

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) 06-02-2020		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 9-Mar-2018 - 31-Aug-2019	
4. TITLE AND SUBTITLE Final Report: Identifying the Commercialization Path of Novel Carbon Nanofibers for Enhanced Structural Composites and Energy Storage			5a. CONTRACT NUMBER W911NF-18-1-0128		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 106011		
6. AUTHORS			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Texas Engineering Experiment Station SRS 400 Harvey Mitchell Parkway South, Suite 300 College Station, TX 77845 -4375			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 72636-SD-ICR.2		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:		17. LIMITATION OF ABSTRACT		15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU	UU		Mohammad Naraghi
					19b. TELEPHONE NUMBER 979-862-3323

RPPR Final Report
as of 11-Feb-2020

Agency Code:

Proposal Number: 72636SDICR

Agreement Number: W911NF-18-1-0128

INVESTIGATOR(S):

Name: Yijun Chen
Email: andychen.tamu@gmail.com
Phone Number: 2174024893
Principal: N

Name: John Beckerdite
Email: johnbeckerdite@tamu.edu
Phone Number: 9796657197
Principal: N

Name: Mohammad Naraghi
Email: naraghi@tamu.edu
Phone Number: 9798623323
Principal: Y

Organization: **Texas Engineering Experiment Station**

Address: SRS, College Station, TX 778454375

Country: USA

DUNS Number: 847205572

EIN: 741974733

Report Date: 30-Nov-2019

Date Received: 06-Feb-2020

Final Report for Period Beginning 09-Mar-2018 and Ending 31-Aug-2019

Title: Identifying the Commercialization Path of Novel Carbon Nanofibers for Enhanced Structural Composites and Energy Storage

Begin Performance Period: 09-Mar-2018

End Performance Period: 31-Aug-2019

Report Term: 0-Other

Submitted By: Mohammad Naraghi

Email: naraghi@tamu.edu

Phone: (979) 862-3323

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 1

STEM Participants:

Major Goals: The market for various types of nanomaterials, such as carbon nanotubes (CNTs) and carbon nanofibers (CNFs), is growing at a staggering rate; the market for CNTs alone is estimated to be \$670 million in 2019. This is due to a combination of remarkable properties of these nanomaterials, such as exceptional strength, which brings hope for new composites with superior performance metrics. However, major limitations exist in commercialization of nanomaterials, such as extremely prohibitive costs (e.g., the cost of CNTs can be 10-100x that of carbon fibers), extremely limited capabilities to generate continuous strands of nanofibers and nanotubes (as required to weave them into fabrics for more elaborate design of composites), and poor controllability over their microstructure (inherent in CVD production methods). We believe we have developed a form of CNFs which can overcome the above limitations by introducing continuous bundles of CNFs with significant control over the microstructure and geometry, all facilitated via proprietary and scalable processing methods. By controlling the processing parameters, we have managed to develop CNFs with a variety of forms: highly graphitic, wavy, hollow and porous. We believe that this technology has the potential to compete in two somewhat distinct product segments: carbon fiber/carbon nanofiber and carbon nanotube. Though fibers and tubes have somewhat different property sets, they can compete in the same markets. With the premise of reduced production cost and a unique set of properties (high aspect ratio, continuous strands, controllable properties such as strength reaching as high as 7-10 GPa, and electrical conductivity of 104 S/m), our goal in this funded work is to study the market potentials of our CNFs and to evaluate a specific market approach providing tailored fiber offerings to areas such as structural composites and energy storage.

With this goal in mind, our objectives have been to get trained on basics of startup formation through the I-corp program, perform 100+ interviews with experts in the field of energy storage and composites to identify their needs, and to come up with a minimum viable product (CNFs with specific microstructure and properties) that can meet the needs of industry.

RPPR Final Report as of 11-Feb-2020

Accomplishments: We formed a team to study the market potentials of CNFs. Our team consisted of the following people:

- PI: Dr. Mohammad Naraghi, Citizen of the United States of America, Associate professor in Texas A&M University, Aerospace Engineering Department. He has more than 10 years of experience in processing and characterization of nanomaterials, especially graphitic materials, such carbon nanofibers and carbon nanotubes. Naraghi has served as the PI and co-PI of several federally funded projects and National labs, with a total budget of over \$1.5 million, including DOD-AFSOR-YIP, from which the notion proposed here was born. He is the author of ~50 Journal publications. The PI will be teaching one course during his involvement in I-Corps.
- Entrepreneurial Lead (EL): Mr. Yijun Chen, Citizen of China, Ph.D. candidate of Dr. Naraghi, co-advised with Dr. James G Boyd since 2014. Yijun is on a student visa. The student is on I-20, which is valid even after the visa expires. He received an M.S. in Material Science at the University of Illinois Urbana-Champaign in 2014. He has more than four years of research experience in material development. He has passed his Ph.D. thesis proposal exam, and expected to graduate in December 2018. The EL will take at most one course during his involvement in I-Corps.
- Mentor: Dr. John Beckerdite, Entrepreneur-In-Residence in Texas A & M. Prior to assuming this role, he spent 26 years in various technology development and commercialization roles within The Dow Chemical Company. While at Dow, he served as the Senior Intellectual Capital Leader for Dow's Performance Materials division and also led R&D for the both the Amines and Oxygenated Solvents businesses. In a subsequent role John served as the Chief Technology Officer of Exothermix. He is also the founder of P&N Technology Consulting, which provides intellectual property services in the natural sciences.

So far, our team has accomplished the followings:

(before the Interim Progress report, and reported in the Progress Report)

- Our team (all the members) attended the 3 day opening workshop of I-Corp supported by NSF and held in New Jersey (July 16-18 2018).
- We have performed over 90 interviews so far with people in composites manufacturing industry and energy storage industry (mainly batteries and supercapacitors). The majority of the interviews were in person, and took place in various location across the country, including state of Texas (Houston, Austin, and College Station), New York and New Jersey, Ohio (Hudson, Akron, Solon, Avon Lake and Toledo), and Michigan (Detroit). We also interviewed with people a wider geographic via Skype and telephone. Our interviews included people in Oil and gas industry, Aerospace engineering, piping, plastic compounding. We interviewed people in large companies, even CEOs of some companies, as well as people in startup companies.
- We prepared business models for our to-be-founded startup, we re-iterated on the model several times based on the output from interviews.
- We attended the weekly I-corp virtual meetings to get trained on the basics of business model development. (Since the Interim Progress report, and reported herein as a part of the final report)
- Our team (all the members) attended the 2 day closing workshop of I-Corp supported by NSF and held in New Jersey (August 27-28 2018).
- We have performed additional 20 interviews with people in composites manufacturing industry, energy storage industry (mainly batteries and supercapacitors) and influencers such as Senior Editor at CompositesWorld.com.

Training Opportunities: (before the Interim Progress report, and reported in the Progress Report)

Our team members, including Mohammad Naraghi (PI), John Beckerdite (Industry mentor) and Yijun Chen (Entrepreneurial lead) have received training on basics of founding startups by the NSF I-corp team. The training took place as follows:

- 3 day workshop with face to face meetings and presentations, July 16th to 18th of 2018, New Jersey. Topic: Customer development and identifying value proposition,
- Weekly online meetings and training lectures via Webex on Mondays of each week, from Monday July 23rd to August 27th of 2018. Topics: Distribution channels, Get/Keep/Grow customers, Payment flows, Resources and activities.

(Since the Interim Progress report, and reported herein as a part of the final report)

- Our team (all the members) attended the 2 day closing workshop of I-Corp supported by NSF and held in New Jersey (August 27-28 2018).

Results Dissemination: We have filed PCT patent application on the related invention, in which the customer and end use was identified through I-Corp. PCT patent application title: "Architecture-, Geometry-, and Microstructure-Controlled Processing of Carbon Fibers and Nanofibers via Pyrolysis of Multicomponent Hot-Drawn Precursors", It was filed in July 2019. The patent is filed by Texas A&M University, and the IP is owned by them.

RPPR Final Report as of 11-Feb-2020

Honors and Awards: We have filed PCT patent application on the related invention, in which the customer and end use was identified through I-Corp. PCT patent application title: "Architecture-, Geometry-, and Microstructure-Controlled Processing of Carbon Fibers and Nanofibers via Pyrolysis of Multicomponent Hot-Drawn Precursors", It was filed in July 2019. The patent is filed by Texas A&M University, and the IP is owned by them.

Protocol Activity Status:

Technology Transfer: The results of the I-Corp in August 2018 was a No Go decision, simply because we need to do more customer discovery, which we did. After the I-Corp the tem founded Carbon Wire Technology llc, and got an exclusive license from the university to commercialize the related product. Work is ongoing on the private side.

PATENTS:

Intellectual Property Type: Patent

Date Received:

Patent Title: Architecture-, Geometry-, and Microstructure-Controlled Processing of Carbon Fibers and Nanofibers via Pyrolysis of Multicomponent Hot-Drawn Precursors

Patent Abstract: The scope of the invention is carbon fibers and carbon nanofibers (CNF) fabricated via pyrolysis

Patent Number:

Patent Country:

Application Date: 15-Jul-2019

Application Status: 1

Date Issued:

Final Report for the project titled:

“Identifying the Commercialization Path of Novel Carbon Nanofibers for Enhanced Structural Composites and Energy Storage.”, W911NF-18-1-0128

PI: Mohammad Naraghi, Texas A&M University, naraghi@tamu.edu

1 Major Goal:

The market for various types of nanomaterials, such as carbon nanotubes (CNTs) and carbon nanofibers (CNFs), is growing at a staggering rate; the market for CNTs alone is estimated to be \$670 million in 2019. This is due to a combination of remarkable properties of these nanomaterials, such as exceptional strength, which brings hope for new composites with superior performance metrics. However, major limitations exist in commercialization of nanomaterials, such as extremely prohibitive costs (e.g., the cost of CNTs can be 10-100x that of carbon fibers), extremely limited capabilities to generate continuous strands of nanofibers and nanotubes (as required to weave them into fabrics for more elaborate design of composites), and poor controllability over their microstructure (inherent in CVD production methods). We believe we have developed a form of CNFs which can overcome the above limitations by introducing continuous bundles of CNFs with significant control over the microstructure and geometry, all facilitated via proprietary and scalable processing methods. By controlling the processing parameters, we have managed to develop CNFs with a variety of forms: highly graphitic, wavy, hollow and porous. We believe that this technology has the potential to compete in two somewhat distinct product segments: carbon fiber/carbon nanofiber and carbon nanotube. Though fibers and tubes have somewhat different property sets, they can compete in the same markets. With the premise of reduced production cost and a unique set of properties (high aspect ratio, continuous strands, controllable properties such as strength reaching as high as 7-10 GPa, and electrical conductivity of 10^4 S/m), our goal in this funded work is to study the market potentials of our CNFs and to evaluate a specific market approach providing tailored fiber offerings to areas such as structural composites and energy storage.

With this goal in mind, our objectives have been to get trained on basics of startup formation through the I-corp program, perform 100+ interviews with experts in the field of energy storage and composites to identify their needs, and to come up with a minimum viable product (CNFs with specific microstructure and properties) that can meet the needs of industry.

2 Accomplished:

We formed a team to study the market potentials of CNFs. Our team consisted of the following people:

- **PI: Dr. Mohammad Naraghi**, Citizen of the United States of America, Associate professor in Texas A&M University, Aerospace Engineering Department. He has more than 10 years of experience in processing and characterization of nanomaterials, especially graphitic materials, such carbon nanofibers and carbon nanotubes. Naraghi has served as the PI and co-PI of several federally funded projects and National labs, with a total budget of over \$1.5 million, including DOD-AFSOR-

YIP, from which the notion proposed here was born. He is the author of ~50 Journal publications. The PI will be teaching one course during his involvement in I-Corps.

- **Entrepreneurial Lead (EL):** Mr. Yijun Chen, Citizen of China, Ph.D. candidate of Dr. Naraghi, co-advised with Dr. James G Boyd since 2014. Yijun is on a student visa. The student is on I-20, which is valid even after the visa expires. He received an M.S. in Material Science at the University of Illinois Urbana-Champaign in 2014. He has more than four years of research experience in material development. He has passed his Ph.D. thesis proposal exam, and expected to graduate in December 2018. The EL will take at most one course during his involvement in I-Corps.
- **Mentor:** Dr. John Beckerdite, Entrepreneur-In-Residence in Texas A & M. Prior to assuming this role, he spent 26 years in various technology development and commercialization roles within The Dow Chemical Company. While at Dow, he served as the Senior Intellectual Capital Leader for Dow's Performance Materials division and also led R&D for the both the Amines and Oxygenated Solvents businesses. In a subsequent role John served as the Chief Technology Officer of Exothermix. He is also the founder of P&N Technology Consulting, which provides intellectual property services in the natural sciences.

So far, our team has accomplished the followings:

(before the Interim Progress report, and reported in the Progress Report)

- Our team (all the members) attended the 3 day opening workshop of I-Corp supported by NSF and held in New Jersey (July 16-18 2018).
- We have performed over 90 interviews so far with people in composites manufacturing industry and energy storage industry (mainly batteries and supercapacitors). The majority of the interviews were in person, and took place in various location across the country, including state of Texas (Houston, Austin, and College Station), New York and New Jersey, Ohio (Hudson, Akron, Solon, Avon Lake and Toledo), and Michigan (Detroit). We also interviewed with people a wider geographic via Skype and telephone. Our interviews included people in Oil and gas industry, Aerospace engineering, piping, plastic compounding. We interviewed people in large companies, even CEOs of some companies, as well as people in startup companies.
- We prepared business models for our to-be-founded startup, we re-iterated on the model several times based on the output from interviews.
- We attended the weekly I-corp virtual meetings to get trained on the basics of business model development.

(Since the Interim Progress report, and reported herein as a part of the final report)

- Our team (all the members) attended the 2 day closing workshop of I-Corp supported by NSF and held in New Jersey (August 27-28 2018).
- We have performed additional 20 interviews with people in composites manufacturing industry, energy storage industry (mainly batteries and supercapacitors) and influencers such as Senior Editor at CompositesWorld.com.

3 Training:

(before the Interim Progress report, and reported in the Progress Report)

Our team members, including Mohammad Naraghi (PI), John Beckerdite (Industry mentor) and Yijun Chen (Entrepreneurial lead) have received training on basics of founding startups by the NSF I-corp team. The training took place as follows:

- 3 day workshop with face to face meetings and presentations, July 16th to 18th of 2018, New Jersey. Topic: Customer development and identifying value proposition,
- Weekly online meetings and training lectures via Webex on Mondays of each week, from Monday July 23rd to August 27th of 2018. Topics: Distribution channels, Get/Keep/Grow customers, Payment flows, Resources and activities.

(Since the Interim Progress report, and reported herein as a part of the final report)

- Our team (all the members) attended the 2 day closing workshop of I-Corp supported by NSF and held in New Jersey (August 27-28 2018).

4 Dissemination:

We have filed PCT patent application on the related invention, in which the customer and end use was identified through I-Corp. PCT patent application title: "Architecture-, Geometry-, and Microstructure-Controlled Processing of Carbon Fibers and Nanofibers via Pyrolysis of Multicomponent Hot-Drawn Precursors", It was filed in July 2019. The patent is filed by Texas A&M University, and the IP is owned by them.

5 Invention Disclosure title:

We have filed PCT patent application on the related invention, in which the customer and end use was identified through I-Corp. PCT patent application title: "Architecture-, Geometry-, and Microstructure-Controlled Processing of Carbon Fibers and Nanofibers via Pyrolysis of Multicomponent Hot-Drawn Precursors", It was filed in July 2019. The patent is filed by Texas A&M University, and the IP is owned by them.

6 Tech Transfer:

The results of the I-Corp in August 2018 was a No Go decision, simply because we need to do more customer discovery, which we did. After the I-Corp the tem founded Carbon Wire Technology llc, and got an exclusive license from the university to commercialize the related product. Work is ongoing on the private side.

7 Protocol:

Nothing to report.

8 Participations:

- **PI: Dr. Mohammad Naraghi**, Associate professor in Texas A&M University.
- **Entrepreneurial Lead (EL):** Mr. Yijun Chen, Citizen of China, Ph.D. candidate of Dr. Naraghi.
- **Mentor:** Dr. John Beckerdite, Entrepreneur-In-Residence in Texas A & M.