Implications of a Nano-Energy World: An Assessment of the Health Risks of Carbon Nanotubes

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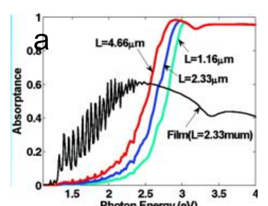
Nanomaterial Outlook Positive but Uncertainties Exist

- Increasing focus on the installation carbon-free energy sources
  - Forecasts renewable capacity addition of 2000 GW globally by 2035
  - Wind and solar PV account for 1200 GW and 600 GW, respectively
- Nano-enabled devices almost certainly play a role in future energy portfolios
  - Nanomaterials exhibit unique properties that differ from bulk
  - Applicable in areas such as solar, wind, storage, and catalysis
  - Pilot studies underway studying nano-composites in wind turbine blades
- Production and sales of nanomaterials projected to increase
  - Total value of nano-enabled products estimated at $254 billion in 2009
  - Commercial carbon nanotube production, 2500 tons in 2010
- Little is known about long term exposure of nanomaterials or probability of inhalation
- Health risks can impede widespread implementation of nanomaterials

NANOMATERIAL ENERGY APPLICATIONS

SOLAR:

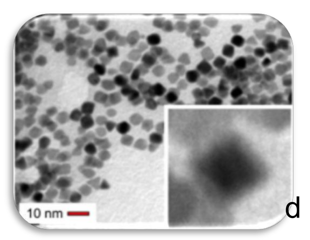


Enhanced Light Absorption

Tunable Bandgaps

STORAGE AND FUEL CELLS:

Supercapacitors[c]



Enhanced Reaction Rates for Pt NPs

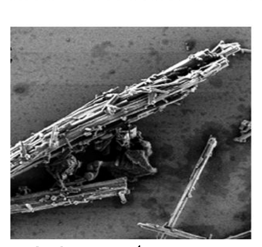
a -Hu, L. and G. Chen (2007); c- Amama, P. B., C. L. Pint, et al. (2008).; Lee, I., R. Morales, et al. (2008)

Review of Inhalation Health Effects of Carbon Nanotubes

CNTs are likely to be inhaled in an industry setting, intensive studies regarding toxicity from inhalation have focused on the effects of CNTs in the lung cavities. Studies can be organized into the following:

- **Intratracheal instillation studies**: analyze the response that the body has to direct introduction of CNTs in the lung cavity
- **Inhalation studies**: study the entire process of entering the body, moving through the body and entering the lungs

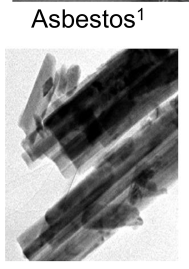
Inhalation studies of CNTs may provide more definitive information about their potential toxicity in humans better represent the exposure and correlated health effects.



Asbestos[1]

Toxicity of CNTs has been attributed to the following:

- Due to long and thin geometry, CNTS can behave like asbestos and other pathogenic fibers which induce inflammation and granuloma formation in the lung. Due to carbon composition, are expected to be biopersistent similar to graphite

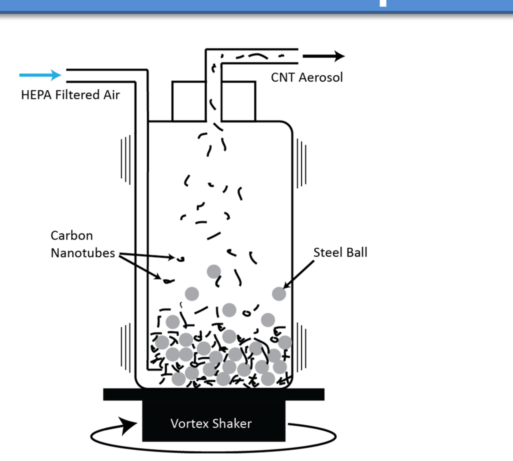


CNT[1]

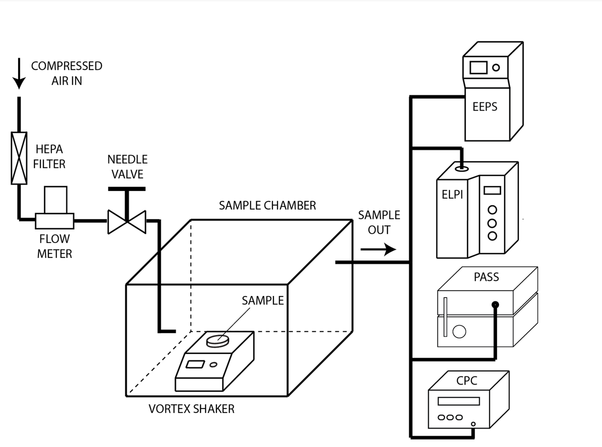
Shvedova *et al.* estimate that workers may be at risk of developing lung lesions if exposed to SWCNT over a period of 20 days at the current deposition and clearance of MWCNTs from the conducting airways of mice following the inhalation exposure OSHA PEL for graphite (5 mg/m^3)[2]

1. P. Wick, *et al.*, "The degree and kind of agglomeration affect carbon nanotube cytotoxicity," *Toxicology Letters,* vol. 168, pp. 121-131, 2007.
2. A. A. Shvedova, *et al.*, "Unusual inflammatory and fibrogenic pulmonary responses to single-walled carbon nanotubes in mice," *American Journal of Physiology - Lung Cellular and Molecular Physiology,* vol. 289, pp. L698-L708, November 1, 2005

Experimental Setup



Schematic of CNT Agitation



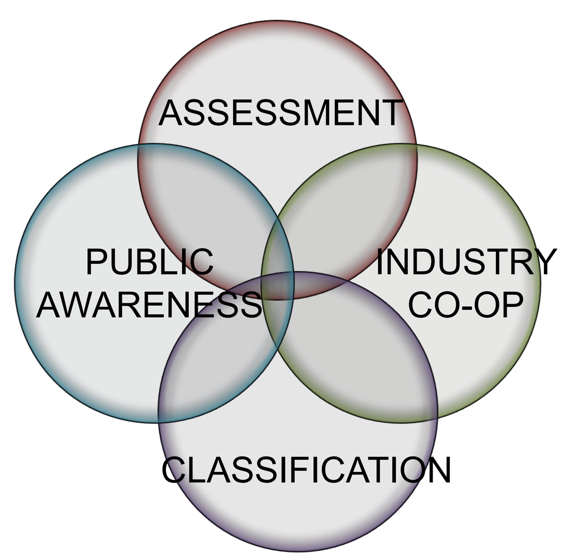
Schematic of Fracture and Handling Testing

Key Findings

The challenge of developing a renewable energy sector capable of meeting the world's growing demand requires significant advancements in energy technologies as well as an acute political role in the development, commercialization, and adoption process. Integral to the success of a variety of energy technologies is advancements in the applications of nanomaterials. In many ways, nanomaterials are not only the parts but also the means to a future capable of sustainable industrial growth. Our team believes that if nanomaterials are in fact the building blocks of our energy future, then greater attention should be given to any uncertainties surrounding the social and environmental implications. While recently, the United States has paid significant attention to potential environmental health and safety concerns surrounding nanomaterials, there exist several policy barriers to constructing effective regulation. These policy barriers include the complexity of classifying nanomaterials separate from their base chemicals, an inadequate assessment process in regards to risk and life cycle analysis, public awareness, and industry cooperation.

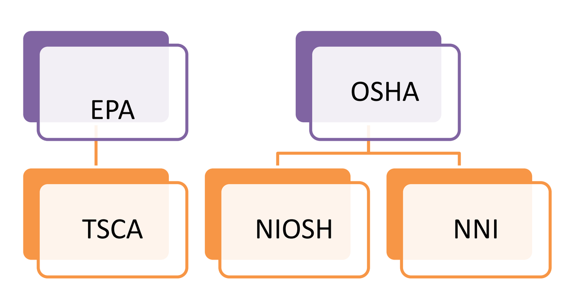
In hopes of filling in some of the apparent knowledge gaps in understanding and analyzing the environmental health and safety concerns surrounding nanomaterials, our team examined a nanomaterial touted for use in advanced energy technologies, carbon nanotubes. Studies have suggested that the inhalation of carbon nanotubes may pose a health risk. Many studies have likened the health effects, such as inflammation and lung lesions, to that of asbestos. To assess the potential health effects associated with carbon nanomaterials we conducted a series of experiments to characterize common exposure mechanisms in terms of airborne nanotubes. In these experiments we measured exposure levels in terms of number concentration (part./cm³) and mass concentration (mg/m³) for vertically aligned carbon nanotubes and dispersed single and multi-walled carbon nanotubes. From our study we concluded that carbon nanotubes may pose an inhalation risk to people in a manufacturing or laboratory setting. We find that more work needs to be done to understand the risk and develop test processes that can be used to understand any nanomaterial inhalation risk. Additionally we believe new exposure levels need to be set for nanomaterials to secure a safe working environment and ensure that the next generation of clean energy does not reduce levels of greenhouse gas emissions at the expense of workers' health.

Policy Barriers to Regulating Nanomaterials



Review of the current literature, including government and non-government agency reports, highlight four major barriers to constructing environmental health and safety (EHS) regulation for nanomaterials.

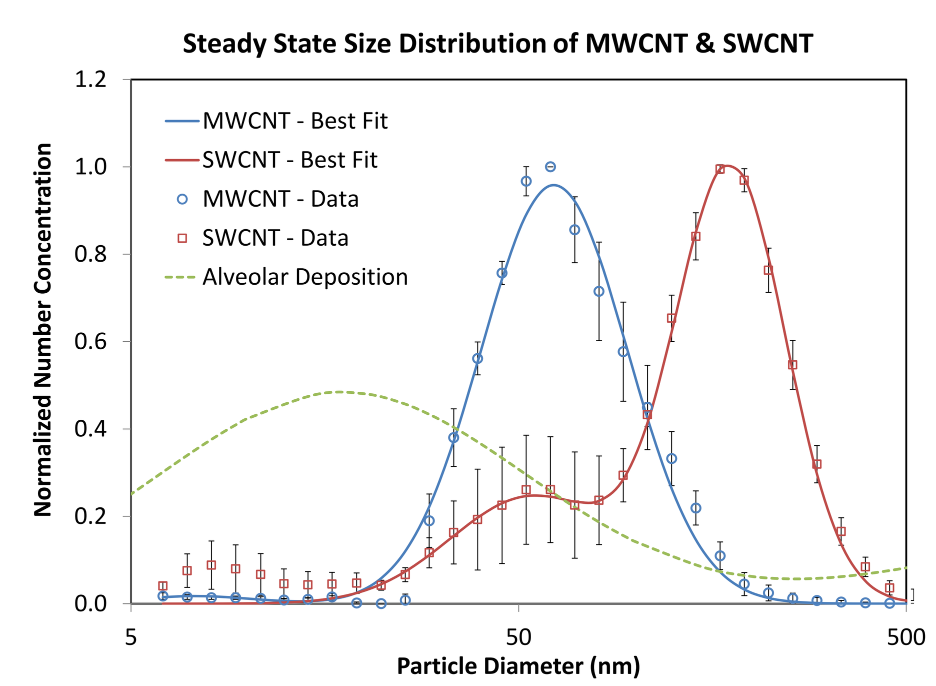
These include: Assessment, Public Awareness, Industry Cooperation, and Classification.

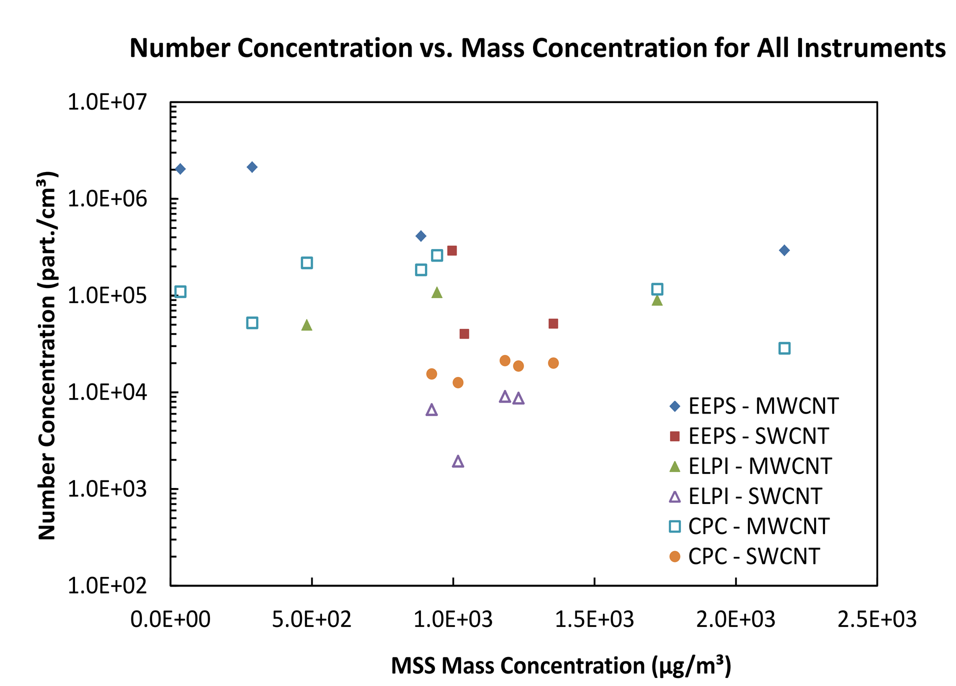


The regulatory agencies charges with evaluating the EHS implications of nanomaterial and regulatory usage are the EPA, TSCA, and OSHA.

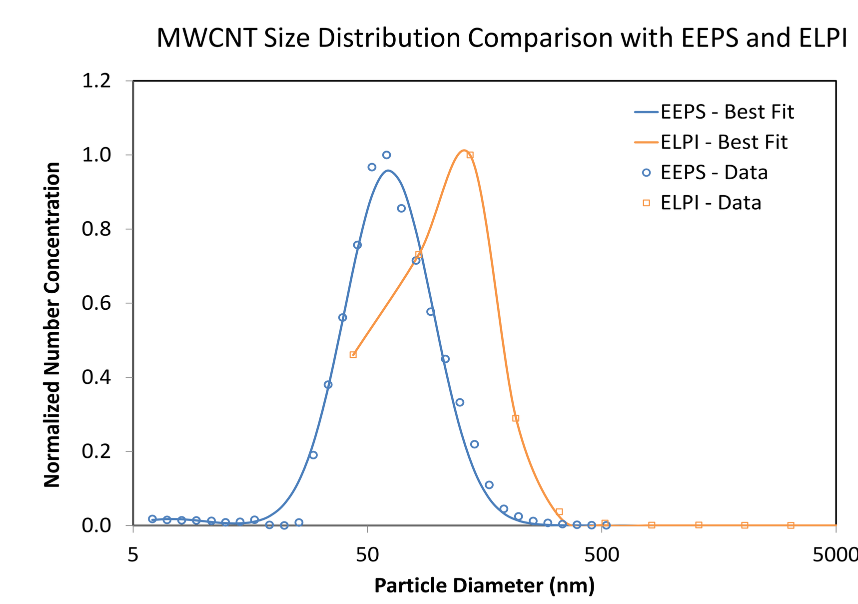
These three agencies are supported by the NNI and NIOSH.

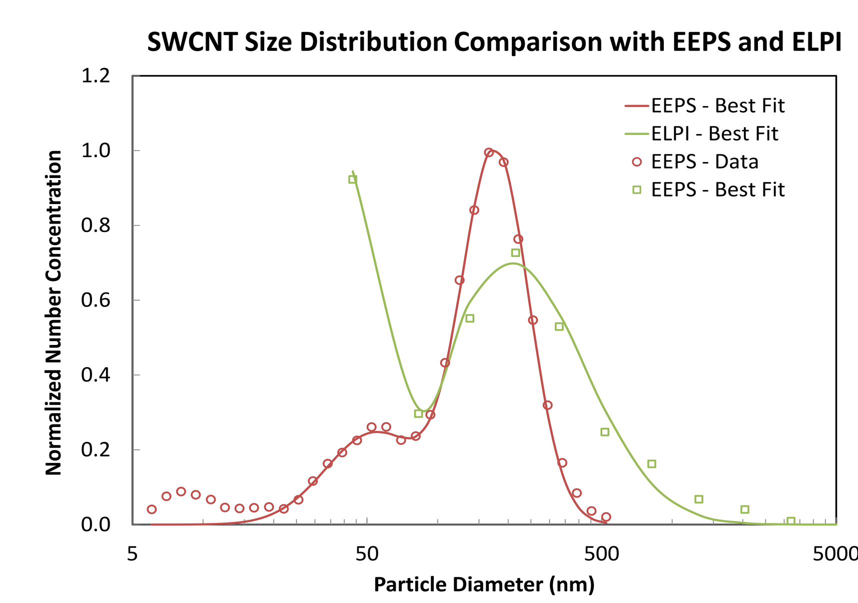
Results

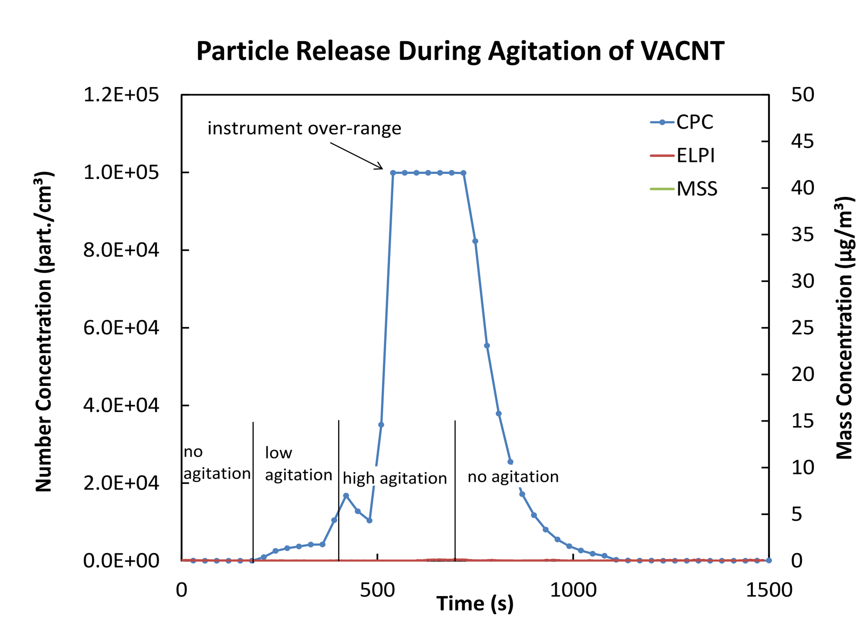


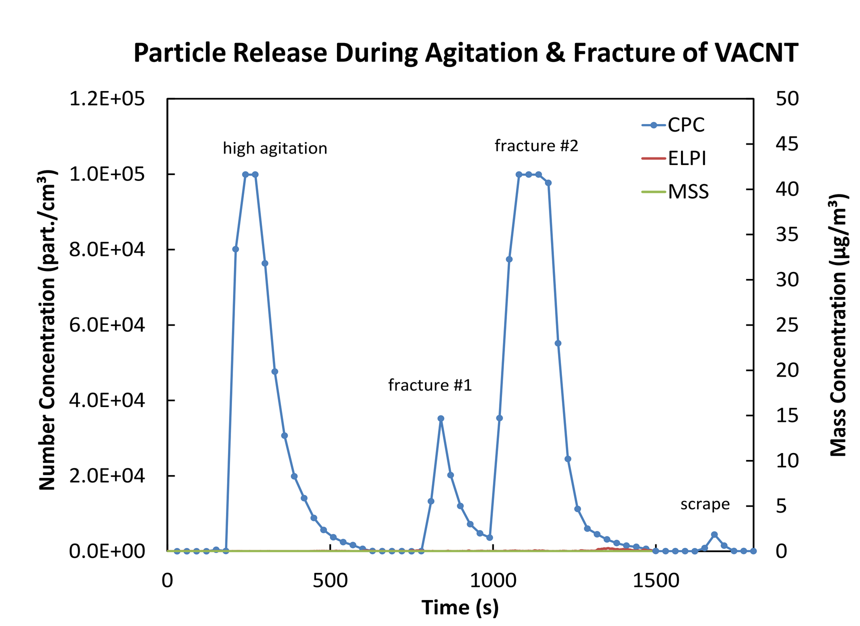


Results (cont.)









Discussion

While the MWCNTs are six times larger than the SWCNTs in terms of an equivalent physical diameter, they appear to be approximately three times smaller than the SWCNTs in terms of the mobility diameter when airborne. This suggests that a number of SWCNTs are clumping together to form a single airborne particle, which is similar to what previous studies found.

Separate from the details of the comparison of the two instruments, the most important result is that each instrument supports the result that the SWCNT aerosol particles are larger than the MWCNT particles. This is important as no previous study compares MWCNT and SWCNT aerosols generated by the same technique. A larger aerosol size for the smaller physical nanomaterial is a strong warning that the inhalation risk of these materials cannot be understood by comparing their physical dimensions.

The peak number concentration measured by the CPC goes above 1.0x10^5 part./cm³ (maximum concentration limit) and only up to 300 part./cm³ for the ELPI. No detectable mass is released according to the MSS. This would indicate that the particles released are fairly small in size and cannot be detected by mass measurements.

The CPC instrument reaches its maximum concentration range again for the high agitation level and for the fracture of the wafer. Again virtually no release is detected by the ELPI and MSS. It is interesting that this VACNT wafer was the high adhesion formulation and were still easily ejected from the surface at a high rate when agitated. The first fracture broke a smaller piece of the wafer so its unsurprising that it caused a smaller release of particles compared to the second fracture. The small release at the end is when a large area of the wafer is scraped clean of CNTs. It is actually surprising that no more particles were detected during this test, but it is likely that the scraping motion forced the CNTs together forming large clumps that could not become airborne.

Conclusions & Policy Recommendations

The current regulatory framework for EHS regulation is sufficient, however, we believe that these recommendations should be put in place:

The amount of aerosol CNT research needs to be increased to develop a larger body of data for developing standards and to better understand and improve the measurement techniques and aerosol generation methods. This process could begin immediately with an increase in funding for nanomaterials aerosol research.

A labeling program should be initiated that gives every nanomaterial a safety level or (NSL) similar to the bio safety level system already in place. The nano safety level would be a number from 1 to 4 rating the health risk from lowest to highest. The NSL would take a number of factors into account such as the aerodynamic diameter, the aspect ratio, the chemical composition, and the ease with which the material can become airborne. In addition the label would be color coded so it could easily be viewed from afar with green, yellow, orange, and red corresponding to levels 1 through 4. Lastly the label should include a list of the recommended personal protective equipment that should be used when handling the material. Although the logistics of implementing the labeling itself should not be too difficult a task, developing the volume of data and modeling to determine the NSLs will require a considerable amount of time. It is believed that it would be feasible to implement this program within five years.

In the long term a new OSHA permissible exposure limit needs to be implemented based upon the number concentration of airborne nanomaterials in labs and manufacturing facilities. The current mass based particle standard is insufficient to protect against CNT inhalation hazards, but the current regulatory framework is sufficient to implement a new standard through OSHA with the support of research and recommendations from NIOSH. In conjunction with the implementation of a new number based PEL, a new standardized number concentration sampling method needs to be developed in order to facilitate straightforward and relatively inexpensive enforcement of the standard.

Acknowledgements

We graciously thank Dr. Imad Khalek for the use of the Southwest Research Institute Nanoparticle Lab and Daniel Preece for his aid during the testing. We also thank Dr. Baratunde Cola and Dr. Elsa Reichmanis for their material and financial support.