Presentation Submission Information

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- Presentation Title: **Next Generation Ultra-Conductors for High Efficiency Transformers**
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- Organization(s): **Pacific Northwest National Laboratory**

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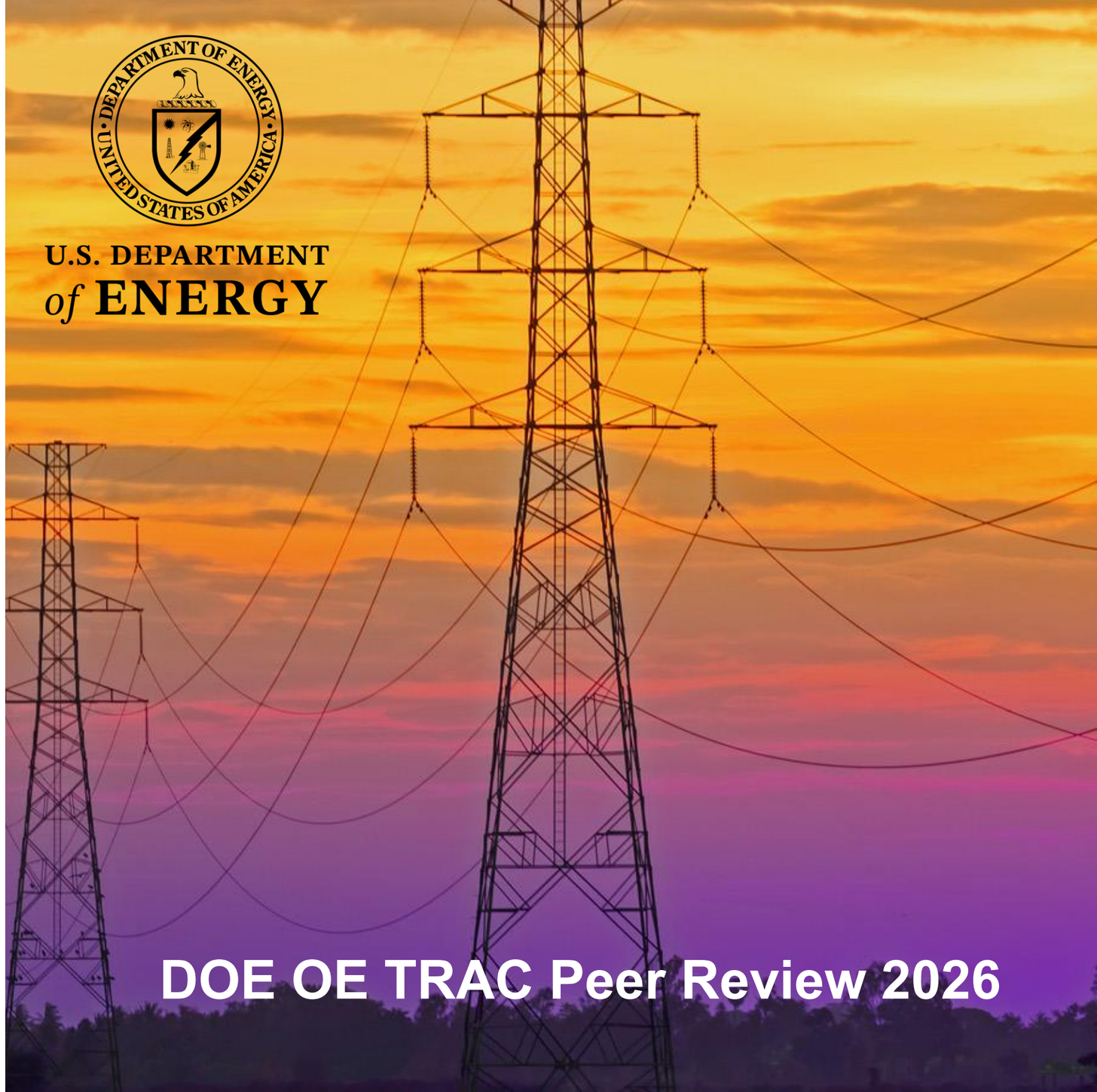
Next Generation Ultra-Conductors for High Efficiency Transformers

October 19, 2026

Keerti S. Kappagantula
Director, Grid Materials Program
Energy & Environment Directorate

U.S. DEPARTMENT of ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy



DOE OE TRAC Peer Review 2026

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Project Overview

- **Project Description:**
  Developing ultra-conductor winding supply chains for improved transformer efficiency
- **Period of Performance**: **10/1/24 – 9/30/27**
- **Award Amount**: **$2,000,000**
- **Prime Awardee:** Pacific Northwest NATIONAL LABORATORY
- **Partners:** EATON Powering Business Worldwide; EPRI ELECTRIC POWER RESEARCH INSTITUTE; Southern Company; Southwire®

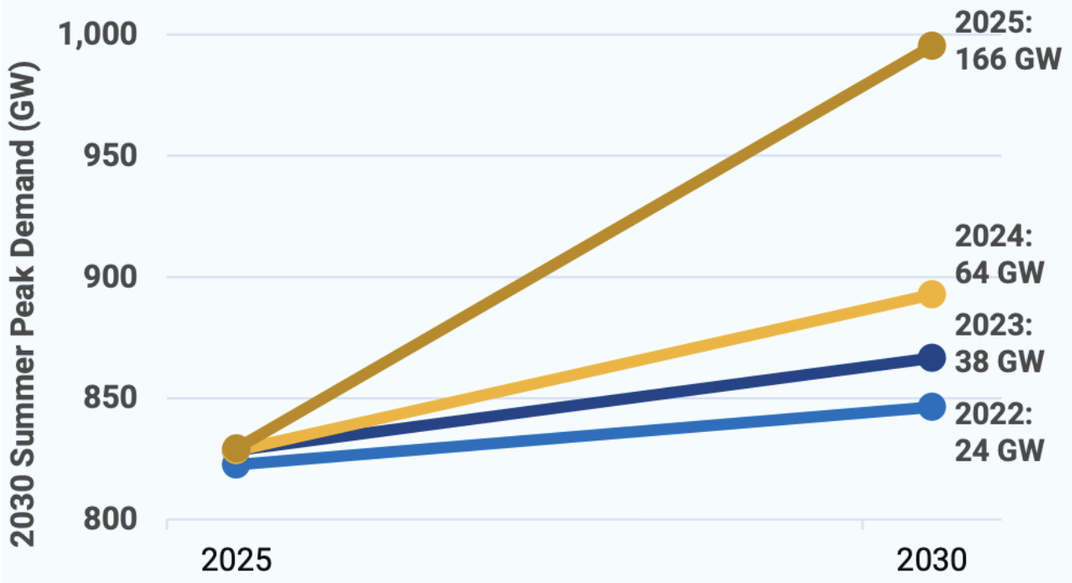
- **Technology Area:**
  - **Advanced Transformers**
  - **Transformer Materials**
  - DC Circuit Breakers
  - Advanced Power Electronics
  - **Advanced Conductors**, Busbars, and Dielectric Materials
- **Alignment/Supports strategic pathway:**
  1. **Stabilize** the grid to address the immediate, acute conditions that strain reliability
  2. **Optimize** the grid to enhance performance and strengthen security
  3. **Grow the grid by enabling innovation, advancing new technologies, and building capacity for a future-ready electricity system**

High-performance materials → **Improved capacity without infrastructure buildout**

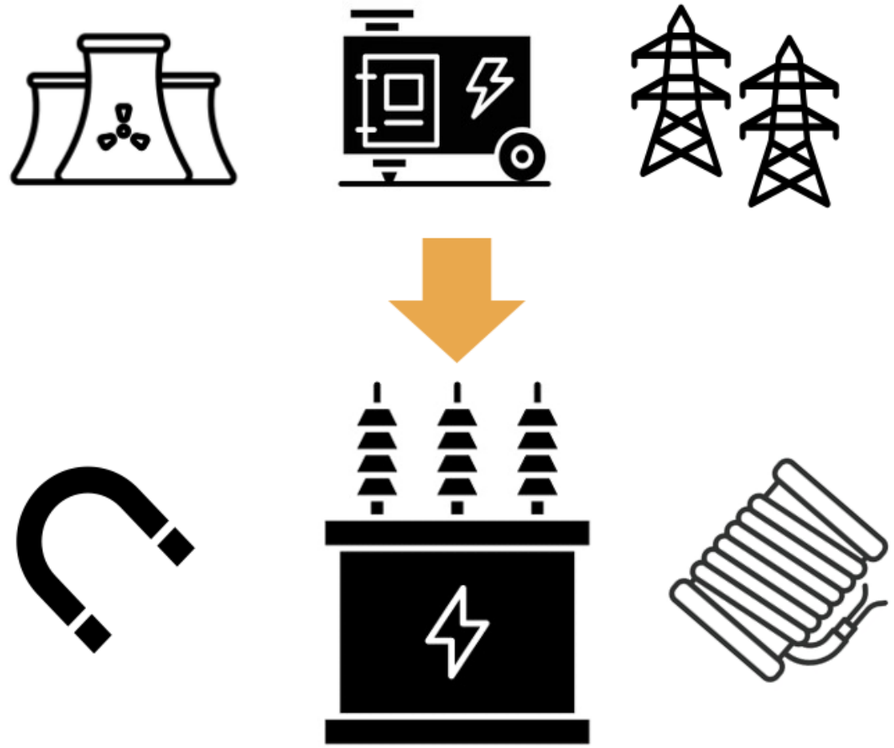
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Problem Statement

Need to expand grid within available infrastructure while reducing critical material usage/dependence



5-year nationwide summer peak electricity growth projected as aggregate of forecasts (FERC) in '22-25[1]



Growing AI Infrastructure

Industrial Manufacturing

Rising Urban-center Density

Mining, Oil & Gas Sector

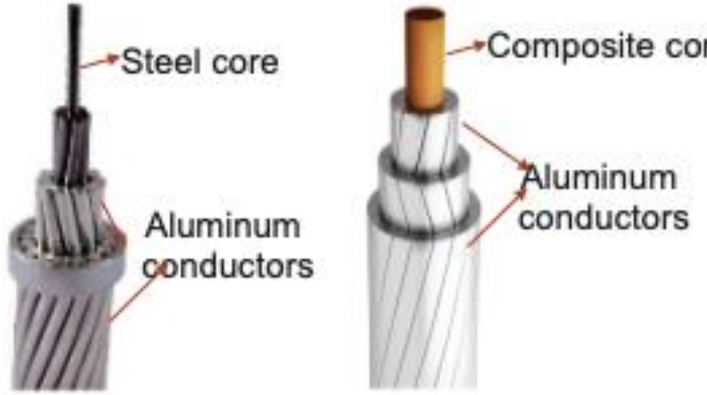
More critical materials for components

Limited equipment footprint

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Proposed Solution

High-performance, lower CM, drop-in ready components increasing grid capacity within existing infrastructure



Steel and composite core overhead cables with aluminum conductors



Distribution transformers and aluminum windings

10% higher electrical conductivity components in place of aluminum → **Higher current carrying capacity** → **Need smaller cross sections for same capacity**

Replacing aluminum wires with high performer conductors in transformers or transmission cables

- **25% higher capacity in same footprint**
- **Reduction of critical material usage by 20%**

Performance at operating temperatures

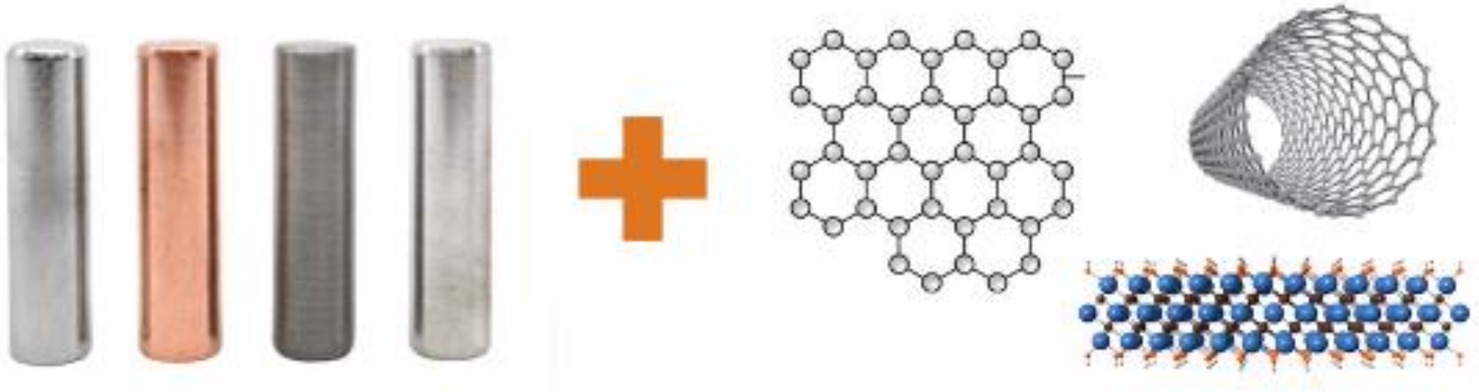
Scalable manufacturing pathways

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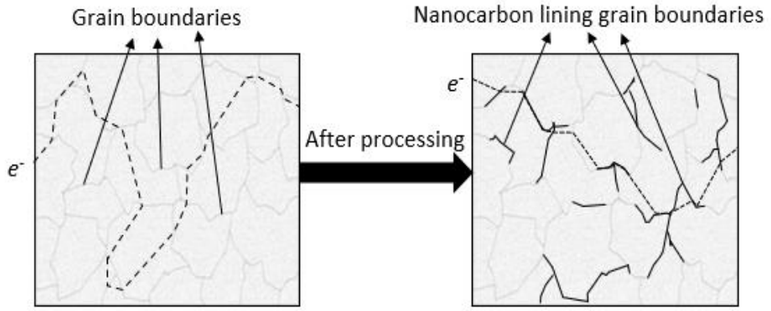
Proposed Solution

Ultra-conductors: a new paradigm in electrical conductors with improved properties over commercial products

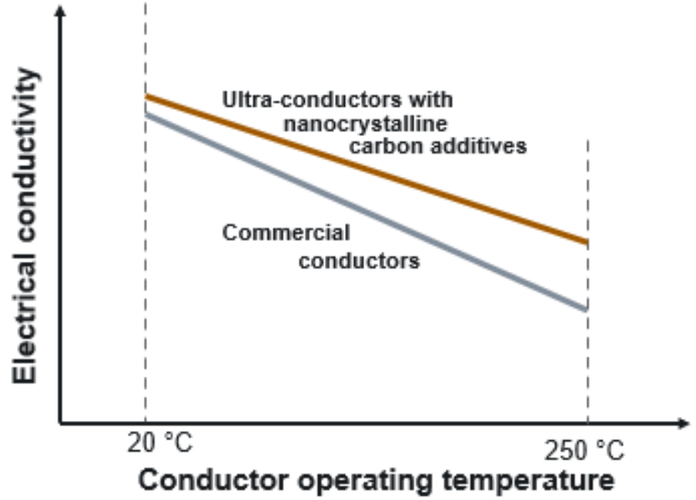
- **Metals with conductive additives showing higher local carrier (electron, phonon) velocities.**
- **Demonstrate enhanced electrical conductivity and lower temperature coefficient of resistance (TCR) at T > 20°C, *unlike superconductors*.**
- **Advantages of ultra-conductors include**
  - **Reduced critical material usage**
  - **Higher grid capacity**



Ultra-conductors are composites of metals (aluminum, copper) and nanocrystalline additives CNTs, graphene, MXenes)



High velocity carrier pathways developed in metals through the addition of nanocrystalline additives



Representative plot of conductor conductivity as a function of temperature

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Background – Challenges in ultra-conductor development

Industry adoption of ultra-conductors needs bulk forms, not films/foils/particles

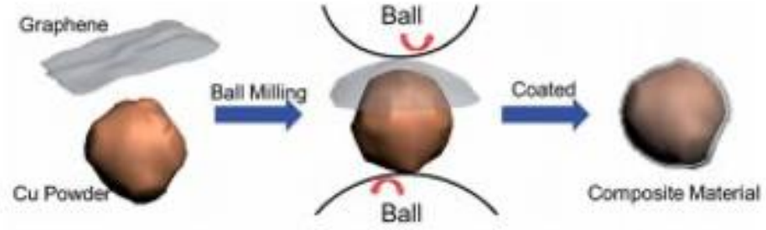
Current state-of-the-art material systems with proven enhanced electrical performance



Graphene coated copper film (sold commercially)



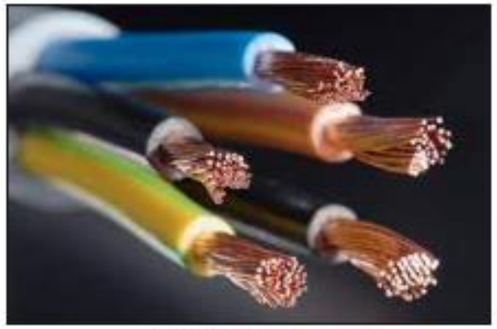
Graphene coated aluminum film (sold commercially)



Graphene coated copper powders (lab scale demonstration)

?

Industrially relevant conductor forms



Building wires



Overhead power transmission cables



Busbar assemblies



Electric machine components

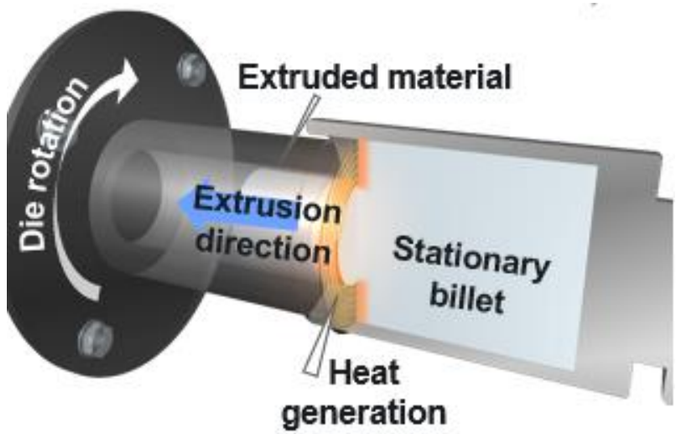
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Proposed Solution

ShAPE – a new paradigm for bulk-scale high-performance conductor development



First gen shear assisted processing and extrusion (ShAPE) machine

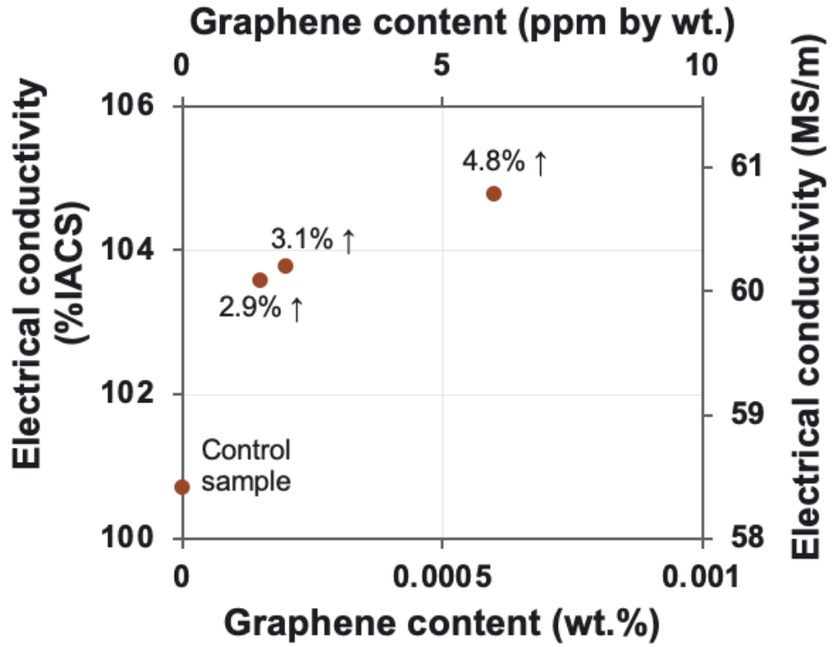


Schematic of ShAPE process showing die, billet and extruded material

- **ShAPE™ - Shear Assisted Processing and Extrusion**
  - **Can form metal, composites and alloy feedstocks**
  - **Final products are rods, tubes, bars**
  - **Wide variety of feedstocks**
  - **Homogeneous microstructures with minimal porosity**



Graphene coated copper foils (procured commercially) feedstock for ShAPE

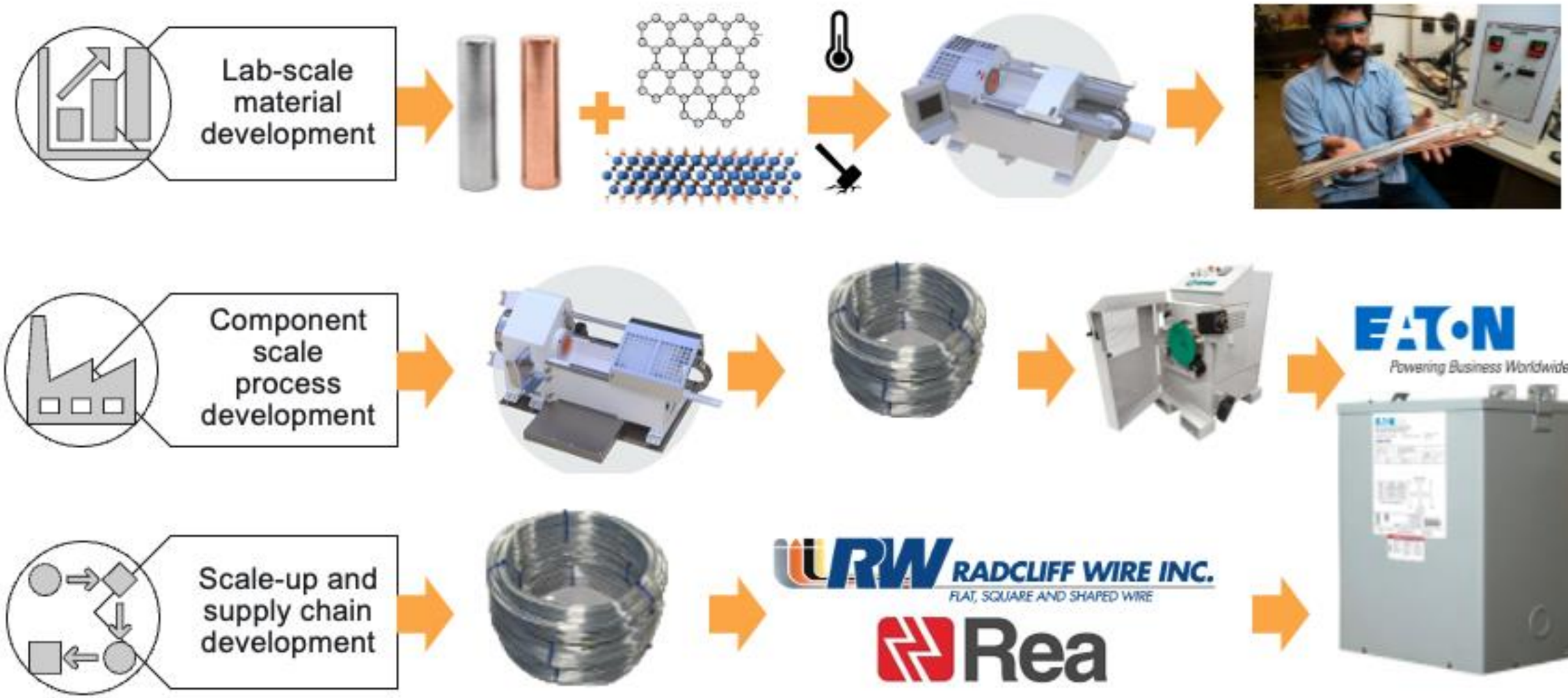


Electrical conductivity of copper + graphene composites as a function of graphene content

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Proposed Solution

Ultra-conductors with ↑ electrical performance in relevant form factors for component-scale demo

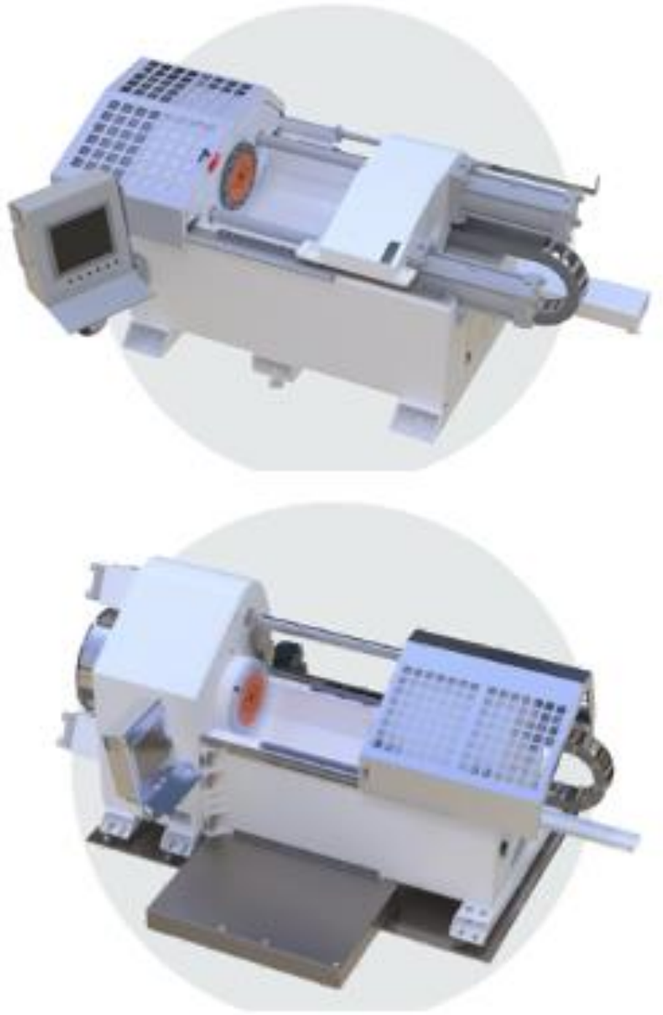


Schematic showing lab-scale material development, component scale process development and scale-up and supply chain development activities

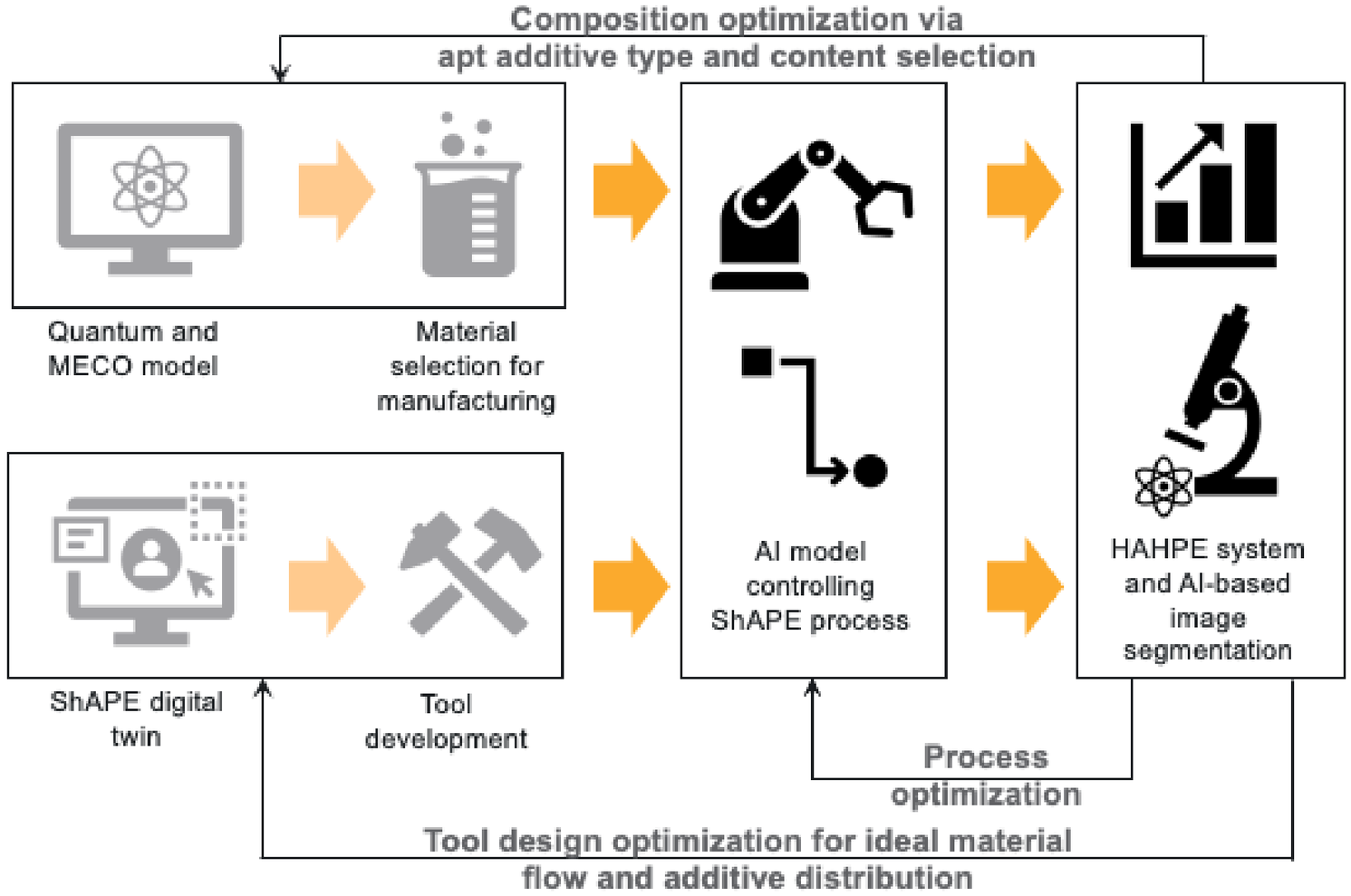
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Technical Approach & Innovation

Developing ultra-conductors with nanocrystalline additives demonstrating enhanced electrical properties



First and second-generation ShAPE machines at PNNL

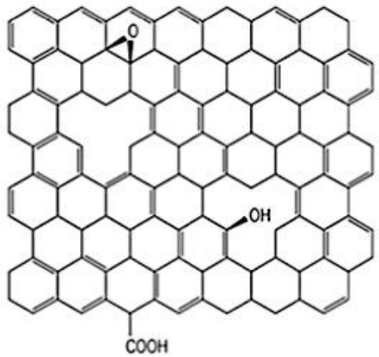


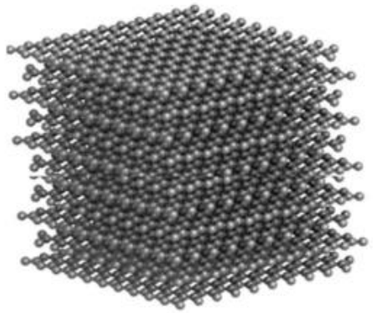
Schematic for lab-scale material development cycle adopted for ultra-conductor material (composition) discovery

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Significant Results

Lab-scale ShAPE ultra-conductors with ↑ electrical performance at elevated temperatures





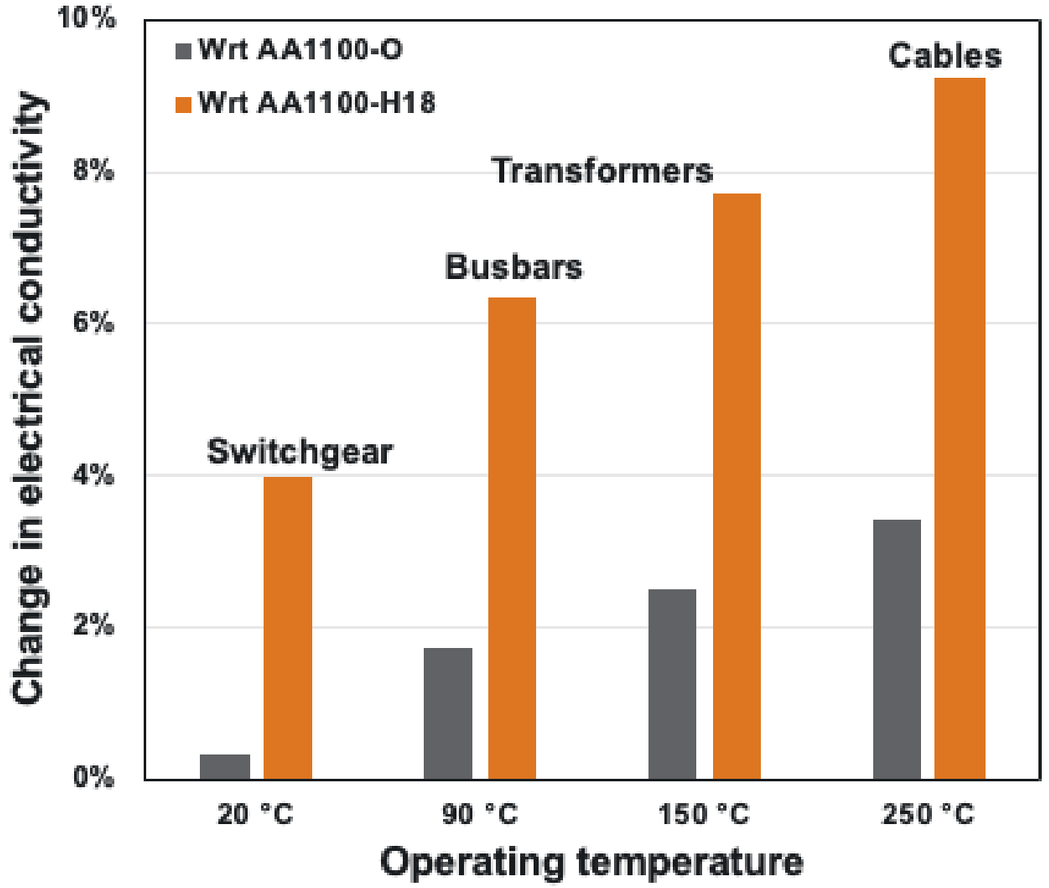
0.1 wt.% additive

0.5 h sonication

Reduced graphene oxide structure (left), and side view showing multi-layers (right)



Introduction of reduced graphene oxide additives into the AA1100O/H18 billet prior to the friction extrusion into 1-m-long 10AWG wires

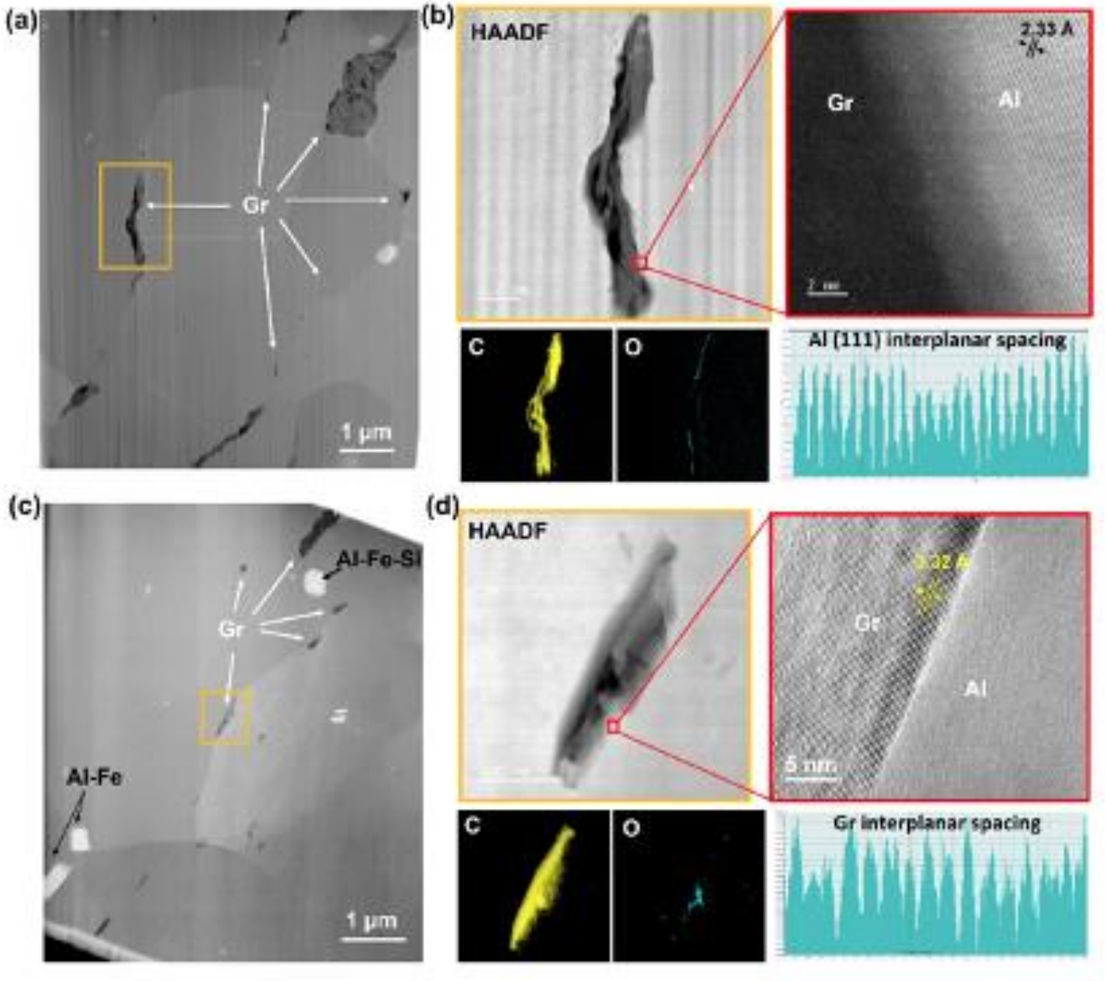


Change in electrical conductivity (%) of ShAPE ultra-conductors with respect to (wrt) AA1100-O and AA1100-H18 wires at different operating temperatures relevant for grid equipment

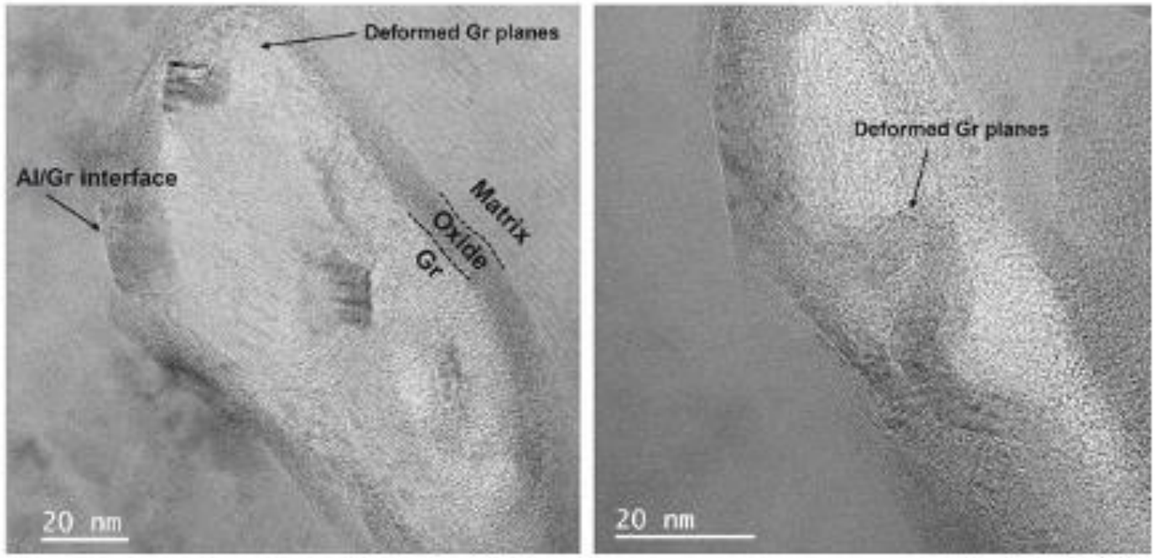
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Background & Significant Results

Unique microstructures and defect-free interfaces in ShAPE ultra-conductors



Reduced graphene oxide additives at different locations in ultra-conductors with graphitic structure along with oxygen species



Close-up images of reduced graphene oxide additives with pore-free interfaces with aluminum matrix

- **Graphitic additives (suspected to be semiconductor in nature), present at grain boundaries and grain interiors.**
- **Minimal porosity observed in the microstructures.**
- **Oxygen present at the interfaces (confirmed by atom probe tomography*).**

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Significant results

Eaton distribution transformer windings manufactured using ShAPE ultra-conductors

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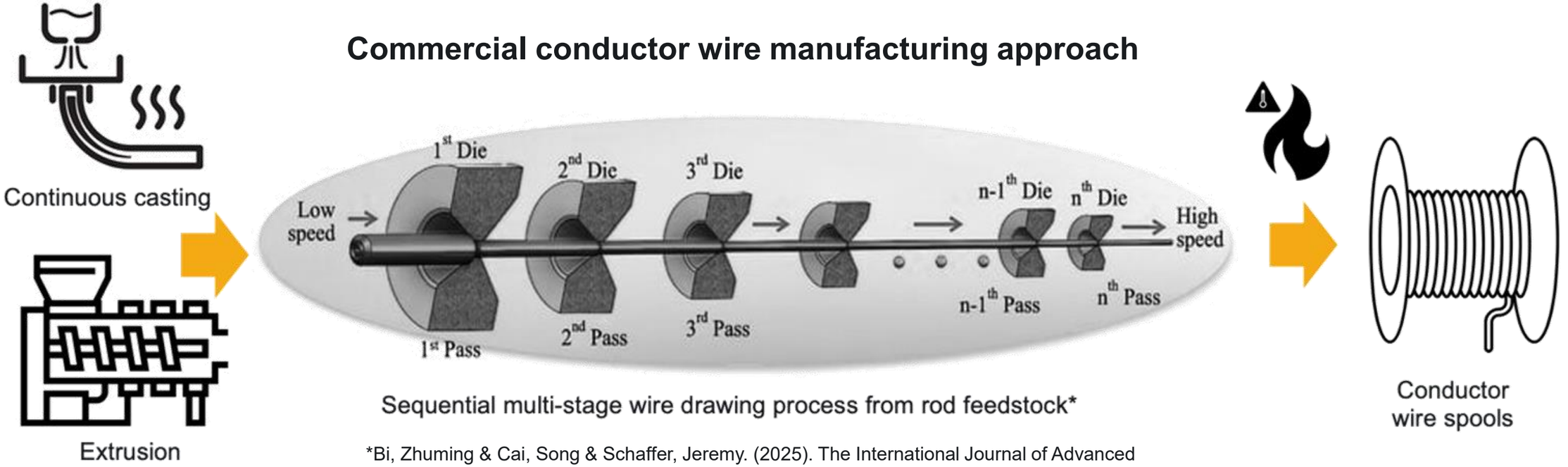
Lab-scale dimensions

Geometry	Diameter	Length
Circular	AWG10-19 (0.91-2.5 mm)	3 m
Square	5-mm-side	0.5 m

Component-scale dimensions

Section	Geometry	Diameter	Length	# of wires
HV	Circular	AWG19 (0.91 mm)	1400 m	1
LV	Trapezoid	eq. AWG4 (4-5 mm)	67 m	4

Commercial conductor wire manufacturing approach



Sequential multi-stage wire drawing process from rod feedstock*

*Bi, Zhuming & Cai, Song & Schaffer, Jeremy. (2025). The International Journal of Advanced Manufacturing Technology. 140. 3393-3413.

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Significant results

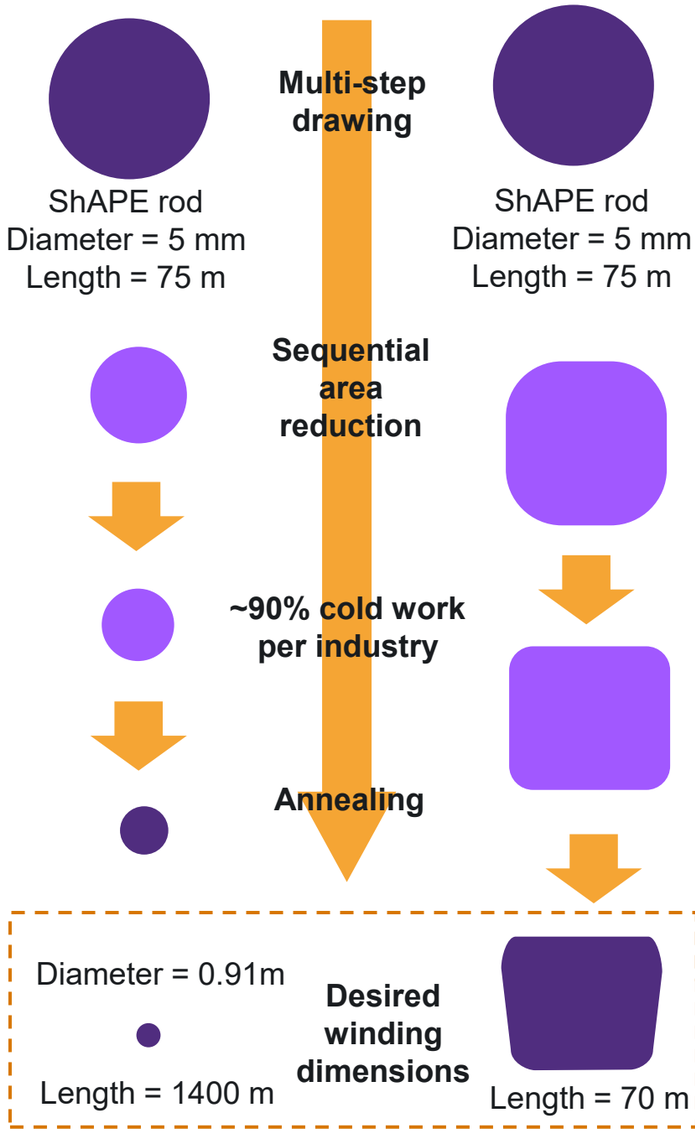
ShAPE ultra-conductor distributi transformer windings



Second generation ShAPE 2.0 machine

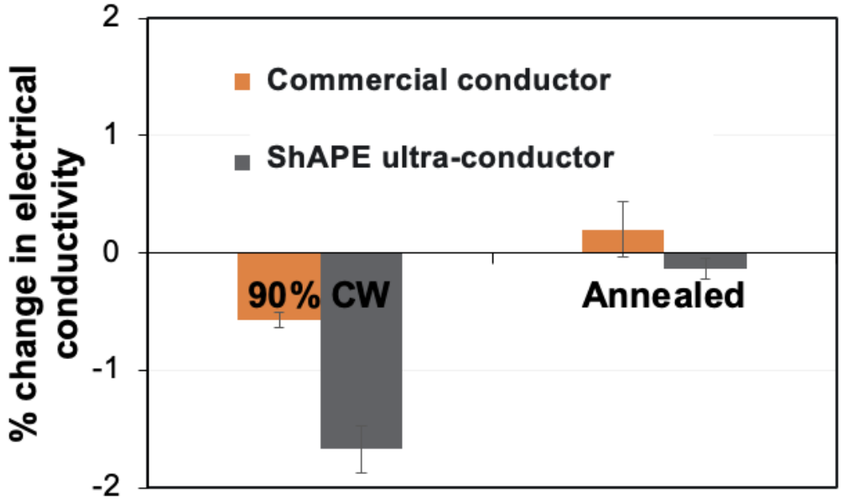


Representative 5-mm-diameter 75-m-long ultra-conductor rods extruded via ShAPE 2.0





Component scale wire drawing equipment

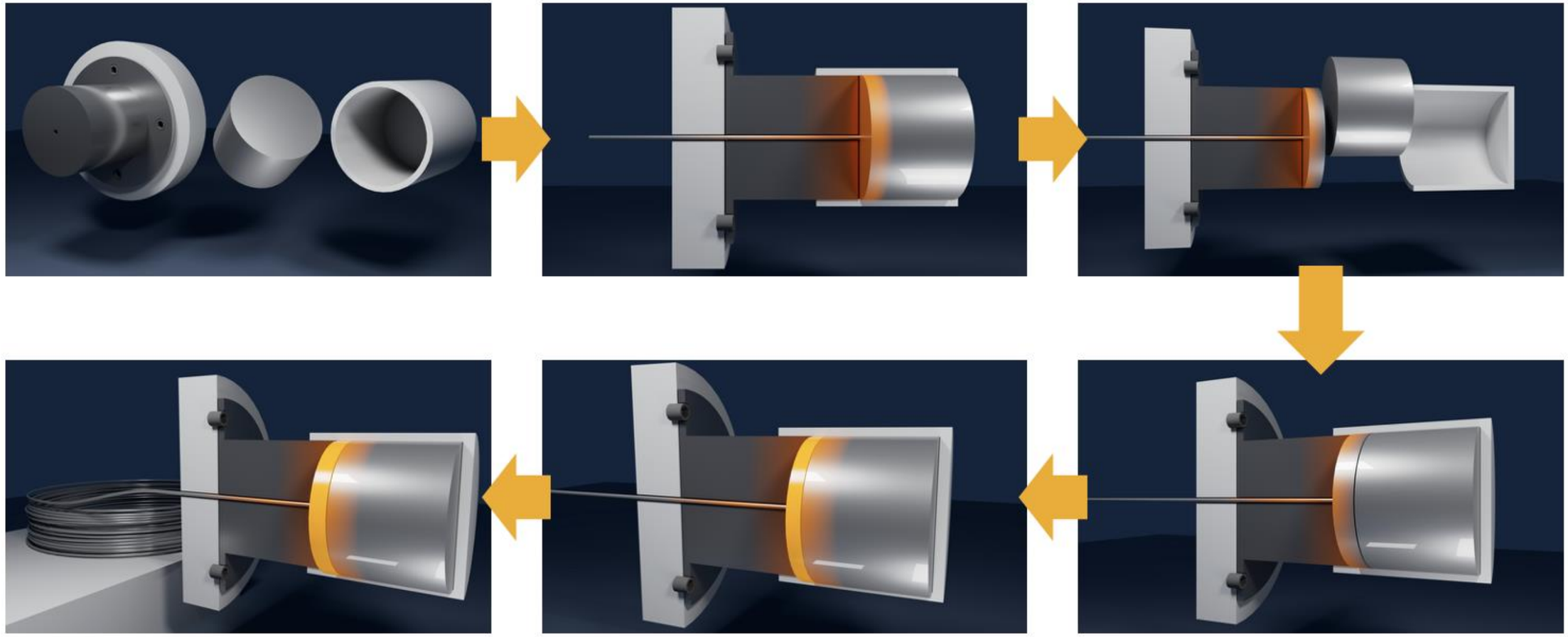


Electrical performance of ultra-conductors post-drawing to ~90% cold work (CW) and annealing

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Significant results

Ultra-conductors manufactured in scalable pathways for industry-ready supply chains

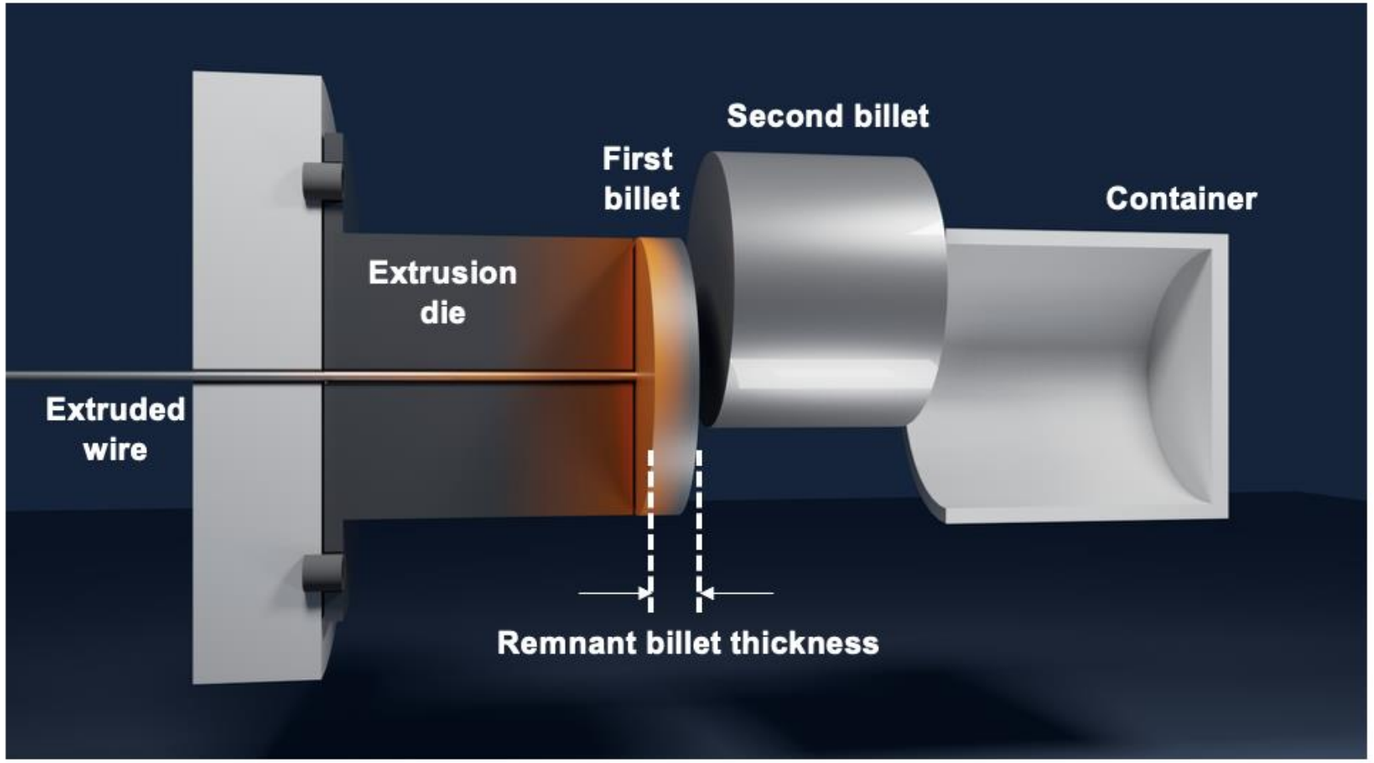


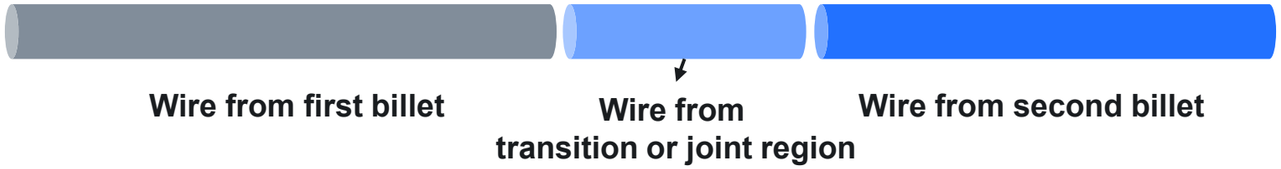
Schematic of friction extrusion of ultra-conductor on ShAPE platform in semi-continuous process to make wire spools that can be drawn, annealed and tested

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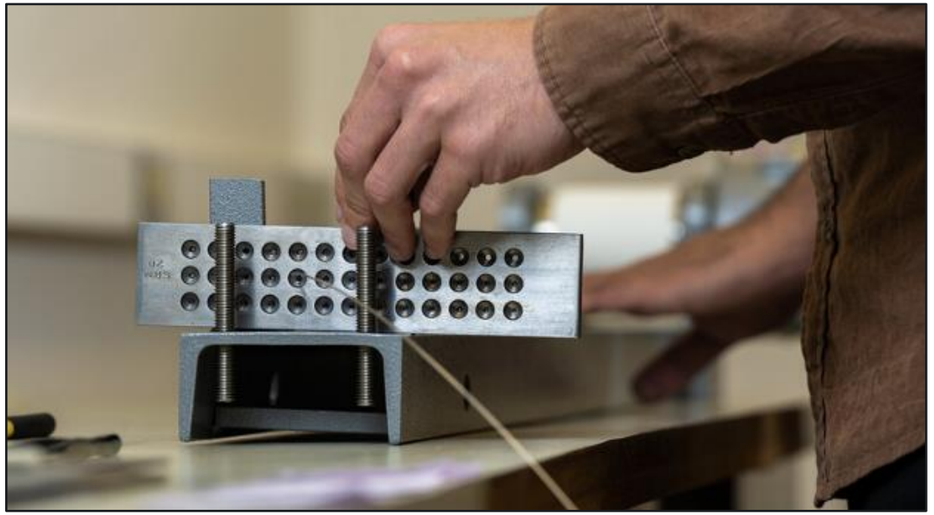
Significant Results

Robust semi-continuous extrusion process envelopes developed for industry adoption

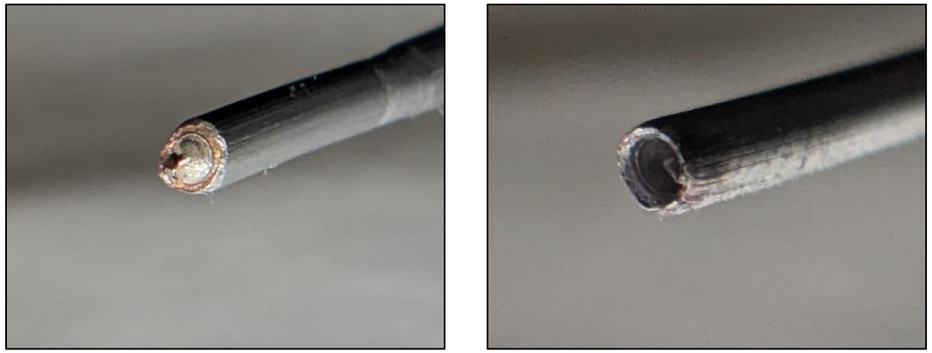




Schematic showing different portions of the semi-extruded ShAPE wire corresponding to the different portions of source feedstock billets



Bench-scale drawing of semi-continuous ShAPE ultra-conductor wires



Post-drawing failure cross-section of ShAPE semi-continuous wire made with sub-optimized parameters

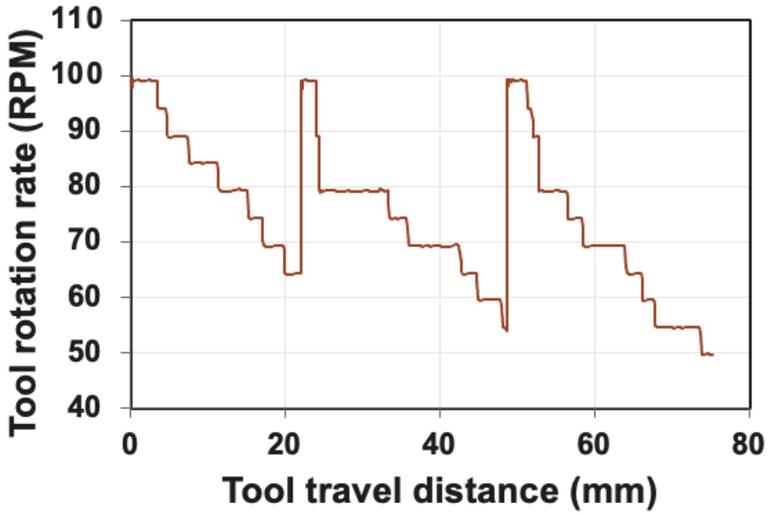
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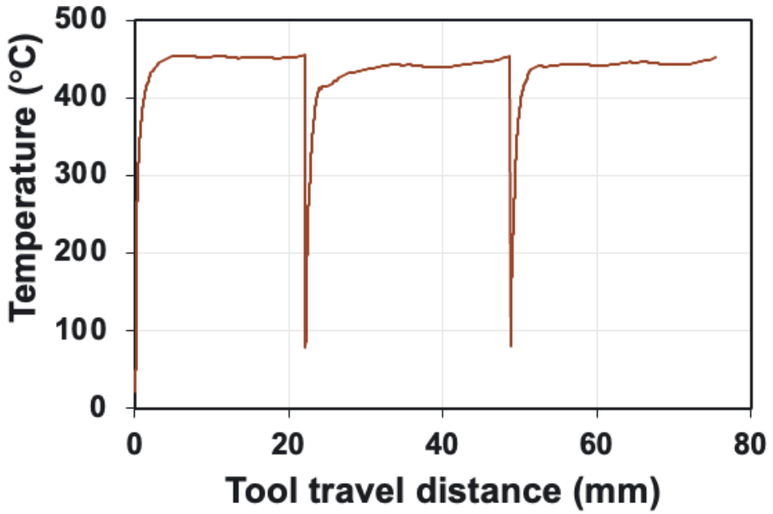
Significant Results

Robust semi-continuous extrusion process envelopes developed for industry adoption

Number of drawing passes tolerated by semi-continuous ShAPE wires and corresponding cold work as well as diameter:

#	Parameters	Number of pass												
		P0	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13
A	Cold work (%)	0	19.7	33.4	44.6	56.2	61.3	65.4	69.6	Wire broke					
	Diameter (mm)	2.53	2.27	2.07	1.88	1.67	1.57	1.49	1.39						
B	Cold work (%)	0	18.7	32.2	43.7	55.5	60.6	64.5	69.1	73.5	76.9	80.3	83.1	84.5	86.8
	Diameter (mm)	2.51	2.26	2.07	1.88	1.67	1.57	1.49	1.39	1.29	1.20	1.11	1.03	0.99	0.91





Optimized tool rotation rate and temperature as a function of tool travel during semi-continuous ShAPE ultra-conductor wire extrusion

Paper submitted (Nature family journal)

Invention disclosure filed

Non-provisional patent application

Research licensing in progress

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Technical Approach & Innovation

Developing commercial ultra-conductor transformer winding supply-chain pathways

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R&D Organization

Performance standards, costing, production volume

OEMs

Need vendors for advanced materials

EATON Powering Business Worldwide

Tech. dev., lab-to-market plans for US supply chains

Market pull for adv. mat. component US supply chains

Component manufacturers

Small businesses
Deep-tech investors

Ultra-Conductor Supply Chain Development



Ultra-conductor spools from ShAPE 2.0

RW RADCLIFF WIRE INC.

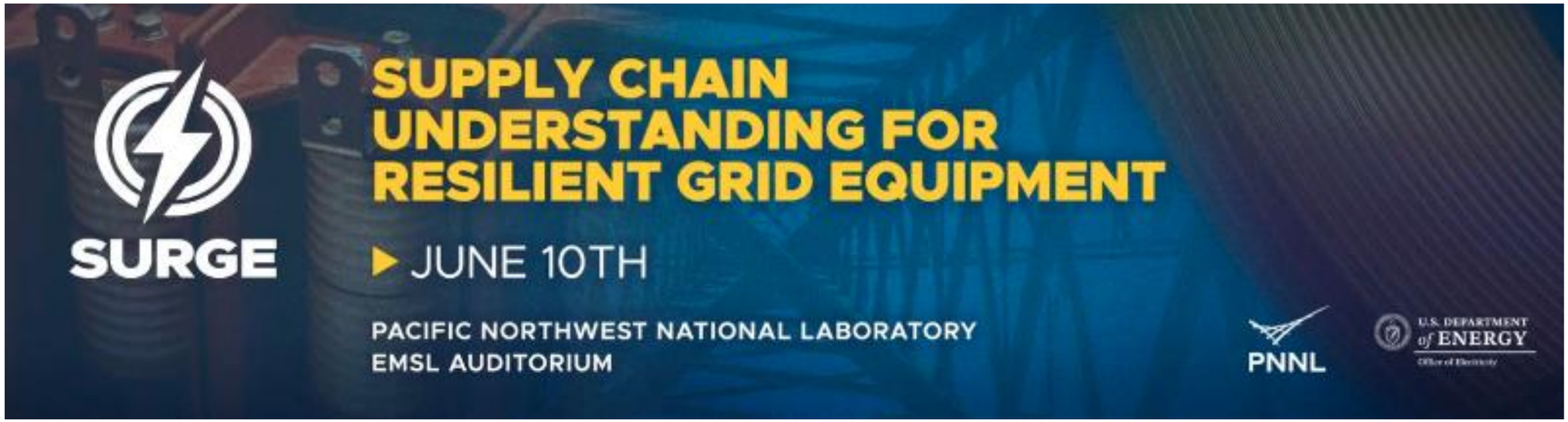
Rea

- Drawing
- Rolling
- Annealing
- Coating

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Significant Results

PNNL convened the grid equipment supply chains to understand the delivery issues



Utilities and End Users

Seattle City Light

Bonneville POWER ADMINISTRATION

PSE PUGET SOUND ENERGY

Original Equipment Manufactures

Hitachi Energy

GE VERNOVA

SIEMENS energy

Schneider Electric

Component Manufacturers

Metglas®

prysmian

EATON

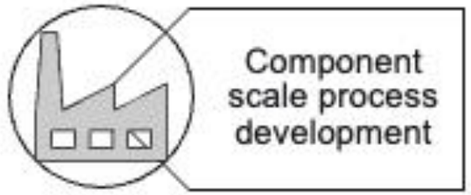
COREPOWER MAGNETICS

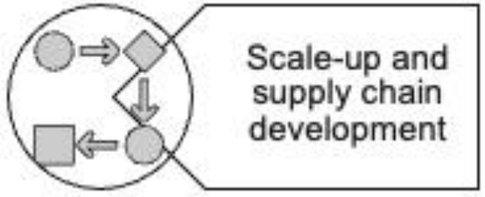
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Conclusions and Impact

Ultra-conductors developed and demonstrated at component scales leading to supply chains













RW RADCLIFF WIRE INC.
FLAT, SQUARE AND SHAPED WIRE

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Powering Business Worldwide

- **Bulk-scale ultra-conductors with ~2-8% higher electrical performance over commercial conductors demonstrated**
- **Component scale ultra-conductor feedstocks for distribution transformer windings manufactured**
- **Ultra-conductor supply chain pathways in US identified**
  - **Invention disclosure reports for continuous ultra-conductors manufacturing**
  - **Supply-chain insertion points for technology**
  - **Deep tech investors engaged for commercialization**

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Acknowledgements

Widespread interest, support and engagement from OE and industry

U.S. DEPARTMENT of ENERGY







Southwire®

Southern Company

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Utilities and End Users

Original Equipment Manufactures

Component Manufacturers

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PSE PUGET SOUND ENERGY

SIEMENS energy

Schneider Electric

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COREPOWER MAGNETICS

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Project Manager



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Lab-scale ShAPE



Aditya Nittala
Conductors SME



Scott Taysom
ShAPE Scale-up



Hrishikesh Das
Manufacturing SME



Kevin Schneider
OE Sub-Sector Manager



Shivakant Shukla
Microstructure



Tej Poudel
Lab-scale ShAPE



Tyler Tueller
Feedstock Prep



Areesa Trevino
Measurement SME



Kate Rader
Castings

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Thank you

