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Advanced Materials and Manufacturing Technologies Office

CABLE 2022

Big Idea Workshop

Workshop Summary Report

July 20–21, 2022

Within the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), the Advanced Materials and Manufacturing Technologies Office (AMMTO) supports a globally competitive U.S. manufacturing sector that accelerates the adoption of innovative materials and manufacturing technologies in support of a clean, decarbonized economy.

This document was prepared for DOE EERE's AMMTO as a collaborative effort by AMMTO, Argonne National Laboratory (ANL), and Energetics.

Other acknowledgements as necessary. A special thank you this year to DOE's Office of Electricity including panel leader Andre Periera and CABLE SBIR Technology Manager Ben Shrager. The report also benefitted from ANL's Santanu Chauduri for his leadership on the Read Ahead document that provided the foundation to this report. Last but not least, all the following panel leaders deserve a special mention for their efforts before, during, and after the workshop in providing leadership and invaluable input to this report:

- Andre Pereira (DOE Office of Electricity) – Electric Conductors Panel
- Antonio Bouza (DOE Building Technology Office) – Thermal Conductors Panel
- Claudia Mewes (DOE Office of Science Basic Energy Sciences) – CABLE Theory and Modeling Panel
- Dava Keavney (DOE Office of Science Basic Energy Sciences) – Testing, Characterization, and Computing for CABLE Researchers Panel
- Henry de Groh (NASA) – Electric Conductors Panel
- Jake Russell (DOE Advanced Research Projects Agency–Energy) – Superconductors Panel
- Kim Tran (DOE Advanced Manufacturing Office) – Testing, Characterization, and Computing for CABLE Researchers Panel
- Santanu Chauduri (ANL) – CABLE Theory and Modeling Panel
- William Worek (ANL) – Thermal Conductors Panel.

Finally, a special thank you to Cameron Bordinat of Energetics now supporting the new EERE Office of Industrial Efficiency and Decarbonization, who despite being reorganized into a different organization kept working with the AMMTO CABLE team to finish this report—and do so faster than we finished the previous CABLE Workshop Report.

Disclaimer

List of Acronyms

ACCC	Aluminum conductor composite core
ACCR	Aluminum conductor composite reinforced
ACSR	Aluminum conductor steel reinforced
AI	Artificial intelligence
ALCC	ASCR Leadership Computing Challenge
ALCF	Argonne Leadership Computing Facility
ALS	Advanced Light Source
AMMTO	Advanced Materials and Manufacturing Technologies Office
AMO	Advanced Manufacturing Office
ANL	Argonne National Laboratory
AOHC	Advanced overhead conductors
APS	Advanced Photon Source
ARPA-e	Advanced research projects agency–energy
ASCR	Advanced Scientific Computing Research
ASTM	American Society for Testing and Materials
BCS	Bardeen–Cooper–Schrieffer
BES	Basic Energy Sciences (U.S. Department of Energy)
BNL	Brookhaven National Laboratory
CABLE	Conductivity-enhanced materials for Affordable, Breakthrough Leapfrog Electric and thermal applications
CF	Carbon fiber
CFD	Computational Fluid Dynamics
CFN	Center for Functional Nanomaterials
CFTF	Carbon Fiber Technology Facility
CHiMaD	Center of Hierarchical Materials Design
CINT	Center for Integrated Nanotechnologies
CNM	Center for Nanoscale Materials
CNMS	Center for Nanophase Materials Sciences
CNTs	Carbon nanotubes
CRDA	Cooperative Research and Development Agreement
CVD	Chemical vapor deposition
DD	Director’s Discretionary
DFT	Density functional theory
DMMC	Deformed metal-metal composites
DOE	U.S. Department of Energy
DS	Dry-spun
EBM	Electron beam melting
EERE	Energy Efficiency and Renewable Energy
FANTASTX	Fully-Automated Nanoscale To Atomistic Structures from Theory and eXperiment
FOM	Figure of merit
FY	Fiscal year
FTIR	Fourier-transform infrared spectroscopy
GF	Graphene fiber
GHG	Greenhouse gas
GNS	Graphene nanosheets
HD	High defect
HFIR	High Flux Isotope Reactor
HPC	High-performance computing
HPC4EI	HPC4Energy Innovation

HVAC	Heating, ventilation, and air conditioning
HVDC	High voltage low current
HTSs	High-temperature superconductors
IACS	International Annealed Copper Standard
IBS	Iron-based superconductors
ICMD	Integrated Computational Materials Design
ICME	Integrated Computational Materials Engineering
iCMHX	Integrated cross-media heat exchanger
INCITE	Innovative and Novel Computational Impact on Theory and Experiment
ISO	International Standards Organization
ITC	Interfacial thermal conductance
LBNL	Laurence Berkely National Laboratory
LCLS	Linac Coherent Light Source
LD	Low defect
LLNL	Lawrence Livermore National Laboratory
MCTS	Monte Carlo Tree Search
MD	Molecular dynamics
MEPs	Manufacturing Extension Partnerships
ML	Machine learning
MMCs	Metal matrix composites
MOCVD	Metal–organic chemical vapor deposition
MWCNTs	Multi-walled CNTs
NASA	National Aeronautics and Space Administration
NETL	National Energy Technology Laboratory
NMR	Nuclear magnetic resonance
NREL	National Renewable Energy Laboratory
NSRC	Nanoscale Research Centers
ORNL	Oak Ridge National Laboratory
PCM	Phase Change Material
PNNL	Pacific Northwest National Laboratory
PRISMS	PRedictive Integrated Structural Materials Science
Q&A	Question and answer
R&D	Research and Development
REBCO	Rare-earth barium copper oxide
SBIR/STTR	Small Business Innovation Research/Small Business Technology Transfer
SC	Office of Science
ShAPE	Sheer assisted processing and extrusion
SLAC	Stanford Linear Accelerator Center
SMEs	Subject matter experts
SNS	Spallation Neutron Source
SWCNTs	Single-walled CNTs
TCR	Temperature conductivity resistance
TEM	Transmission electron microscopy
TMF	The Molecular Foundry
TRL	Technical readiness level
USAXS	Ultra-small angle x-ray scattering
VHP	Vacuum hot pressing
WS	Wet-spun
XPS	X-Ray Photoelectron Spectroscopy

Executive Summary

Several very strong messages came from the second CABLE workshop.

First, and new for this workshop, was the strong need to deploy advanced conductor systems for power line applications within the next 5 to 7 years if CABLE is to contribute to the Biden Administration goal to create a zero-carbon grid by 2035. The CABLE Team had become aware of the importance of so called "advanced overhead conductors" (AOHC) to the grid in early 2022 with the March publication of the report, "Advanced Conductors on Existing Transmission Corridors to Accelerate Low Cost Decarbonization" by a broad coalition of AOHC manufacturers, renewable energy, trade, and environmental groups[1]. Consequently, The CABLE Team expanded the "contests" for the CABLE prize to include "Beat a conductor system" and invited representatives from the nascent domestic AOHC industry to speak at the workshop. The results of AOHC presentations and the discussion that followed will be a valuable input for funding opportunities being developed.

Second was the need for separate investment in thermal conductivity—especially scaleup and deployment. It was noted that several key applications for high thermal conductivity materials do not need high electrical conductivity. For example, in high thermal conductivity materials for 1) microelectronics electric insulator materials are often preferred or 2) for thermoelectric materials ratio of thermal to electric conductivity is part of the Seebeck coefficient figure of merit (FOM). As for what the investment should be, in most cases, the development of a thermal conductivity FOA was preferred to development of a separate prize. In addition to thermal conductivity, many such applications had other stringent minimum requirements for key properties such as small footprint, light weight, high voltage, (e.g., compact heat exchangers). We expect these metrics to influence funding opportunity preparations for FY24 and beyond.

A third new message was about the impending commercial emergence of superconductivity—after decades of applied and manufacturing research and development (R&D) several innovations—including thin films—are nearly ready to deploy in hot new markets such as compact fusion energy. In this workshop, superconductors---both low temperature (e.g., MgB2) and high temperature (e.g., REBCO) were recognized as a vital part of the CABLE innovation ecosystem needed to help meet 2035 and 2050 grid and economy emissions reduction goals. Several speakers noted the need to ramp up scale-up and production of REBCO tape superconductors, which appear to be the preferred—or even the only technology that could make sufficiently high and small footprint magnetic fields for modular compact nuclear fusion reactors.

Another strong message, repeated from the first CABLE workshop, was the need to bring theory modelling and simulation to bear on the development and scale up of newer (e.g., nano carbon and nanocarbon metal-based) enhanced conductor fabrication technologies. Participants suggested that in addition to SBIR and Prize, a regular applied research funding opportunity that involves labs and universities to do theory, modelling, and characterization, as well as fabrication research, may be needed.

Altogether, the second workshop was an enormous success that squarely addressed the challenges raised in the first workshop and detailed new challenges for the CABLE team. Many thanks to all of the in-person and virtual participants.

[1] Grid Strategies Inc, 2022. https://acore.org/wp-content/uploads/2022/03/Advanced_Conductors_to_Accelerate_Grid_Decarbonization.pdf.

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Background

CABLE Big Idea Overview and History

Conductive materials are fundamental to nearly all energy use applications. Developing manufacturing processes for conductivity-enhanced materials would enable product manufacturers to lower costs, improve performance, and allow their customers and the United States to substantially improve energy efficiency and reduce greenhouse gas (GHG) emissions. The International Energy Agency estimates that 10 million miles of new transmission cable will be needed to connect renewables to the planet's grids in the next decade.[2] As a result, there is an urgent need for enhanced conductivity materials that can lower costs and improve performance of transmission cables—including resilience against extreme weather events.

The Administration has established the following GHG reduction goals to address the climate crisis: 50% reduction by 2030, net-zero grid by 2035, and net-zero economy by 2050. Meeting these goals will require major paradigms shifts in how energy—both electric and thermal energy—is created, delivered, stored, and consumed.[3] The passage of the Infrastructure and Jobs Act provides the United States with a once-in-a-generation opportunity to replace aging electric and transportation infrastructure with new high-performance materials.

As electrification expands worldwide in response to the climate crisis, so too will demand for conductivity-enhanced materials and applications. Decarbonization and electrification are two major pillars of a transition plan that rests on a third important need: reliable conductors that carry electrons safely and efficiently in massively diverse operational environments. In addition, an increasing demand for energy-efficient and compact heating and cooling for buildings is driving demand for improved heat-exchange systems. Conductivity-enhanced materials also support new transformational technologies ranging from electric cars, trains, and planes to smartphones, heat pumps, and other electrical and thermal technologies that improve people's everyday lives.

Table 1: DOE Offices Involved in CABLE

Office of Electricity
Office of Science
Office of Energy Efficiency and Renewable Energy (EERE)

Table 2: EERE Suboffices Involved in CABLE

Advanced Manufacturing Office
Building Technologies Office
Geothermal Technologies Office
Hydrogen and Fuel Cells Technologies Office
Solar Energy Technologies Office
Vehicle Technologies Office
Water Power Technologies Office
Wind Energy Technologies Office

The demand for CABLE materials (Conductivity-enhanced materials for Affordable, Breakthrough Leapfrog Electric and Thermal Applications) will therefore grow rapidly as sectors become increasingly electrified and recover more thermal energy to aid decarbonization. There is also an urgent need to upgrade electric systems for greater grid reliability as more renewables and distributed energy resources are integrated. CABLE materials also can provide increased grid resilience in the face of evolving threats, such as cyberattacks and extreme weather. The emergent energy transition offers a once-in-a-lifetime window of opportunity to upgrade the fundamental materials and applications that support our energy delivery systems.

To supercharge the effort to develop new conductors, the Advanced Materials and Manufacturing Technologies Office (AMMTO) is leading the CABLE Big Idea initiative,

[2] Wanner, B., and L. Cozzi; 2020, "Electricity Security in Tomorrow's Power Systems," International Energy Agency, October 23, https://www.iea.org/articles/electricity-security-in-tomorrow-s-power-systems.
[3] The White House, 2021, The Long-Term Strategy of the United States Pathways to Net-Zero Greenhouse Gas Emissions by 2050, www.whitehouse.gov.

supported by the Office of Electricity, the Office of Science, and seven other offices within the Office of Energy Efficiency and Renewable Energy (EERE) (see Table 2).

The first major effort under CABLE was the development of a CABLE Topic through the U.S. Department of Energy's (DOE's) fiscal year (FY) 2021 Small Business Innovation Research/Small Business Technology Transfer (SBIR/STTR) program, which seeks to increase private-sector commercialization of technology developed through DOE-supported research and development (R&D). SBIR/STTR stimulates technological innovation in the private sector, encourages participation by woman-owned and minority-owned small businesses, and improves the return on investment from federally funded research for economic and social benefits to the nation. Ten CABLE proposals were awarded under FY 2021 SBIR/STTR funding. The submission window for FY 2022 SBIR/STTR proposals closed earlier this year. Phase I included two CABLE-related topics, and successful FY 2021 SBIR/STTR teams could apply for Phase II. 13 CABLE proposals, 8 Phase I and 5 Phase II, were selected for the FY 2022 SBIR/STTR program.

Figure 1: CABLE Prize Stage 2 winners announced April 2023

The second major activity was the launch of the CABLE Conductor Manufacturing Prize in March 2021. The $4.5 million prize encourages researchers and inventors to develop and manufacture breakthrough conductivity-enhanced materials. Competitors in Phase I had to design affordable conductors that demonstrated significant enhancements in conductivity and enable U.S. manufacturers to leapfrog to next-generation materials. Stage 1 of the prize included three technical classes of conductivity-enhanced materials: 1) metal enhanced with nanocarbon, 2) metal enhanced without nanocarbon, and 3) non-metallic materials (e.g., polymer or nanocarbon) enhanced with metal. Ten teams were selected for the Stage 1 prize.

More recently, in April 2022, Stage 2 of the CABLE Prize was launched and 7 winners were announced one year later in April 2023. Stage 2 involved testing of conductivity-enhanced materials and planning for scale-up and manufacture of the materials. This Stage involved the creation of separate contests: Beat Copper (conductivity); Beat Aluminum (conductivity + low density) and Beat a Conductor System. There were four winners competing in the Beat Copper contest. No winners qualified for the Beat Aluminum contest, but two of the three Beat a Conductor System winners competed with aluminum-based systems with a third competing with a superconductor system. This stage also established connections between Prize teams and external support, including national laboratories or other American-Made Challenges Network providers. More information about the CABLE Conductor Manufacturing Prize can be found on the American-Made Challenges website at https://americanmadechallenges.org/challenges/cable/.

More information about the overall CABLE initiative is available on the CABLE website at cable-bigidea.anl.gov/.

Workshop Metrics

The CABLE 2022 Big Idea Workshop took place over two consecutive days, from July 20 to 21, 2022. The event was held in a hybrid format, in-person at Argonne National Laboratory (ANL) and virtually. The agenda for each day lasted approximately seven hours, featuring five separate panel sessions, two showcases, and plenary talks, for a total of 57 speakers and panel moderators (see Appendix A for the detailed agenda).

The workshop brought together over 180 scientific and technical experts to participate in panel sessions and facilitated discussions. There was broad participation from various stakeholder groups, including different federal agencies, national laboratories, academia, and private industry. The breakdown of attendees by stakeholder group is provided in Figure 2. Due to COVID-19 restrictions, a limited number of participants were allowed to attend in person. Those who did attend in person got Lab tours and reception.

The wide array of stakeholders was able to benefit from the communications tailored to all audiences from theorists to manufacturers to modelers.

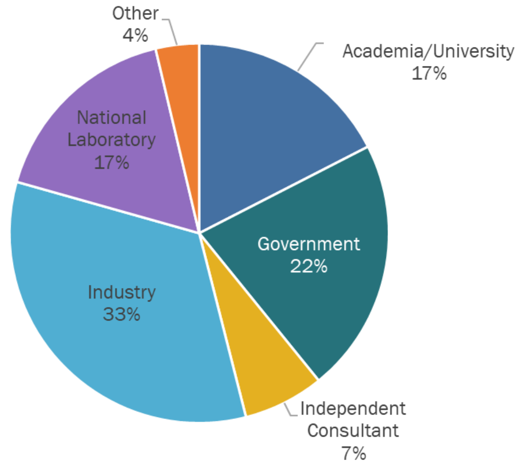

Figure 2: CABLE Workshop participant breakdown by stakeholder group

Workshop Objectives

AMMTO's predecessor, the Advanced Manufacturing Office (AMO) hosted the CABLE 2022 Big Idea Workshop to gather information from stakeholders on the state of the art in conductivity-enhanced materials and facilitate connections between stakeholder groups to build and strengthen collaborative partnerships within the CABLE research ecosystem—especially through in-person contact now that it was allowed! Stakeholders include scientists, engineers, manufacturers, materials experts, utility companies, and other entities within the conductor material and electrical product manufacturing supply chain who can help identify potential areas for future RD&D and program activities.

This workshop featured talks from CABLE Prize awardees and national laboratories outlining their facilities and capabilities to strongly emphasize networking opportunities among stakeholders in the CABLE ecosystem. CABLE research has been funded through a lab call project, two years of SBIR and the 1st Stage of the CABLE prize and continued interactions were encouraged to cross-pollinate ideas and generate potential teaming arrangements for future RD&D and commercialization efforts.

Workshop Overview

To better understand the state-of-the-art and opportunities on the horizon, as well as facilitate interactions within the CABLE research ecosystem, networking activities were interspersed with technical presentations throughout the workshop.

Day 1

For in-person participants, the first day started with tours of various facilities at Argonne National Laboratory. The tours visited Argonne's Advanced Photon Source, Materials Engineering Research Facility, Argonne Leadership Computing Facility, and Center for Nanoscale Materials.

Dr. Tina Kaarsberg, CABLE workshop chair, opened the workshop by welcoming everyone and introducing Dr. Paul Kearns, ANL Laboratory Director, who highlighted the importance of conductivity-enhanced materials and summarized ANL's capabilities. Then, Dr. Mathew Ringer, NREL Laboratory Program Manager for Advanced Manufacturing, briefly noted the national laboratories are a resource with considerable research expertise that can be leveraged by the CABLE ecosystem. The first plenary speaker, Dr. Srinivas Siripurapu, Chief R&D Officer and Chief Innovation Officer at Prysmian Group stressed the importance of the CABLE program by highlighting electricity production and use trends shaping society and application drivers where CABLE innovations are needed.

The opening remarks were followed by the Testing, Characterization, and Computing panel featuring six speakers—notably all women—discussing available capabilities for CABLE researchers; CABLE Prize introduction and competitor showcase introducing CABLE Stage 1 winners; a talk by Paramita Das discussing current trends and their impacts on metal mining and supply chain; and a National Laboratory showcase highlighting the capabilities and resources found at DOE national laboratories. The first day closed with a facilitated discussion, identifying the primary challenge preventing long-term success and contributions from the CABLE ecosystem that can help address them. This activity was meant to stimulate cross-pollination of ideas and facilitate connections among workshop participants. For in-person participants, a reception followed the facilitated discussion.

Day 2

The second day began with opening remarks from Dr. Diana Bauer, AMO Acting Deputy Director, who provided background on AMO and discussed the CABLE program, including recent Stage 1 Prize and SBIR winners and the CABLE program schedule. This was followed by four panel sessions, Electric Conductors, which was held in parallel with Thermal Conductors, Superconductors, and CABLE Theory and Modeling. Following the panel discussions, the participants broke out into small groups to flesh out action plan templates for the top four challenges that were identified on Day 1. The workshop concluded with brief closing remarks from Dr. Tina Kaarsberg.

More detailed discussion on the panels, presentations, and other workshop deliberations and conclusions are provided in the following chapters of this report. To put the workshop presentations and discussions in context, this report also includes additional background and other information that was not presented or discussed at the workshop. The full workshop agenda with links to all presentation slides is provided in Appendix A.

Testing, Characterization, and Computing

Testing and characterization are required for successful modeling of conductivity-enhanced materials. Detailed atomic and bulk characterization of material samples can lead to discovery and validation of the fundamental relationships between composition and microstructure. Many well-established measurement techniques are available to do this at bulk scale, and even at the nanoscale. There is emerging activity in trying to measure properties of atoms, from a single atom to a few atoms, and to develop sub-nanometer measurement techniques.

The Testing, Characterization, and Computing panel session consisted of Dava Keavney (DOE Office of Science), Ilke Arslan (Argonne National Laboratory), Keerti Kappagantula (Pacific Northwest National Laboratory), Saniya LeBlanc (George Washington University), Jini Ramprakash (Argonne National Laboratory), and Robin Miles (Lawrence Livermore National Laboratory). It was co-chaired by Kimmai Tran (DOE AMO) and Dava Keavney (DOE Office of Science). Additional material is included where appropriate from the CABLE National Laboratory Showcase which included presentations and one-on-one sessions with Ames National Laboratory, Argonne National Laboratory, National Energy Technology Laboratory, National Renewable Energy Laboratory, Pacific Northwest National Laboratory, Sandia National Laboratories, and Prysmian Groups' laboratory system. Detailed talk summaries are included in Appendix B.

Conductivity Testing

While the use of American Society for Testing and Materials (ASTM) standards is generally encouraged for measuring sample performance in validation tests to determine electrical properties, such as conductivity and current density, the sample sizes required by ASTM may be too large for early-stage researchers in the CABLE research ecosystem. Uncertainty quantification and measurement repeatability must be emphasized to ensure reliable and honest reporting.

Electrical Conductivity

Electrical conductivity of materials is generally measured in the units of Siemens/meter (S/m), where 1 Siemen is equivalent to 1 amp per volt. While Siemens/meter are common in scientific literature, a more common standard used in industry for electrical conductivity is called the International Annealed Copper Standard (IACS) measured as a percentage. The IACS% is a comparative value of the percent difference of the electrical conductivity of relative to the best measurement of annealed copper at 20°C 1913. Though 100% IACS =58.1 MS/m was thought to be an immutable physical standard at the time, advances in copper purification and fabrication have led to conductivities greater than 101%IACS for bulk copper.

Electrical conductivity of metallic conductors (typically in the form of wires) is measured per ASTM B193. Volume resistivity is determined using Ohm's law normalized over the specimen length and cross-sectional area. Quantifying sample geometry is crucial for ensuring reasonably low uncertainty in measurement. This is all the more important since metal/nanocarbon composites demonstrate ~1 to 10% improvement in conductivity through the addition of nanocarbon which has to be accurately measured and therefore requires a measurement system that has low measurement uncertainty. Typically, there is a preference in measuring the wire dimensions (diameter for round wires, width for square wires) using an optical micrometer. Given that the matrix metals demonstrate high conductivity, a nanovoltmeter is used to measure the voltage drop across a fixed length of the specimen when very low currents are passed through it. Temperature monitoring is essential to ensure that the wire temperature is at 20°C, as required by the ASTM standard since electrical conductivity of metals varies with temperature.

Keerti Kappagantula provided an example of an electrical property measurement set-up at the Pacific Northwest National Laboratory. The set-up comprises of a Keithley 2182A nanovoltmeter, a Keithley 2260B-30-72 DC power supply and an FLIR thermal camera. The DC power supply leads are connected in series and the nanovoltmeter leads that measure the voltage drop are connected in parallel. By measuring the voltage drop across specific lengths at prespecified low currents, electrical conductivity of the test samples is determined. A custom designed 3-foot-long aluminum slab functions as the base to hold the wire samples taut during electrical conductivity testing. The sample is suspended between the brass connectors, held in place by two machined plastic fixtures. One of the fixtures is free to move along the open grooves along the length of the base, which ensures the wire is taut while measuring the distance between the nanovoltmeter leads. The setup can measure bulk electrical conductivity of samples 300–900 mm long at a time. In addition, it is also possible to determine the electrical conductivity of samples at elevated temperature to calculate their temperature coefficient of resistance. The entire set up is housed in a temperature controlled environmental chamber that enables the accurate determination of current density at test conditions as well.

Thermal Conductivity

Thermal conductivity of materials is measured in the units of Watts/meter Kelvin (W/m K). When comparing metrology techniques used to measure thermal conductivity, there are multiple criteria to consider. Perhaps the most significant is the thickness of the film or material – thin films are typically a few microns, while thick samples are on the order of millimeters, and bulk considered larger. Some techniques are better for thin/thick films because the method only interrogates a small amount of material. Using this technique to measure a bulk sample would only provide characterization of a small volume at the surface of the sample. The range of thermal conductivities and the temperature range of the test must also be considered. There are techniques for which high temperature measurements are challenging or lack precedent. Techniques also vary based on whether they are direct or indirect measurements of thermal conductivity. For example, several techniques measure thermal diffusivity, so separate measurements, predictions, or assumptions of density and heat capacity are required to extract thermal conductivity.

Practical factors must also be considered when choosing a thermal conductivity testing technique. The cost, overhead, ease of implementation, and infrastructure required for techniques differ greatly. Users should consider factors such as their ability to build a custom setup in-house, availability of a user-friendly commercial tool, alignment between measurement throughput of the technique and the number of samples that need to be characterized, requirements for in-line characterization during material/device manufacturing, and sample requirements such as specified dimensions required for a given technique.

Saniya LeBlanc described five leading thermal metrology techniques and their associated testing standard, including guarded heat flux/hot plate, heat flow meter, flash diffusivity, transient hot wire, and differential scanning calorimetry. A comparison of common techniques is summarized in Table 3.

Table 3: Comparison of leading thermal metrology techniques

Metric	Guarded Heat Flux	Heat Flow Meter	Flash Diffusivity	Transient Hot Wire	3ω Method	Thermo-reflectance
Direct/Indirect[a]	D	D	I	D/I	D	I
Range of *k*	+	+	++	++	-	-
Temperature Range	+	-	++	+	-	-
Contact/Non-contact[b]	C	C	N	C	C	N
Cost/Overhead	+	+	- -	+	-	--
Ease of Implementation	+	+	-	+	--	--
Bulk/Thin Film[c]	B	B	B	B	B/F	B/F

Characterization

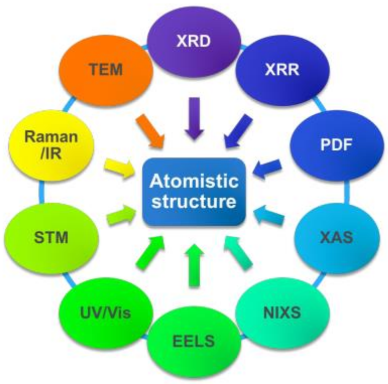

Figure 3: Characterization techniques for elucidating atomic structure (Chan 2022).

While testing techniques are used to measure the conductivity of materials of interest, characterization techniques are needed to evaluate key parameters of the material and atomistic structure to understand the origins of conductivity enhancement. The knowledge gained from characterization can be used to further enhance conductivity through materials development or by optimizing processing conditions. The following characterization data are of particular interest: sample microstructure including grain size, morphology, particle size, vacancies, and defects.

Microscopy techniques are used to probe the microstructure of materials, while elemental mapping capabilities (e.g., atom-probe tomography, x-ray diffraction, and energy dispersive x-ray spectroscopy) are needed to confirm elemental composition and location/distribution of constituents. Multimodal characterization is necessary to identify nanocarbon features, its morphology, and topology with respect to the surrounding metallic and non-metallic matrices. Because defects and contamination are known to reduce conductivity, a responsive application of this type might involve varying key process parameters such as wt.% or vol.% of additives, or temperature, pressure or vacuum results include characterization visualizing defects and contamination and processes that reduce them. If the associated modelling/simulation for the project includes extensive machine learning, then the application should demonstrate the ability to conduct high-throughput experiments to provide sufficient data to cover the space of key composition and processing variables.

The DOE's National Laboratories and User Facilities contain state-of-the-art characterization techniques, tools, and researchers that can help typical inventors gain a full and fundamental understanding of enhanced conductivity and other properties. For example, the Argonne National Laboratory's Advanced Photon Source (APS) is able to produce very high energy photons that can be used with an ultra-small angle x-ray scattering (USAXS) beamlines to determine the dynamics of CABLE materials manufacturing processes at the electron level. Ilke Arslan described Argonne National Laboratory's Center for Nanoscale Materials, one of DOE's five Nanoscale Science Research Centers, which focuses on quantum materials and phenomena, manipulating nanoscale interactions, and nanoscale dynamics, and provided examples of its facilities and capabilities. Appendix C provides a compilation of DOE's User Facilities.

Computing

High resolution, multi-scale modeling and simulation necessary to evaluate, design, and fabricate conductivity-enhanced materials, as noted in the section above, will require significant computational resources. DOE's High Performance Computing assets are well suited to run these complex models. The supercomputers are managed by DOE Office of Science's Advanced Scientific Computing Research (ASCR). These resources are typically 100 times more powerful than computing resources available in other universities, laboratories, and other industrial scientific and engineering environments. Robin Miles gave an overview of DOE's HPC4Energy Innovation program designed to match industry partners with National Laboratory HPC resources to run computationally intensive models to address critical industrial problems and enable improved yield, greater material efficiency, and reduced energy consumption. The program has funded over 140 projects with over 50 manufacturers in the U.S. The companies range from leading edge aerospace companies to legacy industries to innovative small companies.

Jini Ramprakash went into further detail about the Argonne Leadership Computing Facility (ALCF). The ALCF provides insights on cutting-edge artificial intelligence (AI) technology to improve science and evaluates usability and performance of machine learning applications on a deep-learning accelerator, a reconfigurable dataflow unit, and intelligent processing unit-based systems. The ALCF features a number of AI test beds and computing resources, and the facility works with industrial partners to give industry the ability to perform more complex simulations, make better predictions, draw knowledge from data, improve products, accelerate innovations, reduce or eliminate the need to build multiple prototypes, benefit from ALCF's expertise, and engage with domain experts across ANL and its user facilities to form long-term collaborations. The ALCF allocates 60% of its computing resources to a yearly call that is open to prospective users, 20% on DOE priority projects, and 20% from an annual directive from DOE.

As the exascale computing era dawns, technology changes are creating new opportunities for those who must use high-performance computing (HPC) and data systems effectively for solving complex physics- and data-intensive computing problems related to materials and materials processing. The computing facilities are augmenting their strategy to adapt to changing science needs and emerging technologies and to leverage the utility of exascale computing across the federal government. Strategic needs are being assessed in the following technology areas:

- AI and machine learning (ML),
- Advanced data analytics and workflows,
- Heterogeneous accelerated computing,
- Next-generation HPC and data ecosystems—from leadership computing to the edge—and
- Software and hardware technologies to enhance the science mission.

Key Takeaways from the Testing, Characterization, and Computing Panel

- Many capabilities exist across the National Laboratory and university research ecosystem that CABLE researchers can leverage – many are not aware of them.
- The optimal testing or characterization method is dependent on a number of factors, including sample size, material stability, and parameters of interest. Each method has its pros and cons.

Electric Conductors

This section summarizes not only the electric conductor panel but also electrical conductivity related input from Day 1's VSP and competitor showcase Electrical conductivity enhancement is key to realizing a vision for electrification of society and a net-zero decarbonized economy by 2050. Electric conductors can be divided into two broad categories, traditional metal electrical conductors and enhanced electrical conductors, both of which are described in more detail below. All electrical conductors in commercial use are composed of a pure metal or alloy of metallic elements. Physical properties of common electrical conductors are summarized in Table 4.

Table 4: Electrical Conductivity of Common Metal Elements and Alloys[4]

Metal	MS/m	kg/m^3
Silver	63	10,490
Copper (Electrical)	59	8,900
Copper (Annealed)	58	8,930
Gold	41	19,320
Aluminum	35	2,700
Calcium	30	1,550
Al 6061-T6	25	2,700
Magnesium	23	1,730
Tungsten	18	19,250
Zinc	17	7,130
Brass (Electrical)	15	8,500
Nickel	14	8,900
Iron	10	7,860

The Electric Conductors panel session occurred in parallel with the Thermal Conductors panel session. The Electric Conductors panel consisted of Iver Anderson (Ames Laboratory), Mehran Tehrani (University of Texas – Austin), Thomas Kozmel (QuesTek), Frank Kraft (MetalKraft), and Keerti Kappagantula (Pacific Northwest National Laboratory). It was co-chaired by Andre Pereira (DOE Office of Electricity) and Henry de Groh (NASA). The Electric Conductors section was developed with input from the Electric Conductors panel, as well as CABLE Prize Competitor Showcase. Competitor input is from Dr. Nhon Vo (NanoAl LLC), David Lashmore (American Boronite Corporation), Dmitri Tsentalovich (DexMat, Inc.), Mohamed Rahmane (GE Research) Guenther Horn / David Bergmann (NAECO); and Dave Townley (CTC Global) and Jason Huang (TS Conductor). Frank Kraft and Mehran Tehrani provided additional input in the CABLE Prize Competitor Showcase. Detailed talk summaries are included in Appendix B.

Traditional Electrical Conductors

Today, two metals and two applications dominate traditional metal electrical conductors.

General Purpose Electric Conductors

Copper is the most common general-purpose conductor, and its conductivity is the basis for the IACS set in 1913. Its conductivity is exceeded only by that of far more expensive (and weaker) silver. Copper offers the benefit of high electrical and thermal conductivity, along with high strength. Copper-based conductor cables are used in all electrical appliances, motors, and generators where weight is not a critical factor. In the

[4] "Electrical Conductivity and Density for Common Materials @20C" in Appendix A of the CABLE Prize Stage 1 rules.

electrical system, copper is typically used in medium- to low voltage line applications, in underground applications, and applications with extra-high voltages up to 400 kV because its conductivity is higher and corrosivity lower compared to aluminum. Copper composites are also well-suited for underground and underwater transmission lines.

Lightweight Electric Conductors

Aluminum is the predominant conductor material used for overhead electric transmission and distribution cables, given its lighter weight and lower cost. System efficiency of these cables has not historically been considered in transmission planning and selection, so large opportunities exist to improve the operational efficiency of existing transmission hardware. Even leveraging today's commercial AOHCs, such as aluminum conductor composite core (ACCC) and aluminum conductor composite reinforced (ACCR) conductor systems, can improve capacity and reduce transmission line losses by around 30-50%. More broadly, there is significant value in using AOHCs on a select group of lines to increase capacity, reduce thermal loss, and integrate more renewables into the bulk power system.[5,6,7]

If conductivity-enhanced aluminum can be manufactured cost-effectively, resulting in a conductor with a smaller cross-sectional footprint, it could become a notable contender for transportation applications in which both light weight and small footprint are desired.

Electric Conductor Systems

Fully enumerating all of the potential conductor systems was outside the scope of this workshop, but numerous presentations during both the Electric Conductor panel and the CABLE Conductor Manufacturing Prize competitor showcase involving two extremely widespread systems: aluminum based overhead power lines and copper based electric motors.

Overhead Power Lines: According to Jason Huang of TS Conductor, the dominant (>90%) conductor system use in the U.S. is based on a technology first patented in 1908—the Aluminum Conductor Steel Reinforced (ACSR) type. Dave Townley of CTCGlobal showed that, while nearly 6500 miles of his company's ACCC® conductor had been commercially deployed by dozens of utilities in about half of the United States, their product—which has 40% lower losses than ACSR due to system innovations (See Figure 4) —is deployed mainly overseas. Townley also cited a March 2022 report entitled "Advanced Conductors on Existing Transmission Corridors to Accelerate Low Cost Decarbonization[1]" that made the case that policy incentives need to be developed to overcome the current bias against superior conductors with slightly higher first cost. Figure 4 clearly depicts geometry improvements AOHC's: outer Al cross section (trapezoidal vs. circular) and solid vs. wire core. Townley also discussed the material improvements: annealed replaced hard Al in conductors, and lighter carbon replaced steel in cores, which led to a more and more efficient Al conductor that has 2 times higher capacity with a lighter core. This increase in capacity, using the same (or smaller) towers, was accompanied by a 50% decrease in sag.

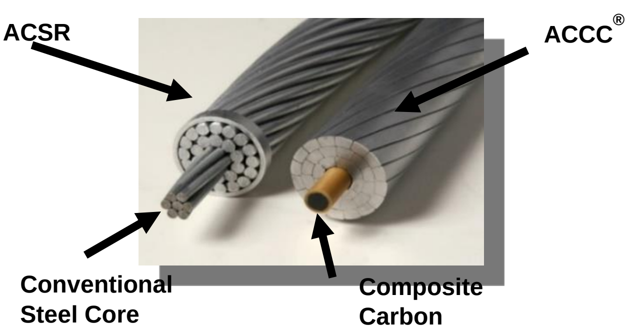

Figure 4 Difference between ACSR and advanced conductor (ACCR®)

[5] EIA, 2022, "U.S. Electric Power Industry Estimated Emissions by State," February.

[6] EPA, undated, "Greenhouse Gases Equivalencies Calculator — Calculations and References."

[7] EIA, 2020, "2020 Carbon Dioxide Emissions at Electric Power Plants," https://www.eia.gov/electricity/data/emissions/xls/emissions2020.xlsx.

Huang also noted that AOHCs with vastly improved performance (see Figure 5) are commercially available but used little in the United States compared to the ubiquitous ACSR. Huang presented on advanced manufacturing methods that produce some of the special attributes of TS Conductor's technology. For example, he discussed how pre-tensioning conductor systems produced superior mechanical performance and showed a video to emphasize this point.

Options for Aluminum (CONDUCTIVITY)							Options for Core (STRENGTH)				
Name	IACS %	Strength MPa	Thermal Limit, °C Cont.	Thermal Limit, °C < 10 hrs	Description	Conductor Types	Description	MoE GPa	Strength MPa	CTE 10^{-6}/°C	Density g/cc
1350-H19	61.2	162-172	90	120	Hard Drawn	ACSR	HS Steel	200	1379-1448	11.5	7.778
5005-H19	53.3	248	90	120	MS Alloy		EHS Steel	200	1517	11.5	7.778
6201b-T81	52.5	317-331	90	120	HS Alloy	ACSS	EXHS Steel	200	1965	11.5	7.778
TAL	60	165-186	150	180	Thermal Resistant		Mischmetal	200	1379-1448	11.5	7.778
KTAL	55	186-252	150	180	HS Thermal Resistant		Invar Alloy	162	1034-1069	1.5-3	6.588
ZTAL & UTAL	57-60	165-186	200	240	Ultra Thermal Resistant	ACCR	Al_2O_3 in Al Matrix	210	1380	6.3	3.337
XTAL	58	165-186	230	310	Extra Thermal Resistant	CFCC	Carbon/Glass Composite	112	2100	1.61	1.88
1350-O	**63 Most Conductive**	55-96	**250 Highest Temp**	310	**Fully Annealed**	**TS**	**Carbon Composite**	165	**3500 Highest Strength**	**0.06 Lowest Sag**	**1.6 Lightest Weight**

Figure 5: Comparison of ACSR conductor and core properties with those of advanced conductors (Source: Huang 2022)

Electric Motors: According to Frank Kraft, machine drives represent a major opportunity for enhanced-conductivity copper to increase energy efficiency and reduce carbon emissions. Nationally, about 2,000 billion kWh are consumed annually by electric motors, 90% of which are alternating-current (AC) induction motors[8]. If just 20% of the industrial AC motors had enhanced-conductivity copper wire, an annual energy savings of 36 TWh and CO2 reduction of 25.5 million metric tons could be realized. Mohamed Rahmane of GE research said that breakthrough system performances (3.5 times power density—See Figure 6) for applications such as motors for transportation are achieved through (1) materials innovation, (2) novel design geometries, and (3) advanced manufacturing methods, such as E-beam additive manufacturing.

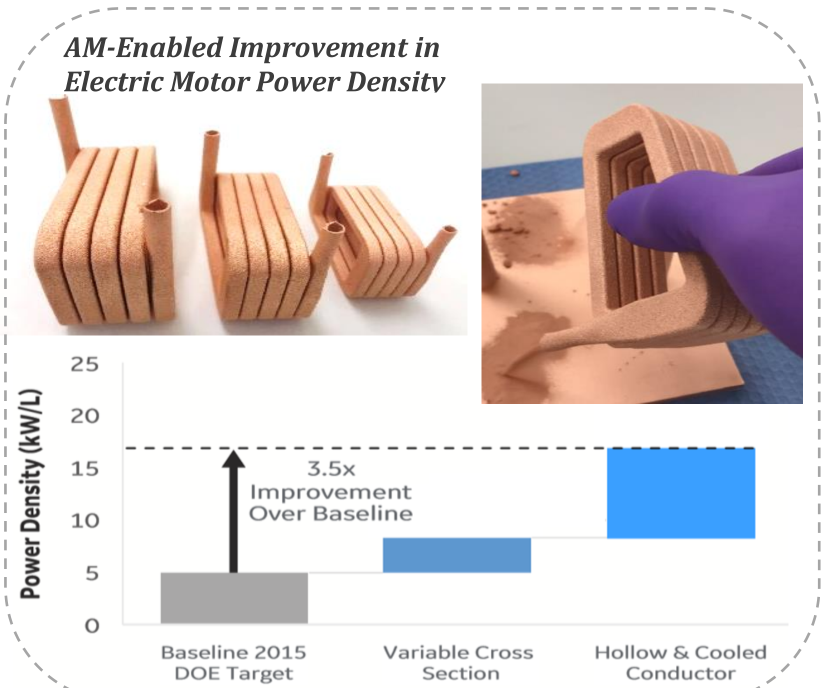

Figure 6 Additive manufactured hollow conductor for use in electric motors with projected power density improvements over baseline DOE target. (Source: Rahmane 2022)

[8] EIA, 2021, What Is U.S. Electricity Generation by Energy Source?

Enhanced Electric Conductors

The oldest form of enhanced conductors are simply more pure versions of traditional conductors. Electrical conductivity in metals is related to the mobility of free electrons, which are impeded or scattered by defects and impurities, as well as metal's grain structure in the crystal lattice. Thus, a metal's electrical conductivity increases with refinement to higher purity levels [2,3]. In addition, such impurity-related conductivity effects, other mechanisms that contribute to conductivity degradation at various temperature scales include 1) electrons scattering off of defects and dislocations (most important at cryogenic temperatures); 2) electron scattering at grain boundaries (most important between cryogenic and room temperature and 3) phonon scattering (increasingly important above room temperature)[9,10]. Thus, resistivity also increases, and conductivity decreases with temperature. Increasing temperature. The purest commercial bulk electrolytic copper today can reach more than 101% IACS. Thus, enhanced conductors must exceed 101% IACS in bulk to be considered truly "enhanced."[11]

The following subsections are organized by the material classes used for the Stage 1 of the CABLE Conductor Manufacturing Prize. First, there are enhanced metal conductors, which have improved conductivity through process innovation and alloying elements. Second, there are non-metal conductors, comprising the new Nobel-prize winning nano-carbon allotropes such as graphene and carbon nanotubes (CNTs) that have been of interest due to their extraordinary properties at the nanoscale. Third, there are metal-nano-carbon composites, composed of both metal and non-metal (nano-carbon), which were shown, both theoretically and experimentally, to achieve electrical conductivity far greater than historical values. Finally, there are other promising new enhanced conductors, including many bulk non-metals such as pure nano-carbons or polymers enhanced with nanoparticles of silver or rare earth elements.

Enhanced Metal Conductors (Without Nanocarbon)

Outside of strictly improving conductivity, the CABLE initiative is also interested in conductors with properties far superior to copper or aluminum with little or no loss in conductivity. The alloys and composites in this class of electrical conductivity-enhanced material come from research aimed at maintaining conductivity while increasing other properties, such as strength, known to be anticorrelated with conductivity. These conductors can include small amounts of other metal or non-nanocarbon compounds.

The best performing composites comprises a ductile metal matrix reinforced with nano-metric ductile metal filaments, known as deformed metal-metal composites (DMMC). The reinforced metal is typically chosen for strength, instead of conductivity. Aluminum- and copper-based DMMC composites are known to have the best performance, as well as high conductivity with increased strength. Traditional reinforcement metals include titanium and tin, while more recently, calcium, niobium, chromium, and iron have been used. These composite systems are formed by co-extrusion at very high levels of true strain and are characterized by extremely low equilibrium solubility of the minor part of the composite.

Iver Anderson reported the latest innovations in Ames Laboratory's effort to develop an aluminum/calcium (Al/Ca) composite conductor for transmission cable applications. Previous results showed impressive strength and conductivity levels for Al/Ca (11.5 vol.%) composite wires that are reinforced by filamentary Ca within an Al matrix, and they are competitive with traditional transmission cables, ACSR and ACCR. More recently, the team developed a scalable gas atomization process for both calcium and aluminum powders for the production

[9] Holm, Ragnar. *Electric Contacts Theory and Applications*. Springer, 1967.

[10] Slade, P.G. (Ed.). (2014). Electrical Contacts: Principles and Applications, Second Edition (2nd ed.). CRC Press. https://doi.org/10.1201/b15640

[11] Noting "bulk" is important because an ultra-pure single crystal of copper has been reported exceed 113 % IACS at room temperature in Cho, Yong Chan et al, 2010 "Copper Better than Silver: Electrical Resistivity of the Grain-Free Single-Crystal Copper Wire," *Crystal Growth and Design*, ACS, Vol. 10 2780–2784, DOI: 10.1021/cg1003808.

of aluminum/calcium DMMC cables. Initial tests from gas atomized commercial purity aluminum powders showed increased conductivity, likely from crystal grain elongation and reduction in iron impurities.

Integrated Computational Materials Engineering (ICME) has also been leveraged to design and manufacture electrical conductivity-enhanced materials. QuesTek used an ICME approach to design new alloys for overhead transmission lines with improved strength and processability, and the ability to withstand high temperatures, while maintaining high electrical conductivity. Nhon Vo discussed NanoAl's Rapid Alloy Screening framework, a computational approach, used to develop their Nano 6000 alloy that modified traditional steel alloys with nanomaterials to improve strength and conductivity over traditional cables.

Nanocarbon Conductors

In this report, "nanocarbon" refers to new carbon allotropes: CNTs, single- or few-layer graphene, doped or undoped, and other carbon allotropes. The excitement surrounding the new carbon allotropes discovered in recent decades (Table 5) led the CABLE Big Idea team and others to consider them first in developing the CABLE concept. An enabling advantage of carbon-based conductors is their low density and high thermal conductivity.

Table 5: Conductivity and Other Properties of Various Forms of Carbon

Carbon Allotrope	IACS (%)	Notes
Diamond	10^{-17} – 10^{-24}	• Hardest and highest thermal conductivity • Natural diamond: 2,200 W/m.K (5X>Ag) • Synthetic: 3320 W/m.K
Graphite	0.3 – 0.5 along plane	• Softest form of carbon
Single-walled CNTs (SWCNTs) in armchair carbon arrangement	17.2 – 50 along axis ~10^{-16} perpendicular	• Varies according to manufacturing and post-processing techniques
Graphene	<172	• Theoretical maximum for monolayer defect-free graphene

Properties of all carbonaceous fibers improve with the order and crystallinity of their constituents. There have been some measurements of graphene's and SWCNTs' electric and thermal conductivities as a function of the dopants/intercalants present and their crystalline structures.[12] Proper comparison of graphene samples is challenging and tedious because there is no standard of the widely varying qualities of graphene. According to the International Standards Organization (ISO), materials comprising as many as 10 carbon monolayers is still referred to as graphene. But even a couple additional monolayers of graphene disrupt the graphene pi-cloud structure and lower the conductivity and other performance metrics compared to monolayer graphene. The CNT arrangement—armchair or zigzag—affects the conductivity of the monolayers, especially at heterogeneous interfaces. Pristine and purified graphene and CNT are free from defects and functionalized graphene (graphene oxide, reduced graphene oxides). Similarly, carbon fiber is the name given broadly to materials consisting of thin, strong crystalline filaments of carbon. Carbon fibers are lightweight and strong materials with low cost of production. Carbon fibers can be intercalated, introducing metal halide ions between the layers, to improve conductivity.

[12] Graphene is the focus here because some metal–nanocarbon results have been tied to potential graphene nanoribbons. CNT is also mentioned because of a CNT paper that features an Al composite with a network structure of multi-walled CNTs (MWCNTs) with electrical conductivity of 3.316 × 107 Sm−1 (half aluminum) and thermal conductivity of 172 W/m K. This paper has been cited in recent metal nanocarbon publications (Ma et al, PRL) as support for enhanced conductivity of covetics:
Shin, S.E., H.J. Choi, and D.H. Bae. 2012. "Electrical and thermal conductivities of aluminum-based composites containing multi-walled carbon nanotubes." *Journal of Composite Materials* 47(18): 2249-2256. doi.org/10.1177%2F0021998312456891.

It turns out none of the speakers or contestants had pure nanocarbons other than CNTs. In addition to excerpts from Mehran Tehrani during the electric panel discussion, this also includes excerpts from Dmitri Tsentalovich of DexMat, Inc. and David Lashmore of American Boronite Corporation.

Dmitri Tsentalovich discussed a CNT conductor that has been developed as a lightweight alternative to metal conductors. The materials have high strength and conductivity with a lower weight than other conductors, 25 times higher flexural tolerance than copper wire, and are not prone to galvanic corrosion. Tsentalovich reported improvements in conductivity and strength of the conductor are possible by using higher quality (longer and with fewer defects) CNTs.

David Lashmore reported that CNTs are promising options for reducing weight of electric cables while maintaining conductivity properties of the base metal. Lashmore discussed a process to produce CNT yarn braided around an aluminum or copper alloy composite. These braids can be put into bundles to build wires that meet customer requirements. These braids can achieve specific conductivity values similar to copper and can handle significant current with lower temperature increases.

Mehran Tehrani reported measurements of various carbonaceous conductors, including nanocarbons with different crystal structures, that showed exciting conductivity measurement results for much more economical intercalated carbon fiber samples that consistently had higher electric conductivity and conductivity divided by density than pristine and purified expensive graphene fiber (GF) and CNT samples (Figure 7)[13]. Note that in Figure 7, A denotes CNTs fabricated by means of aerogel flowing catalyst chemical vapor deposition (CVD); DS denotes CNTs that are dry-spun from a nanotube forest; and WS denotes CNTs that are wet-spun from super acid suspensions.

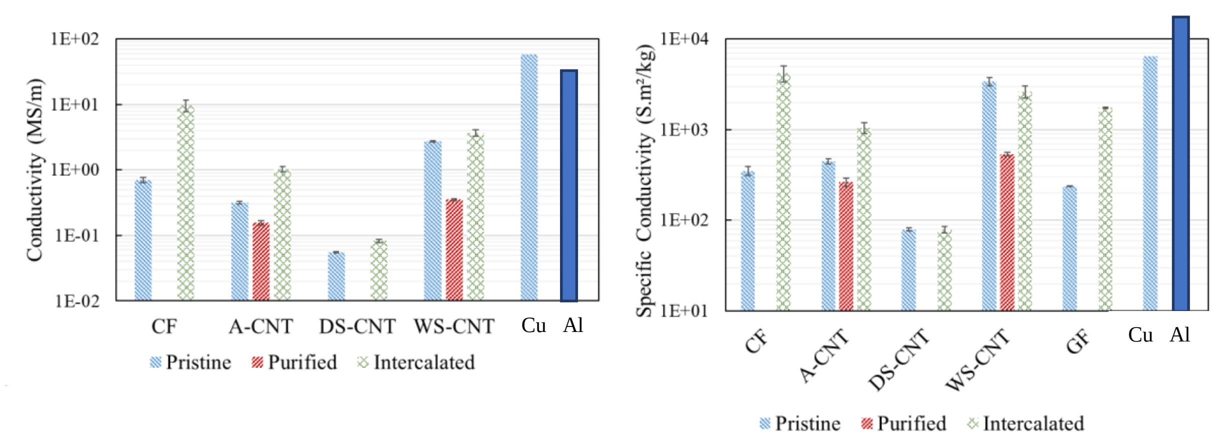

Figure 7: Electrical conductivity (left) and electrical conductivity divided by density (right) of various nanocarbons vs copper and Aluminum. Source (based on Tehrani 2022 updated with Al data)

In the original figure presented at the conference, the intercalated carbon fiber (CF) and CNTs appear to be closer to competitive with the incumbent conductor Cu when the electrical conductivity (left) is divided by its density. However, for the metric conductivity divided by density, the appropriate incumbent conductor for comparison is aluminum, whose specific conductivity (13.91 Sm^2/kg) is more than twice that of copper.

Pristine samples outperformed purified samples, due to a lower concentration of defects, which reduces conductivity. However, pristine copper still outperformed all samples.

[13] Tehrani, M., 2021 "Advanced Electrical Conductors: An Overview and Prospects of Metal Nanocomposite and Nanocarbon Based Conductors," Physica Status Solidi 218(8): 1–17, https://doi.org/10.1002/pssa.202000704

Dr. Tehrani's work shows that, while the improved thermal conductivity of the composite is beneficial for improving the current rating in micro-electronics applications, the tradeoff for decreased electrical conductivity results in lower current-carrying capacity in applications that use longer conductors.

Metal-Nanocarbon Composites

Since the discovery of CNTs and graphene and their extraordinary electrical properties, there has been significant research to embed them in metals such as copper, to improve electrical properties[14,15,16]. While several groups have observed conductivities of >120% IACS in metal nanocarbon combinations, all these values are for nanoscale samples, and none are for microscale and larger (macroscale) samples.

Table 6: Conductivity and density of Metal-nanocarbon Composites

Carbon Allotrope	IACS (%)	Density
Copper–CNT nanocomposite[17]	47[a]	5.2 g/cm³
Ultraconductive copper[18]	117	8.9 g/cm³
Ultraconductive aluminum/GNP	60-62[b]	2.7 g/cm³

[a]Exhibits a better electrical conductivity than copper above 80°C

[b]Extruded wire reported, Nittala, A., 2022 (Doctoral dissertation, Ohio University).

Several prize competitors' efforts focused on improving electrical conductivity involve copper metal matrix composites using carbon nanoparticles such as graphene. There is a significant lack of fundamental science to guide material synthesis and processing. There is also a strong need for analytical and experimental characterization to establish process–structure property relationships to guide process and material design for fabrication of copper–nanocarbon enhanced conductors.

The way in which copper–nanocarbon material is processed is a critical aspect of achieving enhanced conductivity. Proper embedding of nanocarbon particles within the metal matrix is one of the key challenges in fabricating enhanced conductivity metal-nanocarbon composite cables. Solid phase processing of bulk metal and nanocarbon is a promising technique. Pacific Northwest National Laboratory's sheer assisted processing and extrusion (ShAPE) tool has demonstrated cables with varying concentrations and locations of nanocarbon inclusions. Talks from the panelist, as well as those from the CABLE Prize session, referenced the ShAPE tool. Other promising processing approaches include spinning of CNT yarns or braids, with downstream heat treating and electron beam melting additive manufacturing of copper-carbon nanocomposites.

Along with processing innovations, precise characterization of manufactured composites is also needed to inform and optimize the fabrication process. Key parameters of interest include nanocarbon concentration, orientation, distribution, and morphology. Keerti Kappagantula described the results of extensive characterization on metal-nanocomposites fabricated from the ShAPE tool, which was performed using a synchrotron micro-X-ray diffraction tool. Given the tool's deep penetration depths, fast sampling times, and

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[14] Cao, M., D.-B. Xiong, L. Yang, S. Li, Y. Xie, Q. Guo, Z. Li, H. Adams, J. Gu, T. Fan, X. Zhang, and D. Zhang, 2019, "Ultrahigh Electrical Conductivity of Graphene Embedded in Metals," Advanced Functional Materials 29(17):1806792, https://doi.org/10.1002/adfm.201806792.

[15] Pacific Northwest National Laboratory, 2020, "'Better' Copper Means Higher-Efficiency Electric Motors," October 13, https://www.pnnl.gov/news-media/better-copper-means-higher-efficiency-electric-motors.

[16] Subramanian, C., T. Yamada, K. Kobashi, A. Sekiguchi, D. Futaba, M. Yumura, and K. Hata, 2013, "One Hundred Fold Increase in Current Carrying Capacity in a Carbon Nanotube–Copper Composite," Nature Communications 4:2202, https://www.nature.com/articles/ncomms3202.

[17] Subramaniam, C., T. Yamada, K. Kobashi, A. Sekiguchi, D. N. Futaba, M. Yumura, and K. J. N. C. Hata, 2013, "One hundred fold increase in current carrying capacity in a carbon nanotube–copper composite," Nature Communications 4: 2202.

[18] Cao, M., D. B. Xiong, L. Yang, S. Li, Y. Xie, Q. Guo, Z. Li, H. Adams, J. Gu, T. Fan, X. Zhang, and D. Zhang, 2019, "Ultrahigh Electrical Conductivity of Graphene Embedded in Metals," Advanced Functional Materials 29: 1806792.

high spatial resolution, synchrotron light sources provide new characterization opportunities that illuminate key information regarding chemical composition variation and grain connectivity.

Frank Kraft reported electrical conductivity of 12-AWG wire of various graphene content in a copper-graphene wire at two defect densities, high and low. For low defect density graphene, higher graphene content showed an increase in electrical conductivity, all of which were greater than 100% IACS. High defect density graphene was comparatively lower, but all were still greater than 100% IACS.

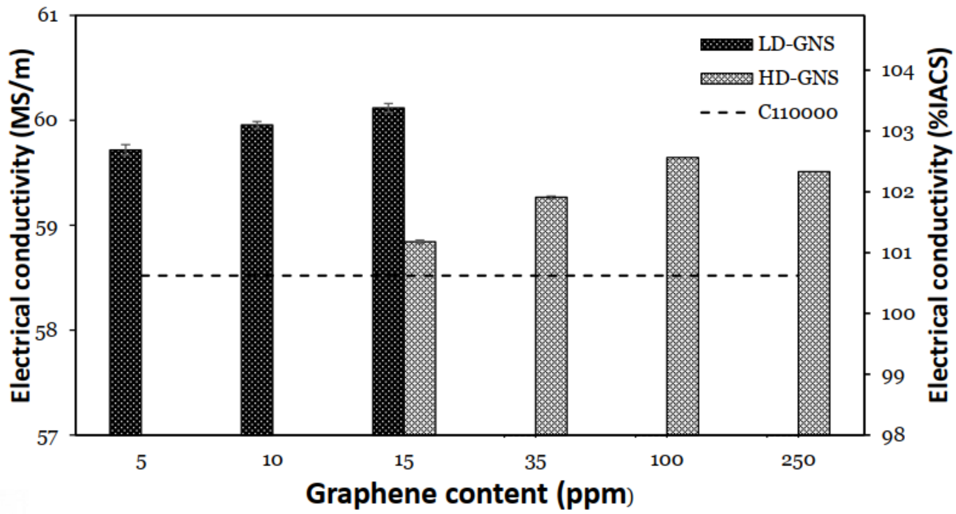

Figure 8: Electrical conductivity for low-defect density (LD) and high defect density (HD) graphene nanosheets (GNS).[19]

However, Dr. Tehrani stressed that understanding metal-nanocarbon interactions is critical. Nanocarbon conductivity rapidly degrades within the metal matrix, due to the negative interactions between the two. While some have proposed using a different metal to buffer the two, he noted that this will likely not work due to increased interfacial resistances from increased copper defects and degradation of nanocarbon structure.

Other Promising Enhanced Conductors

Nonmetallic conductors with electrical conductivity as high as those of metallic conductors may have applications in high thermal environments, such as heat exchanges, condensers or evaporators in air conditioners, and reversible heat pumps. These may also be lighter in weight, offering benefits to land vehicles, power stations, and aerospace applications.

Key Takeaways from the Electric Conductors Panel

- The biggest challenge facing the electrical conductor community is showing reproducible measurements of absolute electrical conductivity enhancement significantly above that of the purest copper at the nanoscale.
- The way in which composite enhanced conductivity material is fabricated and processed is critical to achieving enhanced conductivity.
- Better characterization and modelling of manufactured composites is needed to inform and optimize the fabrication process. Both experimental and analytical characterization are needed to refine process–structure property relationships for optimization of process design for fabrication of enhanced conductors.

[19]Kappagantula KS, JA Smith, AK Mittala, FF Kraft, 2022, "Macro copper-graphene composites with enhanced electrical conductivity," *Journal of Alloys and Compounds*, vol 894, February 15, 2022, https://doi.org/10.1016/j.jallcom.2021.162477

- Near-term deployment of advanced conductor systems with the material innovations closest to commercialization (e.g. Al/Ca DMMC conductors for HVDC transmission) is urgently needed to meet the Administration's goal of attaining a clean electricity-grid by 2035.

Thermal Conductors

The material in this section is from the parallel Thermal conductor panel reinforced with information from the Read-Ahead document and from the discussion panels. Improved thermal conductivity can target many applications, including Heat exchangers for heating, ventilation, and air conditioning (HVAC) and thermal storage. In the case of enhanced thermal conductivity, the focus is above the range of 10 W/m·K (watts per meter-Kelvin).

As shown in Table 7 below, most good thermal conductors are metals, but non-metals include polymers and carbonaceous materials including bulk nanocarbons such as CNTs also are used as thermal conductors because of their other properties. Table 7 outlines the thermal conductivity of common materials.

Table 7: Thermal conductivity of common materials[20]

Element or alloy	W/M.k at 25°C
Diamond	2,200 (3,320 synthetic)
Individual Carbon Nanotube or Graphene	>3,000
Doped Graphene	1,575
Doped Carbon Fiber	>1,000
Doped CNT	625
Doped Graphite	25–470
Copper	398
Silver	428
Graphite	168
Doped Silicon	130–148
Silicon carbide	3.8–120
Phosphor bronze	110
Alumina	36
Boron	25
Antimony	18.5
Bismuth	8.1
Tellurium	4.9
Silica Quartz mineral	1.4–3
Ice (0°C, 32°F)	2.18
Amorphous Carbon	1.7
Polyethylene low density, PEL	0.33
Polytetrafluoroethylene (PTFE)	0.25

The Thermal Conductors panel session occurred in parallel with the Electric Conductors panel session. The panel consisted of Michael Ohadi (University of Maryland), David Cahill (University of Illinois), Jie Li (Argonne National Laboratory), Kashif Nawaz (Oak Ridge National Laboratory), and Geoff Wehmeyer (Rice University). It was co-chaired by Antonio Bouza (DOE AMO) and William Worek (Argonne National Laboratory). Detailed talk summaries are included in Appendix B.

[20] Nadel, S., 2019, "Electrification in the Transportation, Buildings, and Industrial Sectors: a Review of Opportunities, Barriers, and Policies," Current Sustainable/Renewable Energy Reports 6(4): 158–168, https://doi.org/10.1007/s40518-019-00138-z.

One intriguing aspect of enhanced thermal conductivity is the existence of anisotropic enhancement and the unique anisotropic application (directional optimization). Carbon nanomaterials are of great interest not only in electrical applications but also thermal applications, given their extremely high theoretical thermal conductivity. Orientation and configuration of the carbon nanomaterials strongly affect thermal conductivity. Individual multi-wall CNT have thermal conductivity of 3000 W/mK[21], while packed CNT beds, with high disorder, have very low thermal conductivity, 0.2 W/mK[22]. In reality, CNT-based conductors have much lower thermal conductivity, compared with theoretical values, due to interfacial thermal resistance. It is known that single-walled carbon nanotubes with armchair arrangement have good thermal conductivity in one direction and very low conductivity perpendicular to the nanotube axis. However, it should be highlighted that the temperature dependence of electric and thermal properties in new carbon allotropes has not been clearly established and measured, and the identification of the most accurate method of measurement is not straightforward.

Previous studies have shown that aligning CNTs into a fiber can increase axial thermal conductivity and can achieve higher specific thermal conductivity than typical metals. Geoff Wehmeyer reported that electrical and thermal conductivity were both strongly correlated with nanotube length and could be good candidates for thermoelectric active cooling and other applications requiring lightweight, flexible, and high-strength electrical and thermal conductors.

Similar concerns must be addressed for metal-nanocarbon composites. Thermal interfacial resistance can drastically lower thermal conductivity due to acoustical mismatching between metal and nanocarbon. Two typical approaches to mitigate this are surface metallization and matrix alloying. Jie Li discussed a novel approach that modifies the diamond surface using graphene to achieve high effective thermal conductivity. Continued work is needed to further develop surface modification to enhance thermal conductivity of metal-nanocarbon composites.

In real-world applications, thermal properties, which include thermal conductivity, is more than just a single material property or metric. It is an enabling factor for new technologies that requires an innovative design to leverage enhancements. These design improvements cannot be an exercise in simple material substitution/exchange. Thermal conductivity performance enhancements will be driven by additional system design constraints that are specific to the application (e.g., operating temperatures, material compatibility, geometric design constraints, volume, mass requirement). There are opportunities for enhanced thermal conductivity in thermal applications to make devices smaller, lighter, and more cost-effective. Conductivity-enhanced polymers are well-suited to meet these constraints, given their ease of handling and the ability to fabricate into a variety of shapes and sizes. Additive manufacturing has been used to create a cross-media heat exchanger and thermal energy storage system using conductivity-enhanced polymers that outperform traditional designs. Electronics is another key application where polymeric thermal conductors can be leveraged. Thermal interface materials, polymeric adhesives, are used to bond heat-generating microchips to heat sinks. David Cahill reported that thermal conductivity and density of epoxy resins are correlated with crystallinity and found that one epoxy tested was 2.5 times more thermally conductive than common polymers used in electronics.

Thermoelectric Materials

- Thermoelectric materials create a voltage when a temperature gradient is introduced across the material and create a temperature gradient when a voltage is applied. Several applications are

[21] Kim, P., et al. "Thermal Transport Measurements of Individual Multiwalled Nanotubes." *Physical Review Letters*, vol. 87, no. 21, 2001, doi:10.1103/physrevlett.87.215502.
[22] Prasher, Ravi S., et al. "Turning Carbon Nanotubes from Exceptional Heat Conductors into Insulators." *Physical Review Letters*, vol. 102, no. 10, 2009, doi:10.1103/physrevlett.102.105901.

available for thermoelectric materials, including temperature measurement, cooling, and power generation.

- The magnitude of the electromotive force that is developed across thermoelectric materials when a temperature gradient is applied is proportional to the temperature difference and the Seebeck coefficient.
- The Seebeck coefficient is a function of thermal and electrical conductivity (Insert equation). A large Seebeck coefficient is achieved for either or both large thermal conductivity and small electrical conductivity.
- Materials with large Seebeck coefficients are potentially attractive for waste heat recovery applications as they can convert the heat to electricity.
- It is important to note that current CABLE prize metrics are not set up to promote or accelerate thermoelectric materials with large amplitude Seebeck coefficients.

In all cases, extensive testing of conductivity-enhanced materials is needed to evaluate material reliability and lifetime to ensure proper functioning across a range of applications. Thermal shock testing is a common method to evaluate loss of strength after rapid temperature changes. This is especially important for high-temperature applications (higher than 700 °C), as alternative materials are being investigated. Ceramics, such as silicon carbide and aluminum oxide, have shown acceptable performance at reasonable material and manufacturing costs. Kashif Nawaz reported recent results of thermal shock testing of aluminum oxide samples that showed the larger temperature swing resulted in significantly lower flexural strength.

Key Takeaways from the Thermal Conductors Panel

- There is no single research challenge that can be described with a single enhanced conductivity metric but rather system challenges that depend on the equipment and application.
- CABLE Prize does not generally encourage innovative thermal conductors and approaches because materials and techniques for the highest conductivity electric conductors do necessarily produce the best thermal conductors.
- Manufacturing research for lightweight enhanced thermal conductor systems made of low-cost polymer or non-metal for heat exchangers are needed for key industrial and building applications.
- Research for such thermal conductors should have a wide range of geometric design possibilities, and include a focus on corrosion resistance. Research paths include:
    - Development of tools that can be used to optimize for at least two different optimum points such as weight or volume. Other optimization points include cost, life-cycle durability, and quantitative performance metrics.
    - Use of systems engineering approaches that engage material and thermal engineers to address this challenge to understand the mechanisms and how this can result in a real product.
- There is a need to adequately understand the manufacturing mechanisms to decide the best way at scale to manufacture materials having enhanced/desirable thermal properties for use in different heat exchange and thermal energy storage components including single-walled carbon nanotubes (CNTs), graphene, as well as carbon-enhanced metal composites.
- There is a need to determine key properties needed for key equipment and applications and focus research these desirable properties.
- Bio-inspired electrically controlled conductors have been proposed for thermal management but were not considered in scope for this session because of poor realization at scale and lifecycle durability.

Superconductors

The information here is from the Superconductor panel as well as from one of the Superconductor Competitor Showcase presentations. Transporting electricity through conductors is among the most prevalent mechanisms for energy transfer today and poised to grow significantly with increased electrification of the industrial, transportation, and building sectors. Beyond traditional metals, superconductors enable a step change in electrical conductor performance through the utilization of an exotic physical state achievable in certain elements and compounds. By reducing resistance to zero, superconductivity enables lossless transmission of power. With this elimination of electrical resistance comes a set of other characteristic behaviors, including the Meissner effect in which external magnetic fields are rejected from the bulk of the material. Figure 9 traces the historical evolution of high temperature superconductors.[23]

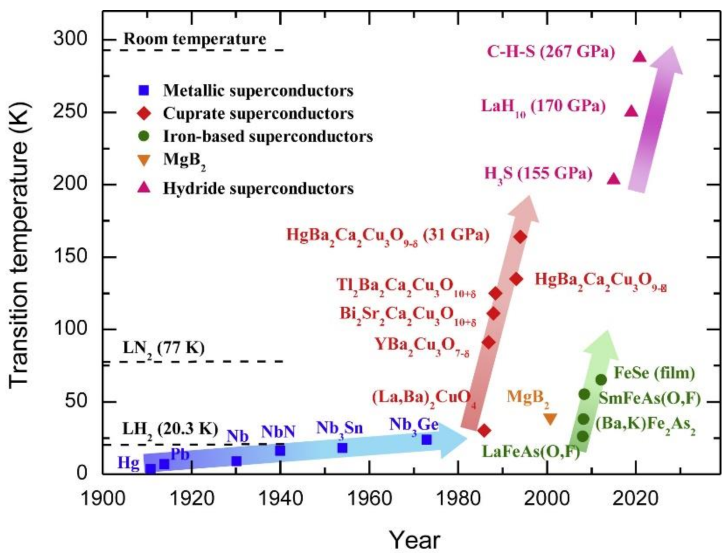

Figure 9: The history of Superconductors (Yao and Ma 2021).

The Superconductors panel session consisted of Venkat Selvamanickam (University of Houston), Yifei Zhang (SuperPower), Michael Tomsic (Hyper Tech Research), and Ranga Dias (University of Rochester). It was chaired by Jake Russell (ARPA-e). This chapter also includes excerpts from the Selva Research Group presentation during the CABLE Prize competitor showcase Detailed talk summaries are included in Appendix B.

The superconducting state exists in a delicate balance primarily controlled by the interaction of three parameters: critical temperature (Tc), critical field (Hc), and critical current (Jc). If the temperature, external magnetic field, or current applied through the material exceed any of these threshold values, the superconducting state will break down, and the material will revert to normal state. Therefore, the performance of a superconducting material is practically limited by its critical parameters. Great effort has been put into increasing these parameters in order to increase performance while maintaining reasonable cost (e.g., minimizing $/kA*m).

Over the past century, significant advances have been made in understanding superconductivity, the Nobel-prize winning Bardeen–Cooper–Schrieffer (BCS) theory (describing superconductivity as a microscopic effect caused by a condensation of Cooper pairs). However, the properties of high-temperature superconductors (HTSs), discovered in the 1980s and that are the Competitors in the Prize are not explained by BCS theory.

[23] Yao, Chao and Yanwei Ma. 2021. "Superconducting materials: Challenges and opportunities for large-scale applications." *iScience*. 24(6). https://www.sciencedirect.com/science/article/pii/S2589004221005095

Most recently, high-pressure hydrides appear to promise even higher temperature, possibly room temperature superconductivity—do appear to be explained by BCS theory. Despite thousands of superconducting materials having been discovered, current applications are dominated by just a few classes of materials, including Nb3Sn, MgB2, rare-earth barium copper oxide (REBCOs), and iron-based superconductors (IBS).

In 2001, MgB2 was discovered to have superconducting properties at a high temperature (relative to other low-temperature superconductors). However, the improved properties are seen only in short samples. Michael Tomsic reported on HyperTech's efforts to achieve these properties in longer samples by adjusting the number of superconductor filaments and the filament diameter. AC loss was a significant limitation for MgB2 superconductors until recently: NASA funded a project that developed a high-temperature, low-loss superconductor. The success of this effort has led to rapidly growing activity in the superconductor space, with several applications (e.g., MgB2 for motors and generators) moving to commercialization.

Figure 10: Visual Size Comparison of REBCO tape superconductor and Copper capable of carrying equivalent current. (Selvamanickam 2022)

The discovery of REBCO generated a significant buzz in the community. However, it took 20 years for the material to become commercially available and another 15 years to grow the market. Its brittleness and challenges in manufacturing bulk quantities may have hindered market growth. Now, REBCO is produced as a thin-film superconducting tape that carries up to 600 times the current of a comparably sized copper wire. (Figure 10). REBCO tape has many applications, including accelerators, power cables, motors, and wind power generation. REBCO tapes' use in compact[24] fusion systems is driving demand and the need for higher-volume manufacturing. However, high costs and limited domestic production capacity constrain production.

Increasing product performance could reduce costs significantly, as less tape would be needed for the same applications. Better performance could be achieved by increasing the tapes' critical current and producing double-sided tapes. Manufacturing throughput could be increased using advanced metal–organic chemical vapor deposition (MOCVD) reactors, which would address deficiencies (e.g., nanoscale defects and low precursor-to-film conversion efficiency) in current REBCO production. Venkat Selvamanickam discussed his group's effort to develop improved double-sided REBCO tapes with MOCVD, which showed 2 times performance over commercial REBCO tape. Yifei Zhang summarized SuperPower's efforts to produce REBCO HTS wires using Hastelloy as a substrate, aiming to increase critical current, improve conductor quality, and customize conductors (e.g., with striations or grading). Challenges include in-field testing and qualification, process monitoring and control, and structural characterization and analysis.

The discovery of superhydrides is the latest development in the search for room-temperature or warm superconductors. These materials use high pressure to change an atom's structure, making it more favorable for superconducting. Metallic hydrogen has been predicted to have high-temperature superconductivity, but the amount of pressure required is enormous (500 GPa). One approach is to use chemical precompression to lower the metallization pressure, trying to mimic the properties normally achieved at higher pressures. Ranga Dias reported promising results that showed rare-earth hydrides produced at significantly reduced pressures. Nitrogen-doped lanthanum hydride is now being synthesized at small scale and shows potential to act as a

[24] "Compact" for a fusion reactor is much larger than compact for other technologies—a conventional fusion reactor like ITER takes up a city block while a "compact" fusion reactor is about the size of a small bedroom with a high ceiling.

room-temperature superconductor at 270 GPa. Using various thermodynamic pathways, researchers showed the material to be metastable to ambient pressure.

Key Takeaways from the Superconductors Panel

- Critical current density must be increased while decreasing manufacturing cost to reach the cost target for REBCO ($10/kA m) superconductors.
- Near-term scale-up of high-critical current technologies is needed for future applications. DOE can help connect R&D labs with commercial facilities to scale their technologies.
- Developing superconductors for AC applications opens an entirely new application space.
- Researchers should work closely with theory and modeling to predict exotic properties of materials.
- Compact Fusion may be a killer application for REBCO
- Demand from fusion alone will outpace supply of superconductors.
- Special focus must be given to supply chain security of the superconductor value chain, including other components in the stack.

CABLE Theory and Modeling

In the past, conductivity-enhanced materials were found through experimental trial and error. An alternative approach that is more likely to inspire confidence in identifying ideal material combinations and nano- and micro-manufacturing methods is theory and modeling. However, a theoretical first principles approach was not previously possible because of the extreme computing demands for complex mixtures of hybrid and homogenous materials. Now, with the wider availability of HPC and programs such as HPC4Energy Innovation (HPC4EI), these complex, multiphysics models can now be resolved.

The CABLE Theory and Modeling panel session consisted of Maria Chan (Argonne National Laboratory), Subramanian Sankaranarayanan (Argonne National Laboratory), Katsuyo Thorton (University of Michigan), Bryce Meredig (Citrine Informatics), and Peter Voorhees (Northwestern University). It was co-chaired by Santanu Chaudhuri (Argonne National Laboratory) and Claudia Mewes (DOE Office of Science Basic Energy Sciences). Detailed talk summaries are included in Appendix B.

The primary challenge for the community is demonstrating scalable and validated approaches to overcoming the cost of first-principles calculations. Extending the length scale to realistic regimes with grain boundaries and defects enables researchers to understand the materials processing challenges. Exploration of possible ways of maintaining the accuracy of the electronic structure and transport calculations will be required for making quantitative predictions to guide materials design decisions in this domain.

Such modeling can take into account several parameters including micro-nano structural geometries, contact morphology, temperature, strain, and electric/magnetic fields. Starting at the smallest length scales (sub-nanometer) is modeling that requires quantum mechanical calculations of interfaces at the atomic level and identification of atomic configurations that can positively or negatively impact conduction processes. Molecular dynamics (MD) and density functional theory (DFT) can enable understanding of transport mechanisms in nanocomposite systems, providing crucial insights.

Maria Chan discussed initial investigations using MD and DFT to understand the effects of carbon nanophase inclusions on the phase transition and thermal conductivity of Cu metallic systems. Dr. Chan found that the simulations were able to calculate lattice thermal conductivities for pure Cu and Cu-covetic materials, which was in agreement with previous reports. Lattice structures were also simulated and showed good agreement with scanning transmission electron microscopy images. These results can help researchers predict transport properties for different structural configurations and bridge the gap between real-world experiments and simulations.

A key goal of physics-based theoretical predictions is to enable simulation over a much larger compositional phase space than is readily accessible by experiment, including identification of metastable states, and their morphological and topological variations in the material architectures due to processing conditions. Predicting the metastable phases of a material with respect to composition, temperature and pressure has long remained a challenging problem. Subramanian Sankaranarayanan shared recent results from using an AI guided inverse design framework to identify the most likely metastable states based on composition, which showed copper rich metastables preferentially formed carbon flakes within the copper matrix, while carbon rich metastables form carbon nanotubes. The workflow and AI algorithm developed by Dr. Sankaranarayanan and his team opens the door for reliably predicting synthesis pathways of metastable materials and thermodynamic domains/conditions for their synthesis. However, he noted that thermodynamics and kinetics are relatively unexplored domains, and more effort is needed.

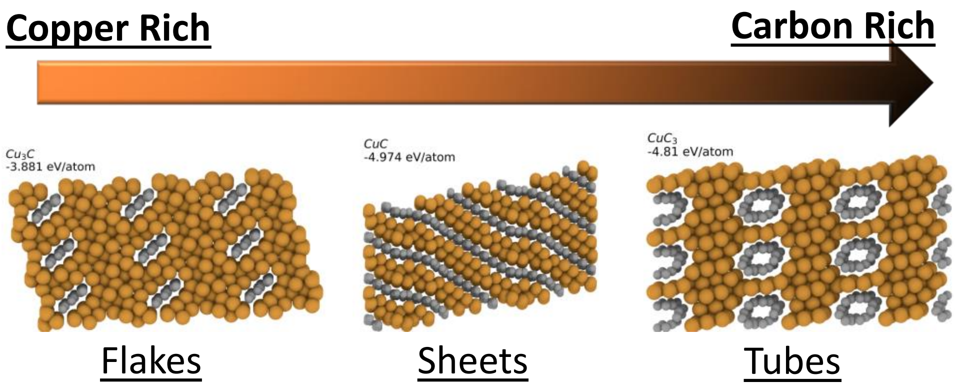

Figure 11: Changes in nanocarbon configuration as a function of chemical composition (Sankaranarayan 2022).

Leveraging AI and data-driven approaches introduces a new paradigm for materials development by moving away from explorative experimental syntheses to precision syntheses. Known as materials informatics, this approach uses data to solve complex problems in materials science. Bryce Meredig discussed the opportunities of using AI to address materials design, a traditionally slow and expensive process. By utilizing an iterative workflow that incorporates data, AI, and domain knowledge, researchers are able to reduce development time by prioritizing the possible chemistries and processing routes. Citrine has taken this a step further and is developing an integrated software platform that enables all material scientists and chemists, especially those that lack computing/computer science expertise, to use the materials informatics approach to dramatically reduce development time.

Expanding the understanding and modeling of a conductor from atomic scale to a realistic prediction at macroscopic scale requires both atomic- and meso-scale modeling. Mesoscale modeling, an intermediate scale of modeling, is required because bulk conductivity is partially dependent on microstructure (micron scale) formed in the manufacturing process. For example, electrical conductivity of copper can degrade due to polycrystalline material with a high density of defects caused by wire extrusion and drawing. It was noted that there are many instances where different research groups study the same materials and get different material properties, likely due to differences in how the material was processed. Katsuyo Thorton discussed the PRISMS Software Framework, which aims to enable predictions of microstructural evolution and mechanical behavior of structural metals. This tool integrates multiple models/simulations, including DFT, statistical mechanics, and crystal plasticity, to predict mechanical behavior. While microstructure is complex, simulation tools are becoming more reliable, more broadly available, and easier to integrate.

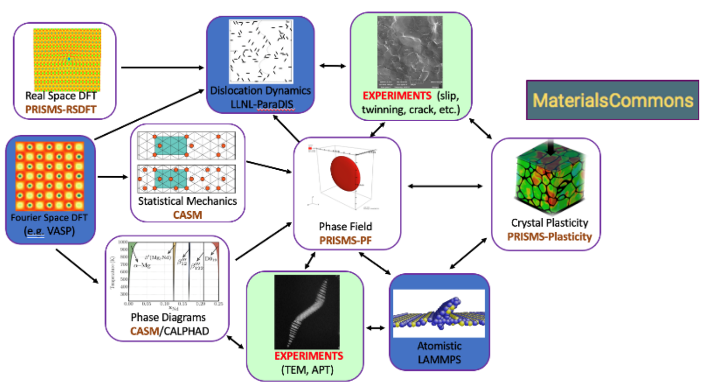

Figure 12: PRISMS Simulation Framework (Thorton 2022).

While confirming enhanced properties at the nanoscale is important to meet the manufacturability goals for CABLE materials, improved abilities to predict how the enhancements at small length scales will translate into bulk properties is the ultimate goal. To address this, holistic integration of modeling results from multiple scales and experimental data is needed. Peter Voorhees discussed the Center of Hierarchical Materials Design (CHiMaD), part of NIST Center for Excellence in Advanced Materials, which combines multiple tools, data sources, and approaches, including those from the Materials Genome Initiative, ICME, and Integrated Computational Materials Design (ICMD), to help researchers accelerate the materials development process.

While theory and modeling provide a strong foundation for materials development and design, all panelists reinforced the importance of experimental data. Without experimental data, models cannot be verified, validated, and refined. Throughout the discussion, several data gaps were noted, including kinetic data, interfacial data, material metadata, and in-situ processing data that would greatly help theory and modeling of conductivity-enhanced materials.

Key Takeaways from the CABLE Theory and Modeling Panel

- Data availability to feed into models is still limited.
- Compatibility of models at different length scales is a key challenge. The interfaces/connections between each scale must be considered carefully.
- Metastable states are intriguing.
- AI/ML is a useful tool to connect synthesis conditions with outcomes, which can ultimately advance theory.

Facilitated Discussion

The objective of the facilitated discussion was to catalyze connections within the CABLE research ecosystem to cross-pollinate ideas and to generate potential new teaming arrangements. The facilitated discussion took place over two days. The first day was focused on identifying key challenges and solutions to commercializing emerging CABLE technologies. First, CABLE innovators offered their perspectives on the primary technical challenge they faced to find long-term success. Then, others in the CABLE research ecosystem, including CABLE manufacturers and national laboratories with processing and characterization expertise, provided potential solutions to specific challenges identified. The group then underwent a prioritization exercise to identify the top four challenges; they were:

1. Scaling from R&D to production.
2. Technology adoption versus technology advancements.
3. Additives for CABLE materials.
4. Carbon fiber metal composite processing.

On the second day, workshop participants broke up into four small groups to complete an action plan, designed to further flesh out the four challenges. Sections of the action plan included further breakdown of the challenge; describing the challenge; key considerations related to theory, modeling, characterization, and testing; key activities within R&D, demonstration, and deployment phases, and stakeholder roles and responsibilities.

The sections below provide a narrative summary of the action plans developed by the four groups. A list of all challenges and solutions volunteered by participants can be found in Appendix D. Individual action plans can be found in Appendix E.

1. Scaling from R&D to Production

The key challenge for the Group 1 discussion on Day 2 of the CABLE workshop was the act of scaling from R&D to Production. Notable primary technical challenge(s) associated with the key challenge were understanding both the requirements for scaling R&D materials, as well as the market for the specified product/process. The definition of material scalability in specific target markets meant understanding the quantitative requirements in terms of kilograms, meters, and tons of wire/cable. Such knowledge of quantitative requirements would further aid in discerning which small scale products would breed success upon scale up. Further breaking down the challenge into sub-challenges from discussion participants gave insight into key aspects of the primary technical challenge(s). These were captured as the knowledge of specific technology designation for a given application, support from subject matter experts (SMEs) and larger companies to promote sustainability for a startup ecosystem, awareness of emerging and competing solutions in market, and barriers to grants from proposal submission(s) to laboratory.

Potential Solutions

- In terms of market penetration, a potential solution provided by participants consisted of laying out the target market paired with the technology area and production implication on the front end, like building a roadmap of target markets.
- Understanding suitable scale up material choices/sizes, as well as pre-requisite qualifications according to the market need, was discussed as an enabler of market permeability.
- Business partnering solutions for increased collaboration were noted as utilizing a manufacturing voucher system for the CABLE prize winner to access production facilities. The stage gating process, which could be tailored to company size, was noted as a system of best common practices. The Apex matchmaking function was unique in that it enabled problem- and solution-pairing for business support. On a similar note, the Department of Commerce Manufacturing Extension Partnerships (MEPs), known as state-based entities, were listed as a potential solution to connect innovators with manufacturers.

Key Considerations

- *Theory:* Early engagement in project phases through roadmap development aids in project efficiency and success in subsequent phases.
- *Modelling:* As another consideration to project success, the modeling efforts should account for process variability to provide the connection point between machine learning, characterization, and real time controls for manufacturing.
- *Testing:* To adhere to customer standards and optimize potential material properties, testing should be implemented in the early development phase(s), as well as post-production for quality control. Furthermore, for optimal testing in the post-production and production phases, it is imperative to utilize measurement devices that are low cost, robust, and high speed.

Key Actions Needed

- *R&D Phase:* Key activities to ensure success in the R&D phase consist of understanding process sensitivities of future production environments, gathering high resolution measurements, and early insight into product scalability by integrating business and economy experts.
- *Demonstration Phase:* As the R&D phase progresses into the pilot or demonstration phase, there are key actions to take such as implementing repeatability testing, establishing product specifications to adhere to, and utilizing trade trials, which are small scale demonstration(s) released in small quantities to market.
- *Deployment Phase:* Subsequently, the deployment phase of a product after the pilot phase should include ongoing quality control testing, as well as validating or refuting failure mode analysis conducted in prior phase(s).

Stakeholders and Their Roles

Various sectors are represented from the support of stakeholders to fulfill a variety of roles for the scale up of a product:

- *End Users/OEMs:* Establish the market requirements, cost, form factor, and quality guidelines for the product.
- *Academia:* Aid in the fundamental understanding of micro and macro material properties to optimize scalability.
- *National Laboratories:* Provide insight through material test data, modeling, and characterization.
- *Other Entities:* Provide support in the form of contract manufacturing to produce small product runs for the pilot phase. Such companies that specialize in contract manufacturing at scale up quantities prior to deployment are not well known within the CABLE community.

2. Technology Adoption versus Technology Advancements

Group 2 in the facilitated small group discussions focused on the challenges associated with the adoption of technology advancements. The group consisted of approximately 12-14 CABLE Workshop attendees, with one virtual attendant and the remainder in-person. Participants represented a wide range of expertise and industry – with individuals from government, academia, manufacturing, and end-user applications, to name a few. The participants displayed a difference of opinion on what the group should discuss during this session – with about half of the group wanting to focus on advancing TRLs in R&D and the other half wanting to discuss understanding the market and its needs. Ultimately, both topics were woven into the group's conversation.

One of the challenges identified in the technology advancement and adoption space is understanding if a technology is viable in the market and what the commercial plan should be. There is also difficulty in discerning whether a market is ready while a technology is in development, or if the technology is ready and needs to be marketed to consumers. Additionally, there are challenges around determining if a technology can be reproduced at a manufacturer-ready scale and understanding what MRL is needed to be able to progress toward that goal.

Potential Solutions

- One solution put forward by participants was to start with an end-goal in mind and encourage/foster healthy ecosystem communication. For example, it was stated that it would be helpful while developing new technologies if there were feedback from the manufacturing or consumer end, so the R&D arm knows what is needed and what end outcomes are desired. That way, those considerations can be incorporated into the R&D phases more proactively, without chasing a technology down a path that ultimately is not desired or pursuable by the manufacturers or consumers. This will lead to less recycling at later TRLs and a more productive use of resources.
- Another popular solution was to push for higher TRLs and MRLs in addition to determining what levels those need to be for stakeholders to adopt a technology. Ecosystem communication ties back to this suggestion because a challenge for both R&D and manufacturing is not knowing what TRL or MRL is needed by the other party to progress a given technology advancement. The group shared their experiences from both the developer and consumer side, noting that each industry (and even sometimes each individual developer or consumer) has different thresholds for progressing a technology. The participants agreed that it would be helpful to communicate across the ecosystem more frequently and regularly so that others' perspectives, limitations, interests, and opportunities are better understood.

Key Considerations

- *Modeling:* The group emphasized that modeling alone isn't sufficient to convince customers to adopt a new technology, and that materials and parameter specifications need to be examined when modeling is performed.
- *Characterization:* Though modeling is helpful, characterization and testing at a higher level is important to ensure that a successful material can be demonstrated for a specific technology.
- *Testing:* It is critical to define the specific conditions that existed when a performance was demonstrated.

Key Actions Needed

- *R&D Phase:* Define metrics and scalability.
- *Demonstration Phase:* it was highlighted that creating an R&D roadmap would be helpful, in addition to demonstrating the system and its interconnects to ensure that the technology will work for the intended, specific application.
- For deployment, group members noted that standardization is key.

Stakeholders and Their Roles

- *Product Manufacturers:* Play an important role in specifying the factors that are needed to build prototypes.
- *National Laboratories*: Useful for their capabilities in testing and metrology.
- *DOE/government:* Set appropriate metrics.

Risks and Potential Impacts

Finally, adopting technology advancements in an efficient and seamless manner is critically important as the U.S. and the world move toward decarbonization goals. The group agreed that deadlines are real, specific, and rapidly approaching – for example, decarbonizing the U.S. grid by 2035 and decarbonizing the entire U.S. economy and reaching net-zero emissions by 2050. These goals dictate the rate at which technology needs to be advanced and adopted, and there is a need to work quickly with a focused, team-based approach to create and adopt the technologies that will enable reaching these goals.

3. Additives for CABLE Materials

Participants in the Group 3 discussion on Day 2 of the CABLE workshop discussed the use of additives in semiconductor application and design. These high-performance additives are integrated into different materials to improve material structure and change their performance. Carbon-related nanomaterials—e.g., graphene, carbon fibers, and CNTs—have excellent characteristics; MXenes (pronounced "maxenes"), a fast-growing family of 2D materials, also show great promise. However, realizing additives' potential faces a range of challenges.

First, these materials are not widely available—a challenge highlighted by recent supply chain issues. In addition, the materials are costly. Furthermore, the current qualities, quantities, and costs of additives from the various manufacturers are not consistent. Quality varies from batch to batch, depending on the commercial source, the manufacturing method, and the quantity being produced. There is a need for a robust pathway that leads to commercialization that includes quality assurance and certification of the product to be procured. The manufacturers need to see a market for these additives, and the market for these products needs to be developed.

Research can be very expensive and does not necessarily produce an additive that can be transferred directly to industry at a full production scale. There is a need for a standard path toward large-scale production that includes scale-up and technology transfer. One path forward is to look at smaller-scale sectors, such as avionics, rather than immediately targeting power cable production. The avionics sector is eager for technology advancements in the semiconductor space and could serve as a bridge to further develop CABLE materials for other applications.

Basic CABLE design knowledge for properties such as fatigue or magnetic properties is critical but lacking. In addition, there has been extensive study of additive (specifically graphene) behavior when layered with metals, but the interactions when additives are embedded into a metal matrix are less understood. CNTs are not very compatible with copper because metals do not bind well when you try to make a matrix with CNTs. The interfacial surface energy is high between metals and CNTs, and high electrical and thermal resistances can occur unless the CNT is modified or a composite structure is used. Although there are some theories for manufacturing graphene and CNTs, the scientific community lacks a fundamental theoretical understanding of manufacturing processes and the impacts of different starting materials on the performance of these additives. Excellent modeling capabilities at the national laboratories or universities should be combined with industry efforts to understand how different processes at different scales can result in different material qualities.

One promising material is epitaxial graphene, which is grown on a substrate and is generally multilayered. Hummers' method is a good chemical process for generating graphene oxide but is poor when used for copper and has the potential to add defects. The process could potentially be used for niobium arsenide, which is a crystalline solid used as a semiconductor. To maximize the graphene properties, a dopant can be used, but good dopants are not commercially available. When graphene is used with copper, a dopant is not needed at the interface.

Potential Solutions

- Companies that possess the intellectual property on low cost and scalable production of graphene and CNT were discussed as an option that could work with any interested partner.
- Participants noted that a certification process that could be supported by DOE would help to ensure that a manufacturer will produce products to common standards.
- A process that would facilitate transitioning a newly developed additive to industry for large-scale manufacturing and would use capabilities at national laboratories and testing agencies was stated by participants to be valuable.

Key Considerations

- *Theory*: There is a need for a better theoretical understanding of the synthesis processes of CNTs and graphene. Computer modeling and simulation will be useful in this endeavor.
- *Modeling*: Modeling of charge transfer between metal and graphene or CNTs would be helpful not just for pristine cases but also materials like carbide (a former intermediary) or dopants.
- *Characterization*: Techniques are currently available for characterization of additive materials, but it would be helpful if these techniques and methods were more generic. For example, Raman spectroscopy is used to determine the quality of graphene, but a manufacturer may refuse to release the data, considering it to be proprietary. The end user would then have to do in-house characterization with their own equipment or find the capability elsewhere, which could require new techniques and standards. For an end user who wants to buy these materials and see how they can be used, a more accessible technique—one that does not need expertise in spectroscopy—would be helpful. Some type of a standard testing capability is needed.

- *Testing*: Testing is driven by applications. There are electrical-specific tests of interest—but only for electrical applications. If an application uses an additive for a specific purpose (e.g., electrical conductivity), then a test standard is needed for the additive in that application.

Key Actions Needed

- *R&D Phase*: Process modeling needs to be developed for the different types of additives. A pathway for large-scale demonstrations needs to be devised.
- *Demonstration Phase*: Quality assurance methodology is needed to ensure that the additive material can be produced with the same quality for each production run. For the bulk material, the outcome will depend on what process is used.
- *Deployment Phase*: The form of the bulk material needs to be determined for production. Market development needs to be done in advance of deployment with an understanding of the potential barriers that could impact product sales.

Overarching Goals and Performance Targets

An important common denominator for any of the additive materials is determining the process modeling required and finding or exploring pathways for making such materials. Then, investments must be made in the research for this type of process modeling. Once a process is defined and modeled, standards for making the additive material consistently should be developed and put in place. Because these are new age materials, markets should be identified for them as they are being developed. This would be an important incentive for the stakeholders.

CABLE is one avenue for these discussions, but perhaps there are others. In addition, discussions should expand beyond enhancing conducting materials to explore other applications for these additives.

DOE and other stakeholders can help by continuing discussions on supporting initiatives, certification standards, and funding mechanisms, improving viability of the goals and targets. Different product manufacturers and end users (original equipment manufacturers) could be identified to assist in filling existing gaps. The national laboratories and universities can partner with these entities. The current academic focus on STEM can be leveraged to boost development of new equipment, new ways of manufacturing materials, and performing cost, techno-economic, and life cycle analyses for producing and supplying additive materials.

Recommendations for specific areas of involvement, stakeholder roles, risks, and impacts for the various agencies are given below:

- *Research Phase:* Investments are needed in large-scale process modeling. Standards are needed that will provide consistency in additive manufacturing and process outputs.
- *Demonstration Phase:* Certification standards and cost targets need to be established.
- *Deployment Phase:* There is a need for an approach for rapidly producing large quantities of product in parallel with development and implementation of a good marketing strategy. The approach will depend on the application, which defines the type of additive and the required production levels. Intermediate standards should be proposed that can be used and accessed while the final standard(s) are being developed. Deviations should be anticipated, such as complex forms (e.g., extruded vs. sheet) that require different process conditions.

Stakeholders and Their Roles

- *Product Manufacturers*: Provide high-quality bulk materials at low cost.
- *End Users/OEMs:* Identify markets.
- *Academia*: Provide research support and the fundamental science.

- *National Laboratories:* Provide computer modeling and simulation, characterization capabilities, and technology transfer mechanisms.
- *DOE/Government*: Support research initiatives and development of certification standards with funding.

Risks and Potential Impacts

- *Product Manufacturers*: High risk that could result in delayed use of additive materials.
- *End-Users/OEMs*: High risk that could result in delayed full deployment of cable materials (i.e., only to niche markets).
- *Academia*: Medium risk for the labor force because academia already focuses on a trained STEM labor force.
- *National Laboratories*: Medium-to-high risk resulting in delayed scale-up of the additive materials.
- *DOE/Government*: None identified.

4.Carbon Fiber Metal Composite Processing

Facilitation Group 4 focused on development of carbon fiber metal composite processing capabilities. Participants stated that adding nanocarbon materials to aluminum can increase the strength significantly, potentially allowing replacement of steel cores in standard aluminum conducting steel reinforced cables. Participants did not believe that the fiber would increase conductivity of the aluminum, but the replacement of the steel cores with lower weight materials that are conductive were stated to add significant benefit to the cables in terms of efficiency, cost, and reducing environmental impacts. Carbon fiber has a surface area three orders of magnitude smaller than other nanocarbons, making them easier to process. Carbon fibers can also potentially be sourced from recycled feedstocks, providing an additional environmental benefit to using the material. The major challenges with utilizing these carbon fibers in cables highlighted by participants were scaling up production and a lack of expertise in carbon fiber metal composite processing into wires.

Key Considerations

- *Modeling:* Participants stated that the theory for predicting properties for carbon fiber aluminum composites is largely understood and can be utilized to develop models for predicting strength and electrical conductivity of these composites to determine their potential to replace steel cores in cables. Some processes were believed to have been developed by others in the past for this material but need to prove cost effectiveness. An analysis of the cost of creating the composites is necessary, including identifying the extra processing steps required to add carbon fibers to aluminum to produce core material compared with current steel core production. An analysis of the supply chain for recycled carbon fibers was stated by participants to be beneficial to determine the feasibility of this as a feedstock material.
- *Characterization:* Sample composite materials produced would require testing and characterization of their mechanical strength and electrical conductivity.
- *Testing:* Participants stated that there are many different types of carbon fibers used across industries, with carbon fiber type potentially having a big impact on performance. If recycled fibers are used, testing will need to be done to determine which type of fibers can be recycled and used with this route.

Key Actions Needed

Participants discussed several steps in the R&D phase that need to be taken to help address this challenge before demonstration and deployment can occur:

- *R&D Phase*

    - Development of the business case, determining the production cost and material properties required to make this process feasible.
    - Once business case is established, develop a method of producing carbon fiber reinforced ingots followed by developing carbon fiber reinforced aluminum wires from the ingots.
    - An additional step discussed was the need to evaluate desizing for spool carbon fiber or recycled carbon fiber, if pursuing these routes, to prevent impurities impacting the wire material.
- *Demonstration Phase*
    - Once a process was developed, evaluating the ability of current production routes was stated by participants to be an important next step in developing the business case, along with connecting with wire manufacturers to evaluate running larger demonstrations.

Overarching Goals and Performance Targets

The overarching goal of these efforts was stated by participants to be replacing current steel core electrical cables with carbon reinforced variants. Therefore, the R&D and demonstration phases should produce wire that matches the mechanical strength of the steel core reinforced cables with good electrical conductivity ("good" as defined during development of the business case).

Potential Impacts

Several benefits were discussed by participants for producing carbon fiber reinforced wires.

- Reducing the environmental impact of wire production by reducing wire quantity requirements. This impact was stated by participants to be even larger if able to use recycled carbon fiber materials as there are few to no current processes recycling these fibers.
- A lighter material core would help reduce sagging in the wires, reducing the chance of fires. This could also have long term impacts of reducing wear and tear on the wires, improving the economic benefits of the wire.
- Participants also discussed adding a carbon coating as an additional processing step to the wire production to help increase emissivity which could reduce energy losses.
- Participants stated that there could be additional economic benefits if the material produced was used for lightning protection.

Appendix A: Agenda

Day 1 - Wednesday, July 20			
Time (Central)	**Segment**	**Speaker/Panelist**	**Presentation Link**
9:00–10:45 a.m.	Optional Tours of Argonne Facilities		
11:00–11:30 a.m.	Opening Remarks	Paul Kearns (ANL) Matthew Ringer (NREL) Srinivas Siripurapu (Prysmian Group)	Industry Plenary Presentation
11:30 a.m.–12:10 p.m.	Panel Discussion: Testing, Characterization, and Computing for CABLE Researchers	Moderators: Kimmai Tran (DOE AMO) Dava Keavney (DOE Office of Science) • Ilke Arslan (ANL) • Keerti Kappagantula (PNNL) • Saniya LeBlanc (George Washington University) • Jini Ramprakash (ANL) • Robin Miles (LLNL)	• DOE X-ray Light Sources • Center for Nanoscale Materials • Electrical Property Measurement Setup and Layout • Thermal Metrology to Measure Thermal Conductivity • Argonne Leadership Computing Facility • National Laboratories Partner with U.S. Industry to Increase Innovation and Energy Efficiency
12:10–12:30 p.m.	Panel Q&A		
12:30–1:15 p.m.	Working Lunch: Reflection on Day 1 Morning Sessions		
1:15–1:25 p.m.	CABLE Prize Introduction	Moderator: Emily Evans (NREL)	
1:25–2:25 p.m.	CABLE Competitor Showcase	Speakers: • Dr. Nhon Vo • David Lashmore • Mohamed Rahmane • Frank Kraft	• Ultra-High Strength Highly Conductive Al Alloys • Light Weight Power Cables • Electron Beam Melting (EBM) Additive Manufacturing of High-Conductivity Materials: Copper-Carbon Composites • Copper-Graphene Ultra Wire

		• Guenther Horn / David Bergmann • Dave Townley • Dmitri Tsentalovich • Selva Venkat • Mehran Tehrani • Jason Huang	• Conductivity Enhanced Alloys with Nano Additives • Modern Advanced Conductors: Introduction to High Efficiency, High-Capacity Modern Advanced Conductors • Advanced Carbon-Negative Materials • Super Cool Conductor: An Affordable, Infinite Conductivity Superconductor • High Conductivity, Stability, and Strength Composite Conductors • TS (Total Solution) Conductor: The Road to Sustainability
2:25–2:40 p.m.	BREAK		
2:40–2:55 p.m.	Presentation: Mining Responsibly—Supply Chain and De-carbonization of Mining	Paramita Das (Rio Tinto)	Mining Responsibly - Supply Chain and De-carbonization of Mining
2:55–4:15 p.m.	National Lab Researcher Showcase	Moderator: Emily Evans (NREL) Speakers: • Peter Sharma (Sandia National Lab) • Nicolas Argibay (Ames National Lab) • Aaron Fluitt (Argonne National Lab) • Keerti Kappagantula (PNNL) • Matt Ringer (NREL) • Martin Detrois (NETL) • Don Parris (Prysmian Group)	National Lab Researcher Showcase
4:15–4:20 p.m.	Facilitation Instructions	Facilitator: Emmanuel Taylor (Energetics)	
4:20–5:30 p.m.	Facilitated Discussion	Facilitator: Emmanuel Taylor (Energetics)	
5:30–6:30 p.m.	Reception		

Day 2 - Thrusday, July 21			
Time (Central)	**Segment**	**Speaker/Panelist**	**Presentation Link**
9:00–9:30 a.m.	Day 1 Review and Opening Remarks	Diana Bauer Tina Kaarsberg	Welcome from DOE's Advanced Manufacturing Office
9:30–10:10 a.m.	Panel Discussion: Electric Conductors	Moderators: Henry de Groh (NASA) Andrea Pereira (DOE Office of Electricity) • Iver Anderson • Mehran Tehrani • Thomas Kozmel • Frank Kraft • Keerti Kappagantula	• Development of AL/Ca Composite Conductor for Mono-Type Transmission Cable • Prospects for Nanocarbons as Electric Conductors • QuesTek Innovations LLC: Materials By Design • MetalKraft Technologies • Synchrotron Characterization of Ultra-Conductors
10:10–10:30 a.m.	Panel Q&A		
9:30–10:10 a.m.	Panel Discussion: Thermal Conductors	Moderators: Tony Bouza (DOE BTO) William Worek (ANL) Speakers: • Michael Ohadi • David Cahill • Jie Li • Kashif Nawaz • Geoff Wehmeyer	• Digital Twin-Enabled Polymer Composite HXs for Heat Pumps and Thermal Energy Storage Applications • Advanced Passive and Active Heterogeneous Thermal Conductors and their Characterization Needs and Gaps • Copper/Carbon Composites With Ultrahigh Thermal Conductivity • Thermal Properties of Ceramics for High-Temperature Thermal Applications • Thermal Properties of High-Conductivity Carbon Nanotube (CNT) Fibers
10:10–10:30 a.m.	Panel Q&A		
10:30–11:10 a.m.	Panel Discussion: Superconductors	Moderator: Jake Russell (DOE ARPA-E) Speakers: • Ranga Dias (University of Rochester)	• Superconductors: Current Status and Future Opportunities • Towards Ambient Superconductivity

		• Venkat Selvamanickam (University of Houston) • Michael Tomsic (Hyper Tech Research) • Yifei Zhang (Superpower)	• Low-cost, High-Performance REBCO Superconductors for Electric Power Applications • Superconducting Technologies for the 21st Century • REBCO High Temperature Superconductors: Increasing Demand and Technical Challenges
11:10–11:30 a.m.	Panel Q&A		
11:30 a.m.–12:15 p.m.	Working Lunch: Reflection on Day 2 Morning Sessions		
12:15–12:55 p.m.	Panel Discussion: CABLE Theory and Modeling	Moderator: Santanu Chaudhuri (Argonne National Lab) Claudia Mewes (DOE BES) Speakers: • Maria Chan (Argonne National Lab) • Subramanian Sankaranarayanan (Argonne National Lab) • Katsuyo Thorton (University of Michigan) • Bryce Meredig (Citrine Informatics) • Peter Voorhees (Northwestern University)	• Modeling and simulations of Metal-carbon composites • Exploring Metastable Metal-Nanocarbon Composites For Enhanced Electrical And Thermal Conductivity • Predicting the Material Properties and Behaviors: The Importance of Microstructures and Their Effects • Efficient AI-driven design of novel materials satisfying multiple property targets • Insights into Nanoscale Control of Microstructure for Conductivity Enhancement
12:55–1:15 p.m.	Panel Q&A		-
1:15–1:20 p.m.	Facilitation Overview	Facilitator: Emmanuel Taylor (Energetics)	-
1:20–1:25 p.m.	Break		-
1:25–2:35 p.m.	Facilitated Discussion		-
2:35–2:40 p.m.	Break		-
2:40–3:25 p.m.	Panel Leads Discussion		-
3:25–3:55 p.m.	Facilitation Report Outs		-
3:55–4:00 p.m.	Closing Remarks		-
	Adjorn		-

Appendix B: Talk Summaries

Day 1

Opening Remarks – Paul Kearns, ANL

Electric and thermal conductors are essential components to modern technologies such as electric vehicles through the electric grid. The Department of Energy's national laboratories partner with federal agencies, sister laboratories, universities, and companies to invent new materials and optimize processes in the U.S. electricity manufacturing sectors. Argonne National Laboratory houses world class capabilities to propel industry research goals such as the Advanced Photon Source, Center for Nanoscale Materials, Materials Engineering Research Facility and Argonne Leadership Computing Facility. Argonne is actively engaging the scientific community through collaboration, which enables partnerships to increase impact.

Opening Remarks – Matthew Ringer, NREL

New conductive materials that carry electrons more efficiently and effectively with greater resilience are imperative to industry decarbonization in the United States. As an example, during electrification of process heating, the ability to drive electrons more effectively towards the process is critical. The focus of NREL is encompassed in renewable energy and driving decarbonization for the future. Furthermore, two key initiatives that stem from such a focus are integrated energy pathways and electrons to molecules. Example technology focus areas under these initiatives are connectivity of devices and the electrolysis to hydrogen process.

Opening Remarks – Srinivas Siripurapu, Prysmian Group

Key challenges lie ahead regarding greenhouse gas emissions reductions that require thousands of gigawatts in renewable installations, digital inclusion with a goal of 90% of the global population having online access by 2050, and sustainable electrification for vehicles and homes. The wire and cable industry enables us to overcome such challenges through avenues such as offshore wind energy, land interconnectors, submarine cable systems, digitalization, and infrastructure for electrical revolution. Detailed in Figure 13. Plans to increase offshore wind energy from 35 gigawatts to over 1,600 gigawatts by 2050 will require over 57,000km of Prysmian cable laid by 2030.

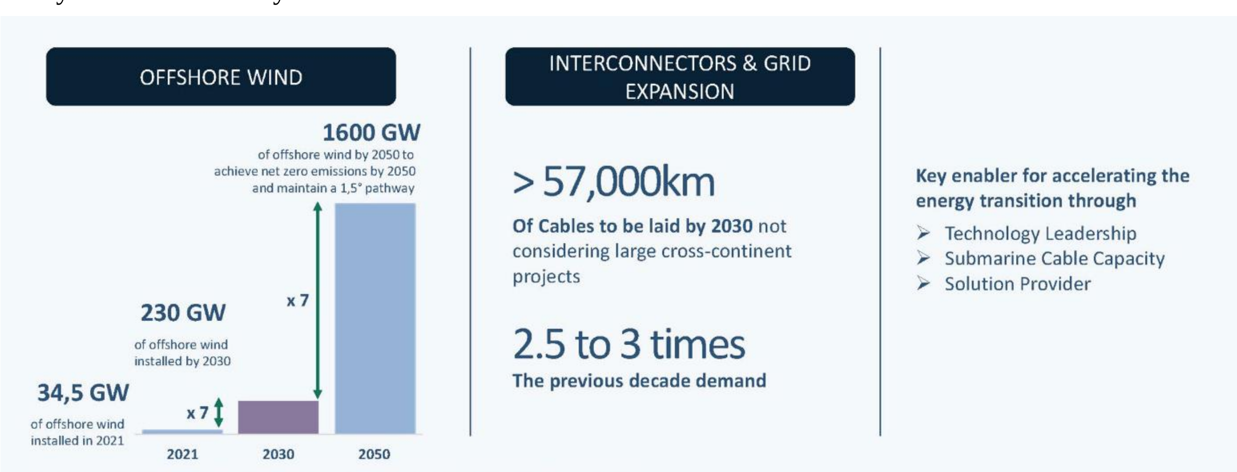

Figure 13: Estimation of growth of offshore wind generation and demand for grid cable expansion. (Prysmian 2022)

To serve as a solutions provider, Prysmian has more than doubled R&D investments in HVDC and HV-AC technologies. Furthermore, over $120 million was invested into R&D in 2021 with an extensive 5,600 patents covering main innovations to date and over 298 product families launched in 2021. As a prime example of R&D investment, current HVDC interconnectors can push over 2 gigawatts of power per cable as a result of material innovation.

Prysmian customers, stakeholders and investors place a key emphasis on sustainability in cable and wire manufacturing to cut emissions inherent to the supply chain for products, transition energy to renewables, and make environmentally friendly choices. The need for a low carbon footprint is a necessity in today's industry, with framework established during the design phase of projects in order to minimize rework. Prysmian has made ambitious climate change resolutions/goals based upon the science-based target initiative to be carbon neutral by 2035 and, in terms of scope 3, by 2050. Avenues to enable such targets will be achieved through energy transition to renewables by utilizing thermoplastic, fully recyclable cross-linked systems and offshore wind farm deployment on the Atlantic coast. Furthermore, the collaboration between Prysmian and DOE labs to validate the use of inorganic material coating on overhead lines for higher transmission efficiency at a lower cost is an example of optimizing grid hardening.

By utilizing Prysmian's expertise in both energy and telecommunications technology, the use of optical sensors can be integrated into industrial hybrid solutions such as electric vehicle charging infrastructure. The optical sensing element integrated into such infrastructure will be used for strain and temperature monitoring to understand the power capabilities of each cable. In addition, a portfolio of AC, DC, and fast charging solutions will assist in developing the electric vehicle charging infrastructure. In conclusion, criteria for sustainability such as carbon footprint, substances of high concern, recyclability and circularity, recycling input rate, environmental benefits, and transmission efficiency are widely being considered across Prysmian's portfolio of technologies for customer needs.

Panel on Testing, Characterization, and Computing for CABLE Researchers

Dava Keavney, DOE: The scientific user facilities available through the Basic Energy Sciences Program (BES) program (at national labs across the U.S.) include light sources, neutron sources, and nanoscale research centers. The total users of these facilities number 11,300, though they numbered over 16,000 annually pre-pandemic and were mostly on-site. Over 60% of current users are remote.

The highlighted facilities included the Advanced Light Source (ALS) at Laurence Berkely National Laboratory (LBNL), APS at ANL, Linac Coherent Light Source (LCLS) at Stanford Linear Accelerator Center (SLAC), and National Synchrotron Light Source-II at Brookhaven National Laboratory (BNL). These light sources allow users to employ three experimental techniques—imaging, spectroscopy, and scattering—all of which focus on X-rays. It was noted that multimodal, in situ, and operando measurements are growing areas. The X-ray facilities are open access, and all work is collaborative. After deciding what they want to do, a prospective user may reach out to someone about designing an experiment.

Ilke Arslan, ANL: There are five nanoscale research centers in the U.S., all of which serve as a network of user facilities for academic, industry, and international users. Facilities are open source for other researchers, who do not have to pay to use these facilities. Some users come from across the U.S. and the world, but most users are local to the states in which the centers are based (and neighboring states). The highest number of users are in Illinois, with the second highest in California. Users can pay to use the facilities to keep data proprietary, or if publishing the data. Access to helping staff and instrumentation is otherwise free. Staff spend approximately 50% of their time helping users and the other 50% doing their own research. Each center has a strategic focus and handles both proprietary and open science, with growing electron microscopy facilities.

The Center for Nanoscale Materials (CNM) at ANL is getting three new SEMs with high-energy, high-resolution capabilities. All use laser excitation. A second microscope used is a TEM that bridges regular- and high-resolution microscopes. The electron microscopy facilities at CNM feature high temporal and spatial resolution. Lab capabilities include 1) ultrafast electron microscopes, which allows users to examine irreversible processes; 2) nanocarbon materials development, featuring clean room capabilities for materials synthesis enabling examination of single and bi-layer graphene films; 3) superlubricity, which entails manipulating friction at nanoscale with impact at macroscale. In the lab, nanocrystal diamonds in graphene layers are used to reduce friction, thereby reducing energy lost. It was noted that nanocarbon technologies are ready for commercialization. ANL's CNM issues three calls for proposals annually, but prospective users can submit proposals anytime during the year.

Keerti Kappagantula, PNNL: Electrical property characterization capabilities of the lab include imaging and tensile testing of cables using a forward-looking infrared camera, which acts as a non-contact means of measuring temperature (and emissivity, using graphite ink or custom black tape). Electrical properties are reported as per ASTM, and voltage drops/temperatures are recorded at a steady state at specific current levels. There is a 1m-long measurement ability for wires, and the lab is equipped to measure conductivity, current density, and temperature coefficient of resistance, with the standard pooled error in conductivity measurement being about 0.01% IACS.

Considerations of importance include conductor dimensional stability, a drawbench for improving dimensional stability, conductor temperature monitoring, and environmental effects. Temperature conductivity resistance (TCR) slope is important for predicting electrical conductivity and resistance over temperature range. Low TCR and high conductivity is the goal. Diameters must be measured carefully for accurate analysis of wire capability. Generally, focus is directed toward error and precise measurements to ensure data is repeatable. This is important because very small measurements are being used and analyzed.

Saniya LeBlanc, George Washington University: Thermal metrology can be used to measure thermal conductivity, but it can be challenging to choose which thermal metrology techniques to use when developing a new material or testing new materials. Criteria to compare metrology techniques are needed (direct vs. indirect measurement of thermal conductivity, temperature range during measurement, contact vs. non-contact measurements, cost/overhead/infrastructure required, simultaneous/close measurement of other properties, ease of implementation, etc.). Other considerations include benefits/issues with each of the thermal conductivity measurement techniques, factors being measured, technique sensitivity to measurement, contact resistance measurement, and the possible range of thermal conductivity that can be measured by the setup in use.

Robin Miles, LLNL: HPC can be used to solve industry problems. Industry and government benefits include reduction of time to market, improved energy efficiency, improved processes and quality, and broadened expertise of PIs. HPC shortcuts the Edisonian approach, enabling multiscale, multiphysics modeling and simulation. This leads to accurate physics, new material discovery, optimization, and AI data analytics.

Labs partner with industry to lower the risk of HPC adoption. Over 140 projects have been funded with over 50 U.S. manufacturers including aerospace leading-edge companies, legacy industries, and innovative small companies. Eleven labs are involved in this program, supported primarily by AMMTO and other offices, and the labs' HPC capabilities are among the largest in the world. Companies apply to the program through a solicitation process, initiated twice per year, wherein industry submits a challenge in the form of a concept paper, which is then matched to a national laboratory expert. AMMTO approves the projects, and agreements are signed. Project leads can be matched up to a computational scientist at the national lab; connections don't need to exist prior to applying.

Jini Ramprakash, ANL: The ALCF was established in 2004 and houses the Aurora HPC, Frontier, and Polaris (the newest machine). The ALCF operates as one facility with two centers (ANL and ORNL), and ANL partners with other HPC facilities at other labs, such as HPC4EI. Today, computational capabilities are 10 to 100 times more powerful than they were previously.

The ALCF provides insights on cutting-edge AI technology to improve science and evaluates usability and performance of machine learning applications on a deep-learning accelerator, a reconfigurable dataflow unit, and intelligent processing unit-based systems. The ALCF features a number of AI test beds and computing resources, and the facility works with industrial partners to give industry the ability to perform more complex simulations, make better predictions, draw knowledge from data, improve products, accelerate innovations, reduce or eliminate the need to build multiple prototypes, benefit from ALCF's expertise, and engage with domain experts across ANL and its user facilities to form long-term collaborations.

The facilities have 375 active projects with 1,168 facility users using 33.5 node-hours of computing time. This resulted in over 230 professional publications. First among the ALCF Allocation Programs is Innovative and Novel Computational Impact on Theory and Experiment (INCITE), which is offered annually in January. Of compute time, 60% is open to all prospective users who have applied and won time, and 20% typically comes from an annual July directive from DOE. Other programs include the ASCR Leadership Computing Challenge (ALCC) and Director's Discretionary (DD) program.

CABLE Prize Introduction

Emily Evans, NREL: The American Made Network started in 2018 with a single prize and has since grown to over 30 prizes from 10 different DOE technology offices. The American Made Network has awarded over $100 Million in cash prizes and support and developed a network of over 250 network members who support prizes and competitors. Prize funding mechanisms differ from typical funding mechanisms. In typical funding mechanisms applications are submitted and put through multiple rounds of review before money is awarded and work is done. In a prize, work is done before application then submitted as achieving the prize goal. Turnaround for a prize is typically 1-6 months versus an estimated 9-12 months for other funding mechanisms. Prize money is a no-strings-attached award, cash awarded can be used at the awardee's discretion.

The CABLE Prize is an important component of the CABLE Innovation Ecosystem. It complements the characterization and modeling work already done in the CABLE SBIR projects to help push the technology forward towards production. The CABLE Prize is structured into 3 stages. Stage 1 sought concepts to develop and manufacture conductors with significantly enhanced electrical conductivity compared to commercially available copper and aluminum. Stage 2 take concepts a step further asking competitors to produce lab-scale samples of these materials and submit them along with written materials describing other high-performance properties and manufacturability. Stage 3 will expand on stage 2 requiring manufacturing scale samples from competitors and the proposed high-performance properties will be verified.

CABLE Competitor Showcase

Nhon Vo, NanoAl LLC: Traditional material development is a lengthy and expensive process, often requiring hundreds of iterations of material fabrication and testing over decades before a material with the correct properties is produced. While computer simulations have reduced the time required to years instead of decades, Rapid Alloy Screening (RAS), which combines simulations with machine learning and high throughput experiments, can further reduce this time to a few months. This process was used to develop Nano 6000, a 6000-series based aluminum alloy with modified chemistry at hundreds of ppm level and optimized thermo-mechanical properties. The material is produced using traditional manufacturing equipment in a specialized order: aluminum rod casting, heat treatment, wire drawing, and then conductor stranding. The standard equipment requirements mean that this process is scalable with lower costs. The produced material has a higher specific strength than galvanized steel while maintaining high electrical conductivity, allowing for potential replacement of steel cores with a more conductive material that reduces transmission and distribution losses and reduces the number of transmission towers required.

David Lashmore, American Boronite Corporation: CNT/metallic composites are a promising option for reducing weight of electric cables while maintaining (or improving) conductivity properties of the base metal. A process has been developed to produce CNT yarn which is braided around an aluminum or copper alloy composite. These braids can be put into bundles to build wires that meet customer requirements. These braids can achieve 6,000 siemens2/kg, which is similar to the conductivity of copper (6,400 siemens2/kg) and can handle significant current with lower temperature increases with test data going up to 500 amps. Significant work is required to commercialize this process, but it shows great promise as an alternative wire material that can help reduce weight of cables and energy demand through increased conductivity, which can help reduce greenhouse gas emissions.

Mohamed Rahmane, GE Research: Electron beam melting (EBM) is an additive manufacturing process that has the potential to enable innovative new materials and designs in high-conductivity materials. This technique allows for manufacturing novel designs that improve a material's performance over standard designs. One example of such designs improving performance is a hollowed and cooled electric motor that was produced with EBM using copper, which showed 3.5 times the power density baseline set by the DOE for the study.

EBM can also assist in developing copper-carbon systems, overcoming some of the challenges inherent in these alloys. Carbon has close to zero solubility in copper and power wettability with liquid copper, creating interfacial resistance between the materials. Carbide-forming elements have been shown to reduce this tension if it reacts with the carbon but not the copper. EBM can enable production of this material with its ability to handle in-situ process materials while manufacturing full components with complex geometries. Preliminary work on this has been focused on evaluating the interface interactions between carbon and copper when using EBM, with next steps focusing on optimization of the carbon type and size used, type and quantity of carbide material required, and process parameters needed to produce the highest quality material.

Frank Kraft, MetalKraft Technologies: The aim of this project is to develop a solid phase processing technique that can embed nano-carbon in copper at the correct amount, orientation, and morphology to achieve at least 65 MS/m conductivity. Embedded nano-graphene layers can work synergistically with the copper matrix, improving the flow of electrons over the base materials. This material could potentially behave similarly to how copper wire behaves today, allowing for this material to act as a drop-in replacement for copper wires, improving performance in equipment where conductivity is important. Next steps include additional analysis to guide processing and production of proof-of-concept material.

Dave Townley, CTC Global: An advanced conductor wire has been produced which utilizes a carbon composite core surrounded by an annealed aluminum conductor. In addition, the aluminum is produced in a trapezoidal shape instead of the traditional round shape to allow for more aluminum to fit into the wire at the same diameter. The lighter core allows for greater transmission capacity at the same weight as standard ACSR wires, while the annealed aluminum means more and better conducting material available for transmission, doubling the conductivity and reducing losses by 40%, all while reducing thermal expansion during heating and reducing thermal sag. The similarity in weights and size also means that the wires can replace ASCR wires without changes to the supporting towers, reducing the cost to rewire by up to 50% along with reductions in installation time. So far, 6,395 miles of this advanced conductor have been installed in the U.S., reducing transmission losses along with associated greenhouse gas emissions.

Guenther Horn & David Bergmann, NAECO: Nano materials, such as graphene, can be added to copper wires to improve their overall conductivity. Attempts were made previously to add carbon to liquid copper while applying a DC electrical field, using copper foil with graphene added as a coating with chemical vapor deposition as the carbon source. The results were minor but inconsistent increases in electrical conductivity. An alternative approach using ShAPE extruded wires has been performed and showed increases in electrical conductivity up to 105% IACS in short run segments of wire, while also showing promising TCR and mechanical properties. Next steps for this process will involve improving consistency in longer lengths of extruded wire, evaluating effects on physical properties of the wire fabrication process (including repeat drawing, annealing, drawing steps), and testing of wires under application parameters. Additional opportunities for improvement that are being pursued include broadening the precursor material used (such as doped copper materials and functionalized graphene variations), evaluating alternative methods of incorporating graphene into precursor materials, and testing different solid phase methods to transform bulk materials into electrically conductive materials.

Dmitri Tsentalovich, DexMat, Inc.: Galvorn is a carbon nanotube (CNT) conductor that has been developed as a lightweight alternative to metal conductors. This material is produced as a fiber via scalable fluid-phase processes: CNTs are extruded with the resulting filaments wound while under tension. The resulting materials have high strength and conductivity with a lower weight than other conductors, 25 times higher flexural tolerance than copper wire, and is not prone to galvanic corrosion. Improvements in conductivity and strength are expected to be made by using longer, defect-free CNTs, improving CNT alignment in the fiber, and by electrochemical doping of the constituent CNTs with halogen compounds. This material has another advantage in that they can be produced from GHG-neutral or GHG-negative sources, further supporting decarbonization. Next steps include identifying a partner or in-house method to produce CNTs, partnering with research institutes to perform doping studies, partnering with chemical and fiber companies on CNT processing improvements, and identifying a partner for testing and evaluation of raw CNTs and fibers.

Venkat Selvamanickam, University of Houston: Rare earth-barium-copper-oxide (REBCO) thin film superconductor tapes have been produced that can carry 5 to 10 times more current than comparable conventional cables. This superconducting material can run at lower voltages without loss, reducing overhead line distance requirements to as low as 1/16th of that required for conventional lines. These cables have been demonstrated in the power grid, but cost prevents widespread adoption, costing four times that of typical copper wires.

REBCO is currently produced by thin film vacuum deposition generating a 1µm thick REBCO-HTS layer on a nickel alloy substrate in a continuous reel-to-reel process. Only 1% of the tape is superconductor, with the size of this layer being limited by the film deposition technique, with the rest of the tape being nickel alloy or copper. Advanced metal organic chemical vapor deposition (MOCVD) is a new technique that is being developed to overcome this limitation and to help improve performance and reduce costs for REBCO superconductor tapes. This technique allows for deposition of up to 5µm thick films, increasing performance by 4-5 times performance increase, along with 5 times increase in conversion efficiency of the thin film raw materials, resulting in a decrease in cost by half. This process is enabled by in-line 2D-XRD which allows for real-time quality checks for the films. These improvements could bring the cost of these semiconductors below that of traditional copper wires.

Mehran Tehrani, University of Texas – Austin: Carbon fiber conductors have been produced that have high conductivity, strength, and thermal conductivity. This conductor is produced utilizing commercially produced carbon fibers and intercalating them with metal halides (intercalation involves introducing metal halide ions between the graphene layers) followed by liquid molding to produce the composite conductors. Scaling up production of this material can be done through an additional furnace step at the end of standard carbon fiber manufacturing processes, followed by pultrusion to form the composite wires or filaments. Once produced, these conductors show a significant increase in conductivity over the base carbon fiber material at 10 MS/m, comparable with copper, a strength of 2,000 MPa, and a thermal conductivity believed to be greater than 1,000 W/m K. Wires produced from this material show good stability, with relative resistance decreasing as temperature increases up to 225°C. For small things (5mm to 5cm), these wires show better temperature properties than copper as it requires higher current density to reach the same temperature for these carbon fiber wires compared with copper, but this advantage disappears at larger wire sizes. This makes them good fits for microelectronics, while their high strength-to-weight and conductivity-to-weight ratios make them potential options to replace steel in aluminum conductor steel reinforced electric cables.

Jason Huang, TS Conductor: Aluminum encapsulation of carbon core wires has many advantages over standard aluminum conductor steel reinforced (ACSR) wires. Carbon core wires weigh less, sag less, have higher conductivity, and have higher temperature limits, but there are concerns about structural integrity of the core. Aluminum encapsulation of the carbon core can overcome this limitation by protecting the carbon from moisture, air, and UV light, while also increasing packing of aluminum, increasing electrical capacity by up to 300%, and reducing line losses by up to half over ASCR wires. Pre-tensioning of the carbon fiber core can help to solve the brittle nature of the core, while encapsulation protects against sharp edge bend compression. Additions of fiber optic cables sensitive to moisture inside the carbon core can allow for real-time monitoring of line sag, line fault, line temperature, and line strength of these wires.

Mining Responsibly – Supply Chain and De-carbonization of Mining

Paramita Das, Rio Tinto: Rio Tinto, the second largest global producer of mined and refined metals, has operations that sit in over 36 different countries with 60 locations. Key metals that pertain to decarbonization produced from both Canada and U.S. operations are aluminum, titanium, copper, iron ore, borates, molybdenum, gold, and silver. As a result of U.S. operations, over 73% of vehicles in the U.S. contain Rio Tinto material. Of the above listed metals and materials, Rio Tinto places key emphasis on the supply chain of copper. Key emphasis is also placed on circularity and decarbonization as they pertain to low carb aluminum and copper. As a means of aligning with the Paris Climate Agreement, Rio Tinto has made a commitment to attain carbon neutrality by 2050 with an investment of $110 billion into such an effort.

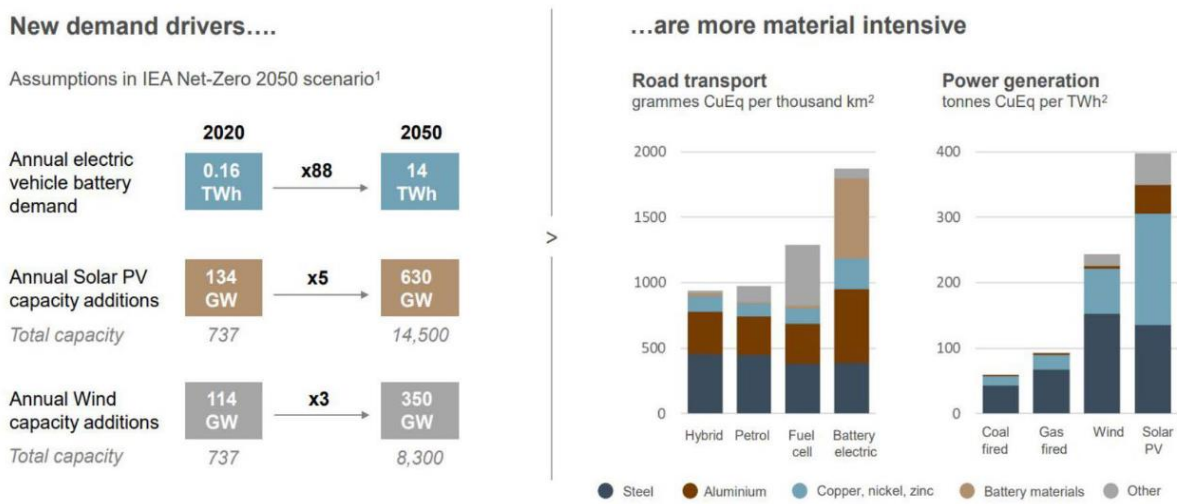

Figure 14: Estimates for resource needs for renewable energy and electrification. (Rio Tinto 2022)

Energy transition will raise demand for key metals and materials in solar panels, wind energy technology and other renewable energy sources. Key metals consist of aluminum, copper, steel, and battery materials. As energy transition advances, the topic of electrification in the U.S. lacks coverage on the infrastructure needed. Innovations in the cable industry are needed to advance electric charging station infrastructure and the grid.

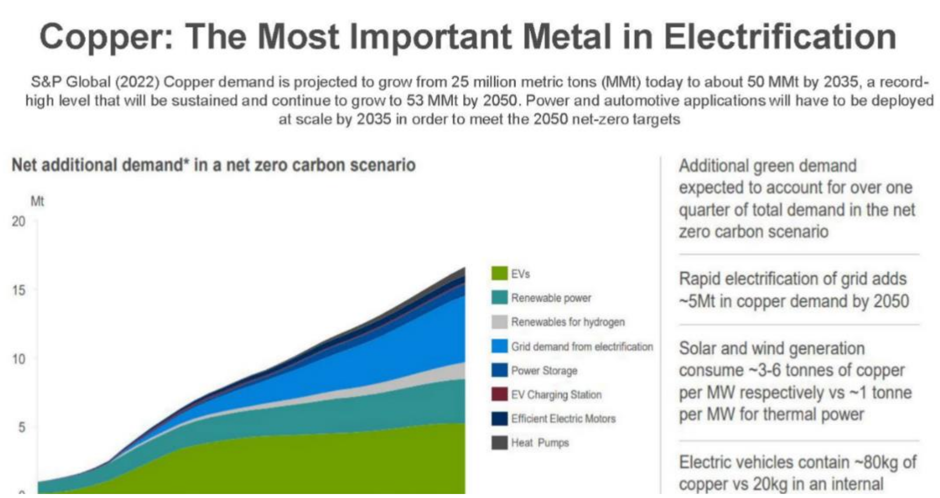

Figure 15: Forecasted copper demand till 2050 by use (Rio Tinto 2022)

The U.S. houses a majority of materials needed for such energy transition that can be extracted and manufactured. One key consideration for the export and import of materials for U.S. manufacturing is the sustainability of the geopolitical environment formed. Copper is the most important metal in electrification. Rio Tinto has plans to further invest in the largest copper mine in Utah to further extend the mine's life. Furthermore, as a parallel effort, there is R&D focus on Newton, which is a method of extraction that can exponentially shorten the copper supply chain.

National Lab Researcher Showcase

Introduction – Emily Evans, NREL

National labs and voucher service providers may provide private innovators and entrepreneurs with technical assistance in areas such as access to hardware and development tools, access to national laboratories, universities, and private laboratories, specialized facilities/resources for modeling, characterization, and manufacturing support, testing and validation capabilities, as well as other expert services.

Ames National Laboratory

Ames has capabilities that can be relevant to CABLE in materials synthesis, advanced characterization, and theory and modeling. Some of the materials synthesis capabilities include alloy synthesis, single crystal growth, combinatorial synthesis, and additive manufacturing. Relevant advanced characterization techniques include advanced electron beam instruments, solid-state nuclear magnetic resonance (NMR), thermal properties measurements, and X-ray scattering. Theory and modeling capabilities that can be found at Ames include electronic structure, atomistic simulations and dynamics, classical MD/MC simulation, transformation pathways & processing simulations, and complex alloy discovery and design.

Argonne National Laboratory

Argonne has tools and expertise in characterization and testing; metallurgical processing; and theory, modeling, and simulation. Some electrical characterization capabilities include conductivity, resistivity, ampacity, dielectric strength, operational voltage, and current range. Thermal characterization capabilities include operational temperature range, thermal conductivity, thermal resistivity, thermal diffusivity, and specific heat capacity. For metallurgical characterization, Argonne can perform microstructural analysis, secondary phase contamination analysis, compositional analysis, and chemical surface probes.

National Energy Technology Laboratory

NETL's alloy development capabilities are anchored by NETL's alloy ingot metallurgy and thermo-mechanical processing capabilities that are unique in scale within the DOE complex. This capability allows researchers to efficiently and cost-effectively prototype alloy concepts at scales that readily translate to industrial practices. Various capabilities are available to CABLE in range across mechanical characterization, metallurgical processes, and analysis. The MEM capability includes scale-up processes utilizing vacuum induction furnaces with crucible sizes ranging from 10 to 500 lb.

National Renewable Energy Laboratory

NREL capabilities include metallurgical/structural characterization, imaging (atomic force microscopy, high-resolution TEM, etc.), mechanical characterization (FTIR, NMR, molecular weight distribution, etc.), thermal characterization (infrared imaging, transient thermos-reflectance, etc.), and high-performance computing.

Pacific Northwest National Laboratory

PNNL can perform electrical characterization, imaging, mechanical characterization, metallurgical characterization, metallurgical processing, structure characterization, and theory, modeling, and simulation. PNNL also has a Shear Assisted Processing and Extrusion (ShAPE) process. ShAPE is a method of consolidating/extruding materials, at scale, with microstructures and bulk properties that cannot be achieved by conventional means and can manufacture wires, rods, and tubes at bulk scale with enhanced performance. ShAPE can also produce extrudates using different precursor formats: powders, chips, ribbons, solid billets, discs, foils, and flakes. ShAPE products can be made from copper, titanium, aluminum, steel, magnesium, and their alloys.

Sandia National Laboratories

Sandia has expertise in a wide variety of characterization techniques for applications including metallurgical processing, microfabrication, nanomaterials and coatings, next generation materials, additive manufacturing, aging and reliability, corrosion and degradation, material failure analysis, contamination and cleaning, and counterfeit detection.

Prysmian

Prysmian Group is new to the voucher service provider network and has the industry standard methods for electrical, thermal, and mechanical testing. There are six Prysmian R&D centers across the US specializing in different types of conductors, systems, and cables. Being part of the cable industry means that Prysmian has significant expertise in the cable market, including product development and deployment.

Day 2

Opening Remarks – Diana Bauer, AMO

The Advanced Manufacturing Office has two main missions: to improve energy efficiency and reduce carbon emissions of the industrial sector, as well as deliver innovations to drive next generation manufacturing technologies. Key areas of focus pertaining to both missions are industrial efficiency and decarbonization, clean energy and manufacturing, material supply chains, technical assistance, and workforce development.

Over the last decade, the AMO congressional appropriated budget has grown by over $300 million. The administration in office for each given year over the last decade influenced the budget growth stated.

The U.S. manufacturing industry accounts for over a third of the nation's primary energy consumption and contributes to almost one-third of total U.S. greenhouse gas emissions. Such high usage from manufacturing and industry warrant AMO goals to yield a secure supply chain with a skilled workforce while utilizing clean energy and decarbonizing technologies. Key areas of emphasis under the current administration are industry diversity, equity, inclusion, and environmental justice. Focus on such areas enables a broader set of personnel to contribute to decarbonization goals across various sectors. The overarching goal of CABLE is to increase both electrical and thermal conductivity in order to increase energy savings across the board by between 10-30%. Examples of avenues for energy savings through increased conductivity are the manufacturing industry, grid, transportation, building, and agriculture sectors. In today's technology, most of the onsite emissions generated are produced from thermal energy. In order to meet decarbonization goals, increased conductivity in both thermal and electrical applications will enable efficient electrification of thermal energy through heat exchangers and corresponding power and control electronics to replace fossil fuel sources in industrial and building thermal applications.

Panel on Electric Conductors

Iver Anderson, Ames Laboratory: Al/Ca mono-type cables are a new type of matrix conductor made from a composite of two metals. They are easy to extrude and can be made into a cable for overhead transmission. Al/Ca cables are promising because of their relatively low material cost and desired material properties.

These cables are only about two to three times the cost of ACSR cables, whereas ACCR cables are about 5 times more costly than ACSR cables. Additionally, compared to sag-resistant ACCR cables, the strength and conductivity of as-drawn Al/Ca (11.5 vol%) mono-type cable is higher in as-drawn form up to 150 °C. At temperatures between 150-220 °C, the strength increases up to 25% without embrittlement. However, conductivity drops to 9% IACS below ACCR (while still above ACSR). As a result, modifications to the Ca and Al content are being explored, including reducing Ca (which increases Al in the matrix) to raise conductivity while sacrificing some strength. This reduced-Ca experiment is being performed using extruded billets and as-drawn wires.

Ames National Laboratory has produced pilot-scale quantities of high-quality Ca and has obtained CP-Al powders for producing a sufficient Al/Ca conductor (1 mm diameter) to test wound cable. Through a Cooperative Research and Development Agreement (CRADA) with Ervin Industries, they have developed a gas atomization method to produce fine (less than 125 µm) passivated Ca powder in a pilot-scale batch, which is sufficient for initial fabrication experiments and performance tests. Experiments have shown that the conductivity of commercial purity Al powder is sufficient for wires, which is especially important for high-voltage DC applications. This work will be headed toward demonstration soon.

If Al/Ca composite conductors are fully developed and their properties verified in cable form, the benefits of this cable can be exploited to build out the U.S. transmission grid with thousands of miles of HVDC and HVAC lines. Calculated estimates show that compared to ACSR, Al/Ca cables will have 12% lower losses and need 11% fewer towers to connect stranded power from renewable or carbon-free energy sources to cities and factories.

Mehran Tehrani, University of Texas – Austin: There are two types of advanced electrical conductor material types: 1) metal-nanocarbon, where there is a metal matrix enhanced with nanocarbons and 2) nanocarbon-based, where a nanocarbon matrix is enhanced with dopants or intercalants. Electricity travels through nanocarbons quickly and without resistance, but nanocarbon conductivity degrades readily. Nanocarbons are not attracted to metals, and carbon nanotubes would ideally be spaced out and long to avoid attraction to one another. However, long nanotubes decrease speed and increase disorder, which results in decreased conductivity.

Conductivity is calculated by multiplying charge carrier density by charge carrier mobility. Metals have a higher charge carrier density than nanocarbons, but the charge carrier mobility of nanocarbons is higher than that of metals. Hybrid conductors combine the charge carrier density of metals and the charge carrier mobility of nanocarbons to achieve better conductivity.

The work at UT-Austin has demonstrated that accurate measurements and standardized testing is critical. Meaningful improvement in conductivity should be at least 5% IACS with small error margins. If that is not possible, specific conductivity could be measured directly from the mass and length of the wire. Research has shown that junction resistance reduction is key to improving the conductivity of carbonaceous wires. Furthermore, intercalated "disordered" graphite has outperformed "highly-ordered" doped CNT yarns. Finally, this work has shown that impurities in copper and defects in nanocarbons degrade conductivity and approaches that degrade nanocarbon structure or introduce a metal buffer will likely not work.

Thomas Kozmel, QuesTek Innovations: This presentation highlighted that the impacts of materials design is linked to process, structure, properties, and performance. Designers can navigate from process to performance or from performance to process to achieve the results they desire.

QuesTek is examining carbon nanotubes in copper and devising models to understand when and why conductivity is lost and how it can be gained. Materials properties are being examined and ways to reduce lifecycle costs are being evaluated.

Frank Kraft, MetalKraft Technologies: MetalKraft is focused on creating a copper-graphene composite wire with maximum conductivity of 110% IACS, at least 64 MS/m. The wire is made of a conductor-grade copper metal matrix which has commercially available and low-defect crystalline graphene nano-additives sufficiently distributed, aligned, and cohered within it. To fabricate this wire, MetalKraft is starting with graphene on a copper precursor material. It's assembled into extrusion billets, and then hot extrusion is performed to turn it into a rod/wire. The challenge for this project is embedding graphene into the copper matrix while achieving the appropriate amount, orientation, and morphology.

The potential impact of this project is to achieve an ultra-conductive copper wire for all applications where conventional copper wire is used. This would enhance performance and energy for electric motors and devices, which would create tremendous energy savings and reduce CO2 emissions.

A result of this project is the 12 AWG composite wire, which has achieved some increase in conductivity compared to base case but has not achieved the full targeted values at this time. Challenges for this project include accurate modeling and scientific analysis to direct material processing, material testing and characterization, prototype production scale-up, funding and support, and demonstrable, repeatable breakthrough with conductivity of at least 61 MS/M or 105% IACS.

Beihai Ma and Keerti Kappagantula, PNNL: The mission of this project is to accelerate the development of advanced materials for electric vehicles by developing bulk aluminum and copper ultra-conductors whose forms (wires, rods) are manufactured by solid-phase processing. PNNL is interested in embedding nanocarbon, particularly graphene, inside grains and inside metal composites.

To obtain data about chemical composition variations and grain connectivity of nanocarbon-enhanced ultra-conductors, a high energy synchrotron µ-XRD is utilized. This device provides results which are used to correlate processing conditions to property optimization because of its penetration depths, fast sampling rates, and high spatial resolution.

Panel on Thermal Conductors

Michael Ohadi, University of Maryland: Heat pumps and thermal energy storage devices will be essential to the next generation of electrification technology, assisting with energy transportation and storage. To help address issues with capital costs, this study addresses the capabilities of additive manufacturing of Cross-Media Heat Exchangers, suitable for, among other things, liquid cooling applications. There are two major differences between the traditional heat exchangers and the cross-media technology presented here. First the Cross-Media design utilizes continuous fins on the liquid side of the heat exchanger, an innovation that enhances liquid-to-air heat transfer. Second is the inherent potential for the new technology to benefit from digital design optimization and additive manufacturing.

The additive manufacturing process for iCMHX involves 3D printing with two types of customized print heads, and a dedicated fabrication process that can print 20 kW in less than 8 hours. The process of 3D printing allows for a high-quality product at a decreased cost, and the autonomous nature of the manufacturing leaves room for further enhancements in manufacturing efficiency, leading to lowered overall costs. However, despite the efficiency benefits, the current manufacturing process has issues producing products that remain leakproof at high temperatures (above 200 degrees Celsius) and pressures (above 450 PSIG).

The work of the research team has yielded several further breakthroughs for integrated cross-media heat exchanger (iCMHX) technology, including a numerical model for assessing the performance of any cross-media based heat transfer and a 1D ROM for thermal energy storage performance that has been validated by experimental performance, a Computational Fluid Dynamics (CFD) model validated to high accuracy by experimental results, and an increase in thermal conductivity of PCM (Phase Change Material) wire from .22 W/mK to 16 W/mK.

Next steps include improving product and manufacturing design, such as the fin/wire shape and size optimization, guaranteeing a leak-free product at high temperatures and pressures, and improving the materials used in the technology.

David Cahill, University of Illinois: The research team set out to characterize what factors lead to high thermal conductivity among heterogeneous thermal conductors. The team conducted several experiments to determine which factors had the highest indication of thermal conductivity.

The research team set out to understand the applicability of adding nanocarbons to metals to increase thermal conductivity. In the experiment conducted, thermal conductivity of aluminum with various nanocarbons was examined at varying temperatures. Nanocarbons were added to aluminum samples, and the thermal conductivity of the materials was measured at different temperatures. The nanocarbon content of the samples was characterized by X-Ray Photoelectron Spectroscopy (XPS). To measure results against the accepted thermal conductivity curve of Aluminum, the research team used resonant proton elastic scattering (a method for studying spectroscopy) to measure the carbon content in the aluminum as a function of depth. The results of the tests showed negligible changes in thermal and electrical conductivities for the samples with nanocarbons. Thus, nanocarbons likely have minimal impact on increasing conductivity across temperatures.

Approximately 80 formulations of thermosetting epoxies have been studied to date. When looking at these epoxy thermosets, the best baseline indicator of thermal conductivity is density, and the highest density epoxies are semicrystalline. Further research should go into examining if crystallinity is essential for producing higher thermal conductivity, or if crystallinity only makes for more densely grouped molecules. Finally, further research can be performed to examine if it is possible to decrease density even further and produce ultralow thermal conductivity polymers.

Jie Li, ANL: Materials with high specific heat are incredibly useful for industrial processes. If cost is not an issue, diamond has the best thermal conductivity of naturally occurring substances. However, on a cost-per-pound basis, copper is the primary material used for high specific heat applications. A composite of carbon structures and copper could lead to an ultra-high specific heat with a market viable cost. There are several ways to fabricate copper-carbon materials. Each method has specific benefits and features and produces materials with a wide range of specific heats. High temperature or pressure fabrication methods create a highly densified material and require temperatures around 1300 degrees Celsius. Vacuum hot pressing (VHP) is a traditional method of introducing additives, requires a temperature of 900 degrees, and produces middle specific heat materials. Electrodeposition is a new approach that does not require high temperatures and creates low specific heat materials.

When characterizing the thermal conductivity of diamond-coated materials, a higher volume percentage of diamond leads to higher conductivity, and the diamond particle diameter is also highly important. Diamond particle radius needs to be around 30 micrometers before increases in volume percentage actually increase the specific heat of the material instead of decreasing it.

There are two state-of-the-art approaches to synthesizing copper-diamond alloys: a surface metallization that involves pre-coating the diamond particles before introducing the copper, and a matrix alloying that involves pre-alloying the copper (with other materials) before adding the diamond. Composites with surface-modified diamond particles show high thermal efficiency, and materials made with both techniques on average show a much higher thermal efficiency than normal copper.

One of the primary goals of synthesizing hybrid materials, such as the ones discussed here, is to increase interfacial thermal conductance (ITC) because of its significance in determining thermal performance of hybrid materials. There are several ways to increase the ITC of the materials discussed above: Van der Waals bonding, surface activated bonding, plasma bonding, and hydrophilic bonding. Each bonding method can develop different high thermal efficiency materials.

Next steps include further improving the performance of high thermal efficiency materials, increasing the effective thermal conductivity of the copper-diamond nanocomposites, designing and fabricating an advanced interfacial layer to reduce mismatching and maximize phonon/heat transfer, and synthesizing a copper composite to take advantage of percolation.

Kashif Nawaz, ORNL: Heat exchangers are incredibly useful for a myriad of applications including high temperature mitigation, ultra-speed aviation and aerospace platforms. Ceramic materials have a promising set of properties for a broad set of thermal applications for which establishment of thermal shock resistance is critical for sustainable performance. Thermal shock resistance is measured by determining the loss of strength for specimens quickly cooled after thermal exposure. The critical temperature difference for thermal shock is derived from the temperature difference between exposure temperature and the water quench temperature that is required to produce a reduction in flexural strength of 30%.

To examine thermal shock testing, a series of specimens are heated across a range of different temperatures and then quenched rapidly in water. After the quenching, the specimens are tested in flexure, and the average retained flexural strength is determined for each set of specimens quenched from a given temperature. Additive manufacturing has enabled the realization of thermal solutions with previously unprecedented performance. Thermo-physical and mechanical properties can be significantly different for additively manufactured parts.

An experiment was conducted to examine the critical temperature difference for Al_2O_3. There was a major change observed above a critical temperature difference of 300 degrees C, wherein the strength of the material reduced significantly. The general trend was a decrease in structural integrity as the delta temperature increased. However, with relatively small delta T, there is a point on the curve where strength increases before decreasing.

Geoff Wehmeyer, Rice University: The thermal conductance of carbon nanotubes (CNTs) increases as the temperature increases but only to a point, after which it starts to decrease. Decreasing the diameter of the CNT impacts the location of the inflection point, with larger diameter CNTs yielding higher inflection points. While individual CNTs have an ultrahigh thermal conductivity (nearly 3000 W/mK), a disordered group of them will have an ultralow conductivity of 0.2 W/mK. However, unsurprisingly, aligning the CNTs yields a higher thermal conductivity. Furthermore, CNT fibers of many different varieties were all found to have better specific thermal conductivity than metals.

Rice University synthesized high tensile strength CNT fibers using a four-step process. The fibers had a unique combination of high electrical conductivity (10 MS/m), high tensile strength (4GPa), and flexibility. These CNT fibers also had a suspended length of less than 3 mm, which kept the heat losses due to radiation relatively small. Both electrical and thermal conductivities depend strongly on the nanotube's length, and both thermal and electrical conductivity had a near linear relationship with nanotube length. The Rice CNT fibers yielded high electrical conductivity and thermal diffusivity when compared to other CNT products and traditional electrical conduits like metals.

There are several potential applications for these CNTs in thermoelectric cooling. CNTs have both a thermoelectric power factor and thermal conductivity higher than metals or other comparable materials. These qualities make CNT fibers the best-known p-type bulk material for thermoelectric active cooling. CNT fibers are also promising for applications as lightweight, flexible high-strength electrical and thermal conductors. There are open fundamental questions about the electron and photon transport mechanisms in aligned CNT materials that need to be further researched.

Panel on Superconductors

Jake Russell, ARPA-E: The rise of electrification is driving interest in new conductors, especially superconductors. Key applications include electrical transmissions and conversion, electrification of the transportation sector, and fusion technology. Superconductors behave differently compared with conventional superconductors – electrons move collectively, electrons couple to phonons, and electrons form Cooper pairs. The defining characteristics of superconductors include zero electrical resistance below the critical temperature, the Meissner effect where the magnetic field is rejected, and heat capacity transition. However, three critical parameters must be considered when using superconductors – the critical temperature (T_c), external magnetic field (H_c), and the internal current (J_c). Other considerations include raw materials, processing, cost, and mechanical properties.

Superconductivity was first discovered in the early 1900s, and since then, intense research has yielded many superconducting materials. Generally, they can be classified into four groups – niobium-based, REBCO, MgB_2, and Fe-based. The latter three are considered high-temperature superconductors. There are three common manufacturing techniques – wiredrawing, powder-in-tube, and coated tapes/wires. One exciting development is hydride-based superconductors that enable near-room temperature superconductivity using low-cost materials.

Venkat Selvamanickam, University of Houston: Currently, REBCO tape is produced by thin film vacuum deposition on a flexible nickel alloy substrate using a continuous roll-to-roll process. Most of the tape (97%) is low-cost nickel alloy and copper. REBCO tapes can carry up to 600 times the current of a comparably sized copper wire. Compact fusion systems are rapidly driving the need for volume manufacturing of REBCO tapes and can enable a 10 times reduction in fusion system size. This application driver alone is making tape manufacturing a major bottleneck. To meet these needs, production must increase, while cost is decreased. High critical current REBCO is the best way to achieve the required cost target. By improving performance, less tape is needed. Advanced processing techniques such as metal organic chemical vapor deposition, with tighter temperature control and improved precursor conversion efficiency, can be leveraged to fabricate high performance REBCO at reduced cost.

Experiments have shown that increased REBCO thickness is correlated with increased critical current. MOCVD has enabled the possibility of double-sided REBCO tapes, which can increase I_c by 10 times Initial experiments have shown a 2 times performance improvement compared with commercial tape. Researchers are working on a pilot-scale system to further scale up their process towards manufacturing. To the demand from industry, Venkat closed by highlighting the manufacturing technology requirements, including increasing the throughput by 20 times, implementing in-line QC with machine learning, and training the future workforce.

Superconductors have many applications, including accelerators, power cables, motors, and wind power generation. REBCO tapes' use in compact fusion systems is driving demand and the need for higher-volume manufacturing.

Yifei Zhang, SuperPower: There are a number of REBCO HTS wire manufacturers across the world. While similar, all of them have their own architectures. Complexity is the key challenge in manufacturing these wires. Key applications of REBCO wires include high field magnets for scientific research and NMR; accelerators found in high energy physics and medical fields; power cables; transportation, e.g., maglev trains; wind power generators; and compact fusion reactors – which are rapidly increasing demand for REBCO wires. SuperPower, Inc. was established in 2000, and REBCO wires are its main product. There are many technical challenges that SuperPower faces, including increasing in-field Ic, improving conductor quality, creating customizable conductors, testing and qualification, processing monitoring and control, and structural characterization and analysis.

Michael Tomsic, Hyper Tech Research: There are many superconductors that can be used for long-wire superconductors, including niobium titanium and niobium tin, which are most commonly used (~95%). Ceramic superconductors include the previously discussed REBCO and bismuth-strontium-calcium-copper oxide (BSCCO). In 2001, MgB2 was discovered to have superconducting properties at a high temperature (relative to other low-temperature superconductors). Traditional superconductors are only superconducting in DC current; under AC, they have hysteresis loss. MgB2 is an AC low-loss superconductor. While MgB2 and Nb3Sn have shown promising results at short lengths, Hyper Tech is focused on maintaining these properties at long lengths. NASA recently funded a project centered around a high temperature, low loss superconductor that can be used in high-density motors. Hyper Tech's expertise is in cable drawing with dramatic area reduction and no annealing, as evidenced by their 12um Nb3Sn wires. They have been to double the performance of Nb3Sn performance.

Non-superconducting but still important – Cu, Al, high purity Al – must be considered. At low temperatures (4-30K), they have very different RRR values, but as the temperature rises, they coalesce. This begs the question: what is needed to enable this increased conductivity of these common materials at room temperature? Cooling of superconductors should not be a reason not to use them. For example, MRIs are cooled to 4K and consume very little power. There has been a lot more activity in superconductors over the last year and a half compared with the past 20 years because of the low AC loss superconductors.

Ranga Dias, University of Rochester: The demand for energy is dramatically increasing. We've relied on fossil fuels and combustible sources, but we would like to transition towards energy sources similar to the fusion found in the sun. Superconductors are needed to enable this transition. Superconducting wires are relevant to a wide range of applications, meaning the deployment of such technology will have a huge impact. Our approach is to use pressure to change the atomic structure to induce superconductivity. Metallic hydrogen has been predicted to have high-temperature superconductivity, but the amount of pressure required is enormous (500 GPa). A diamond-anvil cell must be used to generate such forces.

To lower the metallization pressure, chemical precompression can be used, trying to mimic the properties normally achieved at higher pressures. Promising results (significantly reduced pressure) are being found with rare earth hydrides. Nitrogen-doped lanthanum hydride is now being synthesized at a small scale and shows the potential to act as a room-temperature superconductor at 270 GPa. Using various thermodynamic pathways, researchers showed the material to be metastable under ambient pressure. These breakthroughs have allowed the research team, formerly of the University of Rochester, to found a new company, Unearthly Materials.

Panel on CABLE Theory and Modeling

Maria Chan, ANL: Argonne modeling and simulation efforts focus on two principal areas: (1) properties that include electrical conductivity, thermal conductivity, and structures (atomistic, nano and micro) and (2) approaches that include DFT, tight binding MD, Green-Kubo relations, Boltzmann transport, and AI and ML genetic algorithms. Throughout the process of creating the novel composites, it is necessary to predict what structures give the desired electrical and thermal conductivity. Once the material is fabricated, the actual structures need to be determined.

One fundamental characteristic to be determined is the copper-carbon (Cu-C) interactions or the equilibrium carbon interaction that gives an accurate atomistic structure-property relationship. Interestingly, there are no stable copper or carbon compounds in the phase diagram, so different types of composites need to be constructed artificially, such as a single copper layer on top of carbon or a carbon layer sandwiched between two copper layers (upper right image in Figure 16) or just single carbon inclusions as adsorbates or substitutions in the copper lattice (lower image in Figure 16). DFT calculations are made at the electronic structure level with van der Waals interactions added.

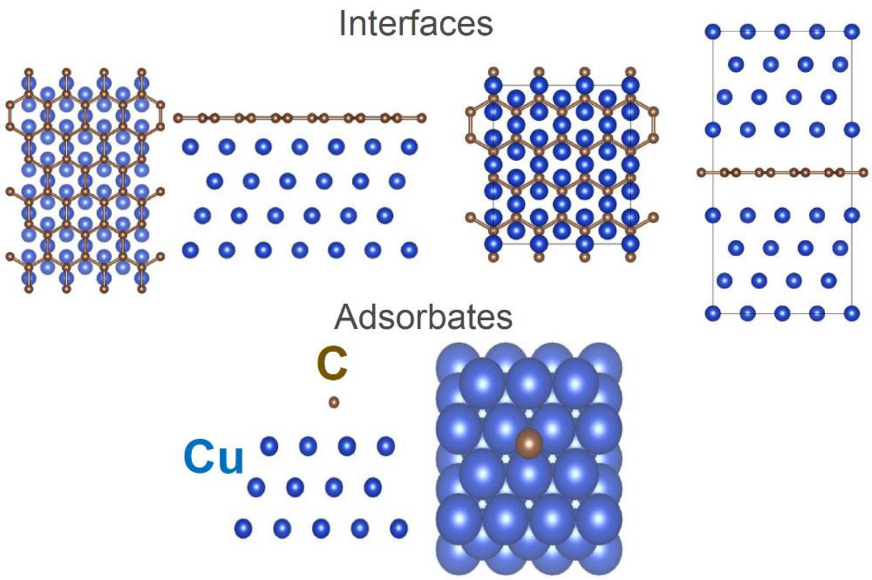

Figure 16: DFT for Cu-C interactions (Chan 2022)

One goal is to validate some of the existing Cu-C force fields and determine why they are not sufficient. MD simulations were performed to understand the actual structure that is formed after quenching when graphene-like sheets are added to copper melts. The simulation results, show that there are no evenly distributed graphene sheets. When evaluating the results of the lattice component for thermal conductivity, a possibility of similar thermal conductivity is seen, but not an increase in thermal conductivity. For future work, Argonne will be using the Kubo-Greenwood approach for evaluating electrical conductivity with the structures that were simulated previously as inputs. A tight binding model can be parametrized to give electrical conductivity. This is work in progress.

Although thermal and electronic conductivities will be characterized, there is a need to understand the nanoscale atomistic structures. Argonne has evaluated a number of Cu-C interactions from DFT calculations, confirmed that the current techniques do a reasonable job, determined interactions, and performed simulations of thermal and electronic conductivity. Future work will involve determining experimentally relevant structures from the characterization data using Fully-Automated Nanoscale To Atomistic Structures from Theory and eXperiment (FANTASTX), using the structures for electronic conductivity calculations, conducting a forcefield and structure search, and investigating the effect of the carbon fraction, nanostructures, temperature, and synthesis conditions on different phase transitions and transport properties of copper and other metal-carbon covetic nanocomposite systems.

Subramanian Sankaranarayanan, ANL: The focus of the research is on metastable materials or materials beyond equilibrium for enhancing electrical and thermal conductivity. The concept was to gain a fundamental understanding of the factors that could contribute to increase thermal and electrical conductivity, mostly looking at the interfaces for any carbon allotropes that can be present combined with copper.

The key elements for this project are algorithm development, model development, and inverse design. The initial effort for any inverse design search is to have an algorithm that allows navigation through the configurational and computational space. The Monte Carlo Tree Search (MCTS) algorithm was adapted to operate in a continuous action space and was able to achieve the solution in far fewer iterations, and in most cases, was able to achieve this for the high-dimensional spaces where other algorithms take longer to achieve the solution. Developing a model that best represents the interactions between the atoms in the system is another key challenge. Some results for the models developed as a framework for the forcefield of a Cu-C system showed good alignment between the predictions of the surrogate model with the DFT training set.

The continuous action space MCTS was combined with various models, and energy was used as an objective to search through the metastable configuration space. Configurations were down sampled by performing a simple components analysis. There are several low-energy metastable configurations that have similar structural features, as shown in Figure 17. The image on the left shows how these features vary as a function of composition for a stoichiometric ratio of 75%:25% Cu:C, where the carbon flakes are embedded in copper. There can also be sheets of carbon in the intermolecular compositions, as shown in the middle image, as well as carbon nanotubes, as shown in the image on the right.

The scalability of the MCTS can be from as few as 50-60 atoms up to millions of atoms. The short-term plan is to compute the thermal and electrical conductivities for each of these metastable configurations using the Green-Kubo method and using the Kubo-Greenwood method to compute the electronic conductivity. A longer-term goal is to use inverse design to predict Cu-C composites with thermal and electrical conductivities as the objectives and generate a database of Cu-C nanocomposite configurations to train FANTASTX validated by experimental data. Future efforts will lead to better and more accurate atomistic models for covetics, new algorithms to search covetic morphologies with atomistic precision, cheaper accurate theoretical prediction of thermal and electrical conductivity, and information extraction via theory and AI-informed experiments.

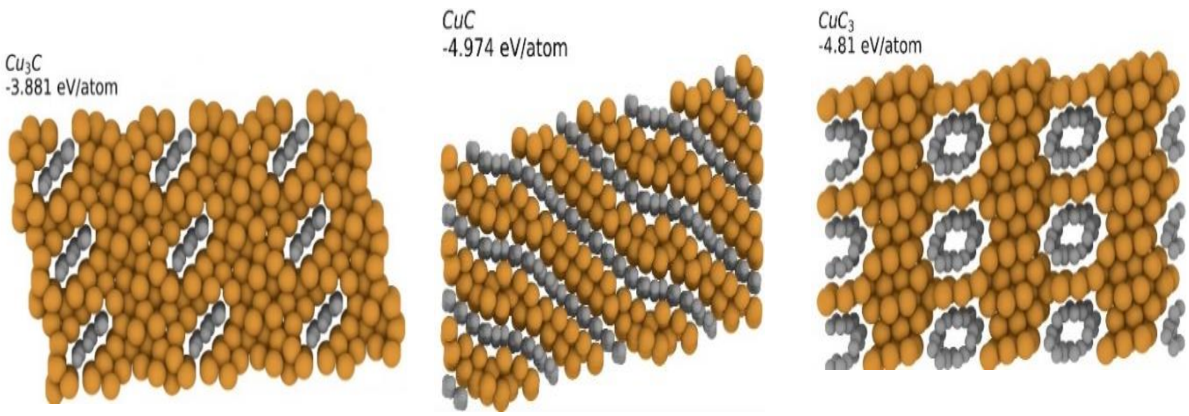

Figure 17: Configurations for different stoichiometries of copper and carbon with carbon flakes, carbon sheets, and carbon nanotubes (Sankaranarayanan 2022)

Katsuyo Thorton, University of Michigan: The research focuses on the importance of constructive microstructure and predicting and optimizing material properties such as electrical and thermal conductivity. The significance of studying microstructure is that it cannot be avoided with manufacturing materials. In the case of electrically conducting metallic wires, typical processing steps involve casting and powder processing to make an ingot, extrusion of the ingot into a cylinder, drawing into thin wires, and annealing the wires. The initial processing typically results in polycrystalline microstructures which undergo mechanical deformation during extrusion and drawing that alters the particles in the microstructure.

The microstructure directly affects the overall material property. Simulated microstructures were generated to examine various size scales and morphologies including isotropic, columnar, and plate configurations as shown in Figure 18. There are two items to note on the graph. First is that the simulated values shown as blue bars clearly illustrate how the transport properties are affected by the microstructure. Depending on the microstructure, the effective diffusivity value ranges from less than 0.3 to more than 0.9. Second, there is disagreement when the simulated model is compared with the mathematical models that are shown as light and dark grey bars in Figure 18. This also indicates that a good understanding of the microstructure is needed either through 3D calculations experimentally or by modeling.

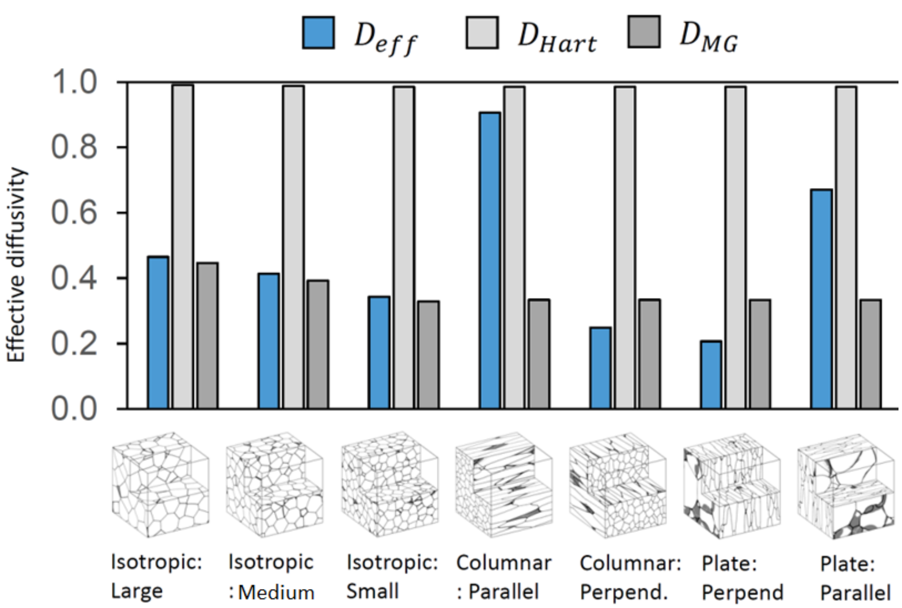

Figure 18: Examples of how microstructure affects material properties (Thorton 2022)

The PRISMS Center integrated framework uses the hierarchical power structure where atomistic-scale calculations are used to inform the continuum-scale models and has developed two specific software packages. First is the PRISMS-PF which is an open-source phase-field modeling framework. The phase-field models are based on the thermodynamics and kinetics of materials and can be used to predict crystalline microstructures, polycrystalline microstructures, and microstructure corrosion. Second, the PRISMS-Plasticity is high-performance crystal plasticity finite element software that can predict the microstructure under various loads and boundary conditions.

By understanding how the microstructure affects the properties of materials, we can avoid features that are detrimental to desired properties and introduce features that enhance these properties. Microstructure evolution is complex, but the simulation tools are becoming more reliable and more broadly available (for example: PRedictive Integrated Structural Materials Science (PRISMS) Software (PRISMS-PF, PRISMS-Plasticity, CASM (atomistic)) and integration of tools are becoming more feasible. There are important questions that could be answered: What composite microstructures can optimize transport properties? How can they be co-optimized with other properties that are required?

Bryce Meredig, Citrine Informatics: AI is a very ample tool when designing materials to meet multiple demanding property targets simultaneously, while also satisfying constraints and costs of manufacturing. Citrine has a robust open research effort for cutting-edge publishable science, which includes work on several R&D programs, historically, for AMO and Basic Energy Sciences.

AI can be thought of as a guidance system as you are doing experiments and simulations that have trials in the design space. Over the course of a materials development program, the benefits of using AI guidance tend to compound. AI increases the "hit rate" or success rate in adjusting many materials' degree of freedom to satisfy multiple targets and constraints, such as composition and processing.

The core workflow used and implemented in the Citrine platform is a workflow that is also employed in their research projects. It is an iterative AI-guided materials developmental process called sequential learning, where there is an initial data set that is often quite small. An example of the sequential learning process can be seen in Figure 19. The design problem was for a perovskite oxide used in solar applications. The AI system was able to identify many more targets more successfully than a random search.

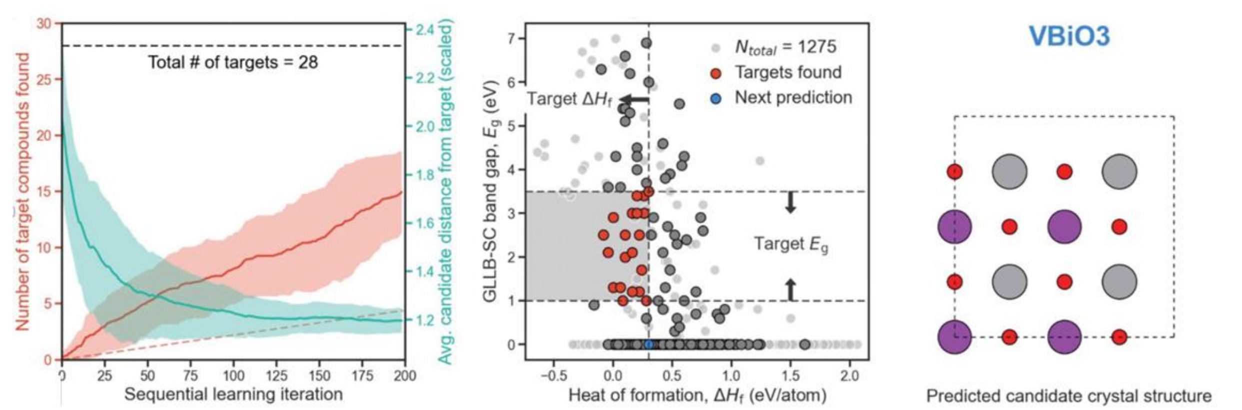

Figure 19: A sequential learning loop (Meredig 2022).

Projects that use AI are consistently and systematically more successful. Citrine was previously involved with building a closed loop for one of the self-driving nanomaterials labs that was guided by AI and investigated nanoparticles for catalytic applications. A closed-loop system was developed to gather data experimentally and provide simulations where AI was selecting the next recipes to make. If the automation is done correctly, the loop can be completely closed with autonomous AI material design.

The AI methods developed by the computer science community often do not work on the first use across many material applications for material science problems because the problems are quite different from those that the software were developed to address. AI enables more efficient materials design, especially for high-dimensional problems that have many chemistry and processing degrees of freedom and many property targets. Sequential learning, using iterative AI-guided materials design, provides acceleration relative to "business as usual." It is important to use materials-specific AI methods in materials design.

Peter Voorhees, Northwestern University: The research is focused on the challenge of materials development. Materials development can take a very long time and can be very expensive. The reason for the high cost is because a non-virtuous cycle is used that involves testing the material composition through the process of building and testing a material just to find out that it does not meet the property constraints needed, and the materials must be re-built and tested again and again. This cycle needs to be replaced.

One approach to this problem is expressed in the Materials Genome Initiative promulgated in 2014, which is intended to bring data, computations, and experiments together and have them work in concert to decrease the cost involved in developing materials and turning them into applications[25]. The key message from the last 10+ years of the Materials Genome Initiative is a new paradigm wherein material and device should be designed simultaneously. If the computational machinery and the databases are available, the materials design process can be drastically accelerated.

It is important to understand that the design process sits on a foundation of data that can be obtained from first principles calculations and experiments. Data are also used for acceleration of the social materials where the same models are used to understand the design uncertainties as the material is scaled up for actual applications at higher technology readiness levels (TRLs).

When dealing with polycrystalline materials in electrical conductors, the rate of grains growth and control of texture must be addressed. Tests were performed at a synchrotron source using diffraction contrast tomography to record the evolution of grains of iron as a function of time. With only one experiment, more than 9,000 grain boundaries can be measured. This information is used to determine grain boundary mobilities and how fast grain growth will occur. Once the data is incorporated into a phase-field simulation, the results are compared to the experimental data to determine the difference between the experimental measured structure and the structure predicted by the simulations. For Fe, when the reduced mobility is graphed as a function of the misorientation angle of the grains, two results are obtained. First, the mobility varies by one to two orders of magnitude (10^{-1} to 10^{-2} $\mu m^2/s$) more, and second, from a modeling perspective, there is very little correlation

[25] Materials Genome Strategic Initiative, National Science and Technology Council, Committee on Technology, Subcommittee on the Materials Genome Initiative, December 2014, https://www.mgi.gov/sites/default/files/documents/mgi_strategic_plan_-_dec_2014.pdf

with the crystallography of the grain boundaries. This shows that it is very hard to predict exactly what the velocity of the grain boundary will be if only the crystallography of the material is used.

Appendix C: DOE User Facilities

The DOE Office of Science's Basic Energy Sciences (BES) Offices manages User facilities that offer unique tools for characterization and offer free (but highly competitive) access for non-proprietary work, or are available for a fee for proprietary work. See an overview of BES User Facilities at: http://science.energy.gov/user-facilities/user-facilities-at-a-glance/bes/

Key Facilities for CABLE-Related Research

Nanoscale Research Centers (NSRCs)

The five NSRCs are DOE's premier user centers for interdisciplinary research at the nanoscale, serving as the basis for a national program that encompasses new science, new tools, and new computing capabilities. Each center has particular expertise and capabilities in selected theme areas. While all NSRCs have CABLE-relevant offerings, those of particular interest to this CABLE topic include synthesis and characterization of nanomaterials; theory, modeling and simulation; electronic materials; imaging and spectroscopy; and nanoscale integration. NSRC user facilities laboratories contain clean rooms, nanofabrication resources, one-of-a-kind signature instruments, and other instruments not generally available except at major user facilities. NSRC resources and capabilities are available to small businesses with research projects that compete successfully in a peer-reviewed process.[9] See http://science.energy.gov/user-facilities/user-facilities-at-a-glance/bes/nanoscale-science-research-centers/

Center for Nanoscale Materials (CNM), Argonne
https://science.osti.gov/bes/suf/User-Facilities/Nanoscale-Science-Research-Centers/CNM

Center for Functional Nanomaterials (CFN), BNL
https://science.osti.gov/bes/suf/User-Facilities/Nanoscale-Science-Research-Centers/CFN

The Molecular Foundry (TMF), LBNL
https://science.osti.gov/bes/suf/User-Facilities/Nanoscale-Science-Research-Centers/TMF

Center for Nanophase Materials Sciences (CNMS), ORNL
https://science.osti.gov/bes/suf/User-Facilities/Nanoscale-Science-Research-Centers/CNMS

Center for Integrated Nanotechnologies (CINT), Los Alamos and Sandia National Laboratories
https://science.osti.gov/bes/suf/User-Facilities/Nanoscale-Science-Research-Centers/CINT

X-ray Light Sources

In the near term, advanced accelerator-based light source technologies providing intense sources of extreme UV radiation could enable higher resolution optical metrology tools. Dava Keavney overviewed DOE's x-ray light sources.

- Advanced Light Source (ALS), Lawrence Berkeley National Laboratory (LBNL) https://science.osti.gov/bes/suf/User-Facilities/X-Ray-Light-Sources/ALS
- Advanced Photon Source (APS), Argonne National Laboratory (ANL) https://science.osti.gov/bes/suf/User-Facilities/X-Ray-Light-Sources/APS
- National Synchrotron Light Source II (NSLS-II), Brookhaven National Laboratory (BNL) https://science.osti.gov/bes/suf/User-Facilities/X-Ray-Light-Sources/NSLS-II
- Stanford Synchrotron Radiation Light Source, SLAC https://science.osti.gov/bes/suf/User-Facilities/X-Ray-Light-Sources/SSRL
- Linac Coherent Light Source (LCLS), SLAC https://science.osti.gov/bes/suf/User-Facilities/X-Ray-Light-Sources/LCLS http://science.energy.gov/user-facilities/user-facilities-at-a-glance/bes/x-ray-light-sources/

Neutron Scattering Facilities: http://science.energy.gov/user-facilities/user-facilities-at-a-glance/bes/neutron-scattering-facilities/

See also HFIR and SNS Data Management Practices: http://neutrons.ornl.gov/users/data

High Flux Isotope Reactor (HFIR), Oak Ridge National Laboratory (ORNL) https://science.osti.gov/bes/suf/User-Facilities/Neutron-Scattering-Facilities/HFIR

Spallation Neutron Source (SNS), ORNL https://science.osti.gov/bes/suf/User-Facilities/Neutron-Scattering-Facilities/SNS

Appendix D: CABLE Innovator Challenges and Community Solutions

The facilitated discussion was meant to cross-pollinate ideas and catalyze connections within the CABLE research ecosystem. The facilitated discussion on the first day occurred in three parts. The first identified challenges innovators faced in commercializing their technologies. Innovators responded to the following question:

- What is the most significant challenge you will need to overcome to guarantee the ultimate success of your CABLE innovation?

Each respondent was allotted a three-minute explanation to describe the challenge and the type of support needed. The second part identified solutions from the CABLE community to address the innovator challenges. Participants responded to the following question:

- In what ways do you believe you can contribute to addressing the challenges identified?

Similarly, each respondent was allotted three-minutes to explain the type of support they could provide and the relevance to a challenge or challenges proposed. Finally, a matchmaking exercise formed the basis of the small groups for the second day of the workshop. Participants responded to the following question:

- Of the challenges listed, which do you believe you can make a personal contribute to solving?

This activity helped coalesce innovators and solution providers to solve the challenges identified. The top four challenges were chosen to complete the action plans, Appendix E.

The following summarize the Innovator Challenges, Community Solutions, and the results of the prioritization. The responses in the tables have been minimally edited to maintain the nature of the participant responses.

Innovator Challenges: What is the most significant challenge you will need to overcome to guarantee the ultimate success of your CABLE innovation?

Primary Challenge for long term success (Short title)	Challenge Description
Supply Chain Security via Permitting process	Permitting process in the US to allow to bring critical materials like copper for use for Cable Innovation
Higher temp insulation to enable higher ampacity in cable	Insulation materials capable of higher temperature and weatherproof
Additives for CABLE materials	Graphene supply chain and cost
Cryo-resistive cable cooling and insulation	Partial Discharge testing and Two-phase cryogenic fluid flow analysis

Continuous manufacturing of carbon fiber composite conductor	Scale up of the intercalation and composite cable pultrusion process
Improvement in performance and quality	Improving performance and quantity consistency
Atomically Precise Graphene-Cu Interaction	Cost, Quality, and scalability
Better CNT and Graphene	100% metallic Carbon Nanotube, how to measure that it is 100% metallic. How to get real single layer graphene flakes. Better functionalization
Scaling from R&D to production	Understanding requirements for scaling R&D materials
Metallic CNT supply	CNT unbundling and metallic/semiconductor separation methods to supply metallic CNT.
Carbon fiber copper composite processing	Expertise in carbon fiber copper composite processing into wires
CNT Production Cost Reduction	• Current production costs of CNT materials are high • Significant production cost reductions as we get to full-scale CNT fiber/film production • To compete with copper and aluminum conductors, significant cost reduction is needed for synthesis of raw CNTs (supply chain issues)
Material cost	Overcoming the high costs of quality graphene.
Tech adoption vs. technology advancements.	
High voltage, high altitude, high thermal conductivity insulation	
Realization of high efficiency energy storage controller	Getting to tape-out of power analog IC and IC fab real estate.
Not super connected.	Patent 10,680,520 IC fabrication next step, wanted collaborators.
Ruggedized transceivers suitable for ubiquitous deployment of self-monitoring conductor in smart grid	Optoelectronic transceivers are available for lab and indoor use. To deploy ubiquitously into PowerGrid, we need robustness and ruggedness in the outdoor deployment environment, besides affordability and reliability.
Thought captured above	Combine all cable and insulators to one big group with subgroups for specific solutions/challenges. Improving metallic conductors, for transmission, for magnetics, for aviation or ground applications, insulators high and low temp. COE and deltas of different conductors. Heat rejecters that stick out like a duster from cable woven into cables. CVD metal covered plastic to save weight add.

Keeping it simple #s, let’s say I live in a state called Overpriced electricity, with an allowed 5% losses for connections from source to transmission, 10% for transmission, 5% distribution, & 5% distribution-substation to transformer, & 4% for transformer (average losses may be higher without good utilization), total is 29% losses, compounded 74%, let’s call it 3/4 delivered of needed generation. Now add reliability overburden of 115% to 145% around the nation. Sticking with fractions let’s call it 4/3 or 1/3 overproduction or 33%. Assume that's all FF derived. Replace the losses in system, the overburden with storage, batteries in all sub-stations with cross feeders between sub-stations added for off-loading a down sub-station. All this fancy cables and batteries will all be paid for by utilities when load based profits are only allowed. So, say they get 8% profit allowance on all costs, 33% reduction in overburden with batteries, 10% reduction in T&D, 1/3 because of battery smoothing. rest better cables.	# issue (can’t find but #1 to write with) For the removal of profits from source, T&D losses present in existing bills
By spacing lower voltage systems below longer distant systems and synchronizing them to cancel EMI on the ground allows:1) lowering EMI health effects from HV lines. 2) split difference in height and cost with cancelation benefits. lower power runs do not need to be everywhere along HV line, if not designed lower, but just near populations. 1st, with benefit of local power corridor adds.	new idea # = old idea time for egg to crack. Lowering EMI in electrical underground and overhead lines with co-located lower power conductors
By itself or in conjunction with other conductors allow both AC and DC power flow. AC coupled AC sourcing and loading and DC flow for general power flow common mode cancelation and power loss recovery, not bad...	Yet another # idea DC & AC transmission on one cable.
Thought captured above	Continuation of losses and true cost of losses. If we have to make 4/3 as much power, that’s 33% more power, for a 25% loss in T&D! When you start at load and map back.

	Now 4/3 production for needed load*4/3 overcapacity for reliability, is 16/9 or 177% production to load ratio! Now remove 3/4 of overburden with ubiquitous batteries, DER, and pumped hydro all quick response. Remove 3/4 of the T&D losses with bigger & better conductors and now we have 33%*3/4=~25% loss removal from the 33% over 100% for ~ 108%. Same for cabling saves. so now 108%*108% = 116.6% Vs 177%. So this example, oversimplified shows the magnitude of savings possible. over 60% reduction in wasted overhead and conductor losses. Less volatility in cables, existing and improved via batteries further reduces cable losses in a secondary effect. Now if we at first allow not 108% charges for 177% electricity generation, but 177% charges for 108% of the electricity PROVIDED AT LOAD. We get the same bill, now whittle it back first by outlawing profits at some rate that allows adopting energy saving technology already mature. Now the utilities will buy or lose money if they are laggards. Bonus profits for early adopters and for helping other utilities like co-ops and rural cable challenge areas.

Community Solutions: In what ways do you believe you can contribute to addressing the challenges identified?

Relevant Challenge Short title	Solution Description	Notes
Scale Up	Large scale manufacturing with scale up experience	• Largest wire/cable manufacturer in US • Can serve as partners & aid in scale in process • Produce over 0.5 billion lbs./yr in Al overhead supply • Market available with IACS improvements (i.e., Carbon nanotubes embedded in Cu, assuming cost can remain relatively similar to Cu
Industry Standards creation	We have extensive experience in creating and maintaining industry standards	• Experience in creating, maintaining, altering standards to accompany various landscapes

Atomically precise graphene-copper interaction	We can help with modeling the interface and precisely characterizing it using advanced microscopy techniques.	• Utilize advanced manufacturing, techniques for cu/carbon interfaces; can model interface(s)
Carbon Fiber Metal Matrix Composites	Clean desizing off of the carbon fiber and then you should be able to perform electrodeposition.	• Removing lubricant using designated chemicals affected carbon fiber
Crosslinking and temp dependence, also designed a cable fatigue tester at Hughes AC	Knowledge, can discuss	• Alter the way electricity is charged to only account for the electricity delivered & not as much in cost of power plus profit to utility companies on loss. Utility companies incentivize losses, and make profit • Utility companies collect profits amidst inefficiencies • Approach via a top-down and bottom-up approach
Market entry, certain types of scale up issues	We have customers in multiple markets, are small, agile and tolerant to innovation challenges and we are hungry to commercialize suitable EC materials.	• Aerospace market supplier; innovation driven • Aid in marketing exposure through aerospace industry
Carbon fiber copper composites processing	We can assist with traditional and advanced manufacturing approaches that can process copper and carbon nanofiber composites	• Use traditional and advanced manufacturing techniques (solid phase processing)
We can process metal matrix composite in solid state	We can provide the technology or material.	• Metal matrix composites (MMC) can supply in wire, tube form
Ubiquitous Transceivers on the grid	Prior work at ABB on this topic	• Prior head of technology, ran research center in NC • Experience in transponders in cable • In situ measurements of strain/temperature within cable
	ORNL maintains a Carbon Fiber Technology Facility (CFTF) - carbon fiber test facility. They can manufacture scaled amounts of carbon fiber that may be beneficial.	

Composite processing (Pultrusion) expertise and conductor manufacturing expertise available	We do composite and conductor processing, including composite pultrusion	• Expertise in composite pultrusion, produce encapsulated core inside conductor • Desire to implement Al, graphene
HT cable insulation	High temp insulation materials up to 250C exist and are sold today for aircraft by multiple manufacturers.	• Gore makes products that suit high temp needs; Consider what other material performance properties are needed
High temp insulation	LM-PAEK is a thermoplastic that can achieve great thermomechanical properties and can be used as an insulator for up to 140C	
Tech scale-up	One of the biggest challenges is connecting with manufacturers. Most likely using their capabilities will help you scale. It's important to partner early, and the Dept of Commerce MEPs (Manufacturing Extension Partnerships) which are state-based entities can help make the relevant connections.	
Cold makes brittle, hot melts, so different solution spaces.	Stress hardening properties of insulation with additives at point of stress. Copper nano particles in a temporary carrier with carbon graphene or other. Cable stress tester designed for Hughes Aircraft company many moons ago.	
Better CNT and Graphene	We have IP on low cost and scalable production of Graphene and CNT. We will be happy to work with any interested company.	• Capability & expertise to produce graphene and CNT are competitive costs
High temp cable insulation	We have a group at NASA who are developing high temperature wire insulations; the group is lead by Dr. Maricela Lizcano (maricela.lazano@nasa.gov)	• Group at NASA working on high temperature wire insulation (email included in response)
Speaking to cost and need to reduce many zeros of cost...agree.... but, look at super	If the lost electricity was not allowed to be charged to customers, or at a minimum, no profits allowed to be made as a first transitional step. Will pay for at least one of the zeros.	

conductor cables, they have uses.	This is called load only energy profit reform. Watch the utilities suddenly care about the environment, cause	
PVC copper on insulator now been done for PCB for heat spreading	Why not for cable, coat the insulators in double and triple insulation, hardens, spreads heat, can be monitored for breakdown! or used for current?	
Angle sensors to measure droop from heating and COE, can be used with temp or IR from ground	Angle sensors to detect droop of hot cables.	
Tech adoption vs technology advancements	We can offer end application and technology adoption by performance system level trade studies, technology integration and building business value.	• Can help in finding the right application/product/integration of innovative technology

Prioritization: Of the challenges listed, which do you believe you can make a personal contribute to solving?

Challenge Short Title	Number of Votes
Additives for CABLE materials	7
continuous manufacturing of carbon fiber composite conductor	2
Atomically Precise Graphene-Cu Interaction	3
Better CNT and Graphene	4
Scaling from R&D to production	12
carbon fiber copper composite processing	6
Material cost	4
Tech adoption vs. technology advancements.	7
High voltage, high altitude, high thermal conductivity insulation	2
Not super connected.	1
Thought capture above	0

Presenter list send out via # and contributors list using presenters number for tracking into subgroups. Had fun today.	0
Keeping it simple numbers, let’s say I live in a state called Overpriced electricity, with an allowed 5% losses for connections from source to transmission, 10% for transmission, 5% distribution, & 5% distribution-substation to transformer, & 4% for transformer (average losses may be higher without good utilization) total is 29% losses, compounded 74%, Let’s call it 3/4 delivered Of needed generation. Now add reliability overburden of 115% to 145% around the nation. Sticking with fractions let’s call it 4/3 or 1/3 overproduction or 33%. Assume that's all fossil fuel derived. replace the losses in system, the overburden with storage, batteries in all sub-stations with cross feeders between sub-stations added for off-loading a down sub-station. All this fancy cables and batteries will all be paid for by utilities when load based profits are only allowed. So, say they get 8% profit allowance on all costs. 33% reduction in overburden with batteries, 10% reduction in T&D, 1/3 because of battery smoothing. rest better cables.	0
By spacing lower voltage systems below longer distant systems and synchronizing them to cancel EMI on the ground allows:1) lowering EMI health effects from HV lines. 2 split difference in height and cost with cancelation benefits. lower power runs do not need to be everywhere along HV line, if not designed lower, but just near populations 1st, with benefit of local power corridor adds.	0
By itself or in conjunction with other conductors allow both AC and Dc power flow. AC coupled AC sourcing and loading and DC flow for general power flow common mode cancelation and power loss recovery, not bad...	0
thought capture above	0

Appendix E: Action Plans

The following pages present the action plans completed by the small groups. Action plan topics were chosen by prioritizing the innovator challenges presented during the first facilitated discussion on Day 1. Those that voted for a specific challenge comprised the small group. The facilitated discussion on the second day was designed to further flesh out each challenge by completing the action plan template.

Group 1: Scaling from R&D to Production

<table>
<tr><th colspan="2">Proposed Project Concept to Resolve CABLE Innovator Challenge</th></tr>
<tr><td>Challenge Short Title</td><td>Primary Technical Challenge Description</td></tr>
<tr><td>Scaling from R&D to production</td><td>• Understanding requirements for scaling R&D materials.
• Understand market for specified product/process</td></tr>
<tr><td colspan="2">Challenge Breakdown: Use this space to consider different aspects of the primary technical challenge, or sub-challenges worth noting.</td></tr>
<tr><td colspan="2">• Understand where technology should be designated for given application
• Understand which components are critical to startup ecosystem (Need expertise/support, mentoring for startup, utilize SMEs. Sustainability of product in market, larger companies hold expertise for new startup
• Understanding competing & emerging solutions
• Aid in proposal submission to laboratory (i.e., barriers to project success and grant award)</td></tr>
<tr><td colspan="2">Description: Write 2-3 sentences/bullets to describe potential solutions to the challenges noted above.</td></tr>
<tr><td colspan="2">• Stage gating process, best practices (Manufacturing voucher process; useful for DOE/AMO, provide a voucher system to cable prize winner to utilize production facilities and others
• 3 prong approach: 1) Process Stability, 2) Supply Chain, 3) Training (i.e. safety, engineering, operations)
• Apex; matchmaking function; enables problem and solution pairing (Better understanding of business functions, one idea is to utilize manufacturing voucher process & enable sourcing for business support services
• Stage gate process (Best practice, can be tailored to company size)
• Create an application family distribution which feeds into the material quantities & choices needed for these applications (Quantities can be further specified by understanding the market need, also understanding pre-requisite qualifications to permeate market
• Create a market by laying out target market paired with technology and production implication on front end (Create a roadmap of Target markets)
• Fundamental understanding is pertinent in situations where the output for product is directly affected</td></tr>
<tr><th colspan="2">Key Considerations</th></tr>
<tr><td colspan="2">Theory: Describe aspects of underlying theory that need to be better understood, to support project success.</td></tr>
<tr><td colspan="2">Phase 1 (lay out plan for phase two via a roadmap which supports results & presents findings; Early engagement enables efficiency in phase 2 for resource allocation</td></tr>
</table>

Modeling: Describe any modeling efforts needed to support project success.
• Understand future process variability with modeling • Train model using fine measurements under same material & conditions to better understand process variability (Connection between machine learning, modeling, characterization etc.) • Modeling can assist the development of real-time process controls for ensuring manufacturing quality • Digital twins, IIoT, inline measurement • AI/ML to assist process understanding, quality impacts, real-time control
Characterization: Describe any characterization needs specific to the proposed project or concept.
Need to classify process stability via testing, modeling, characterization
Testing: Describe the testing needs associated with the proposed effort or concept.
• Distinguish testing in development phase versus quality control to adhere to customer standards in production process(es) • Postproduction • Need measurement devices suitable for real-time production environments; low cost, robust, high speed; measurement in the research phase can afford big, expensive equipment; not so in the production phase / in scale up;

Timing	Key Activities	
R&D Phase	List the key actions to be taken in the R&D Phase.	• Identify the future production environments will be to understand equipment & process sensitivities • Collection of measurements • Understand the scalability of product and cost efficiency early in R&D phase (Integrate business section early on, collaboration with economy experts) • Provide peer review to economic implications of product early on
Demonstration Phase	List the key actions to be taken in the Demonstration Phase.	• Repeatability testing (Use repeatability to determine suitable quantity) • Pilot/Demonstration needs to show repeatability in quantity • Create robust process to adhere to specifications • Trade trials (small scale demonstration released in small quantities to market)
Deployment Phase	List the key actions to be taken in the Deployment Phase.	• Quality of product • Failure mode analysis conducted in demonstration phase to be proven in deployment phase

Stakeholders	
Describe the potential role of each stakeholder in the project, e.g., providing material test data Specify team leads, partners, measurement / characterization facilities, and other technology or solution providers.	
Stakeholder:	Role
Product manufacturers:	

End-users/OEMs:	Market requirements; cost, form factor, product quality guidelines
Academia:	Basic materials understanding to support scale-up
National laboratories:	Modeling, testing, and characterization capabilities
DOE/Government:	• An opportunity may exist for supporting manufacturing centers that specialize in scale up, and are able to re-tool and reconfigure equipment, to help demonstrate products at scale • Large manufacturers have prohibitive costs for small runs of new materials. Specialized manufacturing centers can provide value to the ecosystem. • Provide vouchers that can be used for other critical business services that can pose hurdles to small businesses and startups
Others:	• Contract manufacturers can assist in small runs for deployment phase. Need to understand if you need EPA clearance; i.e. regulatory standards in place prior to deployment during scale up phase • There are companies that specialize in manufacturing at scale-up quantities, or allow for small runs, prior to committing to large-scale production; These companies are not well known within the CABLE ecosystem

Group 2: Technology Adoption versus Technology Advancement

<table>
<tr><th colspan="2">Proposed Project Concept to Resolve CABLE Innovator Challenge</th></tr>
<tr><td>Challenge Short Title</td><td>Primary Technical Challenge Description</td></tr>
<tr><td>Tech adoption vs. technology advancements</td><td>R&R, scaling, cost, supply chain
Satisfies end product improvement and is able to be adopted with above metrics
Connecting with manufacturers
Enhancing conductivity</td></tr>
<tr><td colspan="2">Challenge Breakdown: Use this space to consider different aspects of the primary technical challenge, or sub-challenges worth noting.</td></tr>
<tr><td colspan="2">Defining problem and applications, market demand
Market viability, commercial plan
What are the barriers to adoption?
Suitable metrics, cost reductions
Relaying benefits to customers, even if communicated as incremental improvements in tech
Discerning whether market is ready and tech in development vs. tech being ready but needing to be marketed to consumers
Can you reproduce at a manufacturer-ready scale? What MRL is needed?
What would convince a buyer that the tech is ready?
Consider competition risk</td></tr>
<tr><td colspan="2">Description: Write 2-3 sentences/bullets to describe potential solutions to the challenges noted above.</td></tr>
<tr><td colspan="2">Starting with end goal in mind (ecosystem communication)
Increasing awareness
Consider application qualities, envision pathway to first market (identify first market, set specific metrics for that market)
Capture market's attention
Prize for testers of materials
Enhance/relay credibility of tech/seller
Relay cost/energy savings
Case studies that demonstrate utility
Defined entry point
Higher TRL/MRL</td></tr>
<tr><th colspan="2">Key Considerations</th></tr>
<tr><td colspan="2">Theory: Describe aspects of underlying theory that need to be better understood, to support project success.</td></tr>
<tr><td colspan="2">Metastable state has implications for fabrication (establishing need)</td></tr>
</table>

Modeling: Describe any modeling efforts needed to support project success.	
Modeling alone won't convince customers to adopt. Look at materials and parameters	
Characterization: Describe any characterization needs specific to the proposed project or concept.	
Characterization and testing needed at higher level (to demonstrate what successful material looks like)	
Testing: Describe the testing needs associated with the proposed effort or concept.	
Defining performance under specific conditions	

Timing	Key Activities	
R&D Phase	List the key actions to be taken in the R&D Phase.	• **Define metrics and scalability** • Define properties
Demonstration Phase	List the key actions to be taken in the Demonstration Phase.	• Increase TRL • **R&D roadmap** • Cost justifications of applications • Define business model, establish relationships • **System demonstration, interconnects**
Deployment Phase	List the key actions to be taken in the Deployment Phase.	• **Standardization** • Supplier dependencies (one supplier - to start - can be sufficient), suppliers will increase as market appears

Stakeholders		Impacts - If successful, how does the world change? (Big picture)	
Describe the potential role of each stakeholder in the project, e.g., providing material test data Specify team leads, partners, measurement / characterization facilities, and other technology or solution providers.		Describe the anticipated economic benefits (new products, jobs, economic growth, exports, contributions to the tax base, etc.) as well as impacts on energy, health, safety, environment, or other quality of life aspects. Also, describe any impacts related to energy efficiency, decarbonization, or other DOE goals and objectives.	
Stakeholder:	Role:	Potential Impact	Notes

Product manufacturers:	**Specify factors needed to build prototypes**	Changes in policy, monetary incentives for adoption	**Timing and deadlines matter (e.g., net-zero emissions by 2050, U.S. power grid reaching carbon neutrality by 2035, etc.); will dictate impact and rate at which work needs to be performed -** look for windows of opportunity (five-year window for commercialization). There are deadlines for tech development/adoption, and they matter for the technology.
End-users/OEMs:		Fuel savings, improved mileage, overall energy efficiency	
National laboratories:	**Testing, metrology**		
DOE/Government:	**Set appropriate metrics**		

Group 3: Additives for CABLE Materials

Proposed Project Concept to Resolve CABLE Innovator Challenge	
Additives for CABLE materials	**Primary Technical Challenge Description**
Carbon fiber, C nanotubes, graphene, mx-ines.	Graphene supply chain and cost

Challenge Breakdown: Use this space to consider different aspects of the primary technical challenge, or sub-challenges worth noting.
• Quality varies batch to batch, with quantity, with provider • Not just the additives but how they interact with matrix metal • Chicken-and-egg: manufacturers need to see market, market needs to see product • Basic cable design knowledge and fatigue, also magnet wire as a subject, avionics as a bridge
Description: Write 2-3 sentences/bullets to describe potential solutions to the challenges noted above.
• We have an IP on low cost and scalable production of Graphene and CNT. We will be happy to work with any interested company. • Need certification process that e.g. DOE can use. So if I go to manufacturer, can hold them to standards. • Talking about large-scale manufacturing - what does it take? facilitate transition to industry through national lab, etc., capabilities

Key Considerations
Theory: Describe aspects of underlying theory that need to be better understood, to support project success.
Need to better understand, evolve understanding of synthesis processes of CNT and graphene, can be assisted through computer M&S
Modeling: Describe any modeling efforts needed to support project success.
Modeling of charge transfer between metal and Gr or CNT would be helpful not just for pristine cases but also as suggested carbide former intermediary or dopants
Characterization: Describe any characterization needs specific to the proposed project or concept.
Raman spectroscopy, manufacturer will not provide info, have to do in-house, need standards. New techniques? Need to do with in-house equipment.
Testing: Describe the testing needs associated with the proposed effort or concept.

Testing is driven by applications. There are electrical-specific testing of interest only to electrical applications. What is the purpose of the additives (application-wise)? Need a standard for the additives themselves.

Timing	Key Activities		Overarching Goals/Targets	
R&D Phase	List the key actions to be taken in the R&D Phase.	• Process modeling • Demonstrating a pathway for large-scale demonstrations	List accomplishments and/or performance targets you hope to achieve through the research	• Large-scale modeling • Consistency in manufacturing and output
Demonstration Phase	List the key actions to be taken in the Demonstration Phase.	• Quality assurance • Bulk material - outcome depends on process	List accomplishments and/or performance targets you hope to achieve through demonstration	Certification standards, cost targets
Deployment Phase	List the key actions to be taken in the Deployment Phase.	• Form of the bulk material • Market development, understanding barriers	List accomplishments and/or performance targets you hope to achieve through commercialization	Quantities rapidly produced, good market development - depends on the application (which drives amount, which drives additives, which drives requirements of production) - proposed intermediate standard - anticipate forks - complex forms (extruded vs. sheet) are different

Stakeholders		Impacts	
Describe the potential role of each stakeholder in the project, e.g., providing material test data Specify team leads, partners, measurement / characterization facilities, and other technology or solution providers.		Describe the anticipated economic benefits (new products, jobs, economic growth, exports, contributions to the tax base, etc.) as well as impacts on energy, health, safety, environment, or other quality of life aspects. Also, describe any impacts related to energy efficiency, decarbonization, or other DOE goals and objectives.	
Stakeholder:	Role:	Low - High	Potential Impact
Product manufacturers:	Provide high-quality bulk materials at low cost	High	Delayed use of additive materials
End-users/OEMs:	Identify markets	High	Delayed deployment of cable materials - niche markets
Academia:	Research support, fundamental science	Medium	Labor force - trained STEM labor force

National laboratories:	Tech transfer, characterization capabilities, computer M&S	Medium-high	Delayed scale-up
DOE/Government:	Support initiatives, certification standards, funding		

Group 4: Carbon Fiber Metal Composite Processing

Proposed Project Concept to Resolve CABLE Innovator Challenge	
Challenge Short Title	**Primary Technical Challenge Description**
Carbon fiber metal composite processing	Expertise in carbon fiber metal composite processing into wires
Challenge Breakdown: Use this space to consider different aspects of the primary technical challenge, or sub-challenges worth noting.	
Applicable on a small scale but scale up is more challenging.	
Description: Write 2-3 sentences/bullets to describe potential solutions to the challenges noted above.	
• Addition of carbon fibers to aluminum for strength enhancement to replace steel cores • Potentially use recycle aluminum fibers - environmental benefits	
Key Considerations	
Theory: Describe aspects of underlying theory that need to be better understood, to support project success.	
Modeling: Describe any modeling efforts needed to support project success.	

• Strength and electrical conductivity modeling of fiber enhanced aluminum to determine potential to replace steel cores.
• Business case model:
    ○ Cost of fiber reinforced aluminum vs steel
    ○ Supply chain of recycled carbon fibers
    ○ Extra processing steps required to add carbon fibers to aluminum vs steel core production	

Characterization: Describe any characterization needs specific to the proposed project or concept.	
Measuring strength and electrical conductivity of fiber enhanced aluminum wires	
Testing: Describe the testing needs associated with the proposed effort or concept.	

<table>
<tr><td colspan="5">Conductivity, mechanical strength, recycled carbon analysis</td></tr>
<tr><th>Timing</th><th colspan="2">Key Activities</th><th colspan="2">Overarching Goals/Targets</th></tr>
<tr><td>R&D Phase</td><td>List the key actions to be taken in the R&D Phase.</td><td>• Business case development
• Develop carbon fiber reinforced ingots
• Develop carbon fiber reinforced aluminum wire
• Evaluate desizing for spool fiber and recycled fiber if pursuing</td><td>List accomplishments and/or performance targets you hope to achieve through the research</td><td>• Wire matches strength required for replacement of steel core (as defined by business case)
• Good (as defined by business case) conductivity</td></tr>
<tr><th colspan="3">Stakeholders</th><th colspan="2">Impacts</th></tr>
</table>

Impacts	
Describe the anticipated economic benefits (new products, jobs, economic growth, exports, contributions to the tax base, etc.) as well as impacts on energy, health, safety, environment, or other quality of life aspects. Also, describe any impacts related to energy efficiency, decarbonization, or other DOE goals and objectives.	
Potential Impact	Notes
Reduced environmental impacts of wire production	
Reduced chance of fires from sagging cables	Reduce weight, reduce sagging
Reduce energy losses by increasing emissivity, reducing temperature	If carbon coating is included
Economic benefits if used for lightning protection	

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