



Challenges in Commercializing Carbon Nanotube Composites

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PREFACE

ABOUT THE AUTHOR

Emily Pfautsch is a graduate student in mechanical engineering at the University of Missouri-Columbia, and she will graduate with her master's in May 2008. Her graduate research is in nanofluids. She has been heavily involved with student government and the American Society of Mechanical Engineers.

WISE PROGRAM

Sponsored by several multidisciplinary engineering professional associations, Washington Internships for Students of Engineering (WISE) is a highly competitive internship program for engineering students with an interest in public policy. The goal of the WISE program is to groom future leaders of the engineering profession, who are aware of and can contribute to the intersections of technology and public policy. During the nine-week program, interns learn how government officials make decisions on complex technical issues and how engineers can contribute to legislative and regulatory policy decisions. In addition, each intern researches and presents a paper on an engineering-related public policy issue, which is then published in the WISE Journal of Engineering and Public Policy. More information about the wise program is available at www.wise-intern.org.

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EXECUTIVE SUMMARY

Since 2001, the National Nanotechnology Initiative (NNI) has spent billions of federal dollars on nanotechnology research, which includes the research of carbon nanotube composites. After six years of this research, the technology in the carbon nanotube composite field is ready for commercialization, and companies have begun to do this.

The composite industry faces competition from other countries doing similar research. The United States is currently leading the world in carbon nanotube composite research and development, but other countries are closing the gap every year. Two years after NNI's inception, thirty countries developed similar programs.¹ The U.S. government needs to make efforts to assist start-up companies in their commercialization efforts so that the U.S. can stay competitive in the carbon nanotube composite industry.

Carbon nanotube composites have the potential for becoming "supermaterials." If the unique properties of carbon nanotubes could be utilized in composites, we could have materials that are stronger, stiffer, more thermally conductive, and more electrically conductive than anything that is used today. In addition, they would be light and ductile. As of now, carbon nanotube composites are only used to reinforce materials, which accounts for a ten to thirty percent increase in the materials' performance. This is because the current knowledge and developments in the carbon nanotube composite industry have not reached the point where companies are able to utilize carbon nanotube properties to their full potential. Once carbon nanotube composites are better understood, it is likely that average consumers will see them in things they use everyday. Carbon nanotube composites are already used in sporting equipment, auto parts, and plastics, just to name a few examples.

While carbon nanotube composites offer exciting possibilities, there are also challenges that face this industry. First, there are technical problems, such as agglomeration, dispersion, purification, and sorting, which impede composites from completely utilizing carbon nanotube properties. More research and development is needed to absolve these issues. However, there are other commercialization obstacles in the carbon nanotube composite industry that the federal government and state governments could help alleviate, like: the high cost of equipment; the lack of knowledge about environment health, and safety; the lack of a risk assessment or life cycle assessment; the lack of standards; the need for properly trained workers; and the issue of cross-patenting at the United States Patent and Trade Office (USPTO).

The federal government can lift some of the commercialization barriers by increasing funding for environment, health, and safety research through the National Nanotechnology Initiative (NNI), toxicity research at the Environmental Protection Agency (EPA) and United States Food and Drug Administration (USFDA), and small business research programs (such as Advanced Technology Program (ATP) and Small Business Innovation Research (SBIR) grants), as well as expediting nanotechnology-related cases heard at the USPTO.

¹ Roco, M.C. interview sponsored by PurpleGold Media's New York Times Nanotechnology insert scheduled for mid-September 2007, retrieved June 6, 2007.

Many of the ways state governments can aid this commercialization are specific to small businesses, which can include providing avenues for venture capitalist and start-up companies to interact; issuing tax-free bonds and tax credits for capital investments; reducing capital gains tax; providing mentorship and business planning assistance for companies; promoting NNI research centers; establishing state level government research grants; educating the public; providing workforce training programs; and developing more outreach activities for children in grades K-12.

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1. INTRODUCTION

Carbon nanotubes are hollow cylinders of graphite carbon atoms.^{2,3} These tubes are on the nanoscale (10^{-9} m), which is so small that 10,000 of them could fit in the width of 1 human hair.^{4,5} Since their discovery in 1991 by Iijima,⁶ the synthesis, properties, and applications of carbon nanotubes have become a major research area due to their unique properties. They provide the highest Young's modulus^{7,8} (or stiffness), highest thermal conductivity,^{9,10,11,12} highest electrical conductivity,¹³ and highest current density¹⁴ of any known material, while having a low density.

With such special properties, carbon nanotubes have a vast amount of applications in the fields of materials, electronics, field emission, biology, medicine, and electrochemistry. This paper will focus on carbon nanotubes in composite materials. A

² O'Connell, M. ed. (2006). *Carbon Nanotubes: Properties and Applications*. Boca Raton: Taylor & Francis.

³ Meyyappan, M., ed. (2005) *Carbon Nanotubes: Science and Applications*. Boca Raton: CRC Press.

⁴ NanoNY. (2007). *What is Nanotechnology?*. Retrieved July 20, 2007 from <http://www.nanony.com/whatis.htm>

⁵ Environmental Protection Agency. (2007, January 18). *Fact Sheet for Nanotechnology Under the Toxic Substances Control Act*. Retrieved July 20, 2007 from <http://www.epa.gov/oppt/nano/nano-facts.htm>

⁶ Eindhoven University of Technology. (2003, February 27). *Wondrous World of Carbon Nanotubes*. Retrieved July 14, 2007, from http://students.chem.tue.nl/ifp03/Wondrous%20World%20of%20Carbon%20Nanotubes_Final.pdf

⁷ Carbon Nanotechnologies Incorporated. *Buckytube Properties & Uses, Mechanical Properties*. Retrieved July 6, 2007, from http://cnanotech.com/pages/buckytube_properties_uses/buckytube_properties/5-1-4_mechanical_properties.html

⁸ *ibid.*

⁹ Baddour, C.E., & Briens, C. (2005). Carbon Nanotube Synthesis: A Review. *International Journal of Chemical Reactor Engineering*, 3: R3.

¹⁰ Robertson, J. (2004). Realistic Applications of CNTs. *Materials Today*, October, 46-52.

¹¹ Eindhoven University, *loc. cit.*

¹² Carbon Nanotechnologies Incorporated. *Buckytube Properties & Uses, Electrical Conductivity*. Retrieved July 6, 2007, from http://cnanotech.com/pages/buckytube_properties_uses/buckytube_properties/5-1-2_electrical_conduct.html

¹³ AZoNanotechnology.com. (2007). *Carbon Nanotubes—Overview of Properties, Classification, Fabrication, and Synthesis*. Retrieved July 2, 2007, from <http://www.azonano.com/details.asp?ArticleID=1199>

¹⁴ Carbon Nanotechnologies Incorporated. *Buckytube Properties & Uses, Electrical Conductivity*. Retrieved July 6, 2007, from http://cnanotech.com/pages/buckytube_properties_uses/buckytube_properties/5-1-2_electrical_conduct.html

microscopic photo of carbon nanotubes is shown in Fig. 1. From this photo, which has been magnified, one can see that the carbon nanotubes resemble very small strands of spaghetti.

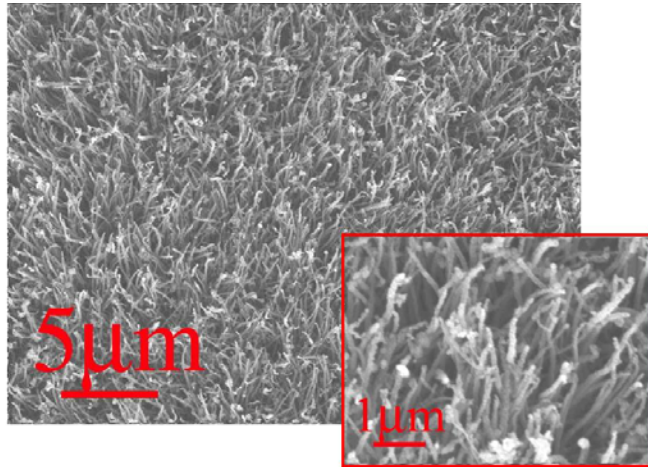


Fig. 1. Photo of carbon nanotubes under a microscope.¹⁵

1.1 NATIONAL NANOTECHNOLOGY INITIATIVE (NNI)

Because the size of carbon nanotubes is on the nanoscale (10^{-9} m), they are categorized as being in the field of nanotechnology. The United States Congress approved a research and development program specifically for nanotechnology in 2001, the National Nanotechnology Initiative (NNI).^{16,17} The initiative coordinates the activities of 26 federal agencies that commit funding to nanotechnology research and development.^{18,19} In 2007, \$1.277 Billion was appropriated for NNI.²⁰ NNI also sponsors over 60 interdisciplinary research centers across the country. The centers are designated as user facilities for researchers from academia, industry, or government and are

¹⁵ The Nanotube Site. (2007, July 8). *Carbon Nanotubes*. Retrieved June 20, 2007 from <http://www.pa.msu.edu/cmp/csc/nanotube.html>

¹⁶ National Nanotechnology Initiative. (2007). *About the NNI*. Retrieved July 8, 2007 from http://www.nano.gov/html/about/home_about.html

¹⁷ Roco, M.C. (2007). *National Nanotechnology Initiative—Past, Present, Future*. Handbook on Nanoscience, Engineering, and Technology, 2, Preprint: Taylor and Francis.

¹⁸ *ibid.*

¹⁹ National Nanotechnology Initiative. (2007). *About the NNI*. Retrieved July 8, 2007 from http://www.nano.gov/html/about/home_about.html

²⁰ American Association for the Advancement of Science. (2007). *National Nanotechnology Investment in the FY 2007 Budget Request*. Retrieved July 23, 2007, from <http://www.aaas.org/spp/rd/07pch24.htm>

equipped with state of the art equipment for nanoscale research.²¹ NNI has been tremendously influential in the progress of all types of nanotechnologies, including carbon nanotubes and carbon nanotube composites.

1.2 WHY COMMERCIALIZATION IS IMPORTANT

Even with all of the interesting outcomes as a result of NNI research dollars, making a marketable product can be a challenge. The NNI funds basic research in nanotechnology and the private sector is responsible for commercialization. There is a gap, sometimes called “the valley of death,” where companies struggle to obtain funding to transition from discovery through production of a marketable product. At this point, with the NNI having been in existence for 6 years, nanotechnology research is beginning to transition into commercial applications, and both start-up and well-established companies are trying to cross “the valley.”

The U.S. was the first country to establish a government-funded nanotechnology research and development initiative, and within 2 years, 30 countries developed similar programs.²² Now, over 60 countries have government-funded nanotechnology programs.²³ Currently, the U.S. is spending one quarter of the world’s research and development nanotechnology funds, but is producing fifty percent of the highly cited papers, sixty percent of the worldwide patents recorded with the U.S. Patent and Trade Office, and seventy percent of nanotechnology start-up companies.²⁴ The U.S. remains the acknowledged leader in nanotechnology research and development based on the quality of research and citations. However, every year, the lead between the U.S. and other countries in nanotechnology developments narrows. Efforts must be made to keep the U.S. competitive in nanotechnology research and development, as well as the engineering and manufacturing necessary to commercialize this technology.

²¹ National Nanotechnology Initiative. (2007). *NNI Research Centers*. Retrieved July 8, 2007 from http://www.nano.gov/html/centers/home_centers.html

²² Roco, M.C. interview sponsored by PurpleGold Media’s New York Times Nanotechnology insert scheduled for mid-September 2007, retrieved June 6, 2007.

²³ *ibid.*

²⁴ *ibid.*

1.3 TYPES OF CARBON NANOTUBES

Carbon nanotubes come in two forms, as single-walled carbon nanotubes and multi-walled carbon nanotubes. Single-walled carbon nanotubes have cylinder walls one molecule thick,²⁵ and multi-walled carbon nanotubes have several single-walled carbon nanotubes embedded inside one another, like Russian nesting dolls. Figure 2 is a photo of a multi-walled carbon nanotube underneath a microscope.

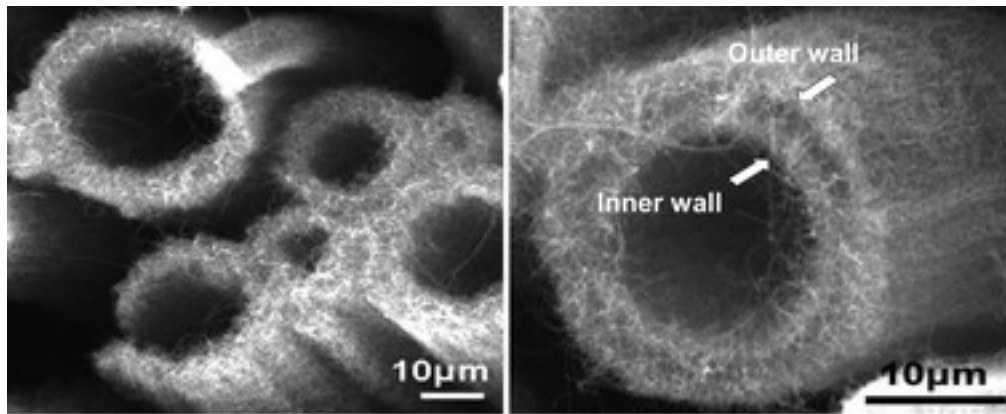


Fig. 2. Multi-walled carbon nanotubes underneath a microscope.²⁶

Sumio Iijima discovered single-walled carbon nanotubes in 1991.^{27,28,29} Single-walled carbon nanotubes tend to be stronger and more flexible than their multi-walled counterparts. One reason that multi-walled carbon nanotubes are weaker, is because the individual cylinders slide inside one another. Single-walled carbon nanotubes are also better electrical conductors and are more transparent. However, their production is difficult and they are challenging to purify. Single-walled carbon nanotubes are also more

²⁵ World Technology Evaluation Center, Inc. (2007, June). *International Assessment of Research and Development of Carbon Nanotube Manufacturing and Applications*. Retrieved July 9, 2007, from http://www.wtec.org/cnm/CNM_final_report.pdf

²⁶ Royal Society of Chemistry Publishing. (2007). *ChemComm*. Retrieved June 15, 2007, from <http://www.rsc.org/Publishing/Journals/cc/article.asp?Type=Issue&Journalcode=CC&Issue=6&SubYear=2006&Volume=0&Page=0&GA=on>

²⁷ O'Connell, M. ed. (2006). *Carbon Nanotubes: Properties and Applications*. Boca Raton: Taylor & Francis.

²⁸ Louisea, A., Launoi, P., Petit, P. et. al., eds. (2006). *Understanding Carbon Nanotubes From Basics to Application*. Berlin: Springer.

²⁹ Baddour, C.E., & Briens, C. (2005). Carbon Nanotube Synthesis: A Review. *International Journal of Chemical Reactor Engineering*, 3: R3.

expensive to make (single-walled carbon nanotubes cost about \$500/g and multi-walled carbon nanotubes cost about \$10/g),³⁰ and this may not change until there is a large-scale market for single-walled carbon nanotubes.³¹ Currently, multi-walled carbon nanotubes are more widely used in composite materials than single-walled carbon nanotubes for these reasons.

1.4 EXAMPLES OF USES FOR CARBON NANOTUBE COMPOSITES

When carbon nanotubes are added to a matrix material, the newly formed composite will take on some of the properties of the carbon nanotubes. Some selected current applications are below.

- *Sporting Equipment.* Carbon nanotubes have already been added to sports equipment such as bats, bicycles, golf clubs, and hockey sticks in order to impart more strength and absorb vibrations.
- *Displays.* Single-walled carbon nanotubes can be used as transparent conductors, and can be used to make any sort of display—from televisions to phones. This is also because they are flexible, can handle large current densities, and have sharp tips that help emit electrons.³²
- *Auto parts.* 60 percent of cars produced today now have fuel lines made with carbon nanotubes. The carbon nanotubes inside the fuel lines are intended to reduce the risk of explosions by inhibiting static electricity. Carbon nanotubes are also being put in exterior auto-body parts.³³

³⁰ O'Connell, M. ed. (2006). *Carbon Nanotubes: Properties and Applications*. Boca Raton: Taylor & Francis.

³¹ World Technology Evaluation Center, Inc. (2007, June). *International Assessment of Research and Development of Carbon Nanotube Manufacturing and Applications*. Retrieved July 9, 2007, from http://www.wtec.org/cnm/CNM_final_report.pdf

³² O'Connell, M. ed. (2006). *Carbon Nanotubes: Properties and Applications*. Boca Raton: Taylor & Francis.

³³ Nanotechnology: Untold Promise, Unknown Risk. *Consumer Reports*, July 2007, 40-45.

- *Conductive polymers.* Normally, polymers are insulators, but when conducting carbon nanotubes are added, the polymer composite becomes conductive. This also makes the polymer more robust.³⁴
- *Thermal grease.* Thermal grease is used on computer processors to help conduct the heat away. Nanotubes are being put in the thermal grease to increase the thermal conductivity of the grease, allowing more heat to be removed from the processor.³⁵
- *Fibers and yarns.* Weaving would allow the carbon nanotubes to be aligned and woven into textile structures that can be used as cables.³⁶

1.5 CARBON NANOTUBE SYNTHESIS

There are many different methods and variations for producing carbon nanotubes, but this section will only cover the three principal methods for carbon nanotube synthesis: arc discharge, laser ablation, and chemical vapor deposition (CVD). There are continual improvements in each of the methods in an effort to produce more nanotubes quicker, and for a lower cost.

1.51 ARC DISCHARGE

The carbon arc discharge method is probably the easiest way to produce carbon nanotubes, although the purity and control over arrangement are not as good as other methods.^{37,38} Inside an enclosed chamber filled with a low-pressure inert gas, such as helium or argon, two graphite rods are placed end-to-end approximately 1mm apart; one

³⁴ Eindhoven University of Technology. (2003, February 27). *Wondrous World of Carbon Nanotubes*. Retrieved July 14, 2007, from http://students.chem.tue.nl/ifp03/Wondrous%20World%20of%20Carbon%20Nanotubes_Final.pdf

³⁵ Carbon Nanotechnologies, Incorporated. ((2007). *Buckytube Properties & Uses: Thermal Materials*. Retrieved July 6, 2007, from http://cnanotech.com/pages/buckytube_properties_uses/buckytube_uses/5-2-6_thermal_materials.html

³⁶ O'Connell, M. ed. (2006). *Carbon Nanotubes: Properties and Applications*. Boca Raton: Taylor & Francis.

³⁷ Louisea, A., Launoi, P., Petit, P. et. al., eds. (2006). *Understanding Carbon Nanotubes From Basics to Application*. Berlin: Springer.

³⁸ Eindhoven University of Technology. (2003, February 27). *Wondrous World of Carbon Nanotubes*. Retrieved July 14, 2007, from http://students.chem.tue.nl/ifp03/Wondrous%20World%20of%20Carbon%20Nanotubes_Final.pdf

is a cathode (negatively charged) rod and one is an anode (positively charged) rod. A direct current of 50 to 100 amps at approximately 20 volts is applied to the rods and creates a high temperature discharge (or plasma) between the two electrodes. The discharge vaporizes the anode rod, and it forms carbon nanotubes, in addition to other substances, on the cathode rod. A large obstacle of the arc discharge method is separating the carbon nanotubes from the soot that is left from the process. This method is usually used to produce multi-walled carbon nanotubes, but if the anode is doped with a metal catalyst, such as Fe, Co, Ni, or Mo, the arc discharge can produce single-walled carbon nanotubes.^{39,40,41}

1.52 LASER ABLATION

In the laser ablation process, an oven filled with helium or argon gas is brought up to a temperature of about 1200 °C, at high pressure, and a graphite target is placed inside. A laser is shot at the target, which vaporizes the graphite on the surface. Very hot vapor forms, expands, and then cools, leaving carbon nanotubes and other small carbon structures. Using this process, multi-walled carbon nanotubes are produced. If the graphite target is mixed with a metal catalyst, single-walled carbon nanotubes will be formed. The carbon nanotubes produced by laser ablation are purer than those that are produced by arc discharge (up to 90 percent in purity). However, the laser ablation process is more expensive due to the high power requirement.^{42,43}

³⁹ Eindhoven University of Technology. (2003, February 27). *Wondrous World of Carbon Nanotubes*. Retrieved July 14, 2007, from

http://students.chem.tue.nl/ifp03/Wondrous%20World%20of%20Carbon%20Nanotubes_Final.pdf

⁴⁰ O'Connell, M. ed. (2006). *Carbon Nanotubes: Properties and Applications*. Boca Raton: Taylor & Francis.

⁴¹ Baddour, C.E., & Briens, C. (2005). Carbon Nanotube Synthesis: A Review. *International Journal of Chemical Reactor Engineering*, 3: R3.

⁴² Eindhoven University of Technology. (2003, February 27). *Wondrous World of Carbon Nanotubes*. Retrieved July 14, 2007, from

http://students.chem.tue.nl/ifp03/Wondrous%20World%20of%20Carbon%20Nanotubes_Final.pdf

⁴³ O'Connell, M. ed. (2006). *Carbon Nanotubes: Properties and Applications*. Boca Raton: Taylor & Francis.

1.53 CHEMICAL VAPOR DEPOSITION (CVD)

Chemical vapor deposition is the most common method for producing carbon nanotubes in industry.⁴⁴ An energy source, such as a plasma-heated or resistively heated coil, transfers energy to carbon molecules that are in the gas phase. Common gaseous carbon sources are methane, carbon monoxide and acetylene. The energy source causes carbon atoms to separate from the molecules and the carbon atoms attach themselves to the metal catalysts.^{45,46} After this, the carbon nanotubes start to grow.

It has been suggested that CVD is a scalable and controllable method for carbon nanotubes synthesis because of the purity,⁴⁷ diameter, and growth rate of the carbon nanotubes can be controlled. CVD also produces the highest yield of carbon nanotubes,^{48,49} and there is less need for purification after the carbon nanotube synthesis. The CVD process produces virtually no amorphous carbon, but the catalysts still need to be removed.⁵⁰ However, this method tends to produce more structural defects than arc discharge or laser ablation,^{51,52} and production takes more time.

Once again, this is a general overview of carbon nanotube synthesis. There are many variations to these techniques that can be used to produce the desired type of carbon nanotubes and to prevent some of the unwanted process effects.

⁴⁴ World Technology Evaluation Center, Inc. (2007, June). *International Assessment of Research and Development of Carbon Nanotube Manufacturing and Applications*. Retrieved July 9, 2007, from http://www.wtec.org/cnm/CNM_final_report.pdf

⁴⁵ Eindhoven University of Technology. (2003, February 27). *Wondrous World of Carbon Nanotubes*. Retrieved July 14, 2007, from http://students.chem.tue.nl/ifp03/Wondrous%20World%20of%20Carbon%20Nanotubes_Final.pdf

⁴⁶ O'Connell, M. ed. (2006). *Carbon Nanotubes: Properties and Applications*. Boca Raton: Taylor & Francis.

⁴⁷ Robertson, J. (2004). Realistic Applications of CNTs. *Materials Today*, October, 46-52.

⁴⁸ Eindhoven University of Technology. (2003, February 27). *Wondrous World of Carbon Nanotubes*. Retrieved July 14, 2007, from http://students.chem.tue.nl/ifp03/Wondrous%20World%20of%20Carbon%20Nanotubes_Final.pdf

⁴⁹ O'Connell, M. ed. (2006). *Carbon Nanotubes: Properties and Applications*. Boca Raton: Taylor & Francis.

⁵⁰ Jacques, D., Villain, S., Rao, A.M, et. al., *Synthesis of Multiwalled Carbon Nanotubes*, Retrieved July 2, 2007, from www.caer.uky.edu/carbon/posters/absulmrs99.pdf

⁵¹ Meyyappan, M., ed. (2005). *Carbon Nanotubes: Science and Applications*. Boca Raton: CRC Press.

⁵² Eindhoven University of Technology. (2003, February 27). *Wondrous World of Carbon Nanotubes*. Retrieved July 14, 2007, from http://students.chem.tue.nl/ifp03/Wondrous%20World%20of%20Carbon%20Nanotubes_Final.pdf

1.6 PROPERTIES

Carbon nanotubes have properties unlike any other substance on earth of which we currently know. Even though carbon nanotubes are made out of graphite carbon, they have different properties than bulk graphite because of their size, shape, and crystallography. While carbon nanotubes may have the potential for being the next supermaterial for our society, actually utilizing all of their mechanical, thermal, and electrical properties is still an unsolved challenge.

1.61 MECHANICAL

Single-walled carbon nanotubes possess incredible mechanical resistance because their carbon atoms are united by the strongest bonds in nature (σ bonds)^{53,54,55} and they have a regular crystal lattice. In addition, they are highly flexible, and can be bent repeatedly up to 90° without being damaged.⁵⁶ They have a very low density, about 1/6 of the density of steel,⁵⁷ but are much stronger than steel. If single-walled carbon nanotubes are positioned vertically, with their diameter being normal to a surface, they would have the highest Young's modulus (or stiffness) of any material—1 TPa,^{58,59,60,61} which is five times the stiffness of steel.^{62,63} However, this is a theoretical value, and

⁵³ O'Connell, M. ed. (2006). *Carbon Nanotubes: Properties and Applications*. Boca Raton: Taylor & Francis.

⁵⁴ Meyyappan, M., ed. (2005). *Carbon Nanotubes: Science and Applications*. Boca Raton: CRC Press.

⁵⁵ Baddour, C.E., & Briens, C. (2005). Carbon Nanotube Synthesis: A Review. *International Journal of Chemical Reactor Engineering*, 3: R3.

⁵⁶ O'Connell, M. ed. (2006). *Carbon Nanotubes: Properties and Applications*. Boca Raton: Taylor & Francis.

⁵⁷ Meyyappan, M., ed. (2005). *Carbon Nanotubes: Science and Applications*. Boca Raton: CRC Press.

⁵⁸ Robertson, J. (2004). Realistic Applications of CNTs. *Materials Today*, October, 46-52.

⁵⁹ Eindhoven University of Technology. (2003, February 27). *Wondrous World of Carbon Nanotubes*. Retrieved July 14, 2007, from

http://students.chem.tue.nl/ifp03/Wondrous%20World%20of%20Carbon%20Nanotubes_Final.pdf

⁶⁰ O'Connell, M. ed. (2006). *Carbon Nanotubes: Properties and Applications*. Boca Raton: Taylor & Francis.

⁶¹ World Technology Evaluation Center, Inc. (2007, June). *International Assessment of Research and Development of Carbon Nanotube Manufacturing and Applications*. Retrieved July 9, 2007, from http://www.wtec.org/cnm/CNM_final_report.pdf

⁶² Carbon Nanotechnologies Incorporated. *Buckytube Properties & Uses, Mechanical Properties*.

Retrieved July 6, 2007, from

http://cnanotech.com/pages/buckytube_properties_uses/buckytube_properties/5-1-4_mechanical_properties.html

aligning the single-walled carbon nanotubes in such a manner is still a challenge. Putting all of these properties together, one can visualize carbon nanotubes as being the strongest, most ductile material for its weight.

1.62 THERMAL

The thermal conductivity of carbon nanotubes is very high in the axial direction and very low in the lateral direction, which makes them a subject of great interest.⁶⁴ Thermal conductivity, along the axial direction, has been found to be at least double that of diamond^{65,66} (1000: 3000 W/m·K),⁶⁷ and diamond has the highest thermal conductivity of any substance we know of today.

1.63 ELECTRICAL

Carbon nanotubes have the unique ability to be insulators, semiconductors, or conductors, depending on the way the carbon atoms are arranged. Chirality is the term used to define the “twist” of the single-walled carbon nanotubes and is directly related to the electrical properties.^{68,69,70} Carbon nanotubes can have an electrical conductivity up to 1000 times that of copper.⁷¹ If the carbon atoms in the carbon nanotubes are arranged a certain way, they can be almost perfect conductors along their axial direction (almost no

⁶³ O’Connell, M. ed. (2006). *Carbon Nanotubes: Properties and Applications*. Boca Raton: Taylor & Francis.

⁶⁴ AZoNanotechnology.com. (2007). *Carbon Nanotubes—Overview of Properties, Classification, Fabrication, and Synthesis*. Retrieved July 2, 2007, from <http://www.azonano.com/details.asp?ArticleID=1199>

⁶⁵ Baddour, C.E., & Briens, C. (2005). Carbon Nanotube Synthesis: A Review. *International Journal of Chemical Reactor Engineering*, 3: R3.

⁶⁶ Carbon Nanotechnologies Incorporated. (2007). *Buckytube Properties & Uses, Thermal Conductivity*. Retrieved July 6, 2007, from http://cnanotech.com/pages/buckytube_properties_uses/buckytube_properties/5-1-3_thermal_conduct.html

⁶⁷ O’Connell, M. ed. (2006). *Carbon Nanotubes: Properties and Applications*. Boca Raton: Taylor & Francis.

⁶⁸ Eindhoven University of Technology. (2003, February 27). *Wondrous World of Carbon Nanotubes*. Retrieved July 14, 2007, from http://students.chem.tue.nl/ifp03/Wondrous%20World%20of%20Carbon%20Nanotubes_Final.pdf

⁶⁹ O’Connell, M. ed. (2006). *Carbon Nanotubes: Properties and Applications*. Boca Raton: Taylor & Francis.

⁷⁰ Meyyappan, M., ed. (2005). *Carbon Nanotubes: Science and Applications*. Boca Raton: CRC Press.

⁷¹ AZoNanotechnology.com. (2007). *Carbon Nanotubes—Overview of Properties, Classification, Fabrication, and Synthesis*. Retrieved July 2, 2007, from <http://www.azonano.com/details.asp?ArticleID=1199>

electrical resistance) at temperatures close to absolute freezing (-273 °C),⁷² which is very rare. Given their high thermal conductivity, tolerance for high current density, and sharp tips, carbon nanotubes are the best field emitters of any material, meaning they are ideal for flat panel displays, such as the ones on tvs, phones, or computers. Single-walled carbon nanotubes can also carry the highest current density of any known material, measured as high as 109 amps/cm².⁷³

1.64 CARBON NANOTUBE COMPOSITES

When carbon nanotubes are added to a matrix material, the composite will take on some of the carbon nanotubes' properties, due to the rule of mixtures.⁷⁴ For instance, plastics are normally insulators, but when conducting carbon nanotubes are added, the plastic can become a semiconductor. Carbon nanotubes can also be added to adhesives or polymers to give the substances enhanced thermal conductivity and improved robustness. Unfortunately, the enhancement from adding carbon nanotubes is modest. In some of the best cases, the measured tensile strength improves ten to twenty percent and the stiffness of the material may double.⁷⁵ To date, companies are not obtaining the theoretical property values of carbon nanotubes in their composites because engineering and manufacturing methods are not yet designed to make fully integrated composites. Currently, carbon nanotubes are used as particulate reinforcement, so the properties of the composite are limited to the rule of mixture. If ways of using more carbon nanotubes in composites were developed, such as in carbon nanotube fiber reinforced mats, the composites' properties should begin to reach the theoretical values of carbon nanotube properties. This is a goal of many carbon nanotube composite companies.

⁷² Baddour, C.E., & Briens, C. (2005). Carbon Nanotube Synthesis: A Review. *International Journal of Chemical Reactor Engineering*, 3: R3.

⁷³ Carbon Nanotechnologies Incorporated. *Buckytube Properties & Uses, Electrical Conductivity*. Retrieved July 6, 2007, from http://cnanotech.com/pages/buckytube_properties_uses/buckytube_properties/5-1-2_electrical_conduct.html

⁷⁴ Meyyappan, M., ed. (2005). *Carbon Nanotubes: Science and Applications*. Boca Raton: CRC Press.

⁷⁵ World Technology Evaluation Center, Inc. (2007, June). *International Assessment of Research and Development of Carbon Nanotube Manufacturing and Applications*. Retrieved July 9, 2007, from http://www.wtec.org/cnm/CNM_final_report.pdf

1.7 EXAMPLES OF STATE INITIATIVES IN NANOTECHNOLOGY

With the nanotechnology industry speculated to be a \$1 Trillion dollar industry by 2015,⁷⁶ some state governments are taking measures to draw nanotechnology businesses and research to their states. Currently, more than 20 states have nanotechnology programs.⁷⁷ Some of the frontrunners of state-sponsored nanotechnology programs are New York, California, and Texas. There are three common elements that these states have, which are helping them to become nanotechnology hubs: they are large in size, with strong footings in technology commercialization, they have venture capitalists within their state to support emerging start-up companies, and they have enough state resources to support special programs and tools for start-up companies.

1.71 NEW YORK

New York is an excellent example of what state governments and institutions can do to promote the commercialization of nanotechnology. The following are some of New York's state programs.

- *New York State Small Business Development Center*. Provides expert management and technical assistance to start-up and existing businesses in the state. There are 23 campus-based regional centers and 29 outreach offices. The center provides seminars and advice in the following areas:
 - Identifying target markets
 - Identifying sources of funding
 - Applying for state and federal research and development grants
 - Contracts and research agreements
 - Patenting, licensing, trademarking
 - Going public, mergers, acquisitions, leveraged buy-outs
 - Referrals to other experts and services⁷⁸

⁷⁶ Roco, M.C. (2007). *National Nanotechnology Initiative—Past, Present, Future*. Handbook on Nanoscience, Engineering, and Technology, 2, Preprint: Taylor and Francis.

⁷⁷ Roco, M.C. interview sponsored by PurpleGold Media's New York Times Nanotechnology insert scheduled for mid-September 2007, retrieved June 6, 2007.

⁷⁸ NYS Small Business Development Center. (2007). *Small Business Services*. Retrieved July 15, 2007 from <http://www.nyssbdc.org/services/services.html>

- *Loan programs.* Programs such as AI Tech Loan Fund and Empire State Development provide lower than average loan rates to small businesses.⁷⁹
- *SmartStart/Unytech Venture Forum.* An annual forum is held for venture-ready and university spin-out companies to showcase their technologies and attract investment partners. In 2007, 25 funding sources participated in the program. Funding varies from year to year, from around \$10 M to \$25 Million.⁸⁰
- *Venture Bplan Series.* Each month, two start-up technology ventures are invited to present their business plans and financial needs before a board of investors and a general audience. Thirty-five percent of companies who present at the Venture Bplan Series have received equity funding. The program is sponsored by the Rensselaer Incubator Program and the Center for Economic Growth, and can be a good way for the start-up companies to find investors.⁸¹
- *NYSTAR.* The program supports technology development, innovation, and commercialization by funding academic research and development, while coordinating New York's science and technology informational resources, and making them publicly available. NYSTAR also recommends policies to the governor and legislature to promote the commercialization and development of technology in New York, which includes several business assistance programs and research grants.⁸²
- *Regional Technology Development Centers (RTDCs).* New York has 10 independent, not-for-profit organizations in different regions of the state, which cultivate the growth of hi-tech industry and help smaller manufacturers modernize by providing business assistance, financial and

⁷⁹ Albany-Colonie Regional Chamber of Commerce. (2007). *AI Tech Revolving Loan Fund*. Retrieved July 15, 2007, from http://ac-chamber.org/doc/loan_eap_programs.pdf

⁸⁰ SmartStart Venture Forum. (2007). *Upstate New York's Largest Venture Forum*. Retrieved July 15, 2007, from <http://www.smartstartvf.com/>

⁸¹ The Venture Bplan Series. (2007). *Details*. Retrieved July 15, 2007, from <http://www.venturebplan.com/>

⁸² NYSTAR. (2007). *Goals*. Retrieved July 15, 2007, from <http://www.nystar.state.ny.us/goals.htm>

venture capital information, and grant information. RTDCs receive state and federal funding.⁸³

- *College of Nanoscale Science and Engineering at the University at Albany, State University of New York.* Begun in 2003, this is the first school of nanotechnology, and it has programs in nanosciences, nanoengineering, and nanoeconomics. Its development came as a result of support of the New York Senate and Governor.⁸⁴
- *Nanovision.* Intended for grades 3-8, this is a multimedia series is distributed to public schools throughout the Public Broadcasting System about nanotechnology.⁸⁵
- *NanoDay.* On March 31, 2007, several colleges within the New York City area sponsored a city-wide event to inspire pre-college students to go into fields of nanotechnology. Approximately 500 selected 10th and 11th grade students came to the City College of New York campus, where they entered discussions with prominent researchers and speakers and observed exhibits and demonstrations.⁸⁶

⁸³ NYSTAR. (2007). *Regional Technology Development Centers*. Retrieved on July 15, 2007, from <http://www.nystar.state.ny.us/rtdcs.htm>

⁸⁴ College of Nanoscale Science & Engineering. (2007). *History*. Retrieved on July 15, 2007, from http://cnse.albany.edu/about_cnse/history.html

⁸⁵ New York Loves Nanotech. (2007). *K-12*. Retrieved on July 15, 2007, from <http://www.nylovesnano.com/education/k12.php?m=1>

⁸⁶ Nanoday in New York. (2007). *About*. Retrieved on July 15, 2007, from <http://www.cise.columbia.edu/nsec/outreach/nanoday2007/about.php>

2. CHALLENGES IN COMMERCIALIZING CARBON NANOTUBE COMPOSITES

2.1 CREATING A UNIFORM (ISOTROPIC) MATERIAL

Since carbon nanotubes inherently want to stick together in bundles,⁸⁷ some companies have challenges dispersing the carbon nanotubes within the matrix material. Companies use various ways of mitigating this problem, some of which are extrusion, ultrasonic processing, and high shear mixing and melt spinning.⁸⁸ All of these techniques help disperse the carbon nanotubes, but none are end-all solutions. Dispersing carbon nanotubes is a very meticulous process that can vary from batch to batch because they are highly sensitive to process parameters.

Another problem in creating an isotropic material is that the carbon nanotubes tend to suffer from insufficient bonding across the interface of the nanotube and matrix material. Multi-walled nanotubes are more widely used in composite materials than single-walled nanotubes because they are lower in cost and better understood. But, they have a problem with their different shells shifting inside the composite.⁸⁹ To alleviate this, many companies are putting coatings on (also known as functionalizing) the carbon nanotubes to strengthen the bond between the nanotube and the host material.⁹⁰

Before carbon nanotubes can be used in a broad range of applications, it is imperative to develop methods that can control the positioning, orientation, chirality, structure, and length of the carbon nanotubes.⁹¹ Because of the size of carbon nanotubes, they are very difficult to manipulate and orient. Producing carbon nanotubes using chemical vapor deposition (CVD) is the best method for controlling the morphology and properties, but even this method still requires sorting the nanotubes. Sufficient progress

⁸⁷ Robertson, J. (2004). Realistic Applications of CNTs. *Materials Today*, October, 46-52.

⁸⁸ World Technology Evaluation Center, Inc. (2007, June). *International Assessment of Research and Development of Carbon Nanotube Manufacturing and Applications*. Retrieved July 9, 2007, from http://www.wtec.org/cnm/CNM_final_report.pdf

⁸⁹ Robertson, J. (2004). Realistic Applications of CNTs. *Materials Today*, October, 46-52.

⁹⁰ *ibid.*

⁹¹ World Technology Evaluation Center, Inc. (2007, June). *International Assessment of Research and Development of Carbon Nanotube Manufacturing and Applications*. Retrieved July 9, 2007, from http://www.wtec.org/cnm/CNM_final_report.pdf

has been made in separating nanotubes by size, by using their buoyant densities.⁹² Researchers have also found that carbon nanotubes tend to sort themselves by length, during mixing, when they are suspended in viscous fluids.⁹³ The shorter carbon nanotubes tend to flow toward the walls of the mixing equipment, while the longer nanotubes congregate in the interior of the mixer. However, there are no completely reliable methods for controlling the chirality of the nanotubes during their production. Controlling the chirality is the most daunting challenge, but doing so is very important, since it affects the whether or not the carbon nanotubes are electrically conductive.

2.2 PURIFICATION

As mentioned in section 1.3, single-walled carbon nanotubes have unique properties that are superior to those of multi-walled carbon nanotubes, especially in strength and electrical conductivity. However, depending on which production method is used, single-walled carbon nanotubes can be coated with unwanted soot. The challenge is figuring out how to separate the single-walled carbon nanotubes from those substances, without changing or damaging the carbon nanotubes. The soot typically consists of amorphous carbon, metal catalyst and fullerenes, which need to be removed because they can interfere with the properties of the carbon nanotubes.⁹⁴ If multi-walled carbon nanotubes are being produced using CVD, there is no need for purification, because virtually no soot is left in the process.⁹⁵

The main processes for purifying single-walled carbon nanotubes are oxidation and acid refluxing. Oxidation is good for removing amorphous carbon: not only are the impurities oxidized, but the single-walled carbon nanotubes are as well. This method is

⁹² BrightSurf.com. (2006, October 5). *Method Could Help Carbon Nanotubes Become Commercially Viable*. Retrieved July 2, 2007, from http://www.brightsurf.com/news/headlines/26704/Method_could_help_carbon_nanotubes_become_commercially_viable.html

⁹³ Brightsurf.com. (2005, July 27). *Researchers Help Sort Out the Carbon Nanotube Problem*. Retrieved July 2, 2007, from http://www.brightsurf.com/news/headlines/20458/Researchers_help_sort_out_the_carbon_nanotube_problem.html

⁹⁴ Eindhoven University of Technology. (2003, February 27). *Wondrous World of Carbon Nanotubes*. Retrieved July 14, 2007, from http://students.chem.tue.nl/ifp03/Wondrous%20World%20of%20Carbon%20Nanotubes_Final.pdf

⁹⁵ Jacques, D., Villain, S., Rao, A.M, et. al., *Synthesis of Multiwalled Carbon Nanotubes*, Retrieved July 2, 2007, from www.caer.uky.edu/carbon/posters/absulmrs99.pdf

still effective because the impurities tend to have more defects and open structures, so they oxidize easier than the single-walled carbon nanotubes. Also, the impurities tend to attach themselves to the metal catalysts and the catalysts act as an oxidizing agent. Acid refluxing, on the other hand, is good at removing the metal catalyst, but leaves the single-walled carbon nanotubes and other carbon impurities alone. Usually, a combination of the oxidation and acid methods is used: oxidation gets rid of the amorphous carbon, and an acid treatment removes the catalyst.⁹⁶ There are many other methods of purifying single-walled carbon nanotubes available, but these are the most common.

2.3 HIGH COST OF PRODUCTION

A start-up company needs clean rooms, microscopes, probes, power and other equipment. A challenge for small and start-up companies is the affordability of the equipment required for nanotechnology production and research. For example, a scanning electron microscope that is used to view objects on the nanoscale can cost upwards of \$15,000. The clean rooms can cost over a million dollars. Aside from the equipment, even the materials used to produce carbon nanotubes can be expensive i.e. the current cost of catalysts for CVD production for single-walled carbon nanotubes represents as much as twenty to fifty percent of the cost of the product.⁹⁷ In the future, the catalyst cost for the CVD process will need to be reduced in order to drive down the cost of carbon nanotube production. Another high cost is the nanotechnology workforce itself. Many companies in the carbon nanotube composites industry are still doing a lot of basic research. This research requires workers who have higher educations, which are, in turn, compensated higher than most workers.

2.4 PATENTS

The patent challenges faced by the nanotechnology industry are not particularly unique from any other new, large, emerging technology. But, there are still obstacles. At the present, it takes about 4 years, from application to approval, to obtain a patent in

⁹⁶ World Technology Evaluation Center, Inc. (2007, June). *International Assessment of Research and Development of Carbon Nanotube Manufacturing and Applications*. Retrieved July 9, 2007, from http://www.wtec.org/cnm/CNM_final_report.pdf

⁹⁷ *ibid.*

nanotechnology, which is about double the time it takes for most patents. This is possibly due to the shortage of patent examiners well suited to deal with nanotechnology patents. One concern among many nanotechnology companies is whether building block patents, or fundamental patents, of the field are novel and not too obvious. Whether or not an invention is obvious or not can be difficult to define, since it mixes technical aspects with the legal framework of laypersons (the judge or jury). With a new technology, it is easier to show that an invention is novel or unexpected to the field. This is especially true with nanotechnology, since nanoscale materials behave differently than the same substances in their bulk state, and any developed properties will generally be unexpected.⁹⁸ Patenting very fundamental aspects of nanotechnology could become a barrier to further developments and it could restrict the growth of the industry, if companies fear infringing on the patents.^{99,100}

There is also the growing problem of cross-patenting. For example, one patent could be for a polymer with carbon nanotubes of 10 nanometers, and another patent could be for the same polymer with carbon nanotubes of 100 nanometers or less. The two patents overlap in some claims. The other overlapping problem would include two institutions achieving the same discovery simultaneously. To prevent this, it is essential for inventors to preserve all invention records.¹⁰¹ Another element that adds to this confusion is that some nanotechnology terms have not been officially defined.

2.5 LACK OF KNOWLEDGE FOR ESTABLISHING STANDARDS, REGULATIONS, A LIFE CYCLE ASSESSMENT, AND A RISK ASSESSMENT FOR CARBON NANOTUBE COMPOSITES

One of the largest obstacles carbon nanotube composite companies face is the lack of knowledge about them, how they should be evaluated, and how they should be handled. There are currently very few standards for carbon nanotubes and carbon nanotube composites, and there is no life cycle assessment or risk assessment. All are

⁹⁸ Busnaina, A. (2007). *Nanomanufacturing Handbook*. Boca Raton: CRC Press.

⁹⁹ *ibid.*

¹⁰⁰ Berger, M. (2007). Growing Nanotechnology Problems: Navigating the Patent Labyrinth. *Nanowerk LLC*. Retrieved July 2, 2007, from <http://www.nanowerk.com/spotlight/spotid=1367.php>

¹⁰¹ Busnaina, A. (2007). *Nanomanufacturing Handbook*. Boca Raton: CRC Press.

important, not only so that companies can make sure that their products and workers are safe, but so that the consumer feels safe about buying them. Standards, risk assessment, and life cycle assessment can influence industry in their product design, marketing, development, and manufacturing, and they can be used to inform the public. This section will cover the issues dealing with the lack of standards, life cycle assessment, and risk assessment.

2.51 STANDARDS AND REGULATIONS

Currently, there are very few standards or regulations for nanotechnology or carbon nanotubes, but several organizations have standards in development. At the present, companies probably will not see a complete list of standards or regulations for the carbon nanotube industry for the next ten years (especially toxicology regulations), but the effort has begun. Aside from environmental, health, and safety standards and regulations, the carbon nanotube composite industry needs standards to quantify the quality of carbon nanotubes¹⁰² so that companies can compare nanotubes more clearly. The Environmental Protection Agency (EPA) is working on nanotechnology regulations, and the Institute of Electrical and Electronics Engineers (IEEE) P1650 committee, American Society of Testing and Standards (ASTM) E56 committee, and the International Standards Organization (ISO) are all working on different nanotechnology standards.

Many companies find the lack of standards, regulations, and information regarding environment, health, and safety of carbon nanotubes to be a barrier to the market because they cannot assure the public and their employees that their products are completely safe. Most carbon nanotube composite companies have taken conservative approaches to handling carbon nanotubes by using personal protective equipment and keeping carbon nanotubes contained in liquids or other materials as much as possible, but the question still remains—is it enough?

Without standards and adequate knowledge of the safety of carbon nanotubes, companies are forced to deal with what the media publishes regarding the environment,

¹⁰² World Technology Evaluation Center, Inc. (2007, June). *International Assessment of Research and Development of Carbon Nanotube Manufacturing and Applications*. Retrieved July 9, 2007, from http://www.wtec.org/cnm/CNM_final_report.pdf

health, and safety, which influences their customers and the public. Even though synthesized nanoparticle safety has been of concern only within the past couple of decades, the public can be misled to think that objects and particles on the nanoscale are something new, which is not true. Nature has been producing its own nanoparticles in the form of volcanic ash, tiny salt crystals near oceans¹⁰³ and candle flames¹⁰⁴ well before the current nanotechnology debate began. People have also created their own nanoparticles in the past through welding fumes and diesel exhaust.¹⁰⁵ The primary matter is that the environmental, health, and safety effects of carbon nanotubes are not known and much more knowledge needs to be obtained before carbon nanotubes can be believed to be safe or hazardous.

Even though there are not many nanotechnology standards to date, companies producing products using nanotechnology must adhere to the regulations of their products' industry. For example, a company that puts nanoparticles in its cosmetics still abides by U.S. Food and Drug Administration regulations for cosmetics. Some sources imply that companies that use nanotechnology to make their products are not complying with these regulations, which is not really true. Most companies are quite conservative with environmental, health, and safety issues.

2.52 RISK ASSESSMENT (RA)

Unfortunately, of the billion-dollar budget that the U.S. government spends on nanotechnology each year, only about four percent is spent on risk assessment.^{106,107} A risk assessment (RA) has not yet been developed for carbon nanotubes or carbon nanotube composites. A RA quantifies the probability of a harmful effect on people or the environment under certain conditions, and identifies product specifications, handling practices, disclosures, and use limits that are necessary to assure that risks from the

¹⁰³ Nanotechnology: Untold Promise, Unknown Risk. *Consumer Reports*, July 2007, 40-45.

¹⁰⁴ AZoNanotechnology.com. (2007). *Carbon Nanotubes—Overview of Properties, Classification, Fabrication, and Synthesis*. Retrieved July 2, 2007, from <http://www.azonano.com/details.asp?ArticleID=1199>

¹⁰⁵ Nanotechnology: Untold Promise, Unknown Risk. *Consumer Reports*, July 2007, 40-45.

¹⁰⁶ *ibid.*

¹⁰⁷ Getting Nanotechnology Right: Improving the Next Industrial Revolution. (2006). Handouts to the House and Senate. *Environmental Defense*.

product are within an acceptable range.¹⁰⁸ Such an assessment is necessary, especially since most of the current regulatory measures only deal with a single event—a cause and its effect—and do not consider the life cycle of the products or its interactions with other events.¹⁰⁹ The International Risk Governance Council (IRGC) is currently working on the risk assessment of nanotechnology. So far, the organization has released a white paper, conducted surveys to identify the role of government, industry, research organizations and non-government organizations, and has held a conference on this topic. What the IRGC has accomplished is a great foundation for creating a RA, but more testing, understanding of metrics, research into disposal, dispersion, waste treatment, exposure methodologies, probability and severity of risk, communication, and education regarding environment, health, and safety needs to be done.¹¹⁰

2.53 LIFE CYCLE ASSESSMENT (LCA)

A life cycle assessment (LCA), which is a comprehensive analysis tool that studies a material's ecosystem and health impacts across its life cycle, has not been developed for carbon nanotubes or carbon nanotube composites. A LCA is a “cradle to grave” look at the life cycle of a specific substance, and can be helpful in understanding a material's properties, toxicity, and decomposition. A LCA is a more holistic approach to evaluating the environment, health, and safety of nanotechnology than an RA. The International Standards Organization's (ISO) 14040 is an applicable framework for creating an LCA for nanomaterials, but some operational issues need to be addressed in more detail.¹¹¹ For instance, looking at large-scale applications of nanomaterials may be different than small-scale applications. Creating a LCA (and a RA) will most likely be

¹⁰⁸ Greenwood, Mark. (March 2007). Thinking Big About Things Small: Creating an Effective Oversight System for Nanotechnology. *Woodrow Wilson International Center for Scholars, Project on Emerging Nanotechnologies*, Retrieved July 2, <http://www.nanotechproject.org/110/31407-thinking-big-about-things-small>.

¹⁰⁹ Renn, O., & Roco, M.C. (2006). Nanotechnology and the Need for Risk Governance. *Journal of Nanoparticle Research*, 8, 153-191.

¹¹⁰ *ibid.*

¹¹¹ Proceedings of the Workshop on Nanotechnology and Life Cycle Assessment. (March 20 2007). *Woodrow Wilson International Center for Scholars*. Retrieved July 20, 2007, from <http://cordis.europa.eu/nanotechnology>.

complex for nanotechnology, since analysis and testing for toxicity may be different than normal toxicity routines, due to the particles small sizes and different shapes.¹¹²

2.54 BARRIERS TO ESTABLISHING STANDARDS, REGULATIONS, RA, AND LCA

The following are barriers to establishing standards, regulations, RA, and LCA:

- *Classification.* There is a disagreement as to how to group different kinds of nanoparticles. For example, the National Academy of Science groups engineered nanoparticles into 4 groups: metal oxides, nanoclays, nanotubes, and quantum dots. However, the U.S. Environmental Protection Agency (EPA) groups nanomaterials into carbon-based materials, metal-based materials, dendrimers, and composites.¹¹³
- *Definition.* There is no universally accepted definition of nanotechnology. However, the NNI defines nanotechnology as “the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications.”
- *Properties of materials vary depending on size.* At the nanoscale, fundamental properties of substances differ significantly from the materials’ bulk properties.
- *Dosimetry.* Nanoparticles have a much higher surface area per volume than larger particles and substances. Since most reactions involving solids occur at the surfaces where chemical bonds are incomplete, nanoparticles are more reactive than larger particles. This poses the question of whether surface area would be a better measure of dosage, as opposed to mass.
- *How the body responds to exposure by nanomaterials.* It is uncertain if nanoparticles enter the body and where they go. Depending on the nanoparticles size, different parts of the body can absorb the nanoparticles.
- *Toxic Substances Control Act (TSCA) Compound Classification.* The TSCA does not always allow engineered nanoparticles to be viewed as new compounds, since

¹¹² Renn, O., & Roco, M.C. (2006). Nanotechnology and the Need for Risk Governance. *Journal of Nanoparticle Research*, 8, 153-191.

¹¹³ Bell, T.E., Understanding Risk Assessment of Nanotechnology. *National Nanotechnology Initiative*. Retrieved July 20, 2007, from nano.gov/Understanding_Risk_Assessment.pdf

many times their molecular structure is the same as the bulk form of the nanoparticles, even though their properties and toxicities can vary drastically.

- *Purity of Nanoparticles.* Until the purity of nanoparticles is evaluated, the actual effects of the nanoparticles on health and safety are difficult to quantify because the effects may be from the nanoparticles or from the impurities that are attached to the nanoparticles.
- *How to test for toxicity.* It is unknown if testing on animals or invetro methods are true approximations of how humans will react to exposure to nanoparticles.
- *Risk criteria.* It is uncertain which environmental, health, and safety effects of a material constitute a problem, and how much risk is acceptable.¹¹⁴

¹¹⁴ Greenwood, Mark. (March 2007). Thinking Big About Things Small: Creating an Effective Oversight System for Nanotechnology. *Woodrow Wilson International Center for Scholars, Project on Emerging Nanotechnologies*, Retrieved July 2, <http://www.nanotechproject.org/110/31407-thinking-big-about-things-small>.

3. CASE STUDY: ZYVEX¹¹⁵

3.1 COMPANY OVERVIEW

Zyvex Instruments was founded by James Von Ehr, II in 1997 and was the first molecular nanotechnology company. It is private, and considered to be one of the most stable and successful nanotechnology companies in the United States. It has been very effective in the nanocomposite materials sector, and also provides tools, instrumentation, and applications for the semiconductor and advanced research markets. Some of its carbon nanotube composite applications are present in sporting equipment and sail boat masts. Zyvex sees a ten to thirty-five percent increase in a product's properties (such as strength, stiffness, thermal conductivity, electrical conductivity etc.) by adding a mere fraction of a percent of carbon nanotubes to the material. Along with Zyvex Instruments, three spin-off companies have recently been established to focus on individual products, markets, customers, and new technologies: Zyvex Performance Materials, Zyvex Labs, and Zyvex Asia. Zyvex's headquarters is in Richardson, Texas.

3.2 SCALING-UP

Von Ehr has identified two main problems Zyvex has had in scaling-up its production. The first problem is that the carbon nanotubes do not disperse themselves uniformly in the matrix, and experience phase separation, aggregation, and poor adhesion to the host material. To counteract this problem, Zyvex invented Kentera™, a coating for carbon nanotubes that helps them bond to the material as well as disperse. Kentera™ is made up of two components: one part has a strong affinity to attach itself to the carbon nanotubes, while the second part, which is different depending on the type of host material, makes the carbon nanotube stick to the matrix material.

The second scaling-up issue in production is the mixing of the carbon nanotube concentrate. Carbon nanotubes tend to cluster together, and must be mixed in order to separate the tubes to distribute them evenly in the substance. Due to the unique properties of carbon nanotubes, it took Zyvex years to develop an appropriate mixing process. Von Ehr noted that an important component of Zyvex is teaching their customers about the

¹¹⁵ J. Von Ehr (personal communication, July 12, 2007)

technology and techniques they use because many clients are not accustomed to working with carbon nanotubes, which abide by different principals and methods than other materials.

Another problem that many companies have in scaling-up production, is purchasing or producing quality, similar nanotubes. Zyvex purchases most of its carbon nanotubes from Arkema, Inc., a French company, which Zyvex has found to have carbon nanotubes of good, reliable quality. In response to the challenge of finding carbon nanotube producers that are able to consistently make quality carbon nanotubes, Zyvex created the Zyvex Supply Chain Certification program for carbon nanotube suppliers. The program was started in 2004, and it verifies quality and batch-to-batch consistency using market-accepted analytical tests.¹¹⁶ The certification is a very important tool, since there are currently no standards for evaluating the quality of carbon nanotubes. Without these standards, it can be difficult to compare nanotubes from different suppliers, and buyers are often unsure of what they are purchasing.

3.3 CHALLENGES IN COMMERCIALIZING SINGLE-WALLED CARBON NANOTUBES

Zyvex works with both multi-walled and single-walled carbon nanotubes, but finds itself using more of the multi-walled nanotubes per its customers' request. While single-walled nanotubes possess superior properties, they are harder to process and manipulate. They tend to bundle together, and are more difficult to disperse. "Customers usually aren't willing to pay 100 times more for a product when the performance isn't 100 times better," Von Ehr said, "and using single-walled carbon nanotubes doesn't always provide a performance boost that is in line with their increased cost."¹¹⁷ With the exception of a few uses, multi-walled carbon nanotubes will most likely dominate the nanocomposite industry until single-walled carbon nanotubes become dramatically cheaper and easier to manipulate.

¹¹⁶ Zyvex Instruments (June 25, 2004). Zyvex's Press Release. (<http://www.zyvex.com/News/CNTAdditives.html>). Press Release. Retrieved on July 6, 2007

¹¹⁷ J. Von Ehr (personal communication, July 12, 2007)

3.4 ENVIRONMENT, HEALTH, AND SAFETY

The environmental, health, and safety effects of contact with carbon nanotubes are largely unknown. Zyvex takes a conservative approach to this issue, and treats any nanoparticles as if they could be toxic, even though there is no solid evidence showing that they are. Such precautionary measures include: having the correct personal protective equipment for all workers and minimizing airborne carbon nanotubes by using methods such as immersing them in a liquid that will contain them.

Zyvex is an active participant in stakeholder meetings with the U.S. government. It sends a company representative, if it is not Von Ehr himself, to many workshops, conferences, and meetings to partake in the government and private industry's development of health and safety standards for nanotechnology. Von Ehr is an invited member of the Nanotechnology Technical Advisory Group (NTAG) to the U.S. President's Council of Advisors on Science and Technology (PCAST).¹¹⁸

3.5 EMPLOYEES

One obstacle that Zyvex has faced is that many of its workers are not U.S. citizens; a majority of Zyvex's employees are Indian, Chinese, and Eastern European. Some of Zyvex's employees have had problems getting H-1B visas (a primary work visa for technically-trained workers in the U.S.), since Congress decreased the number of H-1B visas from roughly 124,000 per year in 2005 to 65,000 per year in 2006. In 2007, after only two days of accepting H-1B visa applications, the 65,000 quota was reached, and approximately half of H-1B visa applicants were not awarded.¹¹⁹ A number of students in U.S. science and engineering graduate schools are foreign-born, and as a result, many U.S. nanotechnology companies hire foreign workers, who have completed a U.S. education. When the foreign workers are denied H-1B visas, they must return to their original country, where they then use their education there.

¹¹⁸ Zyvex Instruments (April 4, 2007). Zyvex's Press Release. (<http://www.zyvexpro.com/news/ZPMPR070404.htm>). Press Release. Retrieved on July 6, 2007

¹¹⁹ O'Brien, C. (2007, July 15). How Many H-1B Workers? Counts Vary. *Mercury News*. Retrieved July 24, 2007, from http://www.mercury.new.com/business/ci_6380617?nclick_check=1

Another workforce problem for Zyvex is related to the U.S. State Department's International Traffic in Arms Regulations, which restricts who has knowledge on certain applications. The government has classified some of Zyvex's breakthroughs as defense-related, so foreign employees who invented the technology are no longer permitted to work on their discoveries any further. Von Ehr said, "It's challenging because on one hand we are mandated to not discriminate when we hire, but then our foreign workers aren't allowed to use the technology they develop."¹²⁰

3.6 NETWORKING AND PARTNERSHIPS

As a research-oriented company, Zyvex has partnered with several schools around the country, such as the South Dakota School of Mines, Texas State Technical College, University of Texas at Dallas, Baylor University, Del Mar College, and University of California at Berkeley, for research capabilities and future workers. In Texas, Zyvex established the Nanotechnology Workforce Development Initiative to develop a pipeline of potential workers in nanotechnology. To do this, it approached the state and convinced the Texas government to sponsor about 25 interns to work at Zyvex and other local companies. Currently, four of those interns hired from this initiative are still working at Zyvex.

Another program that was established in Texas, with Von Ehr's assistance, is the Texas Nanotechnology Initiative (TNI). The goal of TNI is to foster awareness and growth of nanotechnology in Texas, in effort to cultivate knowledge and business in the state. The program brings together industry, government and academia to discuss the development of nanotechnology within the state. Beginning in 2002, the group has met quarterly, and almost all of the funding came from personal donations by Von Ehr. From TNI, a new organization has been formed entitled, "Strategic Partnership for Research in Nanotechnology" (SPRING). SPRING is a Texas alliance to develop joint research, education, technology transfer, and community outreach in nanotechnology.¹²¹

¹²⁰ J. Von Ehr (personal communication, July 12, 2007)

¹²¹ Strategic Partnership for Research in Nanotechnology. (2006, February 19). *Nano @ the Border*. Retrieved July 15, 2007, from <http://cohesion.rice.edu/naturalsciences/nanokids/mission.cfm>

Zyvex has also sponsored several outreach programs, one of which is called NanoKids™.¹²² The program has been developed by Rice University, and caters to kids in grades 6-12. NanoKids™ consists of an online interactive program and a DVD that teaches kids the basic principals of nanotechnology.¹²³ Sponsoring such outreach programs raises awareness about nanotechnology and the needs for a future nanotechnology workforce.

3.7 GOVERNMENT GRANTS

As a small business, Zyvex is eligible for several government research grants, and has received several grants from the Small Business Innovation Research (SBIR) program and one grant from the National Institute of Standards and Technology's (NIST) Advanced Technology Program (ATP). Several federal agencies award SBIR grants to small businesses to do research and development on topics related to the department's mission. The award is intended to stimulate technological innovation and increase private sector commercialization of federal research and development. The National Institute of Standards and Technology's ATP grants are usually larger, and are intended to help companies commercialize technology that meets an industry's needs, not necessarily the government's need. This is one of the characteristics that distinguishes an ATP grant from an SBIR grant. Of the two types of grants, Von Ehr felt the ATP grant was the most helpful to small nanotechnology businesses.

- In 2001, Zyvex was awarded a NIST ATP grant, which was for \$25 M over 5 years. The objective of the grant was to develop low-cost assemblers for micro and nanoscale components and subsystems, which includes nanoelectromechanical systems (NEMS) and microelectromechanical systems (MEMS).
- In 2002, Zyvex received a DOE SBIR award for assembling and testing stick-slip linear actuators built within mini-sized piezotubes.

¹²² Zyvex. (2007). Academic Alliances. Retrieved July 15, 2007, from <http://www.zyvex.com/Alliances/academic.html>

¹²³ NanoKids. (2003). *Mission*. Retrieved July 15, 2007, from <http://cohesion.rice.edu/naturalsciences/nanokids/mission.cfm>

- A NASA SBIR grant was awarded to Zyvex in 2003, with the goal of creating a high-strength, low-weight material using carbon nanotubes. Zyvex was awarded this grant from a Phase I to a Phase II. This research led to technology that is used in some of its composites now, i.e. the baseball bats, bicycles, and hockey sticks Easton Sports makes using Zyvex materials.
- Also in 2003, Zyvex was awarded a DARPA SBIR award with the goal of miniaturizing a scanning electron microscope, which went through a Phase I.

Zyvex has also been involved in other SBIR grants as a partner with other companies.

3.8 ZYVEX ASIA

Zyvex has recently opened up a division in Singapore, a country with less regulated worker restrictions than the U.S. Zyvex has found the Singapore government to be very ambitious, focused, and eager to help Zyvex with its commercialization.

Singapore even has a program that pays a portion of the salaries for a few Singaporeans to come to the U.S. to be trained at Zyvex under temporary visas. After completing their training, the employees will return to Singapore to work at Zyvex Asia. The Singapore government has also helped arrange partnerships with some of its universities (such as National University of Singapore,) and research institutes (such as the Institute for Materials Research and Engineering).

4. DISCUSSION AND RECOMMENDATIONS

In a survey of nanotechnology companies conducted by NSF in 2005, nearly ninety-five percent of the respondents favored government involvement in the commercialization of nanomanufacturing.¹²⁴ Not all of the challenges in commercializing carbon nanotube composites, discussed in section 2 of this paper, can be solved by public policy, but the federal government and state governments can help to alleviate some of the challenges. It is noted that the following suggestions can apply to the commercialization of all fields of nanotechnology, not solely carbon nanotube composites.

4.1 RECOMMENDATIONS FOR THE FEDERAL GOVERNMENT

In the past 6 years, through the National Nanotechnology Initiative, the U.S. federal government has spent billions of federal dollars for nanotechnology research. While the carbon nanotube composite industry still needs funding for basic research, the government now must find a way to assist companies with commercialization and to address more issues dealing with standards and environment, health, and safety that will arise as the nanotechnology industry progresses.

- ***Increase funding of environmental, health and safety research through NNI.*** More funding for NNI research grants in environment, health, and safety would help advance the amount of knowledge that we currently have in those areas.
- ***Increase toxicity research at EPA and USFDA.*** The EPA and USFDA have the responsibility of determining the toxicity of carbon nanotubes. Neither agency has the funds necessary to do the amount of research required.
- ***Increase funding of nanotechnology (particularly carbon nanotube composites) through the Advanced Technology Program (ATP) and Small Business for Innovation and Research (SBIR) programs at the Federal Science and Technology Agencies.*** More research grants relating to carbon nanotube

¹²⁴ Busnaina, A. (2007). *Nanomanufacturing Handbook*. Boca Raton: CRC Press.

composites would advance technology in the area, and possibly create products that can be commercialized.

- ***Increase number of nanotechnology cases expedited at USPTO.*** Due to the emerging nature of the nanotechnology industry, nano-related patent cases must be expedited through the USPTO. This will ensure fewer cross-patenting issues.

4.2 RECOMMENDATIONS FOR STATE GOVERNMENTS

As discussed in section 1.7, many states have already taken steps to attract nanotechnology businesses to their states, as they have the primary responsibility of promoting commerce within their states. The following are recommendations on what states can do to foster commercialization of nanotechnology. Many of these cater toward the development of small or start-up nanotechnology businesses.

- ***Provide avenues for venture capitalists and start-up companies to interact.*** State governments should organize events to bring together start-up businesses with venture capitalists or angel investors. Both parties will benefit from these interactions.
- ***Tax-free bonds.*** Tax-free bonds for nanotechnology would be especially helpful to businesses just starting, since they are more attractive to investment bankers.
- ***Reduced capital gains tax.*** The carbon nanotube composite industry is not incredibly profitable yet, since the technology is new, and it is hard for companies to stay afloat. A reduced capital gains tax would help companies keep more of their profits.
- ***Tax credits for capital investments.*** With the extraordinarily high cost of equipment and facilities required for a company in the carbon nanotube industry, any financial assistance in covering these costs would help.
- ***Provide mentorship and business planning assistance to large and small companies.*** Companies, large and small, need networking opportunities to discuss their challenges in commercializing and manufacturing carbon nanotube composites. Partnerships between industry and universities are essential to a properly trained nanotechnology workforce.

- ***Establish state level government research grants.*** Similar to the federal government's ATP and SBIR programs, states should establish government research programs. The developments from these grants could be commercialized.
- ***Promote research centers.*** States that have nanotechnology research centers in existence need to advertise their facilities to companies and universities in their state and region. With these centers fully utilized, there could be more discoveries and new businesses.
- ***Provide workforce training programs.*** With the carbon nanotube composite industry expected to grow rapidly, workforce training programs are needed. For example, the California Institute of Nanotechnology has paired with the International Association of Nanotechnology to establish professional training certificates in nanotechnology. The U.S. Department of Labor is partially funding this effort, and the program will assist three types of workers: business executives and professionals, scientists or engineers, and apprentices.
- ***Educate the public.*** The more people that know about carbon nanotubes and their potential, the easier it is for states to develop programs to help the industry. In addition, the public would be more aware of the employment and investment opportunities within the industry.
- ***K-12 outreach.*** States should implement nanotechnology curriculum into their classrooms, which will help the students become more aware of nanotechnology. This will present the idea to them that nanotechnology could be a career for them in the future.

5. GLOSSARY

Agglomeration—tendency for carbon nanotubes to “stick” together

Carbon nanotube—cylinder of graphite carbon atoms with the diameter on the order of a nanometer

Catalyst—a substance that causes an accelerated chemical reaction without being affected itself

Composite—a material made from two or more constituent materials

Cross-patenting—multiple patent applications attempting to patent the same technology

Current density—measure of the density of electrical current

Electrical conductivity—a measure of a material’s ability to conduct an electric current

Electrodes—electrical conductor used to make contact with a metallic part of a circuit

Fullerenes—molecules entirely composed of carbon atoms

Functionalization—a coating for carbon nanotubes that is used to help them disperse and adhere to the matrix material

Isotropic—uniform properties throughout a material

Life cycle assessment— a comprehensive analysis tool that studies a material’s ecosystem and health impacts across its life cycle

Matrix—the material that surrounds and supports the carbon nanotubes in a composite

Microelectromechanical systems (MEMS)—devices or machines on the microscale

Multi-wall carbon nanotube— several imbedded one atom thick cylinders of graphite carbon atoms with a diameter on the order of a nanometer

Nanoelectromechanical systems (NEMS)—devices or machines on the nanoscale

Nanoparticle—a particle with at least one dimension of less than 100 nanometers

Nanotechnology—the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications

Risk assessment— quantifies the probability of a harmful effect on people or the environment under certain conditions, and identifies product specifications, handling practices, disclosures, and use limits that are necessary to assure that risks from the product are within an acceptable range

Scale-up—the process of transitioning a production process from a small-scale to a large-scale

Single-wall Carbon Nanotube—a one atom thick cylinder of graphite carbon atoms with a diameter on the order of a nanometer

Thermal conductivity—the property of a material that indicates its ability to conduct heat

Transition metal—an element whose atom has an incomplete d sub-shell, or which can give rise to cations with an incomplete d sub-shell

Young's modulus—the measure of the stiffness of a material

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