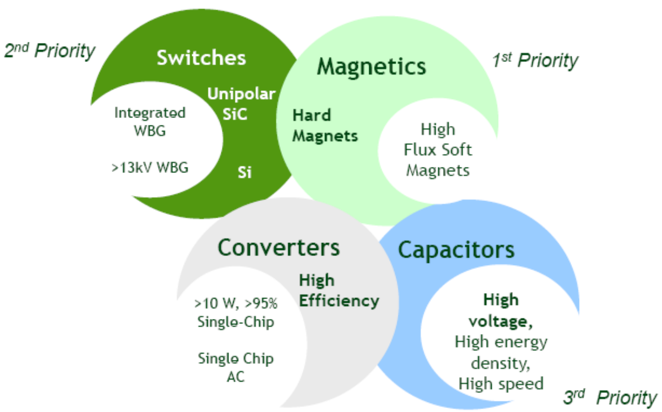
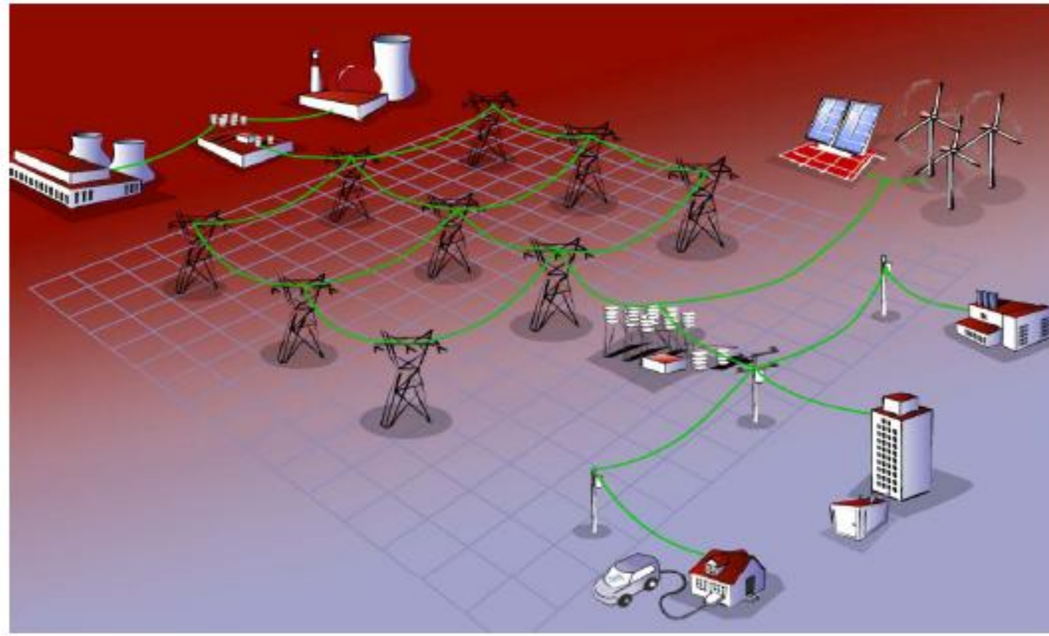
NATIONAL ENERGY TECHNOLOGY LABORATORY



www.arpa-e.energy.gov



Overview of Grid-Related Research and Collaborations in Power Magnetics and Sensors

Dr. Paul Ohodnicki, Materials Scientist / Team Lead

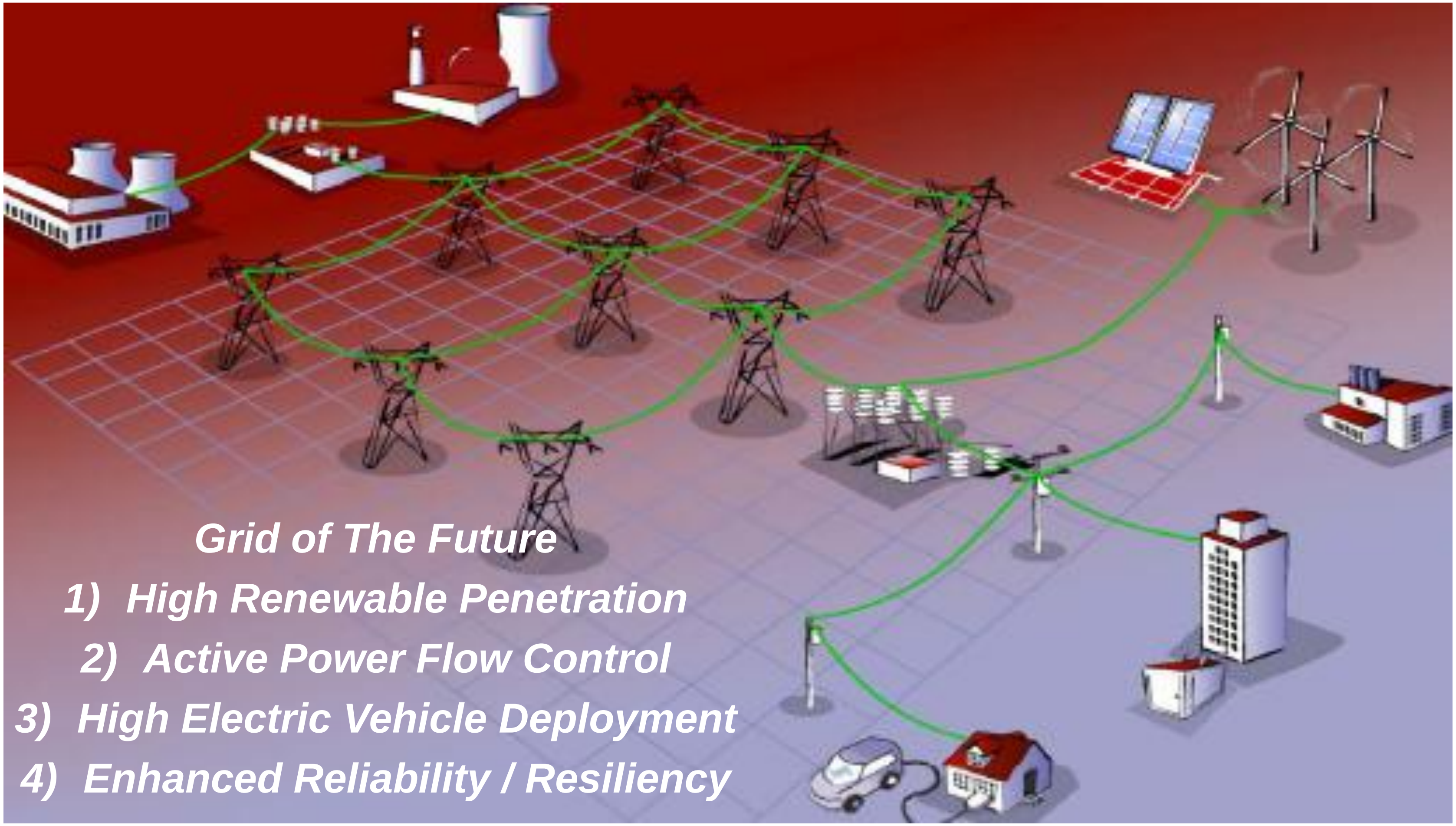
The Electrochemical and Magnetic Materials Team

Functional Materials Development Division

NETL Office of Research and Development

U.S. DEPARTMENT OF ENERGY

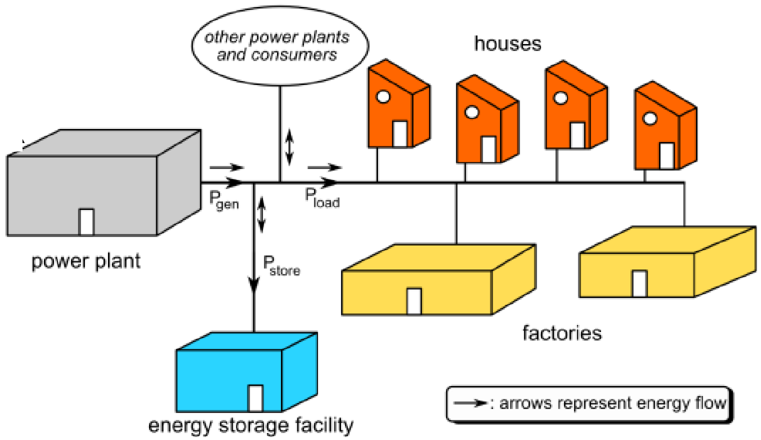
Future of Transmission and Distribution



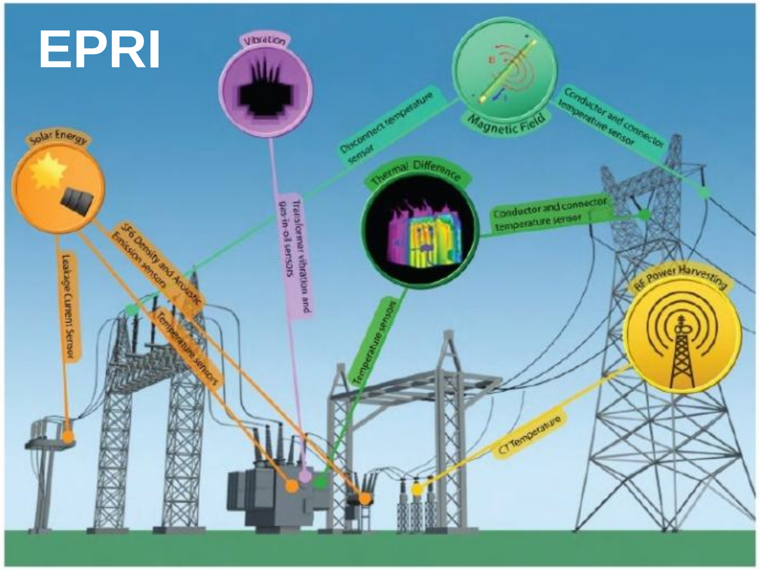
Successful Realization of the T&D System of the Future Will Require:

- **Short Term Efficiency Improvements (Sensors, Controls, etc.)**
- **Long Term Investments in New Technology Development (Devices)**

Urgent New Technology Developments Required

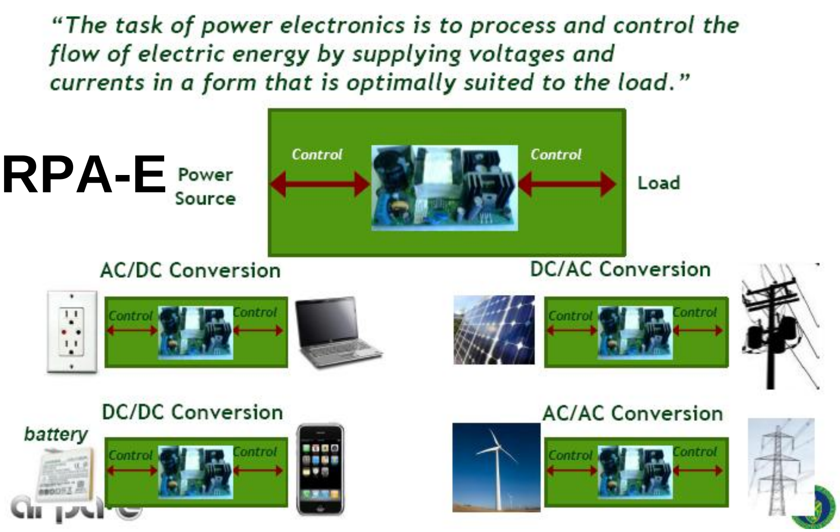


Grid-Scale Energy Storage Devices



Sensors and Controls

ARPA-E



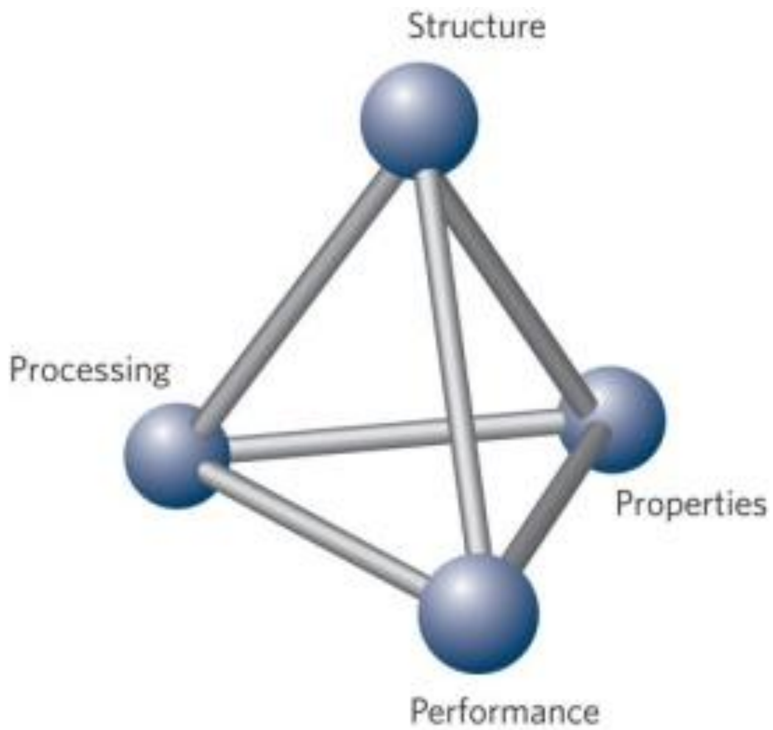
Technological Advances Are Required

Solid State Materials Enable Revolutionary Advances in Devices

Grid-Scale Power Electronics Devices

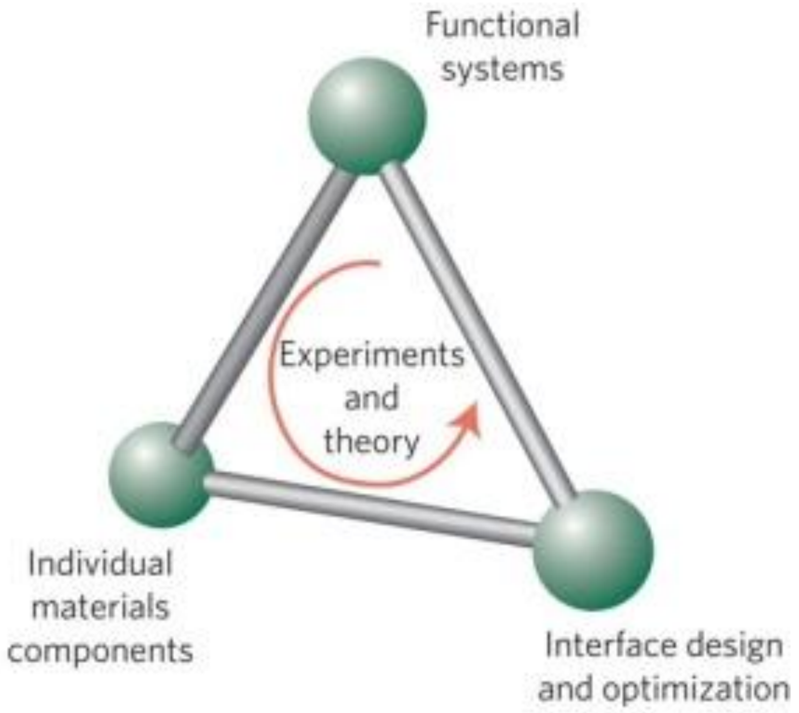
Material Development for Grid-Scale Devices

Classic Materials Science Paradigm



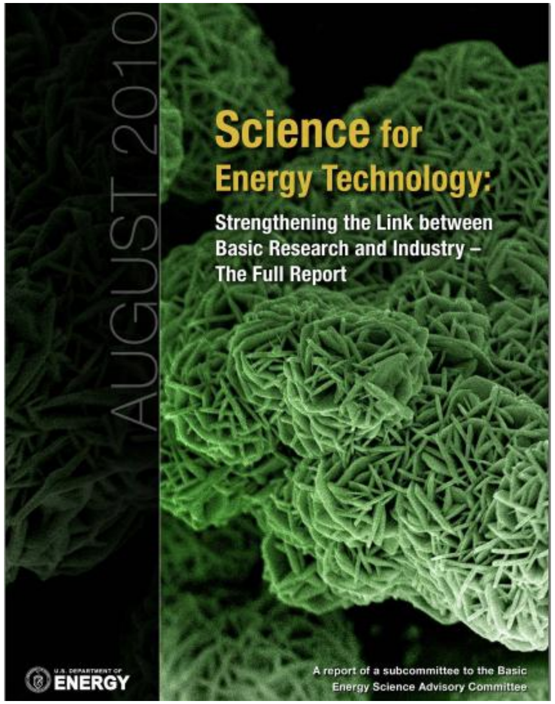
Emerging Paradigm

Materials Interface with Functional Systems and Devices



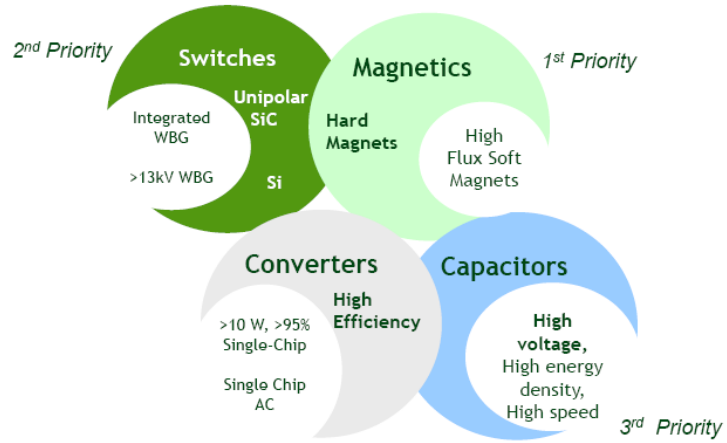
The Electrochemical and Magnetic Materials Team at NETL Places a Unique Focus on the Interface Between Functional Materials and Actual Devices

Needs for Advanced Power Electronic Materials



Basic Energy Sciences 2010 Report: Emphasis on Grid Technologies

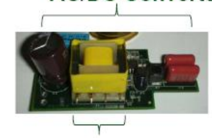
Key Research Priority: Power Electronic Materials



Overwhelmingly the workshop attendees cited magnetics (inductors & transformers) as the primary limit to cost, size, weight, manufacturing.

"For forty years the inductors haven't changed."

AC/DC Converter



Magnetics

largest, most expensive part of the converter

arpa·e

ARPA-E 2010 Workshop: Soft Magnetic Materials for Inductors Highest Priority for Their Program Due to Historic Lack of Federal Investment.

www.arpa-e.energy.gov

Needs for Advanced Power Electronic Materials

TMS2015
144th Annual Meeting & Exhibition

March 15-19, 2015 • Walt Disney World
Orlando, Florida, USA

Organized by:
Paul Ohodnicki, National Energy Technology Laboratory (USA)
Michael Lanagan, Penn State University (USA)
Michael McHenry, Carnegie Mellon University (USA)
Rachael Myers-Ward, Naval Research Laboratory (USA)
Clive Randall, Penn State University (USA)
Matthew Willard, Case Western Reserve University (USA)

Advanced Materials for Power Electronics, Power Conditioning, and Power Conversion III

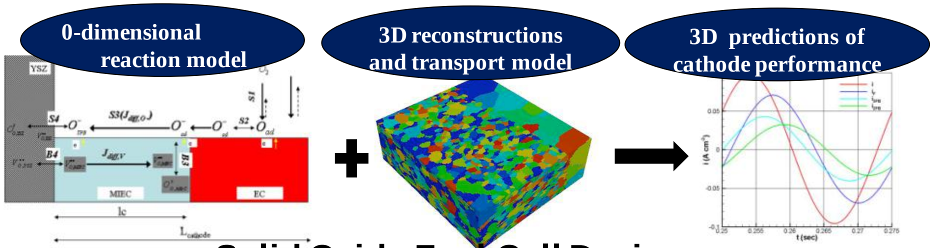
Independent of the means by which electrical power is generated (conventional fossil, advanced fossil, nuclear, solar, wind, etc.), power conditioning and conversion is required to transform power into an appropriate form for efficient and cost-effective integration into the grid. By 2030, it is also projected that 80% of all electricity will flow through power electronics. Advanced materials including soft magnetic materials, semiconductors, and dielectric materials for capacitors are crucial for enabling the next generation of advanced power electronics technologies.

These technical communities have historically worked independent of one another, and materials development efforts have often been carried out in the absence of frequent and meaningful interactions with the power electronics community. The proposed symposium aims to bridge these historical gaps through a number of technical symposia devoted to relevant materials systems including soft magnets, dielectric materials for capacitors, and semiconductor materials. The primary focus of the proposed symposium will be in the area of advanced materials for power electronics and power conditioning systems. A range of invited and contributed talks will be presented by the top materials scientists in each field. To supplement the traditional technical sessions, a selected group of technical experts from the power electronics community will also be invited to present and to engage the materials community. These invited talks are intended to promote interactions between the materials and power electronics communities, to educate the materials community about critical materials needs, and to educate the power electronics community about state-of-the-art material developments.

We Have Recently Organized a New Symposium at TMS Annual 2015 to Help Address these Emerging Needs.
Soft Magnetic Materials, Semiconductors, Capacitors, and Packaging Materials are All Included in the Programming

http://www.tms.org/meetings/annual-15/AM15home.aspx

Recent NETL Grid-Related R&D Activity

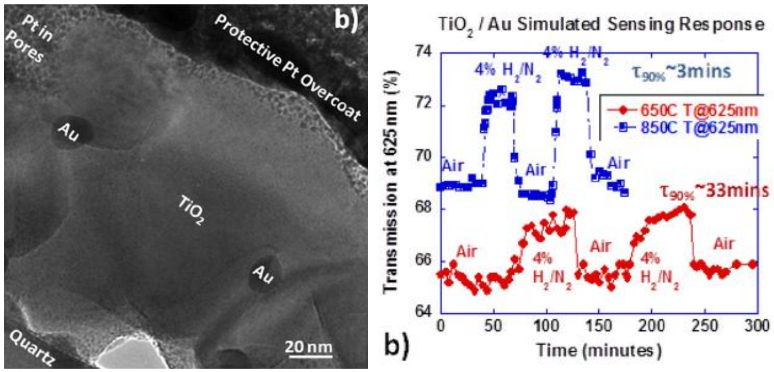


Solid Oxide Fuel Cell Devices

Modeling + Characterization → Optimal Device Performance

Solid Oxide Fuel Cell Materials

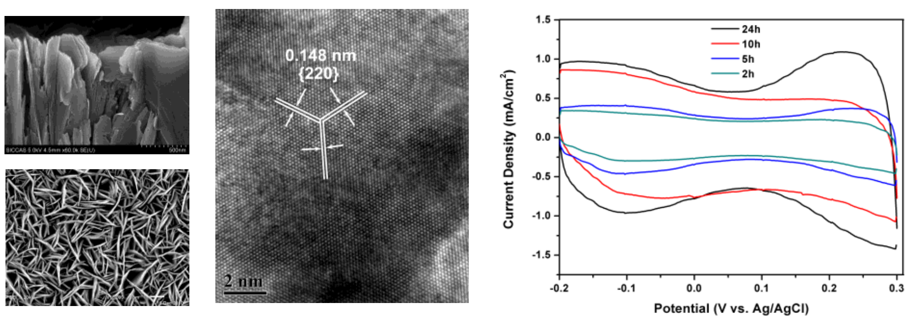
Function and Durability
(DOE FE SECA Program)



Sensor Materials

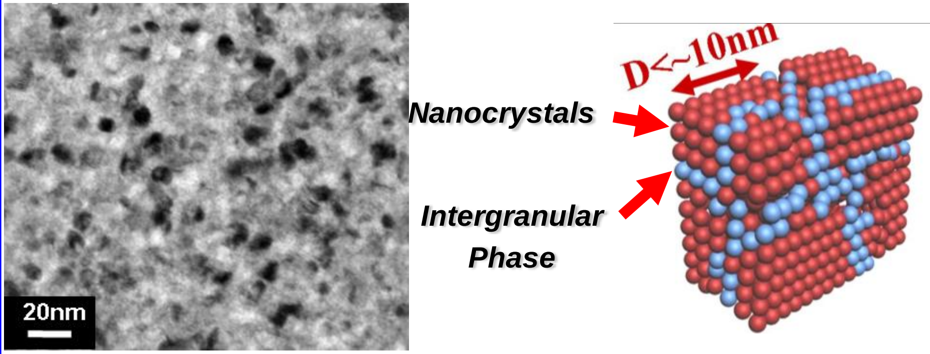
Chemical and Temperature Sensing
(DOE FE Cross-Cutting Program)

Energy Storage and Supercapacitor Materials



Energy Storage Materials

(DOE EERE Program)



Soft Magnetic Materials

Inductors and Sensors
(ARPA-E, URS, CMU RAMP)

Materials for Power Magnetics Applications

Classes of Materials	Low Loss Frequency Range	Maximum Saturation Induction	Maximum Curie Temperature	Microstructure Stability Temperature	Magnetic Response Stability
Bulk Metallic Alloys	DC – 1kHz	2.5T	Up to 1000°C	Up to 1000°C	Up to 400-500°C
Ferrites	DC – MHz	0.5T	Up to 500°C	Up to 1000°C	Up to 300°C
Amorphous Alloys	DC - 100kHz	1.5T	Up to ~700°C	~50-300°C	<~200°C
Amorphous / Nanocrystalline Alloys	DC - 100kHz	1.9T	Up to ~900°C	~400-600°C	Up to 400-500°C

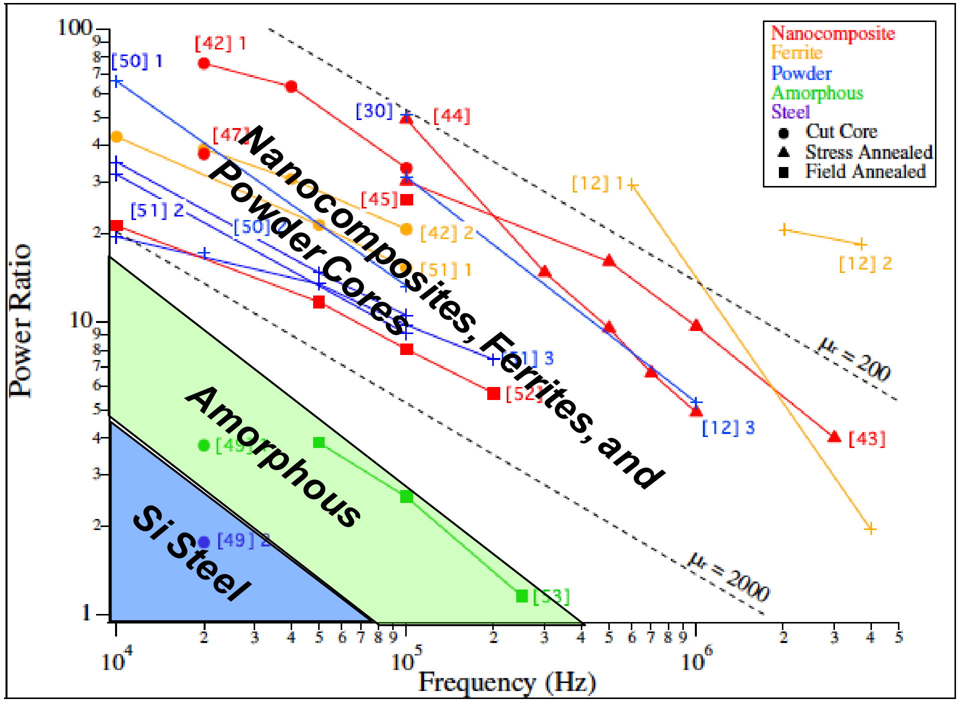
Carnegie Mellon University / NETL Collaborative Interactions Have Focused on Alloy Development and Processing of Amorphous and Nanocrystalline Alloys.

University of Pittsburgh / Los Alamos National Laboratory / Carnegie Mellon Univeristy / NETL Collaborations Have Focused on Advanced Converter Designs and Associated Economics.

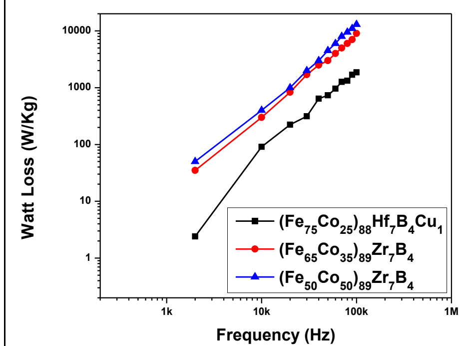
Materials for Power Magnetics Applications

"Soft Magnetic Materials in High-Frequency, High-Power Conversion Applications"

A. Leary, P. Ohodnicki, and M. McHenry, JOM, Vol. 64 #7 pp. 772-781 (2012).

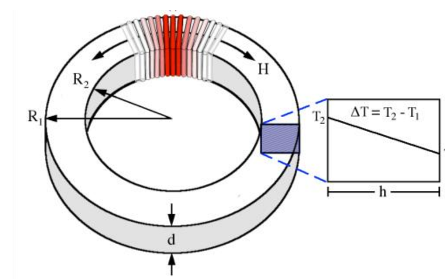


Material Losses Increase Significantly at High Frequencies



$$V = -NA\frac{dB}{dt} = -L\frac{dI}{dt} = -LI_0\omega\cos(\omega t)$$

$$= \frac{-\mu N^2 A}{l} I_0 \omega \cos(\omega t)$$



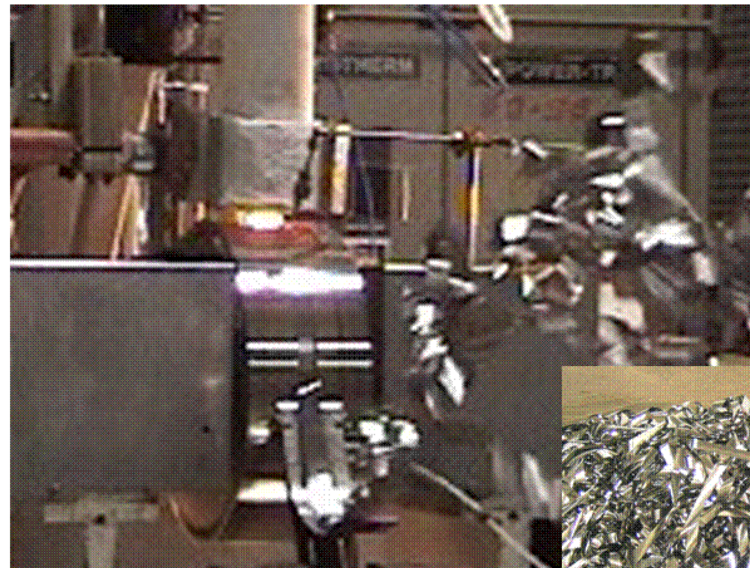
Smaller Core Volumes / Areas Enabled by Higher Frequency Operation.

Applications Demanding Increased Operational Frequency and A Combination of High Frequency and High Power Requires Advanced Soft Magnetic Materials.

Higher Frequency Operation Enables Dramatic Reductions in Overall Size and Cost of Devices as Well as Increased Functionality.

Power Magnetics Research and Collaborations

Rapid Solidification Processing Enables Synthesis of Large-Scale Advanced Soft Magnetic Alloys to Enable High Power Device Fabrication



Several Trends Related to the Next Generation Transmission and Distribution System Require Advances in New Alloys and Novel Processing Strategies.

DOE Mandated Transformer Efficiency Standards

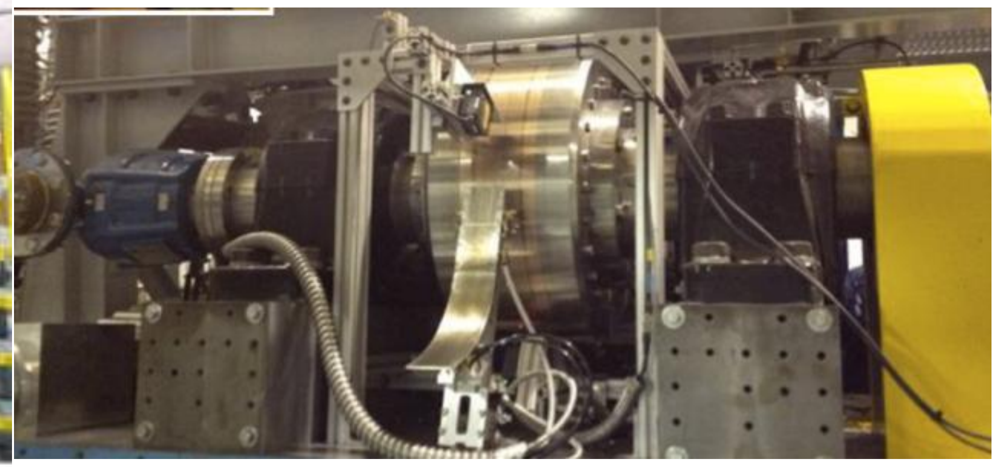
2010 and Amended (2016) Energy Conservation Standards for Liquid-Immersed Distribution Transformers					
Single phase			Three phase		
kVa	Efficiency (%) 2010	Efficiency (%) 2016	kVa	Efficiency (%) 2010	Efficiency (%) 2016
10	98.62	98.7	15	98.36	98.65
15	98.76	98.82	30	98.62	98.83
25	98.91	98.95	45	98.76	98.92
37.5	99.01	99.05	75	98.91	99.03
50	99.08	99.11	112.5	99.01	99.11
75	99.17	99.19	150	99.08	99.16
100	99.23	99.25	225	99.17	99.23
167	99.25	99.33	300	99.23	99.27
250	99.32	99.39	500	99.25	99.35
333	99.36	99.43	750	99.32	99.4
500	99.42	99.49	1000	99.36	99.43
667	99.46	99.52	1500	99.42	99.48
883	99.49	99.55	2000	99.46	99.51
			2500	99.49	99.53

Trend #1:

Increasingly Aggressive DOE Efficiency Standards Being Imposed On Power Distribution Transformers

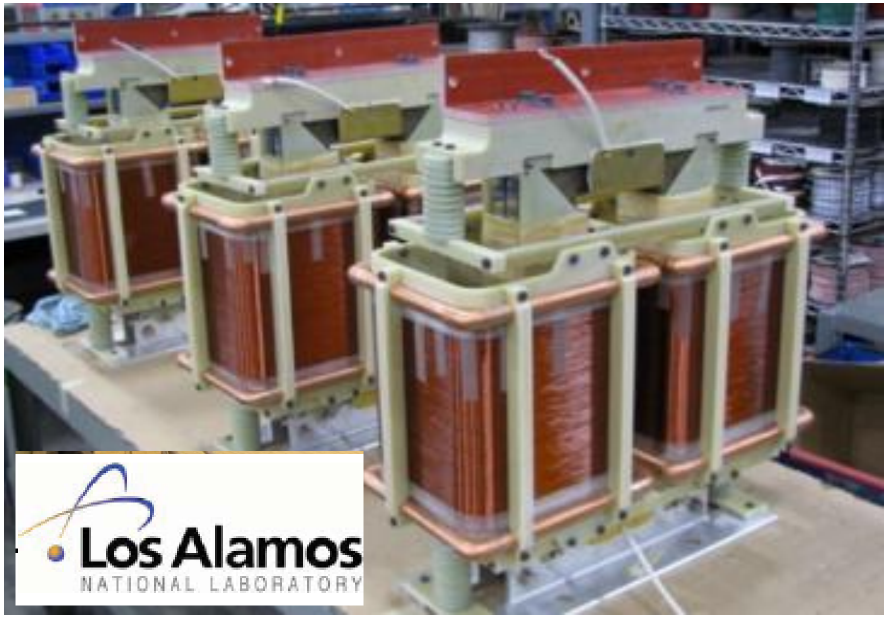
Amorphous Alloy and Scale-Up R&D

Commercial Scale Casting Facility:
250kg Maximum VIM Capacity
Up to 6 Inch Wide Ribbons
Unique Facility in the US



Large-Scale Amorphous Alloy Casting Expertise and Technical Support is Needed to Support the Electric and Power Industry.

High Frequency Power Conversion Devices



Conventional 60Hz Power Transformer (60Hz, 100kV, 20A RMS, >30 tons)

20kHz Resonant High Frequency Device (20kHz, 140kV, 20A RMS, 3@150lbs)

Trend #2:

Increased Renewables, Advanced Fossil Generation, and Power Flow Control Requires New Inverters, Converters, and Transformers that Leverage Recent Advances in Wide Bandgap Semiconductors and Devices.

Example Applications :
Utility Scale Solid Oxide Fuel Cell Grid Integration

SECA Fuel Cell Plant

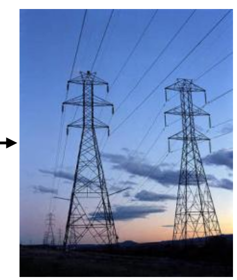


Fuel Cell Stack

Power Conditioning System (PCS)

$40-$100 / kW

60 Hz Step-up Transformer



Power Grid

$40-$100 / kW for PCS is a difficult stretch goal !

Advanced Power Electronics Technologies are Important in Many Power Generation Technologies, Including Fossil-Based

Utility Scale SOFC Grid Integration

300 MW PCS

~700 V DC

Approx. 500 Fuel Cells

~700 V DC

Semiconductors
Packaging and Interconnects
HF transformers
Filter Inductors and Capacitors
Cooling System
60 Hz Transformer up to 18 kV
Breakers and Switchgear

18 kV AC → 345 kV AC

$40-$100 / kW

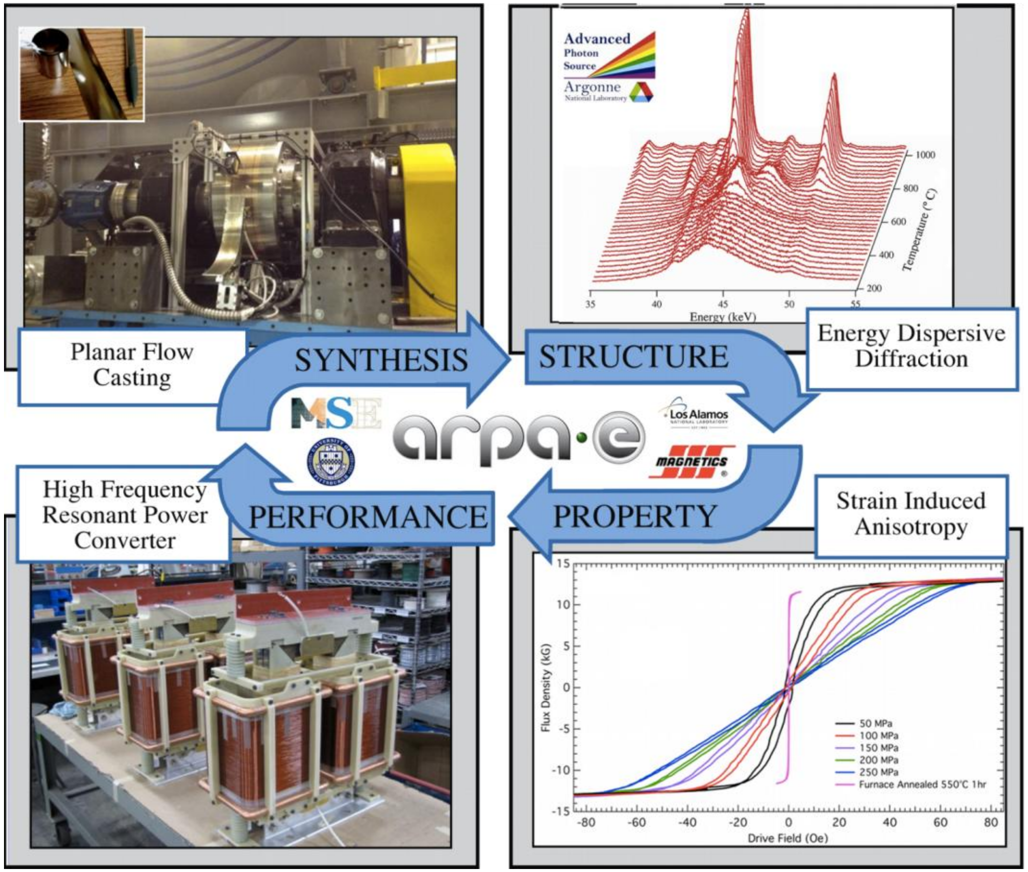
Ripple < 2%
Stack Voltage Range
~700 to 1000 V

IEEE – 519
IEEE – 1547
Harmonic Distortion
Future: HVDC transmission ?

Similar Needs Arise for Grid Integration of Renewable / Energy Storage with Advanced High Power and High Frequency Magnetics Playing a Critical Role as Enabling Technologies.

Allen Hefner : NIST / DOE Interagency Agreement

High Frequency Power Conversion Devices



A Current Funded Project from ARPA-E Couples:

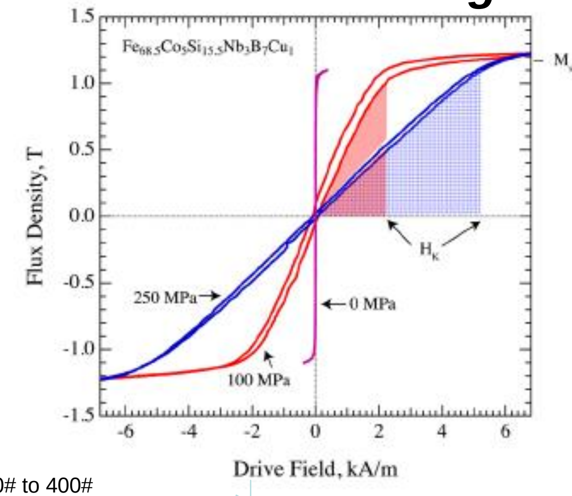
1) Advanced Material Processing
2) New Alloy Development
3) Converter Design
4) Economic Viability Assessment
5) Fundamental Science

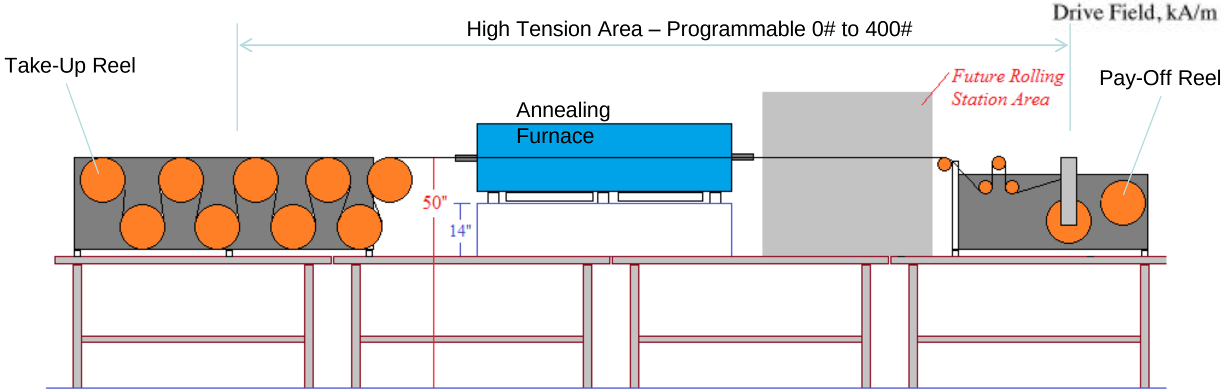
Close Integration of Device Development and New Material R&D. High Power Testing of a 50kHz, 100kW Transformer Will Occur Soon at The Facility of the Industrial Collaborator, Dynapower.

High Frequency Power Conversion Devices

Converter Designers Have Historically “Made Lemonade from Lemons”

Strain Annealing



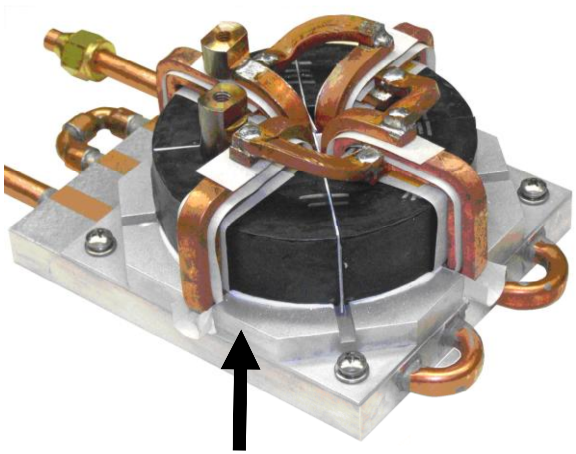


A Combination of Advanced Processing Techniques and Novel Alloy Composition Can Enable Completely New Solutions From the Perspective of Converter and Component Design.

High Frequency Power Conversion Devices

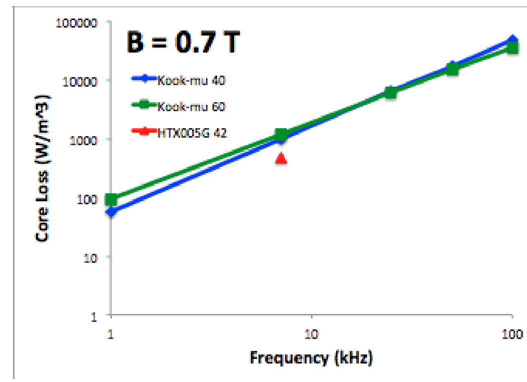
Converter Designers Have Historically "Made Lemonade from Lemons"

CMU / NETL Joint Patent Filed on Strain Annealed Inductor Cores

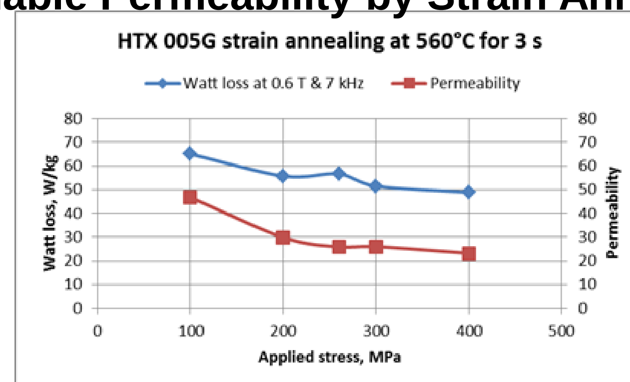


Core Cutting and "Gapping" or Fabrication of a "Powder Core" to Make a Device Introduces Losses

Lower Losses than Powder Cores



Tunable Permeability by Strain Annealing

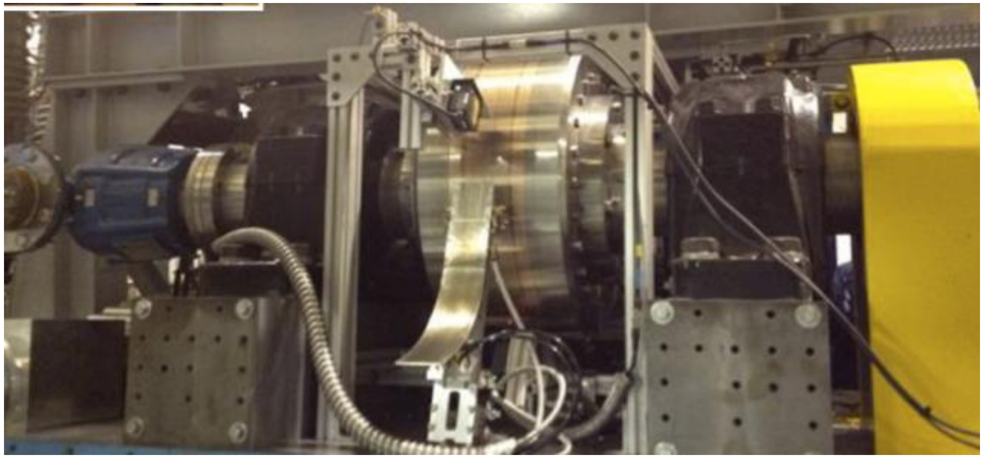


Patent Application Filed

A Combination of Advanced Processing Techniques and Novel Alloy Composition Can Enable Completely New Solutions From the Perspective of Converter and Component Design.

Two Thrusts that Need Urgently Addressed

Large-Scale Alloy Development and Manufacturing Scale-up



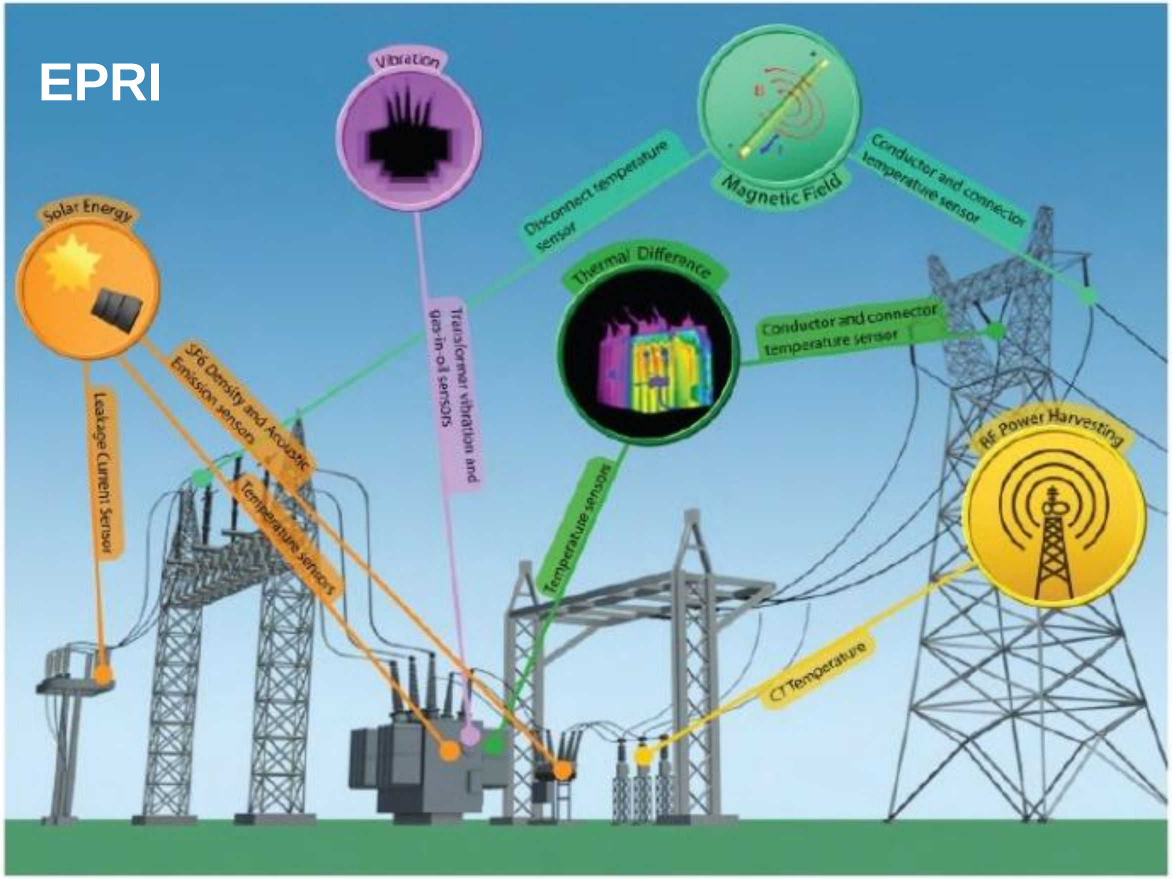
2010 and Amended (2016) Energy Conservation Standards for Liquid-Immersed Distribution Transformers					
Single phase			Three phase		
kVa	Efficiency (%) 2010	Efficiency (%) 2016	kVa	Efficiency (%) 2010	Efficiency (%) 2016
10	98.62	98.7	15	98.36	98.65
15	98.76	98.82	30	98.62	98.83
25	98.91	98.95	45	98.76	98.92
37.5	99.01	99.05	75	98.91	99.03
50	99.08	99.11	112.5	99.01	99.11
75	99.17	99.19	150	99.08	99.16
100	99.23	99.25	225	99.17	99.23
167	99.25	99.33	300	99.23	99.27
250	99.32	99.39	500	99.25	99.35
333	99.36	99.43	750	99.32	99.4
500	99.42	99.49	1000	99.36	99.43
667	99.46	99.52	1500	99.42	99.48
883	99.49	99.55	2000	99.46	99.51
			2500	99.49	99.53

Integrated Converter, Materials, and Processing R&D

Come Talk to Me About How Your Organization Could Get Engaged!

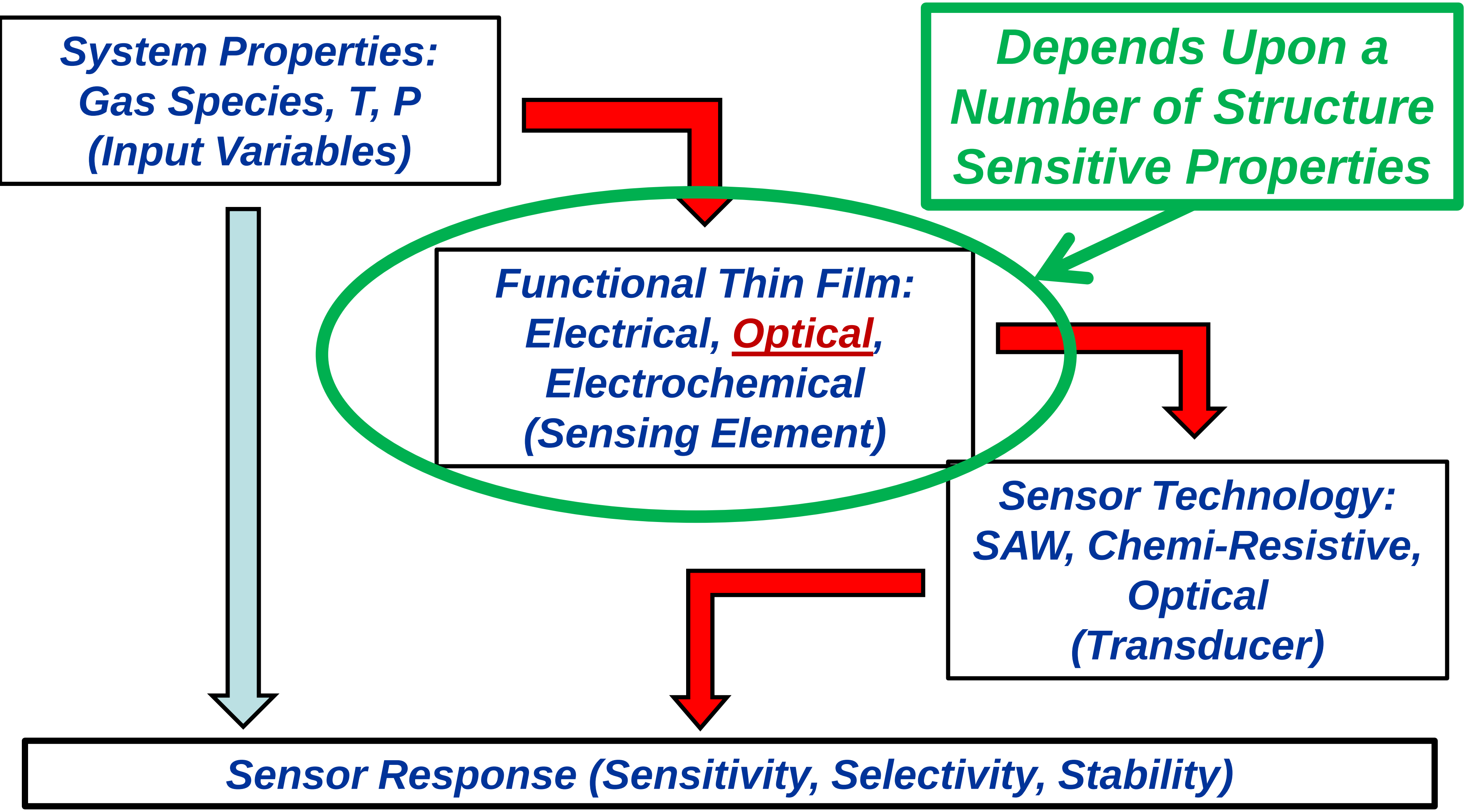
Harsh Environment Sensor Research

Sensor Devices Compatible with High Voltage, Chemically Corrosive, and Harsh Environment Conditions are Needed for the Future Grid



An Increasingly Complex T&D System with Power Flow Control and Advanced Converters and Devices Requires an Unprecedented Level of Visibility and Corresponding Data Management and Controls Schemes.

Functional Materials for Sensors



Our Team Has Placed an Emphasis on Advanced Functional Sensor Material Research and Development to Enable New Types of Sensor Devices.

Sensor Needs in Fossil Energy Applications

Short Term Focus

	Coal Gasifiers	Combustion Turbines	Solid Oxide Fuel Cells ★	Advanced Boiler Systems
Temperatures	Up to 1600°C	Up to 1300°C	Up to 900°C	Up to 1000°C
Pressures	Up to 1000psi	Pressure Ratios 30:1	Atmospheric	Atmospheric
Atmosphere(s)	Highly Reducing, Erosive, Corrosive	Oxidizing	Oxidizing and Reducing	Oxidizing
Examples of Important Gas Species	H_2, O_2, CO, CO_2, H_2O, H_2S, CH_4	O_2, Gaseous Fuels (Natural Gas to High Hydrogen), CO, CO_2, NO_x, SO_x	Hydrogen from Gaseous Fuels and Oxygen from Air	Steam, CO, CO_2, NO_x, SO_x

★ Current Active Research Efforts

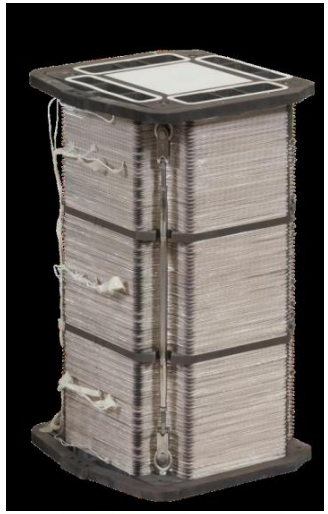
Sensor Development for Embedded Sensing in Power Generation

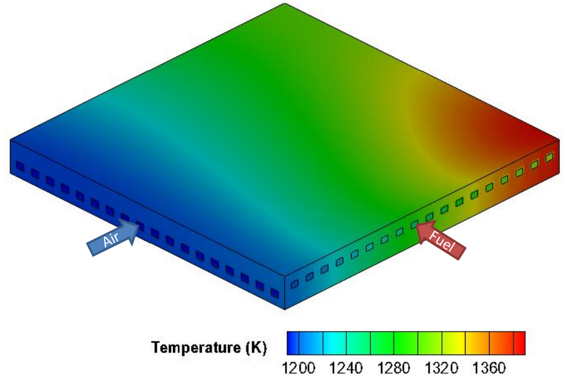
Conditions	Downhole Drilling ★	Deep/Ultra-deep	Geological CO_2 Sequestration (Vilarrasa et al., 2013) ★
Depth of interest (feet)	1,500–13,500	30,000–40, 000	6,000–7,000
Temperature (K)	Up to 470	Up to 580	Up to 370
Pressure (psi)	Up to over 10,000	Up to 30,000	Up to 3,000
Typical pH	4–8	4–8	2–6

Sensor Development for Embedded Sensing in Subsurface Applications

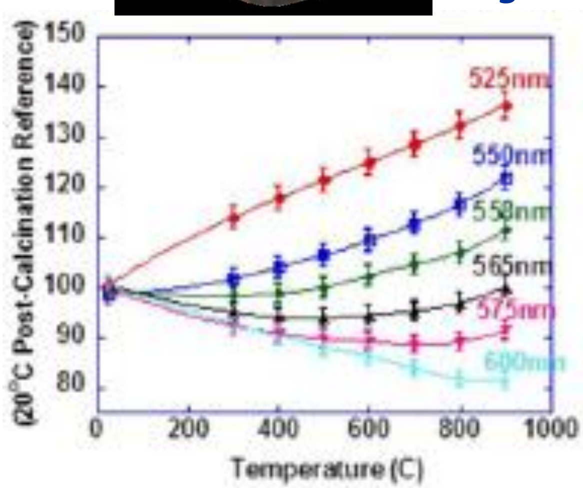
A Well-Equipped Laboratory Has Been Established for Harsh Environment Sensing Spanning a Broad Range of Energy Applications.

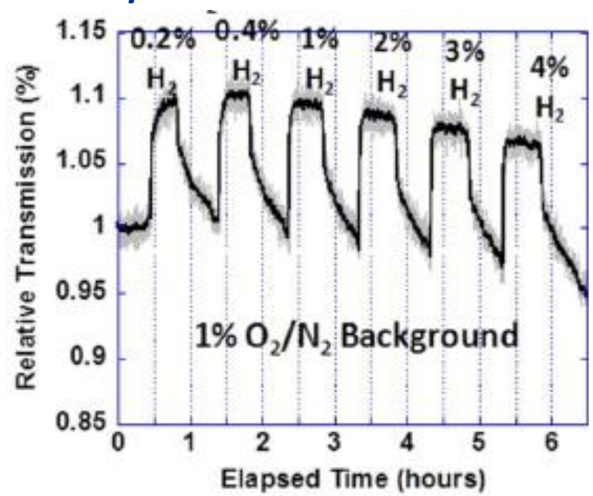
Embedded Harsh Environment Sensor Research





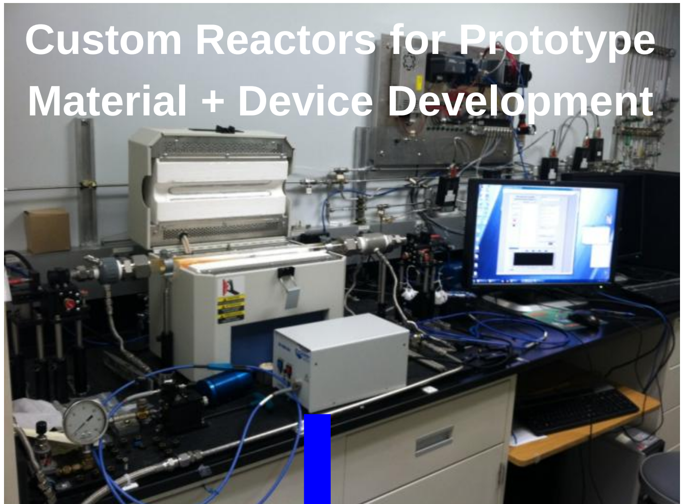
Solid Oxide Fuel Cell internal gas and temperature distribution

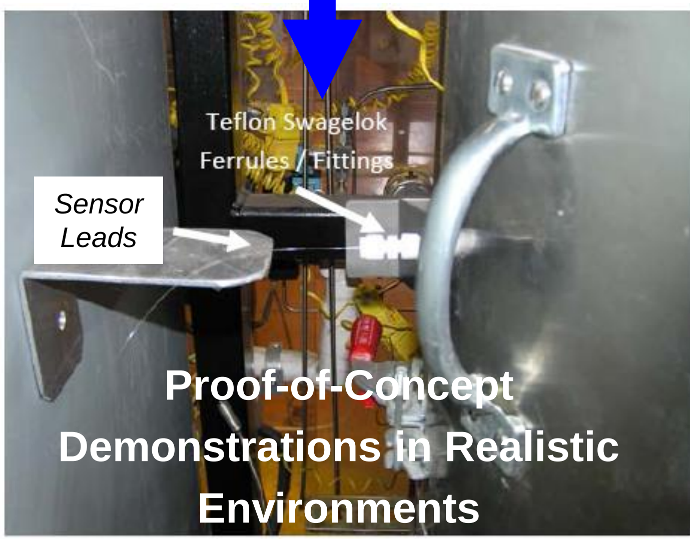


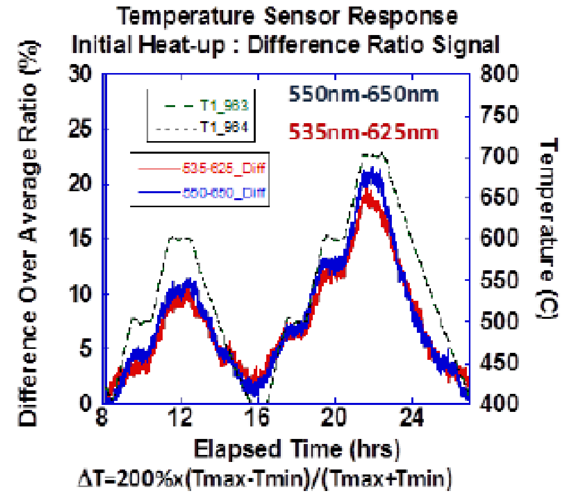


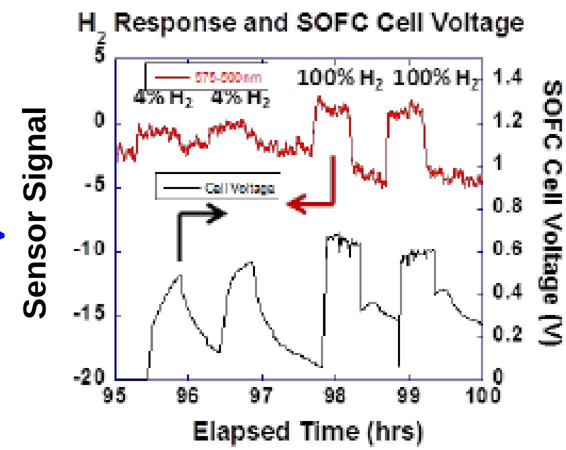
A Sensor Approach Has Been Developed to Enable Embedded Sensing of Both Temperature and Chemical Composition of a High Temperature Gas Stream in an Operational Solid Oxide Fuel Cell Environment.

Embedded Harsh Environment Sensor Research







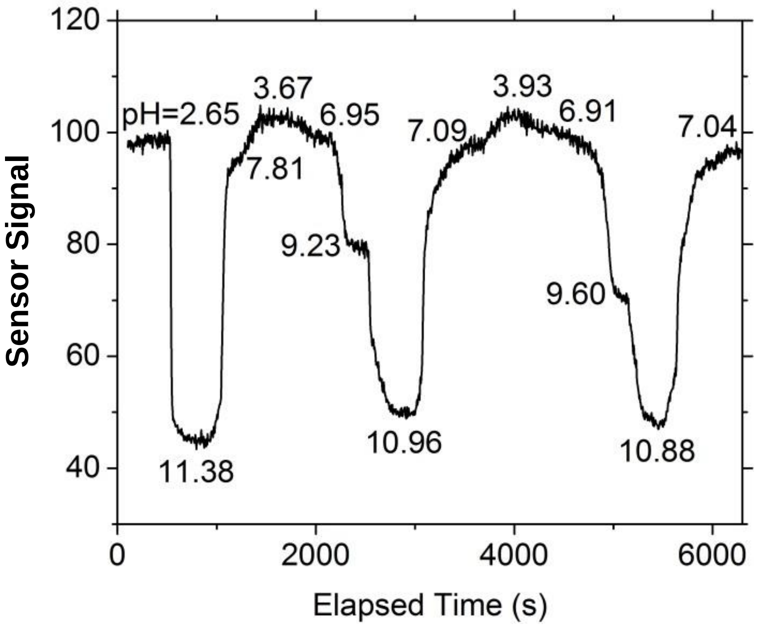


<u>Patent Applications Filed : Licensing Opportunity</u>

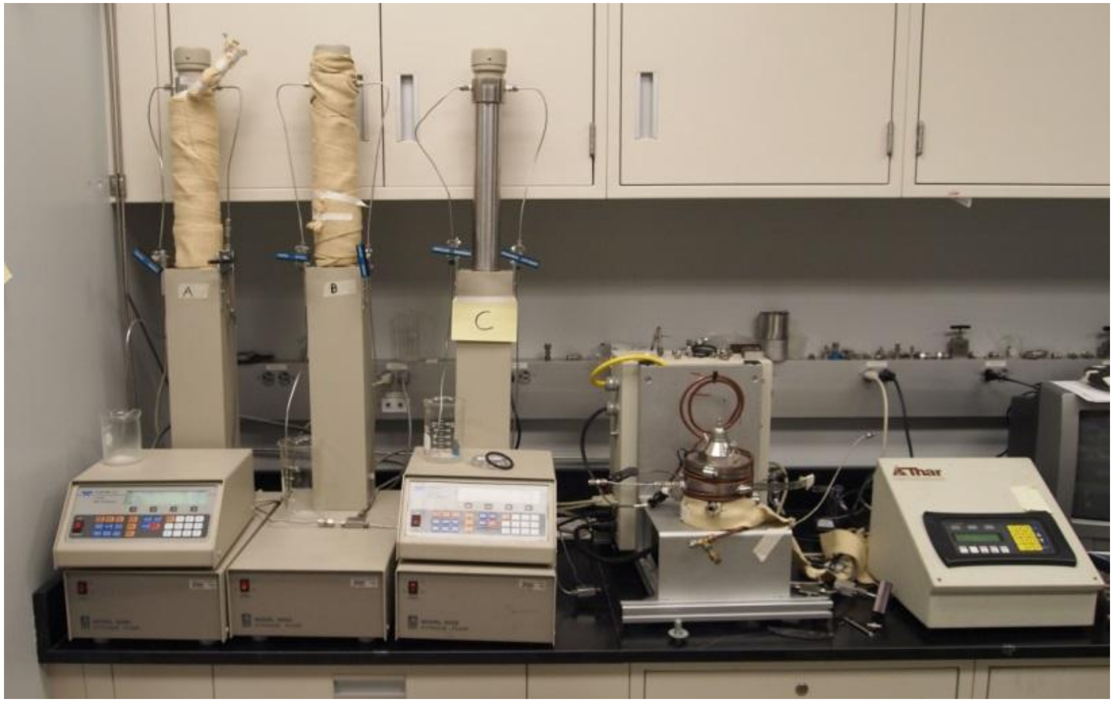
Feasibility for H_2 and Temperature Sensing in the Anode Stream of an Operational Solid Oxide Fuel Cell Has Been Demonstrated.

Embedded Harsh Environment Sensor Research

pH Sensor Response



High Pressure, High Temperature Fluid-Based Sensor Development Reactor



Patent Application Filed : Licensing Opportunity

Early Prototypes of pH Sensing Approaches Compatible with Extreme High Temperature and High Pressure Operations Have Been Developed and Demonstrated in Early Stage Experiments.

Relevance to Power Electronics and Grid R&D

Dissolved Gas Analysis of Transformer Oil

Gas	Normal	Elevated	Abnormal	Interpretation
Acetylene	<15 ppm	>15 ppm and <70 ppm	<70 ppm	Arcing
Carbon Dioxide	< 10 000 ppm	>10000 ppm and <15000 ppm	> 15000 ppm	Severe Overloading
Carbon Monoxide	< 500 ppm	>500 ppm and < 1000 ppm	>1000 ppm	Severe Overloading
Ethane	<10 ppm	>10 ppm and < 35 ppm	> 35 ppm	Local Overheating
Ethylene	<20 ppm	>20 ppm and <100 ppm	>100 ppm	Severe Overheating
Hydrogen	<150 ppm	>150 ppm and < 1000 ppm	>1000 ppm	Arcing, Corona
Methane	<25 ppm	>25 ppm and <80 ppm	>80 ppm	Sparking
Nitrogen	1-10%			Normal ageing
Oxygen	0.2 – 3.5%			Normal Ageing
Total Combustible Gases	< 720 ppm	>720 ppm and <5000 ppm	>5000 ppm	Total Combustible Gas Limit

Sampling and Detailed Laboratory Analysis of Dissolved Gases in Oil is a Common Diagnostic Tool for Transformer Health

Real-Time Harsh Environment Sensors Capable of Monitoring Important Parameters of Interest Could Have a Significant Impact on Asset Monitoring.

Summary

- Device Innovation is Required for Future T&D System
- Materials Innovations Enable Next Generation Devices and NETL Has Particular Expertise in the Following by Working Closely with Regional Partners CMU and U. Pitt Among Others:
  - Advanced Inductor and Transformer Materials
  - Novel Functional Material Enabled Harsh Environment Sensors
- We Are Currently Seeking Commercial Partners to Provide Perspective About Barriers to Widespread Industrial Adoption, to License Patented Technologies, and to Partner on New Technology Development

Come Talk to Me About How You Can Partner with Our Team to Develop the Next Generation of Energy and Power Technology Solutions!

Dr. Paul Ohodnicki, 412-386-7389, paul.ohodnicki@netl.doe.gov