitance winding



Multi-strand wire to reduce loss and enhance heat transfer



Lab prototype

Permeability Engineering: *NGEM Inductor*

Power Inductors for 1 MW-scale Next-Generation Electrical Machinery

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- **Three types of materials compared for 440 µH filter inductor application**
  - Kool Mu powder core
  - Iron-alloy powder core
  - Strain-annealed MANC core
- **Constraints/Considerations**
  - Size/mass, permeability and inductance stability, power density, and cooling feasibility

Kool Mu powder
- Distributed gap
- Glued arc/bar segments
- Edge-wound coil
- Liquid cooling with pump
- **60 kg** total mass

EATON

Iron-alloy powder
- Distributed gap
- Potted assembly
- Liquid cooling with pump
- **100 kg** total mass

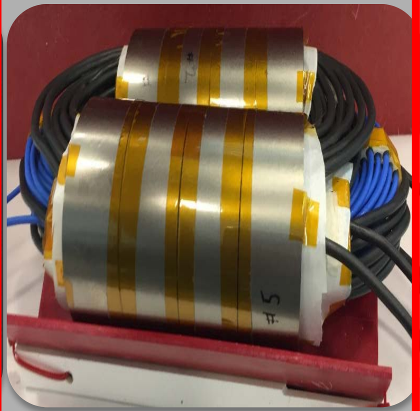
Strain-annealed
- Gapless design
- Custom bobbin and multi-strand wire
- Oil immersion
- **12 kg** metal mass
- **20 kg** total mass
- **2-2.5X** smaller

Design and Prototyping Activities:

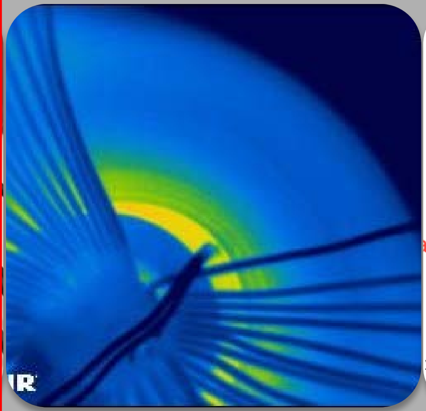
NATIONAL ENERGY TECHNOLOGY LABORATORY

Partner with NC STATE UNIVERSITY, EATON Powering Business Worldwide, NASA, Carnegie Mellon University

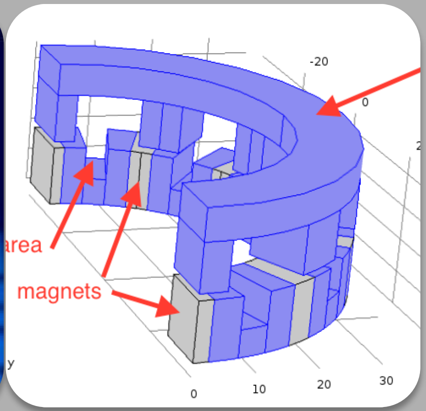
Power Inductors For 1 MW-Scale Next Generation Electrical Machinery



Three-Port High Frequency Transformers For SuNLaMP Program



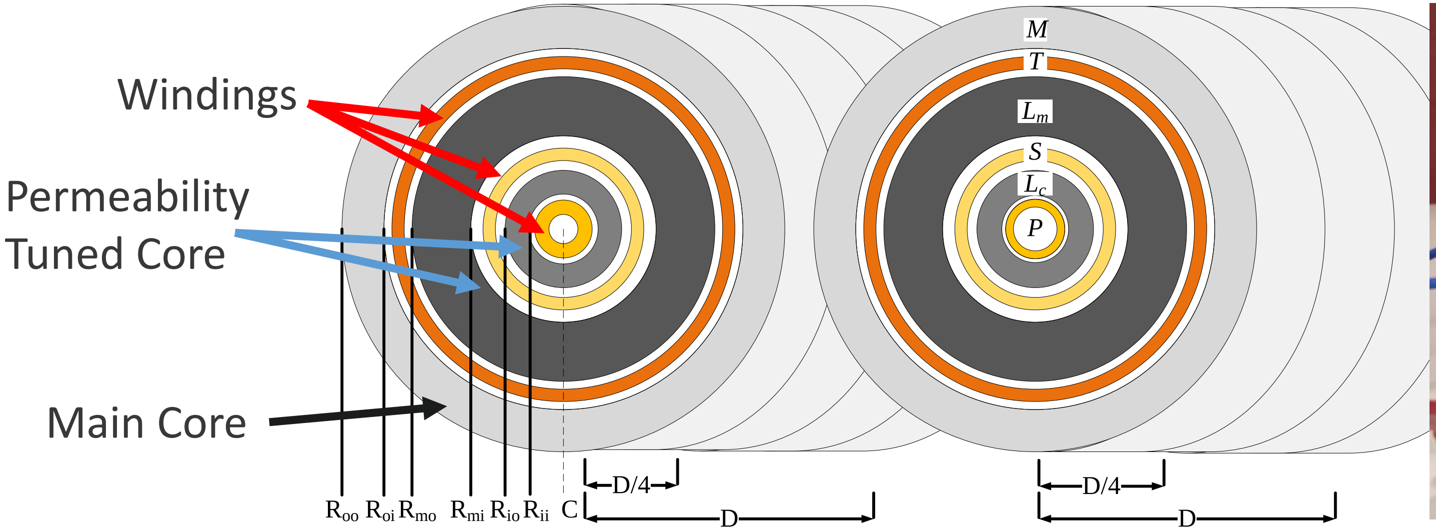
Engineered Permeability Cores Through Advanced Magnetics Manufacturing

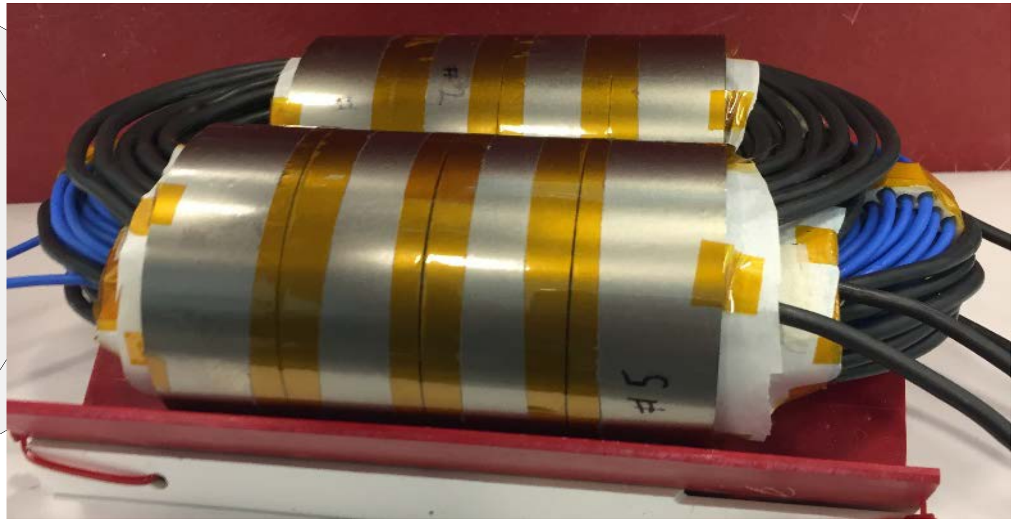


High Speed, High Efficient Motor Project Using High Frequency Design

Tri-Axial Winding Transformers

- **Permeability tuned cores are**
  - placed between primary, secondary, and tertiary windings.
  - utilized to control the leakage inductances.
  - utilized to reduce inter-winding and self capacitances.
  - utilized to minimize the losses due to normal fluxes.





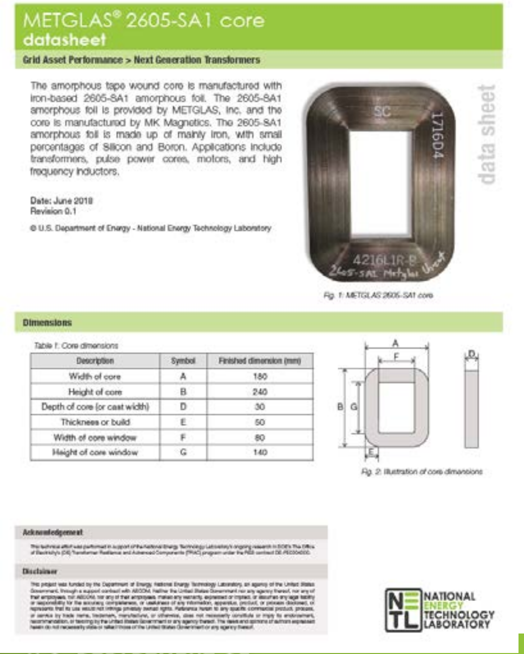
Permeability engineering with strain-anneal manufacturing process

- **Permeability is DIRECTLY engineered and customized**
- **Strain-annealing is an advanced manufacturing process with advantages in**
  - Eliminates the gaps
  - Better core utilization via Flux-smoothing and/or core temperature-smoothing
  - Manufacturability of Large Components
  - Core size reduction (High power density)
  - Efficiency increase (Low losses)
  - Very linear BH characteristic

Pilot-scale Strain Annealing Machine

DOE OE TRAC Program

- DOE’s the Office of Electricity's (OE) Transformer Resilience and Advanced Components (TRAC) program is sponsoring
  - Advanced Data Sheet for soft magnetics materials and
  - Multi-objective genetic algorithm design optimization



METGLAS® 2605-SA1 core datasheet

Grid Asset Performance > Next Generation Transformers

The amorphous tape wound core is manufactured with iron-based 2605-SA1 amorphous foil. The 2605-SA1 amorphous foil is provided by METGLAS, Inc. and the core is manufactured by MK Magnetics. The 2605-SA1 amorphous foil is made up of mainly iron, with small percentages of Silicon and Boron. Applications include transformers, pulse power cores, motors, and high frequency inductors.

Date: June 2018
Revision 0.1

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data sheet

Fig. 1: METGLAS 2605-SA1 core

Dimensions

Table 1: Core dimensions

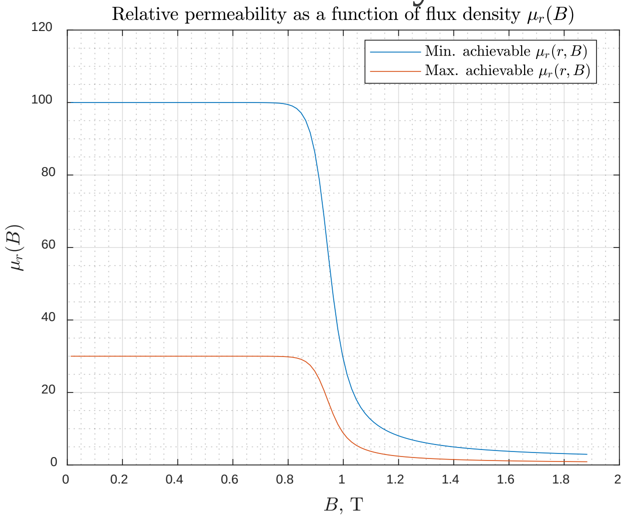
Description	Symbol	Finished dimension (mm)
Width of core	A	180
Height of core	B	240
Depth of core (or cast width)	D	30
Thickness or build	E	50
Width of core window	F	80
Height of core window	G	140

Fig. 2: Illustration of core dimensions

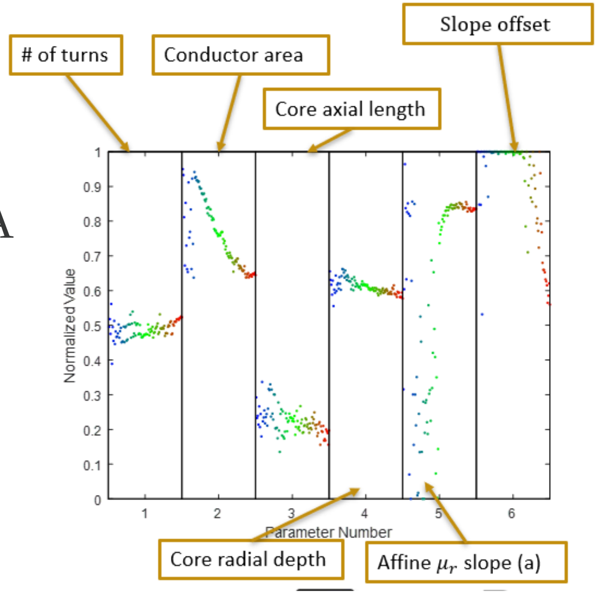
Acknowledgement

Disclaimer

Permeability data



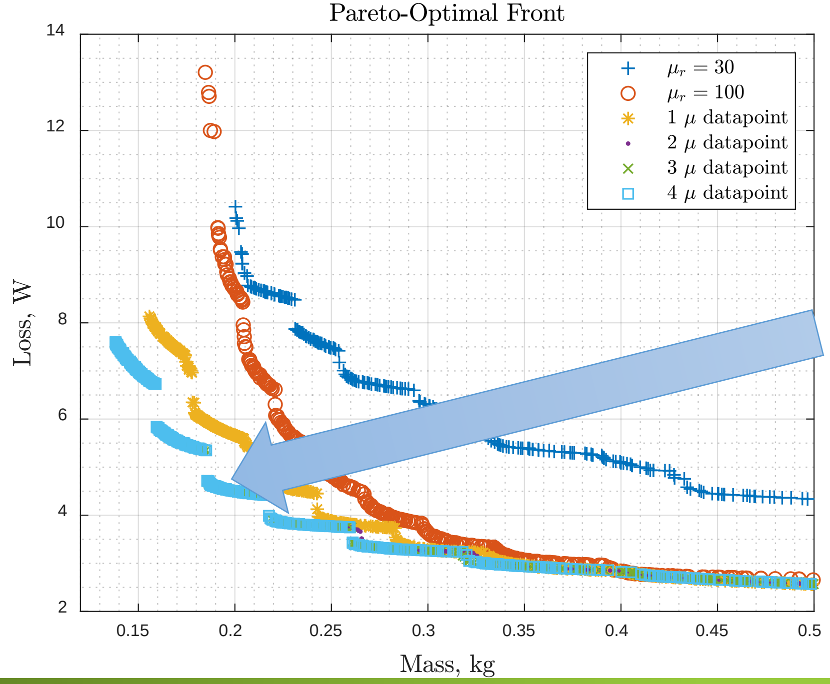
Input to GA



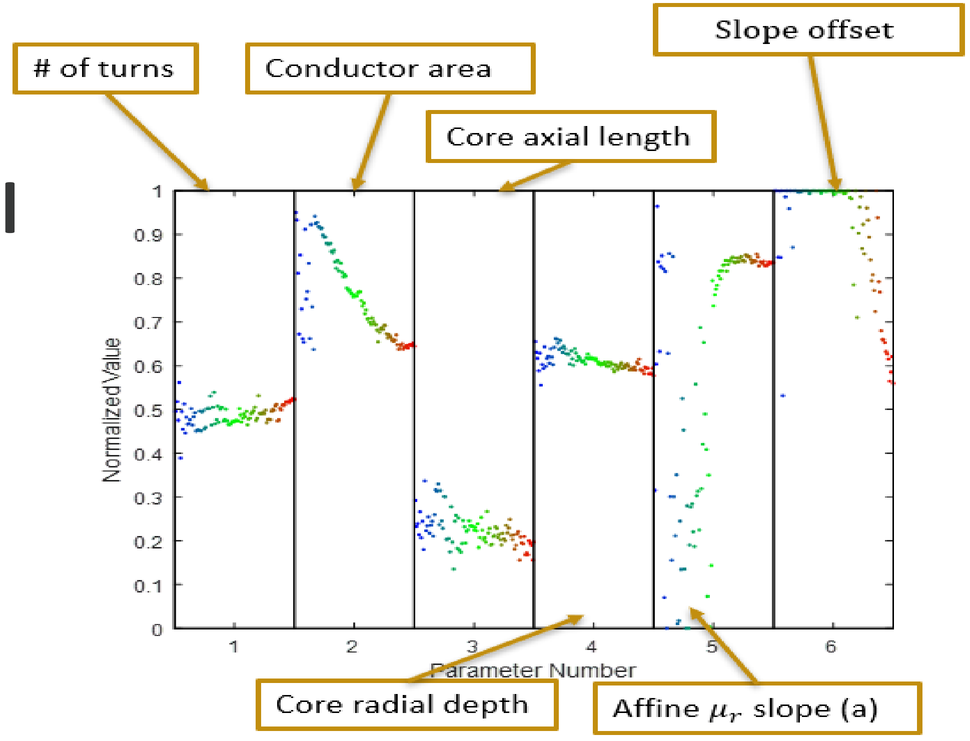
Enabling Magnetics Modeling & Optimization

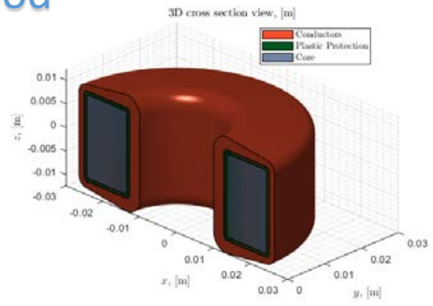
Advanced Optimization methods for Magnetic Componen

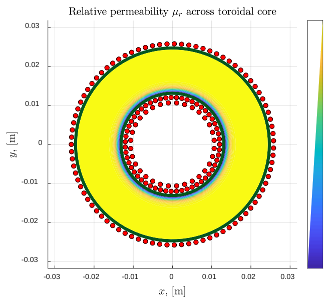
- **A new set of open source tools for component design in this emerging area will be provided to industry and other research groups.**

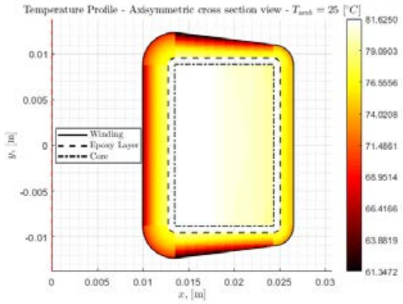


Improvement by "Permeability Engineering" method and multi-objective optimization method









Standardized Magnetic Core Characterization

Published in data sheet format

METGLAS® 2605-SA1 core
datasheet

Grid Asset Performance > Next Generation Transformers

The amorphous tape wound core is manufactured with iron-based 2605-SA1 amorphous foil. The 2605-SA1 amorphous foil is provided by METGLAS, Inc. and the core is manufactured by MK Magnetics. The 2605-SA1 amorphous foil is made up of mainly iron, with small percentages of Silicon and Boron. Applications include transformers, pulse power cores, motors, and high frequency inductors.

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Fig. 1: METGLAS 2605-SA1 core

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Depth of core (or cast width)	D	30
Thickness or build	E	50
Width of core window	F	80
Height of core window	G	140

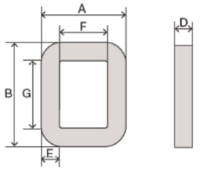


Fig. 2: Illustration of core dimensions

Acknowledgement

This technical effort was performed in support of the National Energy Technology Laboratory's ongoing research in DOE's The Office of Electricity's (OE) Transformer Resilience and Advanced Components (TRAC) program under the RES contract DE-FE0004000.

NATIONAL ENERGY TECHNOLOGY LABORATORY

Characteristics

Table 2: Core physical characteristics

Description	Symbol	Typical value	Unit
Core stacking factor	k_f	0.82	Dimensionless
Effective area	A_e	1,230	mm²
Mean magnetic path length[1]	L_m	583	mm
Mass (before impregnation)		5.22	kg
Mass (after impregnation)		5.95	kg
Lamination thickness		0.001 (0.0254)	inch (mm)
Chemistry		$Fe_{80}Si_9B_{11}$	at%
Grade		Amorphous	
Anneal		Standard – No Field	
Impregnation		100% Solids Epoxy	
Supplier		MK Magnetics	
Part number		4216L1R-B	

Measurement Setup

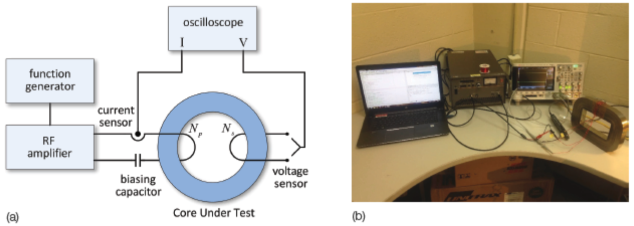


Fig. 3: Arbitrary waveform core loss test system (CLTS) (a) conceptual setup (b) actual setup

The BH curves, core losses, and permeability of the core under test (CUT) are measured with an arbitrary waveform core loss test system (CLTS), which is shown in Fig. 3. Arbitrary small signal waveforms are generated from a function generator, and the small signals are amplified via an amplifier.

[1] Mean magnetic path length is computed using the following equation. OD and ID are outer and inner diameters, respectively. $L_m = \frac{\pi(\mathrm{OD}-\mathrm{ID})}{\ln\left(\frac{\mathrm{OD}}{\mathrm{ID}}\right)}$

Two windings are placed around the CUT. The amplifier excites the primary winding, and the current of the primary winding is measured, in which the current information is converted to the magnetic field strengths H as

$$H(t) = \frac{N_p \cdot i(t)}{l_m}, \quad (1)$$

where N_p is the number of turns in the primary winding. A dc-biasing capacitor is inserted in series with the primary winding to provide zero average voltage applied to the primary winding.

The secondary winding is open, and the voltage across the secondary winding is measured, in which the voltage information is integrated to derive the flux density B as

$$B(t) = \frac{1}{N_s \cdot A_e}\int_0^T v(\tau)\,d\tau, \quad (2)$$

where N_s is the number of turns in the secondary winding, and T is the period of the excitation waveform.

Fig. 4 illustrates three different excitation voltage waveforms and corresponding flux density waveforms. When the excitation voltage is sinusoidal as shown in Fig. 4(a), the flux is also a sinusoidal shape. When the excitation voltage is a two-level square waveform as shown in Fig. 4(b), the flux is a sawtooth shape. The average excitation voltage is adjusted to be zero via the dc-biasing capacitor, and thus, the average flux is also zero. When the excitation voltage is a three-level square voltage as shown in Fig. 4(c), the flux is a trapezoidal shape. The duty cycle is defined as the ratio between the applied high voltage time and the period. In the sawtooth flux, the duty cycle can range from 0% to 100%. In the trapezoidal flux, the duty cycle range from 0% to 50%. At 50% duty cycles, both the sawtooth and trapezoidal waveforms become identical.

It should be noted that only limited ranges of the core loss measurements are executed due to the limitations of the amplifier, such ±75V & ±6A peak ratings and 400V/μs slew rate. The amplifier model number is HSA4014 from NF Corporation. For example, it is difficult to excite the core to high saturation level at high frequency due to limited voltage and current rating of the amplifier. Therefore, the ranges of the experimental results are limited.

Additionally, the core temperature is not closely monitored; however, the core temperature can be assumed to be near room temperature.

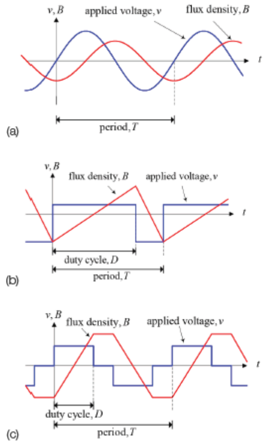
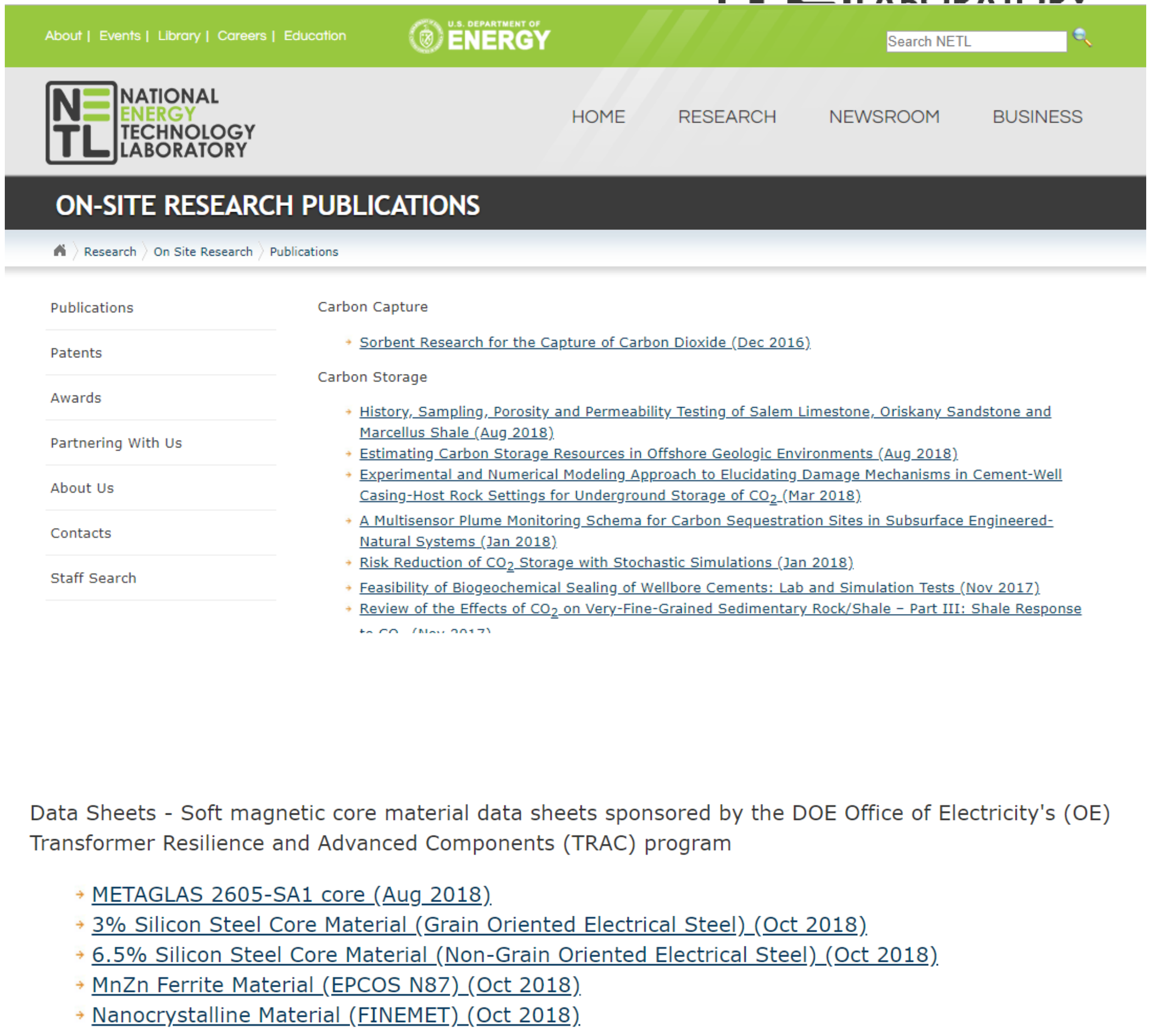


Figure 4. Excitation voltage waveforms and corresponding flux density waveforms (a) Sinusoidal flux, (b) Sawtooth flux, and (c) trapezoidal flux

Magnetic core characteristics of Custom and Commercially Available Cores are published in data sheet format as a Resource for Community. The data sheets include BH loops and core loss measurements as a function of excitation waveform.

Publicly available data sheets

- **Five datasheets of five representative core materials are completed.**
  - Standard Electrical Steel (3% Si)
  - Hi Si content electrical Steel core (6.5% Si)
  - Nanocompsite cores (MK Magnetics)
  - Amorphous Fe-based core (MK Magnetics)
  - Ferrite core (EPCOS/TDK, N87 material)
- **Published to public under "Data Sheets - Soft magnetic core material data sheets sponsored by the DOE Office of Electricity's (OE) Transformer Resilience and Advanced Components (TRAC) program" at**
  - https://netl.doe.gov/TRS
  - https://netl.doe.gov/node/8081
- **More data sheets on different materials are being generated and added as they become available.**



Key Take-Away Messages

- Permeability engineering via Strain-Annealing is an advanced magnetic component design method with advantages in
  - Core utilization, size, peak temperature performance, efficiency, and linear BH characteristic.
- Custom magnetic component design
  - Inductors with “flux-smoothing”
  - Inductors for high power (1MW), high power density, low losses
- Multi-objective optimization method is being researched to fully utilize the capability of permeability engineering.
- Core characterization information of different core materials are being published in data sheet format as a resource for power electronics community.

Patent disclosures

- [Tunable anisotropy of co-based nanocomposites for magnetic field sensing and inductor applications]
- **Patent number:** 10168392
- **Abstract:** A method includes producing an amorphous precursor to a nanocomposite, the amorphous precursor comprising a material that is substantially without crystals not exceeding 20% volume fraction; performing devitrification of the amorphous precursor, wherein the devitrification comprises a process of crystallization; forming, based on the devitrification, the nanocomposite with nano-crystals that contains an induced magnetic anisotropy; tuning, based on one or more of composition, temperature, configuration, and magnitude of stress applied during annealing and modification, the magnetic anisotropy of the nanocomposite; and adjusting, based on the tuned magnetic anisotropy, a magnetic permeability of the nanocomposite.
- **Type:** Grant
- **Filed:** May 15, 2014
- **Date of Patent:** January 1, 2019
- **Assignees:** Carnegie Mellon University, SPANG, INC., U.S. Department of Energy
- **Inventors:** Alex M. Leary, Paul R. Ohodnicki, Michael E. McHenry, Vladimir Keylin, Joseph Huth, Samuel J. Kernion

- [Tunable Anisotropy of Co-Based Nanocomposites for Magnetic Field Sensing and Inductor Applications]
- **Publication number:** 20160319412
- **Abstract:** A method includes producing an amorphous precursor to a nanocomposite, performing devitrification of the amorphous precursor, forming, based on the devitrification, the nanocomposite comprising an induced magnetic anisotropy, and for a first portion of the nanocomposite, determining a desired value of a magnetic permeability of the first portion, tuning, based on the desired value, the induced magnetic anisotropy for the first portion, and adjusting, based on the tuning of the induced magnetic anisotropy of the first portion, a first magnetic permeability value of the first portion of the nanocomposite, wherein the first magnetic permeability value is different from a second magnetic permeability value for a second portion of the nanocomposite.
- **Type:** Application
- **Filed:** July 8, 2016
- **Publication date:** November 3, 2016
- **Inventors:** Alex M. Leary, Paul R. Ohodnicki, Michael E. McHenry, Vladimir Keylin

Acknowledgements:

- DOE Office of Electricity (OE) Transformer Resilience and Advanced Component (TRAC) Program
- DOE EERE SunShot Initiative SuNLaMP Program:
  - Combined PV / Battery Grid Integration with High Frequency Magnetics and Wide Bandgap Semiconductor Enabled Power Electronics (NETL Led)
- DOE EERE Advanced Manufacturing Office NGEM Program (Eaton Led)

Research performed by Leidos Research Support Team staff was conducted under the RSS contract 89243318CFE000003.

This work was funded by the Department of Energy, National Energy Technology Laboratory, an agency of the United States Government, through a support contract with Leidos Research Support Team (LRST). Neither the United States Government nor any agency thereof, nor any of their employees, nor LRTS, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

- **End of Presentation**

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