The New Steel?

Enabling the Carbon Nanomaterials Revolution: Markets, Metrology, Safety, and Scale-up

http://www.nist.gov/cnst/thenewsteel.cfm

Workshop Report

CNST Center for Nanoscale Science & Technology

NIST National Institute of Standards and Technology
U.S. Department of Commerce

The New Steel?

Enabling the Carbon Nanomaterials Revolution: Markets, Metrology, Safety, and Scale-up

http://www.nist.gov/cnst/thenewsteel.cfm

Workshop Report

Principal Editor

J. Alexander Liddle

Sponsored by

The Center for Nanoscale Science & Technology,

National Institute of Standards and Technology

Acknowledgments

We are grateful to the speakers for their stimulating presentations, the attendees for their interested and lively participation and the breakout session facilitators and note takers who helped capture the meeting output so effectively.

Steering Committee

Prof. Wade Adams, Director, Smalley Institute for Nanoscale Science & Technology, Rice University

Dr. William Carter, Manager, Bio and Nanomaterials Technologies, HRL

Dr. Robert Doering, Senior Fellow and Research Manager, Texas Instruments

Prof. John Hart, Assistant Professor of Mechanical Engineering, Applied Physics, Art + Design, University of Michigan

Dr. J. Alexander Liddle, Group Leader, Nanofabrication Research, Center for Nanoscale Science & Technology, NIST

Ms. Sha-Chelle Manning, Founding Partner at Manti Technologies

Dr. Brent Segal, Director & Chief Technologist, Lockheed Martin Nanosystems

Dr. John Ullo, Consultant

Executive Summary

This document is a distillation of the presentations and discussions that comprised the "New Steel Workshop," held at the National Institute of Standards and Technology (NIST) on February 28 and March 1, 2011. The goal of the workshop was to identify the key barriers to the introduction of carbon-based nanomaterials, with an emphasis on the measurement capabilities necessary to enable and even accelerate progress during development and toward their ultimate application. While the participants represented a diverse set of carbon nanomaterial producers, consumers and end-users, a number of common themes emerged.

Raw material manufacturing processes are still in need of improvements in consistency, reliability and control. For carbon nanotubes (CNTs), such improvements will, in part, be achieved by developing a better understanding of the growth process. The successful integration of carbon nanomaterials to form composites with the desired properties depends on establishing the relationship between the properties of individual nanostructures and their aggregate behavior. New characterization and modeling approaches will be required. These approaches need to be accompanied by an increased system-level understanding of how to design with and manufacture these new materials. At every level, new metrology methods are needed to enable manufacturing scale-up to high volumes.

An area of particular concern is the level of uncertainty surrounding issues associated with the environment, health and safety (EHS). Progress in this area is hampered by a lack of basic characterization tools and toxicological studies as well as inadequate understanding of the potential for carbon nanomaterial release at all stages of production, integration, use and disposal. These deficiencies make it difficult for clear, science-based regulations to be produced in a timely fashion.

Table of Contents

Background

Adding nanostructured forms of carbon, such as carbon nanotubes (CNTs), graphene, or any of an array of nanoparticles, to many host materials can dramatically enhance the resulting composites' mechanical, thermal and electronic properties.[1,2,3,4] An indication of the potential for these materials can be gained by noting that single-walled nanotubes exhibit Young's modulus of approximately 1TPa, 50 times that of steel, tensile strengths in the range of 50 GPa[5] to 100 GPa[6] and specific strengths up to 300 times that of high-carbon steel, and thermal conductivities 10 times greater that of copper. In addition, these properties can, to some extent, be adjusted independently, enabling a wide range of new applications in the resulting multi-functional materials. While this potential has been recognized for some time, commercial development of carbon nanomaterial composites has been slow. Among the reasons for this delay, the most significant are: 1) technical challenges to achieving cost-effective, high-volume manufacture of raw nanomaterials of consistently uniform quality; 2) difficulties in integrating carbon nanomaterials effectively into composites; and 3) uncertainty over potential environmental, health and safety (EH&S) effects and the associated regulatory issues. These challenges also apply to emerging materials based on highly organized assemblies of nanostructured materials, such as CNT yarns and sheets.

To identify specific barriers to broader deployment of this class of high-performance materials, a two-day workshop was held at the National Institute of Standards and Technology (NIST) under the auspices of the National Nanotechnology Initiative (NNI) Signature Initiative on Sustainable Nanomanufacturing.[7] The workshop brought together experts from industry, academia and government, representing the full spectrum of activities from raw material production to composite end use. Keynote talks (listed in Appendix A) served to seed discussions during a series of breakout sessions.

The talks and discussions were focused on the use of carbon-based nanomaterials produced in large volumes for high-performance composites for engineering applications. Although an important area of research and development, the application of carbon nanomaterials in electronics was not part of the scope of this workshop. We also note that, although the efforts

---

[1] "Graphene-based composite materials", Stankovich et al., *Nature* **442** 282 (2006)

[2] "Enhanced Mechanical Properties of Nanocomposites at Low Graphene Content", Rafiee et al., *ACS Nano*, **3** 3884 (2009)

[3] "Interlaminar and intralaminar reinforcement of composite laminates with aligned carbon nanotubes", Wicks et al., *Composites Science and Technology*, **70** 20 (2010)

[4] "Joining prepreg composite interfaces with aligned carbon nanotubes", Garcia et al., *Composites: Part A*, **39** 1065 (2008)

[5] "Strength and Breaking Mechanism of Multiwalled Carbon Nanotubes Under Tensile Load", Yu et al., *Science* **287** 637 (2000)

[6] "Measurements of near-ultimate strength for multiwalled carbon nanotubes and irradiation-induced crosslinking improvements", Peng et al., *Nature Nanotechnology*, **3** 626 (2008)

[7] http://www.nano.gov/sites/default/files/pub_resource/nni_siginit_sustainable_mfr_revised_nov_2011.pdf

involving CNT-based materials are more mature and therefore constituted a large fraction of the discussion, both the capacity for volume production and the understanding of the use and applications of other forms of nanoscale carbon such as graphene are increasing rapidly. For this reason the conclusions of this report should be regarded as broadly applicable to all types of carbon nanostructures.

Participants were asked, first, to identify broad technology challenges (what would we like to do?) and barriers (why can't we do it?) before determining the specific measurement needs (what is required to overcome the barrier?) associated with the barriers. A focused discussion on EH&S was held to assess the gaps in our current knowledge and identify means of addressing them. The output from the discussions will help to inform the future directions of the Signature Initiative activities.

The full workshop program, including the presentations, can be found at:
http://www.nist.gov/cnst/thenewsteel.cfm

Broad Technology Challenges and Barriers

Scalable production of CNTs with control over length, diameter, and chirality/conductivity was identified as an area of opportunity in the NNI report *Manufacturing at the Nanoscale* (2007).[8] Although a great deal of progress has been made in recent years, a workshop participants concurred s that much still remains to be done in this area. Lack of consistent control over the structure and morphology of individual nanotubes also remains as an impediment. Nor have we achieved adequate control over the types of defects present and their density. In general the word "defect" implies something undesirable, in which case the aim is to minimize their number. However, we note that defects in carbon nanostructures may also serve as sites for functionalization which may, for example, be essential in creating the right degree of bonding between the nanostructure and a composite matrix.

In composite materials, however, it is not just the properties of individual nanotubes that are important. The alignment and dispersion of the CNTs within the matrix, as well as the nature of the interactions between the nanotubes, have a dramatic effect on the material properties. It is therefore necessary to understand how the interaction of CNTs in bundles and aggregates affects the mechanical, electrical and rheological properties of composites, to develop predictive models that connect structure and morphology with those properties and to engineer raw material synthesis methods and composite processing routes that lead to optimized materials and components.

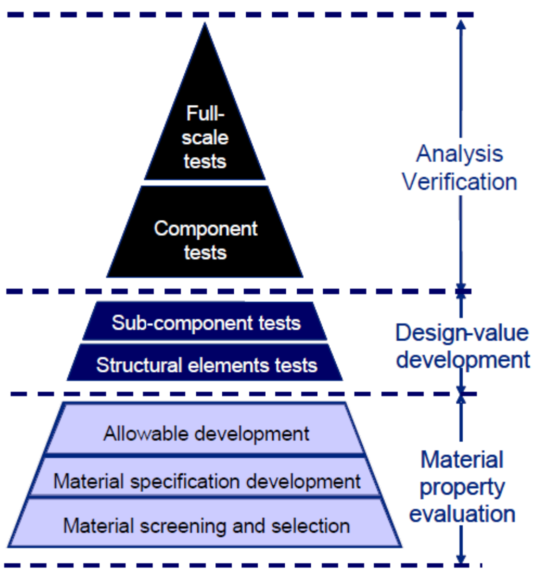
It should be noted that, although much of the discussion centered on CNT-based materials, this is due primarily to the relative maturity of this particular form of nanoscale carbon. It was clear from a number of the presentations that other forms of nanostructured carbon, such as graphene flakes, also have a number of distinct and useful properties and that there has been rapid progress toward exploiting these properties. This trend is expected to continue as methods for the large-scale production of graphene are developed.

In all manufacturing enterprises, cost is a key consideration. Total manufacturing cost is determined largely by the cost of the raw materials and by the cost of the down-stream processing. Naturally, both of these cost elements are influenced by process variability and reproducibility. In addition, the cost of modifying a manufacturing scheme to accommodate a new material can be a significant barrier to the introduction of new technology. It is essential, therefore, to understand and minimize "switching" costs. This issue can be mitigated by the introduction of suitable standards for quality control and for consistent sharing of information between raw-material producer, composite manufacturer and end user.

[8] "*Manufacturing at the Nanoscale*", Report of the National Nanotechnology Initiative Workshops, 2002 – 2004, published in 2007.

One of the principal barriers to the introduction of a new material is the need to develop a detailed understanding of its lifecycle. This issue includes not only how the material performs and ages during its service lifetime, but also whether there are any special end-of-life considerations in terms of disposal, and to what extent these are the responsibility of the manufacturer. For carbon-based nanomaterials, these concerns are amplified by the potential environmental and health effects that might accompany the release of nanostructures from the material.

Figure 1 presents examples of timelines for modifying existing materials and introducing new materials in the aerospace industry. Given current capabilities and knowledge, the introduction of nanocomposite materials for aerospace applications might require one or two decades of development time. There is, thus a pressing need for accelerated ageing studies to help answer questions and concerns surrounding the introduction of novel nanocomposite materials.



Development Phase	Development Time
▪ Modification of an existing material for a non-critical component	▪ **2-3 years**
▪ Modification of an existing material for a critical structural component	▪ **Up to 4 years**
▪ New material within a system for which there is experience	▪ **Up to 10 years** – includes time to define the material's composition and processing parameters
▪ New material class	▪ **Up to 20 years or more** – includes time required to develop design practices that fully exploit the performance of the material and establish a viable industrial base

SOURCE: R. Schafrik, GE Aircraft Engines, Technology Transition in Aerospace Industry, briefing presented at the Worksop on Accelerating Technology Transition, National Research Council, Washington DC, November 24, 2003

Figure 1. Timeline for the modification or introduction of a new material into the aerospace industry (taken from the presentation by David Furdek, Boeing).

A related issue, and one that depends heavily on the availability of high-quality data, is the public perception of carbon-based nanomaterials. It is important not only to obtain a thorough science-based understanding of the benefits and risks associated with carbon-based nanomaterials, but also, through effective communication, to ensure that public perception is aligned with that understanding. Figure 2, is an attempt to illustrate the issue. If perception aligns with reality then intelligent decisions can be made so, as shown, not only are seatbelts "appropriate" and smoking "inappropriate" in actuality in terms of their effects on health, but they are also perceived in such a way. Conversely, if reality and perception do not align correctly, then poor decisions are made.

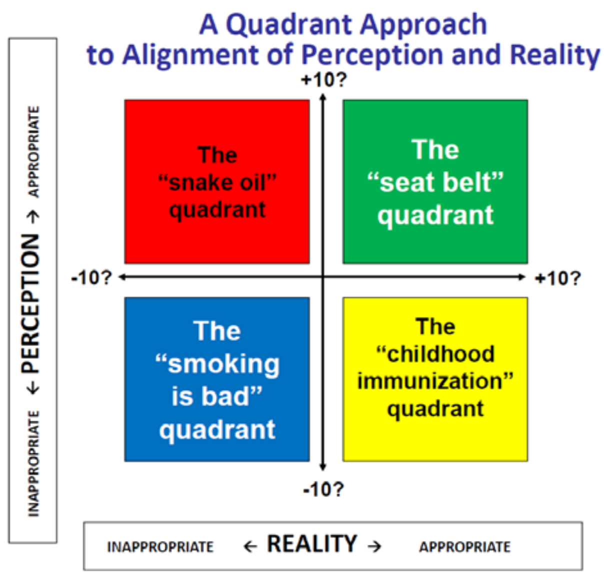


Figure 2. Alignment of perception and reality and the effects on the quality of decisions (taken from the presentation by Mark Hoover, NIOSH).

Summary of Technology Barriers

- Lack of repeatable, reliable manufacturing processes
- Incompatibility with existing manufacturing infrastructure
- Inadequate control of synthesis, including chirality and defect density
- Inadequate control of dispersion, alignment and rheological properties
- High cost of raw materials and manufacturing/manufacturing insertion
- Lack of proven methods for environmentally acceptable recycling/disposal

Summary of Technology Needs

- Understanding growth mechanisms of specific chiralities of CNTs
- Understanding interactions in nanotube bundles/aggregates
- Fabrication of ultra-long (ideally infinite) CNTs and their direct incorporation into yarns and sheets
- Reproducible translation of individual (sampled) CNT properties into behavior of large-scale 2D and 3D products
- Incorporation of design/theory to materials development
- Standards for quality control/repeatability/*in situ* monitoring

- Lifecycle performance data

Technology Measurement Issues and Grand Challenges

Many of the issues highlighted in the previous section can only be resolved if suitable metrologies are available. This workshop underscored the universal need for measurement capabilities and systems tailored to nanotechnology, ranging from the nanoscale to the macroscale. Measurement needs were emphasized in the World Technology Evaluation Center (WTEC) report, *Nanotechnology Research Directions for Societal Needs in 2020: Retrospective and Outlook*, as conveyed in the following excerpt:

> "*The next decade will see many of the early nanoscale science discoveries transition to manufacturing. The need for process metrology, quality control measurements, and associated standards is acute. These unmet requirements apply not only to manufacturing but also to the analysis of workplace safety, environmental impact, and life cycle calculations. … in the case of nanoparticles, nanotubes, etc., reliable fabrication and measurement technologies do not exist for all size regimes.*"[9]

A benefit of CNTs is that their structural diversity enables them to display a similarly diverse set of properties. The corollary to this diversity is that to control the properties it is essential to measure the key characteristics of the nanotubes, including length, diameter, number of walls, chirality, defects, and so on; determine their statistical distributions; and, then, relate all of these measurement results to the conditions under which the CNTs are grown. This latter point may ultimately require the comprehensive use of *in situ* measurement methods, such as environmental transmission electron microscopy (ETEM).

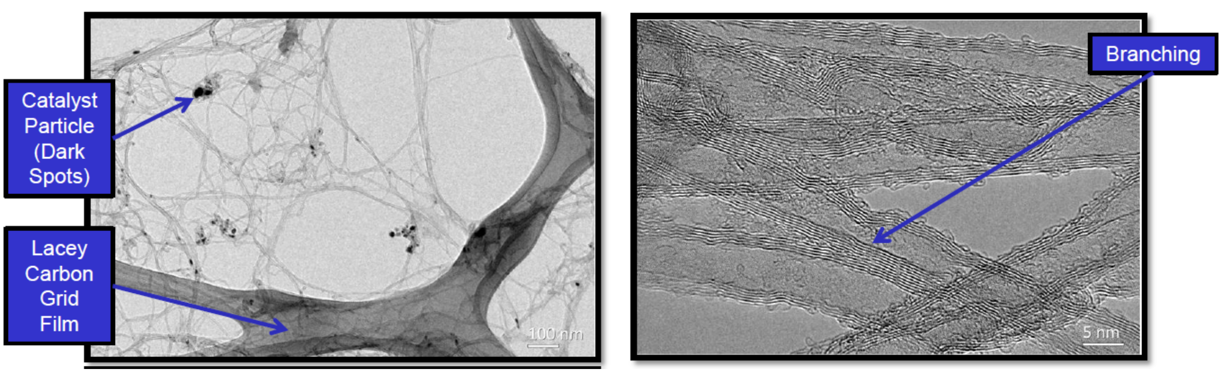


Figure 3. Transmission electron microscope images of CNT networks (from presentation by Tushar Shah, Applied Nanostructured Solutions).

Carbon nanotubes are often not produced as discrete, individual tubes, but, as shown in Figure 3, the figures above show, their morphology can take the form of a dense network. The properties

---

[9] *Nanotechnology Research Directions for Societal Needs in 2020 : Retrospective and Outlook*, WTEC Panel Report (2010)

of the composite depend on the types of CNTs, their interaction with one another and the nature of their surface chemistry and its interaction with the composite matrix.

Method	Dry/Solvent Dispersed			Composite		
	Plates	Spheres	Rods	Plates	Spheres	Rods
Surface Area (BET)		Green				
Static Light Scattering (SLS)		Green		Yellow	Green	Yellow
Dynamic light scattering (DLS)		Green				
Scanning Electron Microscopy (SEM)	Yellow	Green	Yellow			
Transmission Electron Microscopy (TEM)	Yellow	Green	Yellow	Yellow	Green	Yellow
Scanning Probe Microscopy (SPM)	Yellow	Green	Yellow			
Small Angle X-ray Scattering (SAXS)	Yellow	Green	Yellow	Yellow	Green	Yellow

Figure 4. Capabilities of various characterization techniques for measuring nanoparticle size when applied to spheres, plates and rods in suspension and in composite (from presentation by Lee Silverman, DuPont). Green indicates that the technique is capable of yielding an accurate measurement, yellow that a measurement can be made but interpretation is difficult and the absence of a circle that the technique is not applicable.

Currently, although techniques exist to determine the characteristics of individual nanotubes, such as transmission electron microscopy (TEM) or micro-Raman spectroscopy, the measurements are painstaking and/or not suited for measuring statistical distributions. TEM can give good information on statistical distributions, but it is slow. In contrast, Raman spectroscopy is qualitative (though it can measure SWNT diameters via radial breathing mode analysis), but its throughput is much higher.

The techniques that do exist for characterizing the statistical distribution of properties as basic as particle size are of limited use for any shape other than spherical and cannot, in general, be applied to nanostructures in composites (Figure 4).

The description and measurement of more complex nanotube morphologies and their relationship to composite properties are a critical need. Small-angle X-ray scattering has shown promise in this regard, but requires a synchrotron source for rapid measurements.

The types of measurements required for manufacturing need not provide the same level of detail required during process development or initial material characterization. However, they must operate at low cost and high speed to support high-volume production. Depending on the stability of the process and the critical parameters that need to be tracked, metrology may be in-line or *in situ*. Although a number of methods are currently used in manufacturing composites, for example, the majority is empirical and no standards exist.

Finally, as discussed earlier, it is essential to understand the performance of carbon nanostructure-based composites over their service lifetime. Measurements are needed not only to follow evolving material properties, but also to look for the possible release of nanostructures into the environment. The development of validated accelerated testing methods will be critical to the production of data in a timely fashion.

Summary of Measurement Barriers

- Insufficient understanding of the relationship of morphology and individual nanotube properties to composite material performance
- Lack of low-cost, high-throughput measurements for manufacturing

Summary of Measurement Needs

- Standardized methods for the complete characterization of individual nanotube properties and their statistical distributions (diameter, length, number of walls, chirality, presence/absence of end-caps, etc.)
- Standardized measurements of impurity content (species, quantity, morphology)
- Descriptors for and characterization of CNT networks
- Standardized accelerated ageing tests for lifetime assessment (properties and release of nanomaterials as a function of time)
- Standards and specifications for test methods and measurement data for composite properties
- Methods for measuring CNT/matrix interface properties
- Novel, non-contact measurement methods that can report on composite nanostructure

Environment, Health and Safety (EH&S) Concerns

One of the major challenges standing in the way of the introduction of any new nanomaterials is the level of uncertainty that surrounds EH&S, both with regard to the possible level of exposure and the associated level of the potential hazard. The current literature on CNT-related health risks is best described as confusing, with substantial discrepancies between biomedical studies and toxicological studies.[10,11,12] In addition, the biological effects of nanotubes are very strongly

---

[10] "Toxicology of carbon nanomaterials: Status, trends, and perspectives on the special issue", Hurt et al., *Carbon*, **44** 1028 (2006)

influenced by their surface functionalization. Thus, despite considerable, well-designed efforts, there is still a critical shortage of data.

One of the key points to emerge from the workshop presentations and associated discussions is that understanding and management of the risks are fundamentally data driven. Without sufficient, validated data, regulatory bodies, such as the Environmental Protection Agency (EPA), cannot craft appropriate regulations. This dependency means that the types of measurements discussed in the previous section are essential not only for manufacturing process development and control, but can, if appropriately designed, provide valuable input for the analysis of EH&S issues. For example, monitoring the composition of reactant gases in a nanotube growth reactor can provide both process control and effluent data. Figure 5 shows a generalized approach to risk management for new nanomaterials.

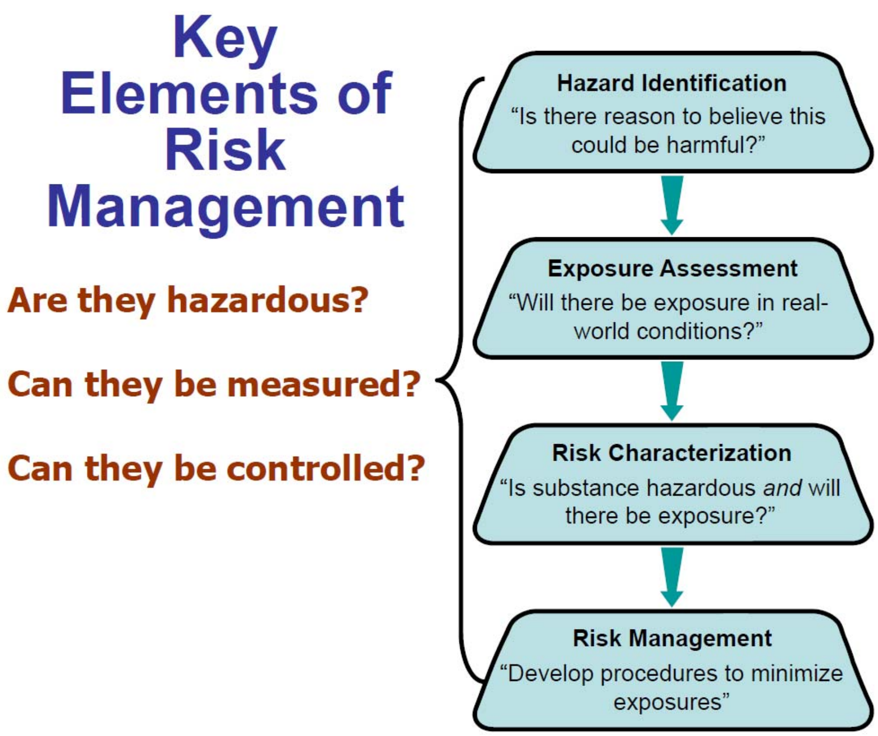


Figure 5. Generalized approach to risk management for new nanomaterials (taken from the presentation by Mark Hoover, NIOSH).

[11] "Carbon nanotubes introduced into the abdominal cavity of mice show asbestos-like pathogenicity in a pilot study", Poland et al. *Nature Nanotechnology*, **3** 423 (2008)
[12] "Nanotube Molecular Transporters: Internalization of Carbon Nanotube–Protein Conjugates into Mammalian Cells", Kam et al., *JACS*, **126** 6850 (2004)

Additional measurements that are specific to assessing the probability of exposure to nanostructured carbon during manufacture, use and disposal and the consequences of such an exposure also are needed.

Summary of EH&S-Related Barriers

- Multiplicity of carbon nanostructures prevents comprehensive understanding of hazards and risks associated with the use of carbon nanomaterials

Summary of EH&S-Related Needs

- Comprehensive, standard nomenclature for the various types of nanostructured carbon
- Methods to measure surface functionality
- Robust methods of detecting and measuring nanostructured carbon in the environment, including in water
- Measurements of nanomaterial release during the manufacturing process, service life and disposal/recycling
- Methods to measure persistence of carbon nanomaterials in the environment
- Measurement of stability of agglomerates
- Standardized methods for assessing toxicity/bio-compatibility, directed towards specific material applications
- Measurement of carbon nanomaterial dispersion characteristics inside organisms

Concluding Remarks

The safe, successful integration of carbon nanomaterials to form composites with the desired properties depends on establishing the relationship between the properties of individual nanostructures and their aggregate behavior. New characterization and modeling approaches will be required. These need to be accompanied by an increased system-level understanding of how to design with and manufacture these new materials. At every level, new metrology methods are needed to enable manufacturing scale-up to high volumes.

Presentation Abstracts

Most talk titles are hyperlinked to the presentations. Please Ctrl-click to follow the links.

Perspective of a Start-up that has moved thru Scale-up into Commercialization – *David Arthur, CEO, SouthWest NanoTechnologies, Inc.*

SouthWest NanoTechnologies (SWeNT) is a leading manufacturer of single-wall carbon nanotube materials. The Company was founded in 2001 as a spinout of Professor Daniel Resasco's research at the University of Oklahoma. In 2008, SWeNT built a large-scale manufacturing plant capable of producing commercial quantities of single-wall carbon nanotubes with consistent quality, at low cost. In 2011, SWeNT is focused on commercializing carbon nanotube ink products for printed electronics and also nanocomposite paste products for battery materials. In my talk, I will provide a historical perspective on SWeNT's evolution from laboratory to production scale, as well as discuss the commercialization challenges that we are facing and how we are addressing them.

Aerospace Structural Materials Certification – *David Furdek, Manager—Next Generation Composite Materials, Boeing Research and Technology*

Manufacturing Process for Carbon Nanostructure Infused Fibers to Fabricate Multifunctional Composites – *Tushar Shah, Chief Technology Officer, Applied Nanostructured Solutions (ANS) LLC*

ANS has matured a revolutionary, continuous, in-line process to grow (infuse) carbon nanostructures (CNSs) directly on mulitiple fiber surfaces, such as glass, carbon, and ceramic. This manufacturing process was developed specifically to create multi-functional composites that provide not only enhanced mechanical performance but also thermal and electrical properties heretofore not possible with the current fiber/polymer composites. The ANS process provides the capability to manufacture fibers with CNS-infusion as high as a mass fraction of 40%.

ANS Lab's continuous, in-line process is evolving from pilot production into the mainstream composites market for high-volume manufacture at low cost. Currently, the CNS-infusion process is at TRL-6 and MRL-5; ANS pilot production lines are producing > 50 kg per week of carbon nanotube (CNT) fibers and fabrics.Since the CNSs are infused on the fiber/fabric surface, as opposed to a CNT powder added to the resin, a much greater percentage of CNS loading is possible in the final composite. The resulting composites posess not only improved mechanical properties but also enhanced physical properties, which, in turn, provide a foundation to custom design fiber-based composites for specific mechanical and physical properties tailored to the end-use or application. This presentation will describe the CNS-infusion process at ANS and discuss the growing need to develop next-generation analytical tools necessary for in line monitoring of CNS infusion processes.

CNT Composites for High Performance Structural Applications: Development, Measurement and Scale-up – *Larry Carlson, Director of Advanced Materials at the Easton Institute for Technology Advancement, UCLA*

Increasing mechanical demands of sporting goods and aerospace markets can be met by the inclusion of carbon nanotubes (CNTs) as a resin enhancement, as a fiber enhancement, and as the fibers themselves. While the potential for strength and toughness gain is huge, technical problems can reduce or even reverse the rewards.

Attention must be given not only to cost, but also to dispersing methods, stability, quality of CNTs and the resulting composite, and measurement methods and their relevance to the finished product. Here, we discuss one case history of an effective supplier value chain, from CNT production to end use. Scale-up issues are discussed, with process continuity from the US-based development lab to a foreign plant.

Multifunctional Carbon Nanomaterials – *Nolan Nicholas, Mid-Atlantic Technology, Research & Innovation Center (MATRIC)*

Though the potential for nanostructured materials to enhance individual properties is by now well appreciated, less recognized is their potential to improve a desired combination of properties to achieve "multifunctional" performance in the resultant material. This key benefit enabled by emerging nano-based materials can produce sets of capabilities that traditionally have required a system of multiple combined materials to achieve. This can lead to significant savings in weight, volume and cost for nano-enabled systems. This talk will introduce concepts of multifunctional carbon nanomaterials, including challenges in manufacturing and technological integration.

Carbon Nanostructures for Energy Storage – *Bingqing (B.Q.) Wei, Department of Mechanical Engineering, University of Delaware*

Electricity storage is a growing challenge among a broad range of renewable energy sources. Of the many types of rechargeable power sources that are currently being investigated, carbon nanotube-based supercapacitors have attracted much attention due to their capability to generate energy and power densities much higher than conventional dielectric capacitors and lithium-ion batteries, respectively. In the meantime, flexible/stretchable electronics have attracted considerable attention in recent years and have opened the door to many important applications that current, rigid electronics cannot achieve. In order to accommodate these needs, power source devices must be flexible and stretchable in addition to their high energy and power density, light weight, miniaturization in size, and safety requirements.

I will report our research efforts in assembling two-dimensional carbon nanotube macrofilms using a carbon vapor deposition method, and the applications of these films in supercapacitors and Li-ion batteries. I will also discuss our understandings of compressive stress and temperature effects on electrochemical behavior of supercapacitors.

Partnering for Success in the Semiconductor Industry *– George Scalise, President Emeritus of the Semiconductor Industry Association*

Where does the semiconductor industry stand today?

How did we get here?

What do we need to do to lead the NANO Era in the years ahead as we have the Semiconductor Era for the past sixty years?

What are the challenges that must be addressed to accomplish that objective?

How has the semiconductor industry been able to establish consortia (e.g., SRC and SEMATECH) and a technology roadmap (the ITRS)?

How was the SIA able to coordinate these initiatives? – i.e., "what were the obstacles, what were the key ingredients for success, how was consensus built, and how have the companies benefitted?"

Carbon Nanotube Metrology for Science and Manufacturing *– John Hart, Assistant Professor, University of Michigan*

Reliable and repeatable metrology is essential to continued advances in both the science and manufacturing of carbon nanotubes (CNTs) and CNT-based materials. I will review methods for characterizing CNTs and related production parameters, from both an academic and commercial perspective. Emphasis will be placed on capabilities and limits of these techniques for probing the fundamental mechanisms of CNT growth, and for enabling online characterization of CNT product quality at high speed and low cost.

The New Steel? Enabling the Carbon Nanomaterials Revolution: Markets, Metrology, Safety, and Scale-up *– Michael Valenti, Emerging Technologies Research Analyst, Technical Insights, Frost and Sullivan*

This presentation will focus on the markets for nanotechnology in advanced materials, electronics, and authentication. Each of these opportunities is subdivided into market segments that themselves offer promising applications for nanotechnology. This research was conducted by analysts for Frost & Sullivan, a 50-year-old advanced technology market research firm that specializes in tracking emerging technologies, such as nanotechnology, from laboratory through commercialization.

2011 NNI Environment, Health and Safety Research Strategy – *Treye Thomas, Co-chair, Nanotechnology Environment and Health Implications Working Group, Nanoscale Science, Engineering and Technology Subcommittee*

Nanoparticle Characterization Needs— From Composite Properties to Product Stewardship – *Lee Silverman, DuPont Nanocomposite Technologies, Central Research and Development*

Characterization of nanoparticle size, size distribution and shape has product stewardship implications, and affects the property entitlement of polymer nanocomposite materials. This presentation discusses why non-spherical particles are interesting from a polymer nanocomposite property perspective, and why additional characterization methods are needed to fully characterize and describe nanoparticle characteristics in order to better address safety, health and environmental issues.

Which material properties and features determine the biological response to carbon nanotubes? – *Robert Hurt, Director of Brown University's Institute for Molecular and Nanoscale Innovation*

The carbon nanotube (CNT) industry has been given a window of opportunity to develop methods for managing environmental and health concerns before CNT-based products become truly widespread in the marketplace. One of those methods is, in principle, the design of nanotubes for safety, but this requires solid mechanistic links between the fundamental material properties we can control and the adverse biological responses we wish to avoid. This talk describes recent efforts, rooted in materials science, to identify and control the fundamental CNT properties that trigger biological responses, considering hydrophobic surface area, surface chemistry, bioavailable metals content, and geometry.

EPA Approach to Regulating Carbon Nanomaterials – *Zofia Kosim, Office of Pollution Prevention and Toxics, U.S. Environmental Protection Agency*

The paper presents information-related challenges the EPA encounters while regulating carbon nanomaterials. Included is discussion of typical data gaps, parameters the Agency needs, and the recommended measurement methods for these parameters.

Some Key Elements for Nanomaterial Exposure Assessment and Management to Advance Sustainable Manufacturing – *Mark Hoover, National*

Institute for Occupational Safety and Health **Advanced Energy Consortium** *– John Ullo, Consultant*

The Advanced Energy Consortium (AEC), which is based at the Bureau of Economic Geology, the oldest research unit at the University of Texas at Austin, is currently supporting a multi-year portfolio of projects at universities around the world. The consortium membership, comprised of seven major oil companies and three oilfield service companies, fund and direct the effort of nearly 200 researchers working on pre-competitive, high-risk research projects aligned with the development of novel micro- and nanoscale sensors that can be used to advance the exploration and production of oil and gas. Global energy demand supports high industry interest in exploring novel technologies that promise to improve the surprisingly low recovery rates from existing oil fields (typically 25 % to 40%). The mission, processes, research challenges and some emerging research results will be discussed.

About the Speakers

David Arthur - David J. Arthur has 30 years experience commercializing products utilizing advanced materials, including work at Rogers Corporation, A.T. Cross, TPI Composites, Helix Technologies, and Eikos. He holds a Bachelor of Science degree in chemical engineering from Tufts University, Master of Science degree in chemical engineering from the University of Connecticut and a master of business administration degree from Northeastern University. In 2005, Arthur co-founded Chasm Technologies, a consulting firm that helps its clients commercialize new products through smart application of materials science and process technology. For the past four years, he has been CEO of SouthWest NanoTechnologies (SWeNT), a leading producer of specialty carbon nanotube materials for coatings and composites applications.

David Furdek – Dave Furdek manages the Next Generation Composite Materials and Labs group for Boeing Research and Technology (BR&T). Dave's group spans three sites including Seattle, St. Louis, and Huntington Beach, has over 60,000 sq ft of lab space, and is responsible for developing future generations of composite materials for the Boeing Defense Systems and Boeing Commercial Aircraft business units. Dave has over 22 yrs experience with the Boeing Company in a variety of Materials and Processes and Manufacturing Research and Development assignments. Recently, Dave led the Materials Technology team in St. Louis where he established the Emerging Materials portfolio. In a previous assignment as the Phantom Works (now BR&T) Enabling Technology program manager, he was responsible for the long range technology development plans for over 15 core technology focus areas. Dave also has a significant background supporting Boeing's F/A-18 E/F, C-17, and F-15 production programs. He started his career focused on polymer matrix composites materials and processes including thermoplastic composites, composite tooling, and automated fabrication technology development. Dave has significant background in aircraft materials and structures, polymer matrix composites materials, processes and fabrication, advanced manufacturing technology, assembly operations, automation/ robotics for both assembly and fabrication. He received his BS in Chemical Engineering from the University of Illinois-Urbana/Champaign and his MBA from the Olin School of Business, Washington University - St. Louis.

Tushar Shah – Dr. Tushar Shah was appointed as "Chief Technology Officer" of ANS in 2010. In this position he is responsible for indentifying, researching and developing advanced nanomaterial technology solutions that can resolve complex customer challenges and in turn create a competitive advantage for ANS in developing next generation products. He is currently leading a team of engineers in developing "Carbon Nanotube" infused fibers that will revolutionize their use in advanced fiber reinforced composites for multiple current and future product applications. He received "Technology Innovation" award from Lockheed Martin Corporation in 2010 for his research in this area.

Dr. Shah joined Lockheed Martin Laboratories in 1981 as a research and development specialist in materials department and has spent large portion of his carrier as an innovator in this area of advanced materials. He currently has 15 issued patents under his name with 26 pending. He also has 18 technical publications. He is recipient of two “Jefferson Cup Awards” from Lockheed Martin Corporation and three outstanding achievement awards from Lockheed Martin Laboratories. He was named “Inventor of the Year” by MS2 in 2007 for his work on advanced composites.

Dr. Shah holds B.S. in Chemistry/Physics from Gujarat University/India. He has an M.S. in Textile Sciences from M.S. University/India and in Chemistry from N.C. A. & T. State University. His doctorate is in Organic Chemistry from Gujarat University/India.

Larry Carlson – Larry Carlson served as Vice President – Research and Development, at Easton Sports Inc. from 1995-2008, working on new materials, products, and processes for sporting goods. Much of his involvement was in getting nanomaterials effectively into products for strength and toughness enhancement. He is now Director of Advanced Materials at the Easton Institute for Technology Advancement at UCLA. In this position he leads a research group involved in producing stronger composites, fibers, and resins through nanotechnology.

Nolan Nicholas – Nolan Nicholas received his PhD (2009) and MS (2007) degrees in Applied Physics from Rice University under the tutelage of Dr. Richard Smalley and Dr. Robert Hauge and B.S. (2004) degrees in Physics, Metallurgical Engineering and Materials Science Engineering from the University of Idaho. Starting with his thesis work on the topics of graphenic and carbon nanotube based materials synthesis and application his research has focused on carbon nanomaterials. His ongoing research at MATRIC Inc. focuses on the application of carbon nanotubes and related materials for high-performance and multifunctional applications including transparent, high-performance polymer composites and self-assembled, multi-functional nanotube materials.

Binqing Wei – Bingqing Wei received his Bachelors degree (1987), M.S (1989), and Ph.D. (1992) in Mechanical Engineering from Tsinghua University, China. His research expertise lies in nanomaterials and nanotechnology.

Dr. Wei is currently an Associate Professor in the Department of Mechanical Engineering at the University of Delaware. He was an Assistant Professor in the Department of Electrical & Computer Engineering and Center for Computation & Technology at Louisiana State University from 2003 to 2007. He had worked as a Research Associate at Rensselaer Polytechnic Institute, Department of Materials Science and Engineering and Rensselaer Nanotechnology Center from 2000 to 2003. Dr. Wei was a visiting scientist for Max-Planck Institut für Metallforschung, Stuttgart, Germany in 1998 and 1999. He was a faculty at Tsinghua University in Beijing from 1992 to 2001.

Dr. Wei is a member of The Materials Research Society (MRS), The Electrochemical Society (ECS), The International Society for Optical Engineering (SPIE), and The American Society of Mechanical Engineering (ASME). His scholarly achievements in the field of nanomaterials and nanotechnology and, particularly in the research of carbon nanotubes are fully reflected from his 176 papers published in refereed international journals, including *Nature* and *Science*, more than 94 scientific conference presentations and 80 plus invited talks and seminars in academia and industry worldwide. His research work has been cited more than 6300 times by peer scientists with *h*-index of 44 and has also been highlighted many times in scientific journals, web journals and public media. His recent research focuses on controllable synthesis of macroscale nanotube architectures with 1-, 2-, and 3-dimensions; physical, chemical, electrochemical and mechanical property characterizations of nanotubes; and nanotube device applications.

George Scalise - George M. Scalise has served as President of the Semiconductor Industry Association, an association of semiconductor manufacturers and suppliers, since 1997. Mr. Scalise served on the Board of Directors of the Federal Reserve Bank of San Francisco from 2000 to 2005, including as Deputy Chairman from 2001 to 2003 and as Chairman from 2003 to 2005. Mr. Scalise served as Executive Vice President and Chief Administrative Officer of Apple Computer, Inc. (now Apple, Inc.), a company that designs and manufactures consumer electronics and software products, from 1996 to 1997. Mr. Scalise also served as Senior Vice President of Planning and Development and Chief Administrative Officer of National Semiconductor Corporation, a semiconductor company, from 1991 to 1996. Mr. Scalise served on President George W. Bush's Council of Advisors on Science and Technology from 2001 to 2009. Mr. Scalise also serves as a director of MindTree Ltd. As the President of the Semiconductor Industry Association, a former board member of the Federal Reserve and a former Chief Administrative Officer of Apple Computer, Inc. (now Apple, Inc.), Mr. Scalise has significant semiconductor and financial expertise and substantial international experience.

John Hart - John Hart has Ph.D. (2006) and S.M. (2002) degrees from the Massachusetts Institute of Technology, and a B.S.E (2000) degree from the University of Michigan, all in Mechanical Engineering. John received the 2006 MIT Senturia Prize for best doctoral thesis in micro/nano technology, and graduate fellowships from the Fannie and John Hertz Foundation, National Science Foundation, and MIT Martin Foundation. Since joining the faculty at Michigan, John has been recognized by a DARPA Young Faculty Award (2008), two R&D100 Awards (2008, 2009), the American Society of Mechanical Engineers Pi Tau Sigma Gold Medal (2009), the Society of Manufacturing Engineers Outstanding Young Investigator Award (2010), the University of Michigan Mechanical Engineering Faculty Achievement Award (2010), and the Air Force Office of Scientific Research Young Investigator Program Award (2010). At the University of Michigan, John directs the Mechanosynthesis Group, whose research focuses on manufacturing and applications of nanostructured materials. John also teaches undergraduate and graduate courses in design and manufacturing, nanotechnology, and research methods.

Michael Valenti - Michael Valenti's 20 years of technological reporting, data gathering, and information analysis expertise includes 7 years as a research analyst for Frost & Sullivan. There he has covered a broad range of sectors, including energy, aerospace & defense, environmental technologies, and advanced materials, including nanotechnology. Michael has presented customized research to international audiences on topics that include graphene versus carbon nanotubes, medical adhesives, and concentrated solar power. Michael launched, contributed to and edited Frost & Sullivan's Homeland Security Technology Alert.

Treye Thomas – Dr. Thomas is a toxicologist and leader of the Chemical Hazards Program team in the U.S. Consumer Product Safety Commission's (CPSC) Office of Hazard Identification and Reduction. His duties include establishing priorities and projects to identify and mitigate potential health risks to consumers resulting from chemical exposures during product use. Dr. Thomas has conducted comprehensive exposure assessment studies of chemicals in consumer products and quantified the potential health risks to consumers exposed to these chemicals. Specific activities have included conducting exposure and/or health hazard assessments of flame retardant (FR) chemicals, combustion by-products, indoor air pollutants, and other compounds. Dr. Thomas is the leader of the CPSC nanotechnology team, and is responsible for developing agency activities and policy for nanotechnology. Dr. Thomas has served as a CPSC representative on a number of nanotechnology committees including the ILSI/HESI Nanomaterial Environmental, Health, and Safety Subcommittee, the Federal NSET and NEHI sub-committees, and the International Council on Nanotechnology (ICON).

Dr. Thomas received a Bachelors degree in Chemistry from the University of California, Riverside, an MS in Environmental Health Sciences from UCLA, and a PhD in Environmental Sciences at the University of Texas, Health Science Center, Houston. He completed a post-doctoral fellowship in Industrial Toxicology at the Warner-Lambert Corporation (now Pfizer Pharmaceutical).

Lee Silverman - Lee received his B.S. from MIT in Materials Science and Engineering in 1981. He then worked for a two years doing process development for optical waveguide materials for telecommunication at Corning. Lee then went back to MIT, and graduated with a Ph.D. in Ceramic Science and Engineering in 1987. Following graduate school, Lee started work for DuPont, where he has been for the last 23 years. At DuPont, he has worked on materials intended for uses in structural, electronic, optical and sensing applications, and more. Lee is currently Research Manager for Nanocomposite Technologies in DuPont's Central Research and Development Laboratory in Wilmington, Delaware.

Robert Hurt – Professor Hurt received his Ph.D. from M.I.T. in 1987 and before joining Brown held positions in the Central Research and Development Division of Bayer AG in Leverkusen, Germany, and at Sandia National Laboratories in Livermore, California. During 2002 he was a visiting professor at the University of Sydney, New South Wales, Australia. He currently serves as Editor of the materials science journal CARBON, and is on the editorial board of Progress in Energy and Combustion Science. He served as Technical Program Chair for the international conference, Carbon2004, and in the same year received the Graffin Lecture Award of the American Carbon Society. Prof. Hurt also received the Silver Medal of the Combustion Institute in Naples, Italy in 1996 and an NSF CAREER Award in the same year. He is a scientific founder of the environmental start-up firm Banyan Environmental. He currently serves as PI on the GAANN training grant "Interdisciplinary Training in the Applicatinos and Implications of Nanotechnology", and is the Director of Brown's Institute for Molecular and Nanoscale Innovation.

Zofia Kosim - Zofia Kosim has a master degree in chemical engineering from the Technical University of Wroclaw in Poland. She is a registered Professional Engineer and has worked for the US EPA for over 20 years, most recently on nanotechnology-related issues under the Toxic Substances Control Act (TSCA).

Mark Hoover - Dr. Mark D. Hoover is a senior research scientist in the Division of Respiratory Disease Studies at the CDC's National Institute for Occupational Safety and Health, in Morgantown, West Virginia. Mark is a critical area leader in the NIOSH Nanotechnology Research Center and also serves as coordinator of the NIOSH Exposure Assessment Cross-sector Research Program. NIOSH is the leading federal agency conducting research and providing guidance on the occupational safety and health implications and applications of nanotechnology. Mark earned a BS degree in mathematics and English in 1970 from Carnegie Mellon University and MS and PhD degrees in engineering in 1975 and 1980 from the University of New Mexico. He is board certified in the comprehensive practice of health physics and in the comprehensive practice of industrial hygiene. Mark has developed improved approaches, techniques, and instrumentation for aerosol characterization, generation, and control; served as chairman or contributor to the development of many national and international standards; is a past chairman of the AIHA Nanotechnology Working Group; and is author or co-author of more than 180 open literature publications. He recently completed co-editing and writing a new CRC Press handbook on *Radioactive Air Sampling Methods*. Special emphasis areas for Mark's work in nanotechnology include a graded approach to exposure assessment and characterization of nanoparticles in the workplace, development of a prototype *Nanoparticle Information Library*, and promotion of opportunities to apply performance-based occupational exposure limits or control banding approaches to nanotechnology. Detailed information about the NIOSH nanotechnology health and safety research program is available at www.cdc.gov/niosh/topics/nanotech/.

John Ullo – John Ullo received his degrees in Physics (BS) from Rensselaer Polytechnic Institute and Nuclear Physics (PhD) from the Massachusetts Institute of Technology. Currently, he is a private consultant on future research initiatives after a career spanning thirty years with Schlumberger Technology Corporation. Several recent prior positions within Schlumberger include: Senior Management Advisor for research at the Schlumberger-Doll Research Center in Boston focusing on nanotechnology enabled applications for oil recovery and production, Vice President and General Manager of the Schlumberger Austin Technology Center from 2001 to 2004, Director of Research for Reservoir Evaluation at Schlumberger-Doll from 1996 to 2001 and Managing Director of Product Development for Seismic Processing and Evaluation at Schlumberger Geco-Prakla (now Western Geco) in the UK from 1993-1996. Earlier he held several R&D management positions in North America.