Flexible and Wearable Supercapacitors for Fire Fighters and First Responders

10/13/2023 | KAVITHA MULACKAMPILLY JOSEPH | 24TH PILOT RESEARCH PROJECT SYMPOSIUM

University of CINCINNATI

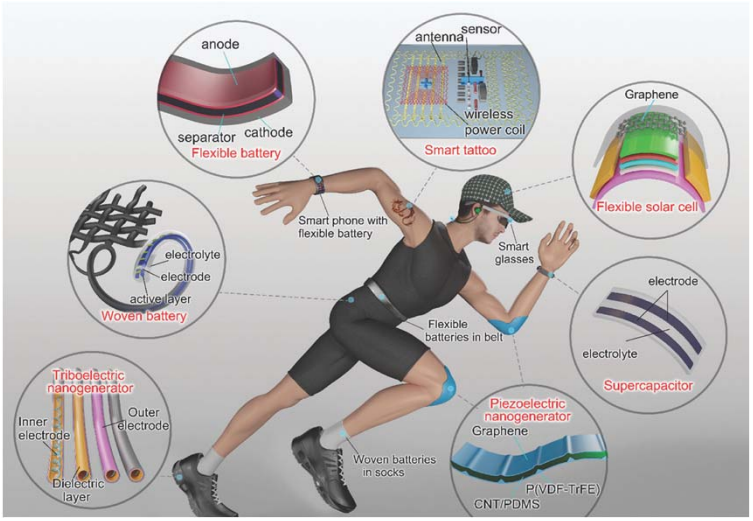
INTRODUCTION

Flexible and Wearable Technologies have a huge impact on various walks of modern life.

- Healthcare
- Environmental monitoring systems
- Military
- First responders
- Construction/ low-wage workers

The greatest challenge?

- Lack of power supply that is equally flexible, lightweight, durable, and strong.
- Traditional energy storage devices are hard, heavy, and bulky
- Therefore, the need for thin, lightweight, and flexible supercapacitors.



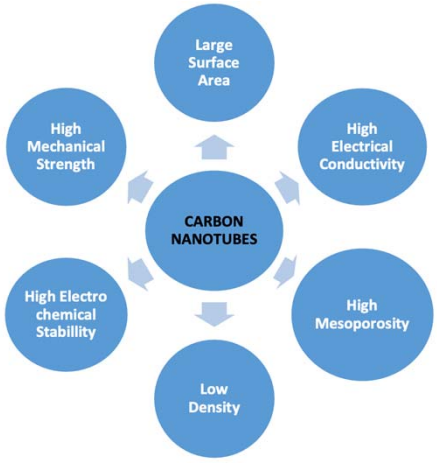
OBJECTIVE

The objective is to design and fabricate high-performing, flexible, lightweight supercapacitors and incorporate them into the garments of firefighters/first responders. The supercapacitor is based on carbon nanotube (CNT) fiber. It could be easily integrated into the fabric as it is in the fiber form [1,2].

Why supercapacitors?

- **High power density**
- **Durability**
- **Safety**
- **Stability**

Why Carbon Nanotubes (CNTs)?



RELEVANCE TO NORA

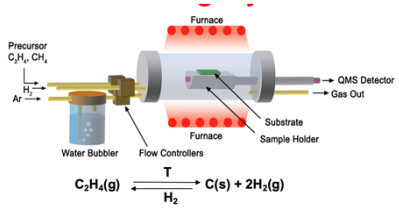
- NORA = National Occupational Research Agenda by NIOSH
- The concept for **Next Generation First Responders** (**NGFR,** started in 2015 by DHS) emphasizes the capabilities of enhanced access to various kinds of information through wearable technologies.
- All these wearables of first responders need a reliable power supply for smooth and uninterrupted emergency operations.
- Traditional energy storage devices are bulky and heavy restricting the mobility and agility of first responders.
- Hence there is an urgent need to develop flexible and lightweight energy storage devices that can power wearable electronics.

FIRST RESPONDERS ARE REAL LIFE HEROES

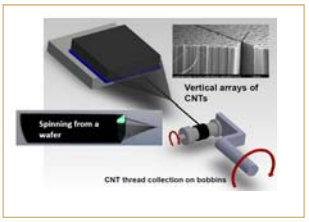
NGFR Concept by DHS

METHODS AND DESIGN

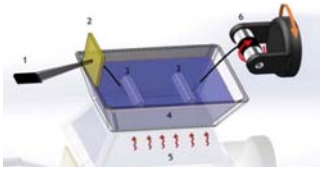
CVD(Chemical Vapor Deposition) process for CNT synthesis [1,2]



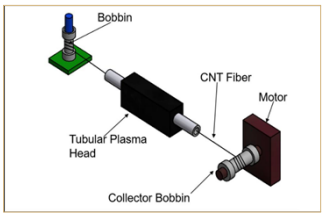
CNT fiber spinning [1,2]



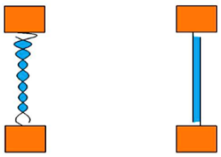
Fiber densification (N-Methyl Pyrrolidone solvent at 180C) [3]



Plasma functionalization (100W ,Oxygen (0.3L/m),He 30L/m) [4]



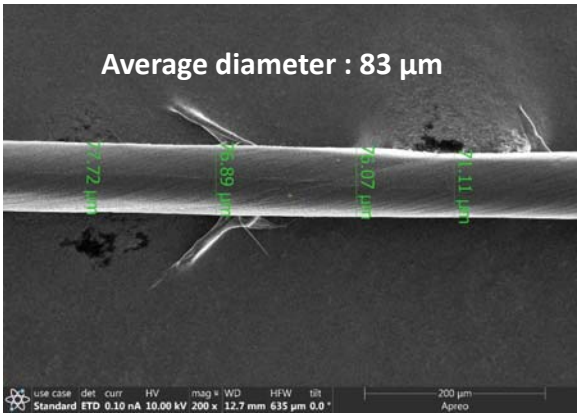
Schematic of supercapacitor design (intertwined(left) or parallel (right))



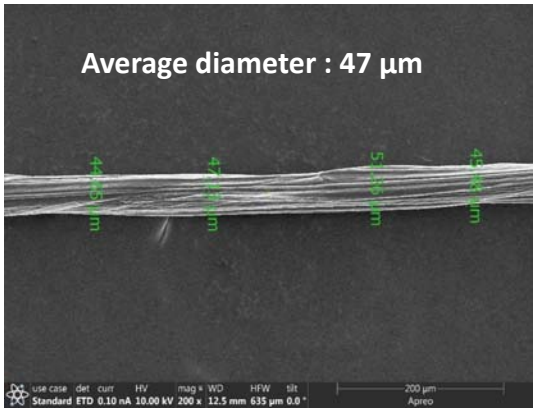
Supercapacitor device

RESULTS: MORPHOLOGY

Pristine fiber

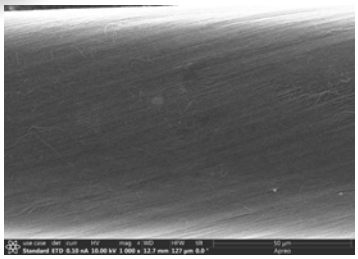


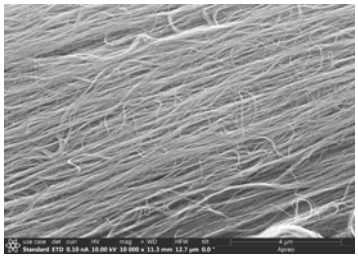
Densified fiber



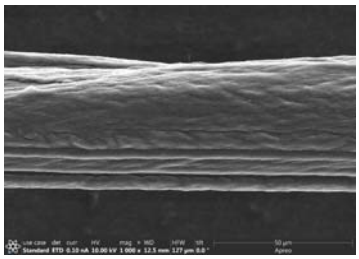
RESULTS: MORPHOLOGY-CONT.

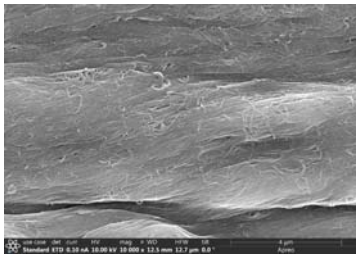
Pristine fiber



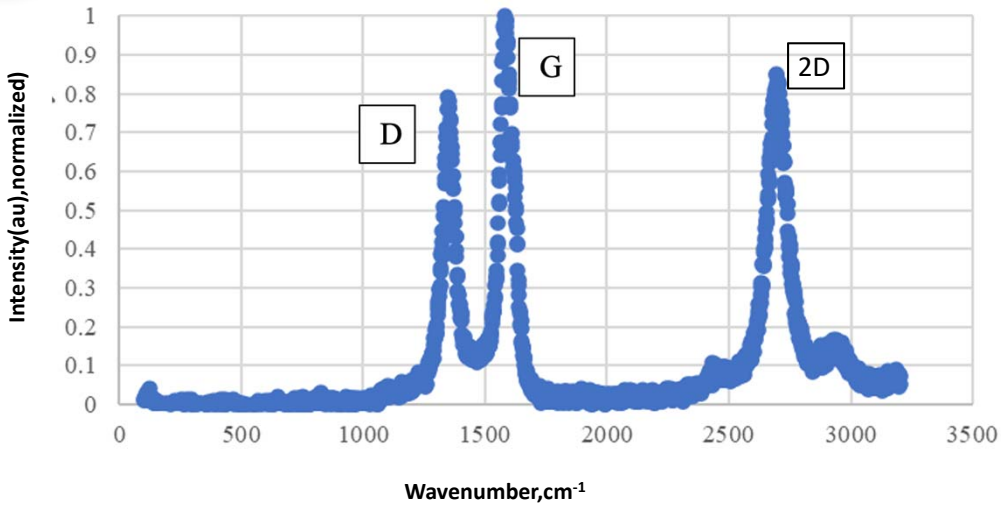


Densified fiber



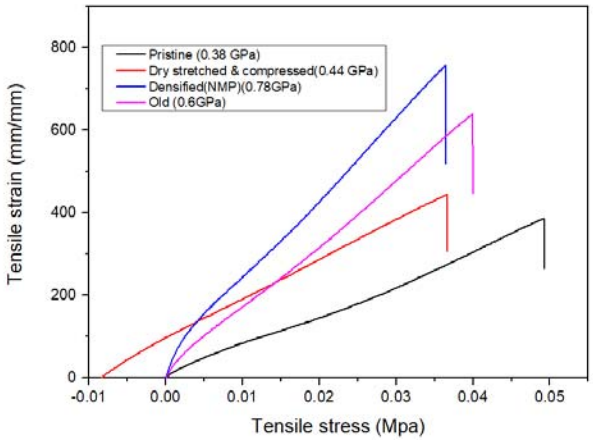


RESULTS: RAMAN SPECTROSCOPY



RESULTS: MECHANICAL STRENGTH

Specimen Name	Tensile strength
Pristine (70-90 µm)	0.38 GPa
Dry stretched and compressed (60-65 µm)	0.44 GPa
Solvent densified (45-50 µm)	0.78 Gpa
Initial (old) pristine sample (35 - 45 µm)	0.60GPa



- Nearly 105% improvement in tensile strength for the densified fiber than the pristine fiber.
- Tensile strength is measured by Instron 5948 pneumatic tensile tester (Strain rate: 1mm/min: Gauge length = 22mm

RESULTS: RESISTIVITY BY FOUR PROBE MEASUREMENTS

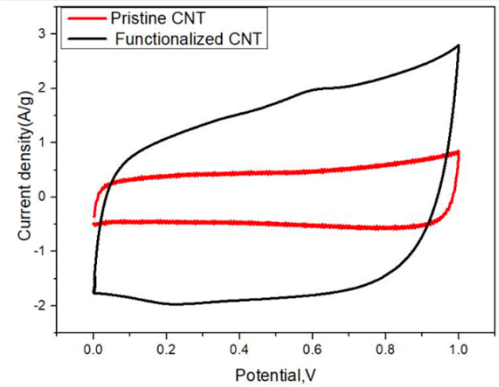
Specimen Name	Equation	Resistance	Diameter µm	Resistivity Ω m
Pristine	y = 37.751x - 14.668	37.75Ω	83	4.3×10^{-5}
Densified	Y = 33.549x - 12.788	33.55 Ω	48.65	1.2×10^{-5}

- Nearly 4 times decrease in resistivity observed in the densified fiber compared to pristine fiber, increasing the conductivity of densified fiber to 8.3 X 10^4S/m from 2.3 X 10^4S/m.

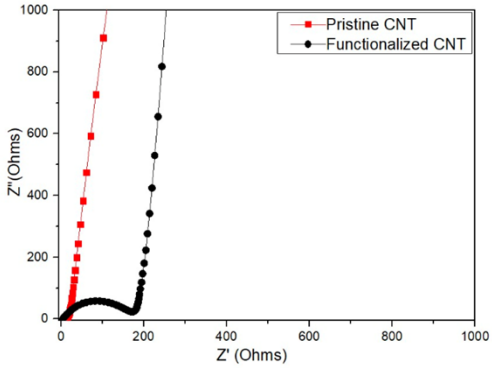
RESULTS: PRELIMINARY ELECTROCHEMICAL TESTS

Comparative CV and EIS of oxygen functionalized (O-CNT) & Pristine CNT (P-CNT)

CV (Cylic Voltammetry)



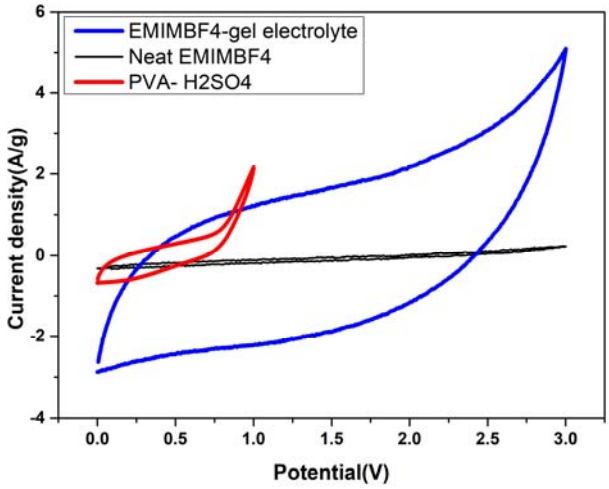
EIS (Electrochemical Impedance Spectroscopy



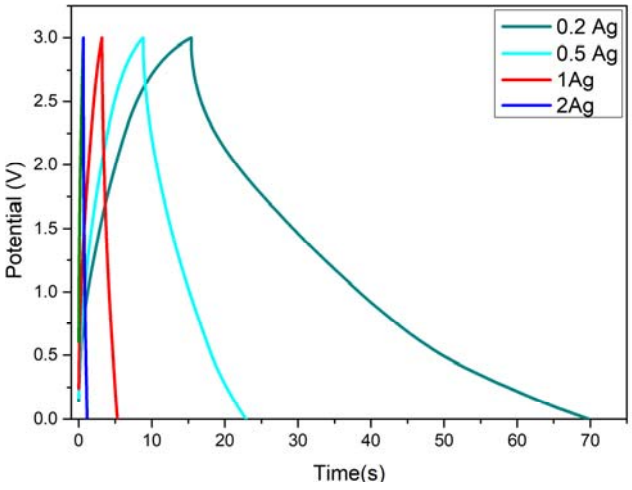
- CV and EIS electrochemical experiments were conducted in a three-electrode format with 1M Na_2SO_4 as electrolyte and Ag/AgCl and Pt as a reference and counter electrode in a Gamry interface 1000 workstation.
- EIS or Electrochemical Impedance Spectroscopy was done within a frequency range of 10^5 Hz to 0.1 Hz.

RESULTS: DEVICE ELECTROCHEMICAL TESTS

Cyclic voltammetry on the device OCNT with three types of electrolytes



Galvanostatic charge-discharge curve of functionalized CNT with EMIMBF4-gel polymer electrolyte



DISCUSSION

- A flexible, strong, and lightweight supercapacitor was fabricated from densified and oxygen-functionalized carbon nanotube fiber.
- The densification process introduced in this project is scalable. The double-step process involving initial dry stretching and compression followed by high-temperature solvent treatment increased the mechanical strength by 105% and electrical conductivity by 4 times compared to the pristine fiber.
- The densified fiber was further oxygen functionalized (O-CNT) which improved the wettability resulting in an increase of capacitive area of 65% more than the non-functionalized fiber.
- The O-CNT was used to fabricate supercapacitor devices with three types of electrolytes with EMIMBF4-PVDF gel polymer device proving superior to PVA-H_2SO_4 and neat $EMIMBF_4$ devices.
- The CV and the GCD curves are quasi-rectangular and triangular shapes which confirms the double-layer capacitive energy storage potential of the O-CNT fiber. A certain amount of non-linearity observed can be attributed to the pseudo-capacitance due to the presence of oxygen group.

CONCLUSIONS

Future work

- Durability testing (Cyclic stability and flexural tests) followed by incorporation of the wearable supercapacitor device into the fabric.

Future funding potential

- The research on CNT fiber-based wearable energy storage devices shows greater potential to power a host of wearable devices in various sectors like healthcare, military, space explorations, sports, and the fashion industry. Options to submit a proposal for external funding, to NSF and other federal agencies are also being explored.

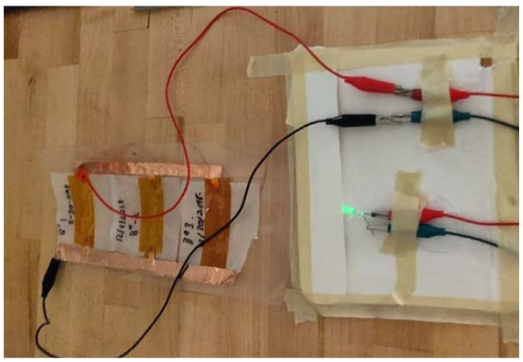
Impact

- The project will be a stimulant to the current innovative research on wearable energy storage devices and will pave the way for first responders and other workers to perform productively during emergencies with safety and ease.
- The project will also greatly impact the DHS initiative of **Next Generation First Responders** (**NGFR)** which emphasizes the capabilities of enhanced access to various kinds of information through wearable technologies.

CONCLUSIONS

RESEARCH TO PRACTICE

- The research can be made easily scalable as most of the steps in the project are scalable (Spinning, densification, functionalization, etc).



Functionalized CNT-EMIMBF4 device connected in parallel powering an LED [4], can be scaled up to illuminate vests,[5] and can be extended to power other applications too.

REFERENCES

- Noe T. Alvarez, Petr Miller, Mark Haase, Nicholas kienzle, Lu Zhang, Mark J. Schulz, Vesselin Shanov. ***Carbon nanotube assembly at near-industrial natural fiber spinning rates***. Carbon **2015,**86:350-357
- Joseph.K, Kasparian J, Shanov. V ***Wearable supercapacitors based on carbon nanotube fiber—A review on recent advances***.Energies **2022,**15,6506
- Joseph, K.M.; Brittingham, K.; Kondapalli, V.K.R.; Khosravifar, M.; Raut, A.A.; Karsten, B.D.; Kasparian, H.J.; Phan, N.; Kamath, A.; Almansour, A.S.; et al. ***Lightweight Copper–Carbon Nanotube Core–Shell Composite Fiber for Power Cable Application.*** C **2023**, 9, 43.
- Adusei, P.K.; Gbordzoe, S.; Kanakaraj, S.N.; Hsieh, Y.Y.; Alvarez, N.T.; Fang, Y.; Johnson, K.; McConnell, C.; Shanov, V. ***Fabrication and study of supercapacitor electrodes based on oxygen plasma functionalized carbon nanotube fibers***. *J. Energy Chem.* **2020**, *40*, 120–131.
- https://glowproducts.com/us/light-up-safety vest?gclid=EAIaIQobChMImvXA8vvsgQMVg0hHAR2S6Ak_EAQYAyABEgLB5vD_BwE

ACKNOWLEDGEMENTS

- ***This research study was supported by the National Institute for Occupational Safety and Health through the Pilot Research Project Training Program of the University of Cincinnati Education and Research Center Grant #T42OH008432***

OTHER PUBLICATIONS/PRESENTATIONS /GRANTS BASED ON THE PRP PROJECT

Publications

- **Joseph. K.M**, Kasparian J, Shanov. V ***Wearable supercapacitors based on carbon nanotube fiber—A review on recent advances***. Energies **2022,**15,6506. {Nominated as one of the best papers in 2022 by the journal 'Energies'}
- **Joseph, K.M**.; Brittingham, K.; Kondapalli, V.K.R.; Khosravifar, M.; Raut, A.A.; Karsten, B.D.; Kasparian, H.J.; Phan, N.; Kamath, A.; Almansour, A.S.; et al. ***Lightweight Copper–Carbon Nanotube Core–Shell Composite Fiber for Power Cable Application.*** C **2023**, 9, 43.{ Joint publication with NASA scientists. The project is based on the densified CNT fiber with enhanced strength and conductivity which could be used in the Aerospace power transmission cable application}.

Conference presentations

- **Joseph**, K.M *Carbon Nanotube Fiber- Based Wearable Supercapacitors – A Review on Recent Advances*, NanoResCon and Mat Sci Con-2023, March 27-29,2023, Rome, Italy, organized by Research Catalyst. (Virtual, **Invited**).

19

Thank You.

Questions?

EMAIL: JOSEPHKA@MAIL.UC.EDU

University of CINCINNATI