U.S. DEPARTMENT OF
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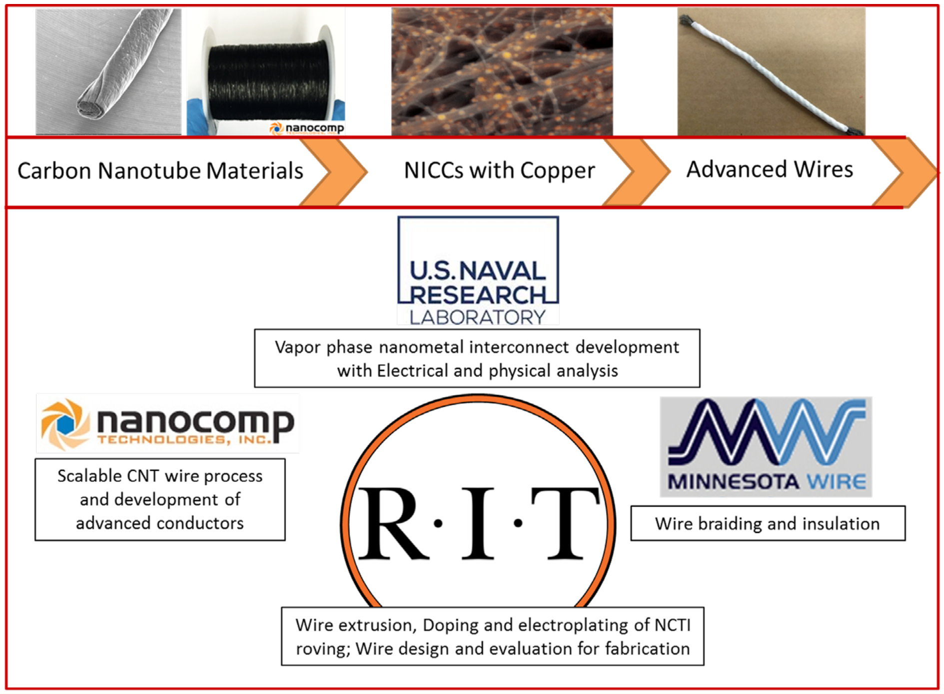
# Nanometal-Interconnected Carbon Conductors (NICCs) for Advanced Electric Machines

Achieving novel, light-weight, high-conductivity wiring appropriate for advanced motor applications




Schematic summarizing the success to scalable CNT wire development for electric motor integration by the current research team. *Graphic image credit Rochester Institute of Technology.*

Lightweighting small to medium induction motors, prevalent in transportation systems, through high performance conducting materials, presents a challenging but high payoff opportunity for life cycle energy savings. These motor systems are typically constructed using wires from metallic materials such as copper and aluminum. While these materials have high carrier densities, enabling high electrical conductivity, they also have high temperature coefficients of resistance, limiting their performance at elevated operating temperatures. In order to improve energy efficiency in the next-generation of advanced motor systems, new conductive materials and technologies need to be developed.

This project will advance the electrical performance of nanometal-interconnected carbon conductors (NICCs) for motor windings. The NICCs consist of a highly conductive, lab-produced carbon nanotube backbone interconnected by nanometal particles to further enhance electrical conductivity. Material development will follow parallel strategies to meet target performance objectives. The first strategy involves improving carbon nanotube wire electrical conductivity through chlorosulfonic acid (CSA) extrusion, electrospinning, and coaxial extrusion. These methods enable higher electrical conductivity through improved alignment and chemical doping of the carbon nanotubes. In addition, carbon nanotube-metal hybrids will be developed to fabricate full-scale NICCs.

In the second strategy, Nanocomp-produced carbon nanotube material is the platform for scalable integration of nanometal interconnects via electroplating and vapor-phase deposition. From laboratory-scale setups, NICC fabrication methods can then be evaluated for roll-to-roll production and ultimately transitioned to Nanocomp for mass-production and leveraged by wire braiding partner Minnesota Wire. Initial electroplating and vapor-phase deposition techniques will focus on copper, aluminum, or silver material for permanent conductivity enhancement.

## Benefits for Our Industry and Our Nation

Using nanometal-interconnected carbon conductors for wires in advanced motor systems has many benefits, including the following:

- Increasing electrical conductivity to enable reductions in stator resistance losses. For example, a 33% reduction in stator resistance losses in industrial motor systems is estimated to yield potential energy savings of approximately 25,633 GWh/yr or 0.96% of total U.S. energy consumption.
- Concurrently decreasing wire weight by 50% at an operating temperature of 150°C compared to an equivalent copper wire.
- Enabling a cost-competitive, commercially-compatible product fabricated from domestically available materials and technologies.

## Applications in Our Nation's Industry

This technology could provide multiple industries with a low-energy, high-performance method of wire fabrication for advanced electrical motor systems. This technology can have immediate impact on any industry where improved, lightweight conductors yield energy savings.

## Project Description

The project objective is to develop, build, and validate advanced nanometal-interconnected carbon conductors (NICCs) with enhanced conductivity and lower temperature sensitivity than alternative conductors (i.e., copper). The proposed NICC wires are produced by integrating nanometal particles within the structure of highly conductive nanocarbon backbones. These backbones are required to have low temperature coefficients of resistance, which is augmented with chemical dopants to increase carrier density and nanometal interconnects to promote inter-nanocarbon conduction.

### Barriers

- Achieving effective electrical coupling of the deposited nanometal to the carbon nanotubes.
- Synthesizing electrically effective metal bridges between the nanometal particles on the nanotubes.
- Fabricating and scaling up the length of the NICC material.

### Pathways

The research team plans to develop advanced nanometal-interconnected carbon conductors to exceed the conductivity performance of conventional metallic wires. For carbon nanotubes (CNTs) production, the team will utilize state-of-the-art fabrication methods like roll-to-roll chemical vapor deposition (CVD) grown CNT wires and extruded high-purity single walled CNTs (SWCNTs). These methods will be adjusted to mitigate network contact resistances through processing and when introducing nanometal interconnects.

The work plan will advance the conductivity of CNT materials. This is accomplished via two parallel paths: chemical extrusions of dispersed SWCNTs followed by doping and densification, as well as modifications of Nanocomp's CNT production process. As a result, the team expects to increase the conductivity in the proposed nanometal-interconnected carbon conductors while reducing weight.

The team will then be able to optimize the synthesis and plating methods for the material. This will be accomplished through vapor and electro-deposition while scaling up the length. This increase in length enables relative electrical performance towards the conductivity of metallic wires. The electrical conductivity of the NICC material will be tested at meter-length.

### Milestones

This 3 year project began in 2017.

- Optimize electroplating and doping conditions to meet targeted conductivity of extruded and/or treated roving approaching 10 MS/m in >10cm-length samples at room temperature (2018).
- Develop meter length NICC wires with suitable insulation and electrical performance to meet specification under relevant testing conditions (2019).
- Optimize CNT roving production, chemical treatment, electroplating, vapor deposition, and doping conditions to meet targeted conductivity of extruded and/or treated roving within 10% of 15-30 MS/m at 150°C in meter-length samples through temperature dependent electrical testing (2020).

## Technology Transition

Upon successful conclusion of the project, the research team anticipates Nanocomp will be the primary commercialization partner for the technology. In addition, Rochester Institute of Technology (RIT) is neutrally positioned to license and disseminate any intellectual property for the technology. RIT is willing to also transfer the technology to other interested industries.

## Project Partners

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