SUSTAINABILITY OF NANOTECHNOLOGY AND ENGINEERING EDUCATION

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ABSTRACT

Sustainability establishes a relationship between humans and nature, and provides a guideline for the protection of the environment and human beings. Engineers and scientists develop new processes and refine existing processes according to new technologies using a collection of raw materials and energy resources and converting them into a desirable finished product. The manufacturing of needed products is accomplished by the production of waste, some of which is unavoidable. Historically, little attention has been given to the effects of producing a product on the environment and the associated risk of the manufacturing process. This trend began to change in the 1990s with the new concept of pollution prevention, which elaborated how to protect the environment from pollution at its source and minimize the risk to human health. The principles of green engineering provide a framework for designing processes and products with minimum pollution at the source and a risk-free atmosphere for humans and the environment. Green chemistry is applied across the life cycle of a chemical product, from its initial design to its uses, and ensures less waste material, less energy usage, and less pollution. Sustainable development of nanotechnology requires analyzing the environmental impact of nanomanufacturing. Unlike much conventional manufacturing, nanomanufacturing requires a unique process control and a unique facility. The effect on the environment as the result of nanomanufacturing is more significant than that from conventional manufacturing. This paper emphasizes the potential environmental and human health hazards from the manufacture of nanomaterials. Nanomaterials often have environmental and human health related issues, which must be considered before evaluating nanoproducts for their "greenness." Incorporating proper decisions at the product-design stage using risk analysis of sustainable nanomanufacturing practices, employing the rules of green engineering and green chemistry and their application on engineering education are seen as possible solutions.

Keywords: Nanotechnology, Nanomanufacturing, Nanomaterials, Sustainability, Green Chemistry, Green Engineering, Engineering.

1. INTRODUCTION

Sustainability is everything that we need for our survival and well-being on this planet depends, either directly or indirectly, on our natural environment. Sustainability provides the conditions under which humans and nature can exist together in productive harmony. This can also permit the social, economic and other requirements of present and next generations. Sustainability is an important issue and will continue to have our demands and natural resources to protect human health and the environment. Sustainability has emerged because of significant development of the unintended social, environmental, and economic consequences of fast population growth, economic growth, and consumption of our natural resources. A sustainable energy supply and clean technologies associated with sustainable energy utilization are big challenges of this century. According to the latest UN report on sustainable energy investment, in 2006, approximately 90.7 billion dollars was invested in clean technology, such as solar, wind, biofuels, and clean coal. Climate change, rising oil prices, and long-term energy security are the main drivers of such rapid growth in sustainable energy industries.

Since the mid-1970s, engineers and scientists have transferred materials into useful products and at the same time have met environmental regulations limiting the amount of pollutants [1]. Little attention has been given to environmental issues in the last 30 years. This trend started to change in the early 1990s with the advent of a pollution-prevention concept that clearly outlines how to protect the environment and stop pollution at its source. In the Pollution Prevention Act of 1990, the United States Congress established a governmental policy on pollution and the environment [1, 2]. It developed the hierarchy shown in Figure 1, showing clearly that source depletion was the biggest form of pollution prevention (P2). P2 means increasing the efficiency in using raw materials and protecting the depletion of natural resources.

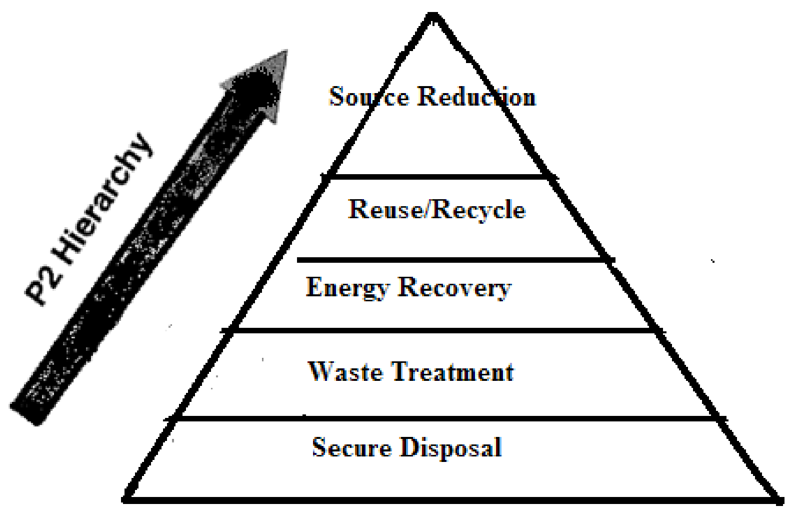

Figure 1: Pollution prevention systematic analysis [1].

Sustainable engineering transforms existing engineering principles to those that ensure sustainability and future developments. Sustainable engineering promotes development and implements economically suitable and accessible products that ensure environmental protection and human welfare. The following principles are considered in order to implement sustainable engineering solutions for various sectors [1]:

1. *To engineer processes and products holistically, use systems analysis, and integrate environmental impact assessment tools.*
2. *To conserve and improve natural ecosystems while protecting human health.*
3. *To use life-cycle thinking in all engineering activities at all stages.*
4. *To ensure that all material and energy inputs and outputs are as inherently safe and benign as possible.*
5. *To control and minimize depletion of natural resources as much as possible.*
6. *To prevent waste as much as possible in stages of processing.*

7. *To develop and apply engineering solutions, while being cognizant of local geography, aspirations, and cultures.*
8. *To create engineering solutions beyond current or latest technologies; improve, innovate, and invent (technologies) to achieve sustainability.*
9. *To develop new engineering solutions.*

These principles were developed by several engineers and scientists at the Green Engineering: Defining the Principles Conference, held in Sandestin, Florida, in May of 2003. The preliminary principles forged at this multidisciplinary conference are intended for engineers to use as guidelines in the design or redesign of products and processes. These issues are mostly dictated by business, government, and society, such as cost, safety, performance, and environmental impact. These principles provide a platform on which engineers can design products and processes to meet societal needs with minimum impact on the environment. These principles should be considered as a philosophy for the development and well-being of a sustainable society in the world [1].

2. SUSTAINABLE NANOTECHNOLOGY

2.1 Nanotechnology and Handling

Nanotechnology, in combination with nanoscience, controls matter at a molecular level on a scale less than 1 micrometer—usually between 1 and 100 nm [3]. Nanotechnology can be precisely defined as the "design, characterization, production and application of structures, devices and systems by controlled manipulation of size and shape at the nanometer scale (atomic, molecular and macromolecular scale) that produces structures, devices and systems with at least one novel/superior characteristic or property" [4]. Nanoscience is a part of nanotechnology that helps to study the manipulation of materials at atomic, molecular, and micro molecular levels, since the properties of the materials differ at these levels when compared to particles on a larger scale.

The burgeoning field of nanotechnology will play a dramatic role in the near future. It is being applied in almost every field—from medicine, automotive, and energy to agriculture. The applications of nanotechnology are many and its benefits, in terms of cost, energy savings, and increased efficiency, are significant. However, despite these benefits, there could be some unintended health and environmental hazards associated with nanomaterials, which heretofore might not have been completely understood and elaborated. There is an urgent need to understand the potential environmental and health hazards associated with nanomaterials and green nanomanufacturing processes that are less troublesome to the environment and health [5].

Research in nanotechnology stays to expand around the globe, and in the next decade, nanotechnology could have as much as a $1 trillion impact on the global economy. With advancement in this burgeoning field, new challenges like waste management, safety, and health risks to workers will arise. The National Institute for Occupational Safety and Health (NIOSH) remains committed to protecting workers now and in the future, as nanotechnology applications and uses expand. Nanotechnology has a broad range of applications and therefore involves safety and health risk issues [6,22].

Until research in nanotechnology completely explores potential health risks, precautionary measures must be taken. Because nanotechnology is a new emerging area of research, there are many uncertainties associated with the use of engineered nanomaterials and whether their unusual properties can have harmful effects on health. The research available to predict the kind of hazards that nanomaterials pose is insufficient. Uncertainties arise due to lack of the knowledge and experience. Animal and human studies on exposure to engineered nanomaterials provide a foundation for preliminary estimates of the harmful effects on humans. Experimental results in rodents and cell cultures have shown that the toxicity of nanomaterials is higher than large particles of the same composition [6]. Nanomaterials have a high surface area, high aspect ratio, and quantum size effect. These factors influence their properties. More research is needed on the adverse effects of nanomaterials on the biological systems of humans. The available information on toxicity of large particles can provide a platform for estimating or predicting the possible harmful effects that may occur from exposure to nanomaterials having the same physical and chemical composition [19-22]. However, this information may not be sufficient to provide proper protection. NIOSH has made the following observations in order to understand and minimize workplace exposure when handling nanomaterials [6]:

- Scientists are examining the potential health risks, when nanomaterials enter human body. Nanomaterials can enter the body through the respiratory system if they are airborne, if they come in contact with the skin, or if they are ingested.
- Results on human and animal studies show that airborne nanoparticles can be inhaled and deposited in the respiratory tract. Nanoparticles can enter into blood stream and can move into other organs.
- Studies on rats show that nanoparticles are more potent than large particles of the same composition and cause pulmonary inflammation and lung tumors.
- Experiments on cultures and animals show that changes in chemical composition, size of particles, and crystal structure can influence the oxidant generation capacity and cytotoxicity.
- Studies on workers exposed to an environment of a nanoaerosol (nanoparticles suspended in air) have shown lung-related diseases.
- Large-scale research is needed to determine the hazardous effects of nanomaterials.

2.2 Nanomanufacturing Methods and Environmental Concerns

Nanoscale manufacturing involves one of two approaches: top-down or bottom-up. The top-down approach begins with micro-systems and miniaturizes them through grinding, such as etching and milling. The bottom-up approach begins at the atomic or molecular level and builds up. The bottom-up approach is often highlighted in the nanotechnology literature, although this approach is nothing new in materials synthesis. Typically, materials synthesis involves building atom by atom on a very large scale and has been in industrial use for more than a century [7]. It is stated that top-down methods generate considerably more waste compared to the bottom-up processes. The bottom-up approach is still in the development stage and will take some more time to get matured.

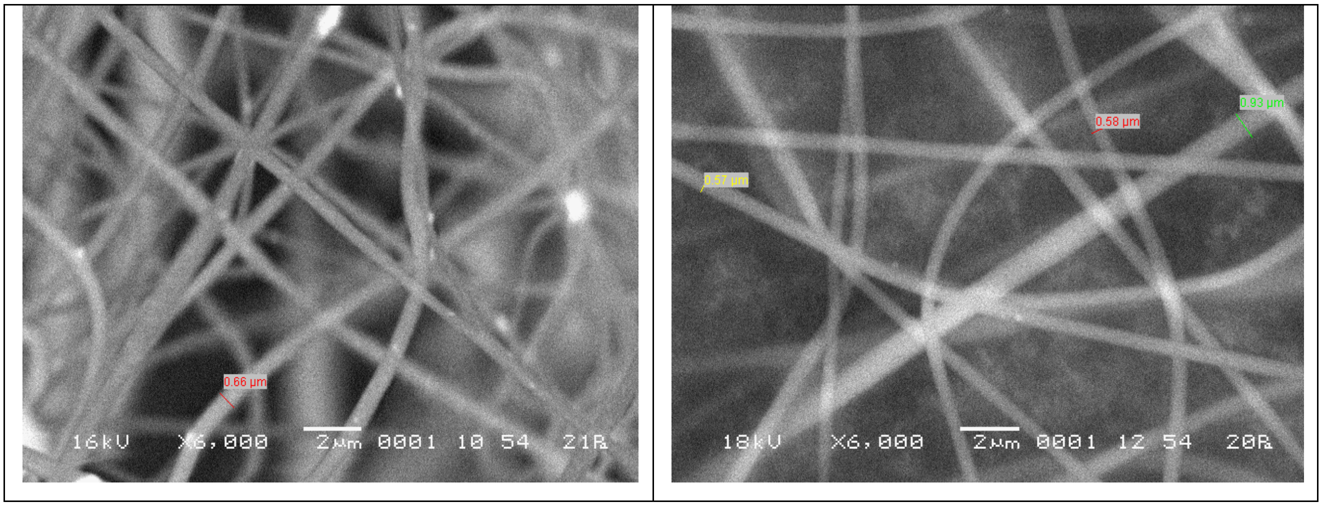

Figure 1: SEM images showing nanocomposite fiber diameters and morphologies (with 10% magnetic nanoparticle [right] and 1% magnetic nanoparticle [left]) as a function of magnetite concentrations.

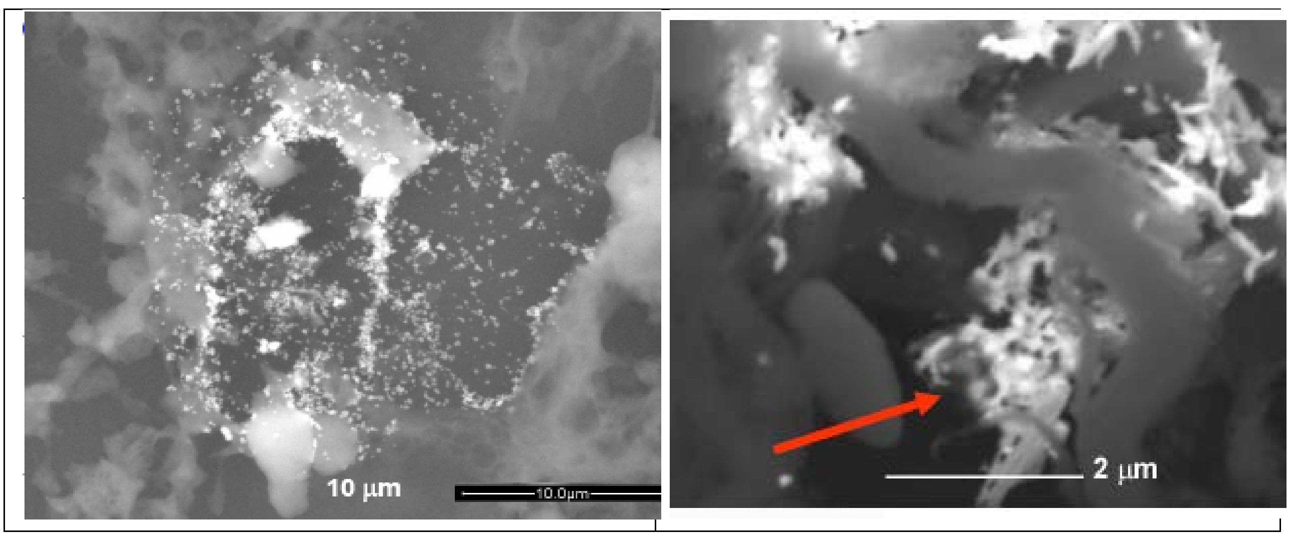

Figure 2: Images showing lead nanoparticles in lung (left) and silver-magnesium nanoparticles in colon cancer (right).

Nanostructured materials can be classified as one-dimensional (1D), two-dimensional (2D), or three-dimensional (3D). 1-D nanoproducts are thin films, 2-D, nanoproducts include nanotubes and nanorods, and 3-D nanoproducts are nanoparticles and fullerences. Most of the processes used in the production of nanoproducts have low yields and low material efficiencies, resulting in enormous waste. In addition to these disadvantages, nanoproducts have the potential to cause unintended acute and chronic human health problems upon exposure. Moreover, the synthesis of nanostructured materials consumes a large quantity of energy, solvent, and water. Sengül *et al.* [7] have outlined the following energy- and resource-intensive features of nanomanufacturing:

Purity requirement: The synthesis of nanostructured materials requires defect-free production. For example, the manufacturing of semiconductors requires a high level of purity in the raw materials, chemicals, and water used. Silicon must meet a "seven nines" standard of purity (99.99999). The energy requirement for conversion of a metallurgical grade to an electronic grade ranges from 110 to 215 kilowatt-hours per kilogram, which is much higher and demands a lot of energy and labor.

Low process yield: In many nanomanufacturing processes, only a small fraction of the initial raw material is converted into the final product, thus resulting in excessive waste and low material efficiency.

Repeated processing in a single batch: Many nanomanufacturing processes require repeating the same process over and over. The manufacture of memory units in mobile and computer electronic equipment requires a large number of manufacturing steps to construct products layer by layer. In order to accommodate increasing transistors in a unit's area, additional layers of wiring are required, which leads to a large number of processing cycles in a batch.

Use of toxic organic solvents and chemicals: Nanomanufacturing requires an excessive quantity of organic solvent, and acidic or basic chemicals, which are toxic. Many of these chemicals are not present in the final products. For example, electrospinning requires an organic solvent for making the polymeric solution; however, the final product (nanofibers) does not contain any solvent.

High vacuum requirement: In manufacturing thin films during layer-by layer deposition, a high vacuum is needed. The pressure needed in molecular beam epitaxy is in the range of 10^{-9} to 10^{-11} Torr. In the annealing of nanostructured material, the temperature ranges from 600 to 1100 ^{0}C.

Uses and generation of greenhouse gases: Greenhouse gases come from two sources: those generated upstream of nanostructure manufacturing, and those that are a direct result of the manufacturing process, such as perfluorocompounds (PFCs) used for cleaning the deposition chambers.

High water and energy consumption: In many nanomanufacturing processes, a large quantity of water is used. Water consumption per square centimeters of silicon ranges from 10 to 60 liters. A semiconductor fabrication facility uses 11 to 19 million liters of water per day and 0.7 KWh/cm^2 to 1.6 KWh/cm^2 of energy.

Occupational exposure: Processes that produce nanomaterials in gaseous, powder, and liquid states pose the greatest risk of releasing nanoparticles. Furthermore, cleaning or disposing of nanomaterials from a fume hood as well as waste disposal are all sources of exposure to nanomaterials. The intensity of exposure depends on the likelihood of particles being released during handling [15,16]. Studies on exposure to single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) have indicated that the raw material may release visible particles into the air when handled, that the particle size of the agglomerate can be a few millimeters in diameter, and that the release rate of inhalable and respirable particles is relatively low (on a mass or number basis), compared with other nanopowders. Maynard et al. [6] reported concentrations of respirable dust from 0.007 to 0.053 mg/m3 when energy was applied (vortexing) to bulk the SWCNTs for approximately 30 minutes. Similar findings were reported by Han et al. [6] at a laboratory producing MWCNTs in which exposure concentrations as high as 0.4 mg/m3 were observed prior to the implementation of exposure controls [6]. The toxic chemicals used in nanomanufacturing also involve potential hazards to workers and environment. For example, the semiconductor compounds gallium arsenide and indium phosphide are potentially carcinogenic.

3. GREEN SCIENCE AND ENGINEERING

3.1 Green Nanotechnology

Green nanotechnology is the development of clean technologies to minimize potential environmental and health hazards associated with the use of nanomanufacturing and nanoproducts, and to design and develop new products or replace existing nanoproducts with those that are friendly to the environment and humans throughout their life cycle. Green nanotechnology has two main purposes: producing engineered nanomaterials without causing any damage to the environment or causing any hazardous conditions to human health, and producing nanomaterials that provide a solution to environmental problems. First, it employs the principles of green chemistry and green engineering to fabricate nanomaterials without toxicity, it uses less energy and renewable resources, and it incorporates lifecycle thinking at all stages. The aim of green nanotechnology is to make nanomanufacturing processes more environmentally friendly.

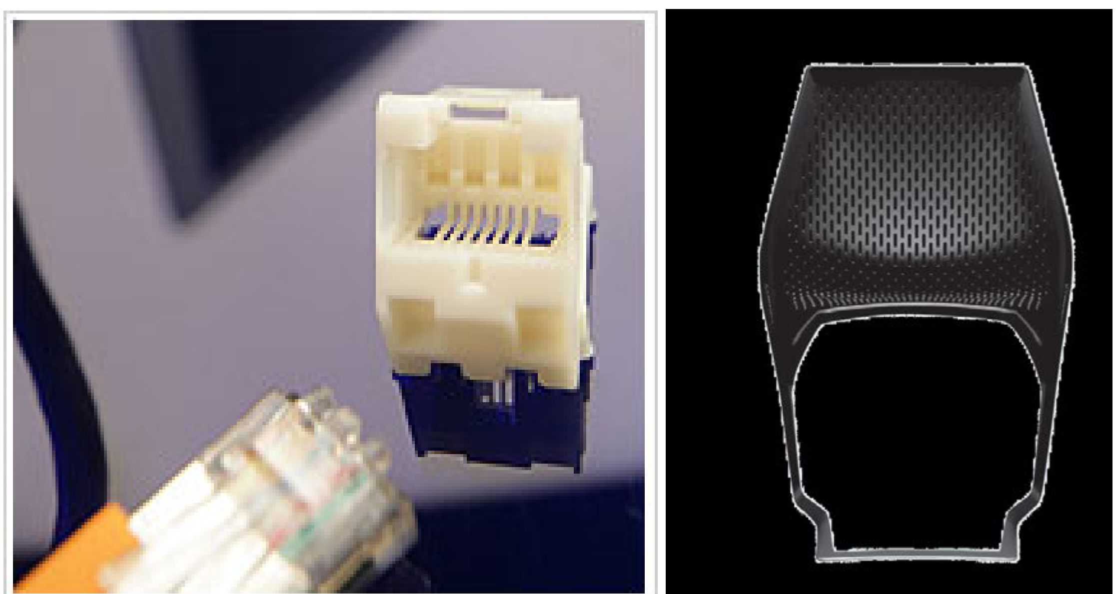

Figure 2: Ultradur® High Speed engineering plastic [17,18].

For example, a nanoscale membrane can be used to separate desired chemical products from waste materials and thereby reduce waste. A nanocatalyst can make a chemical reaction more efficient with fewer waste materials. Relative to the second purpose of using green nanotechnology to fabricate nanoproducts that benefit the environment, either directly or indirectly, the chemical company BASF has developed a new engineering plastic (Ultradur® High Speed) with improved flowability that saves energy (Figure 2). Incorporating a nanoadditive has considerably enhanced the flowability (lower processing viscosity) of this engineering plastic, which not only makes the manufacture of injection molded plastic components more cost effective but also conserves energy and reduces the environmental impact. Ultradur® High Speed is BASF's first engineering plastic to receive the "Eco-Efficiency Label" [8].

BASF is also using nanostructuring on ship hulls (Figure 3) to prevent the adherence of algae and mollusks in order to control the fouling process without the use of biocides and other cleaning processes. It is reported that the ships with fouled hulls require 40% more fossil fuel to travel at the same speed as unfouled vessels [8].

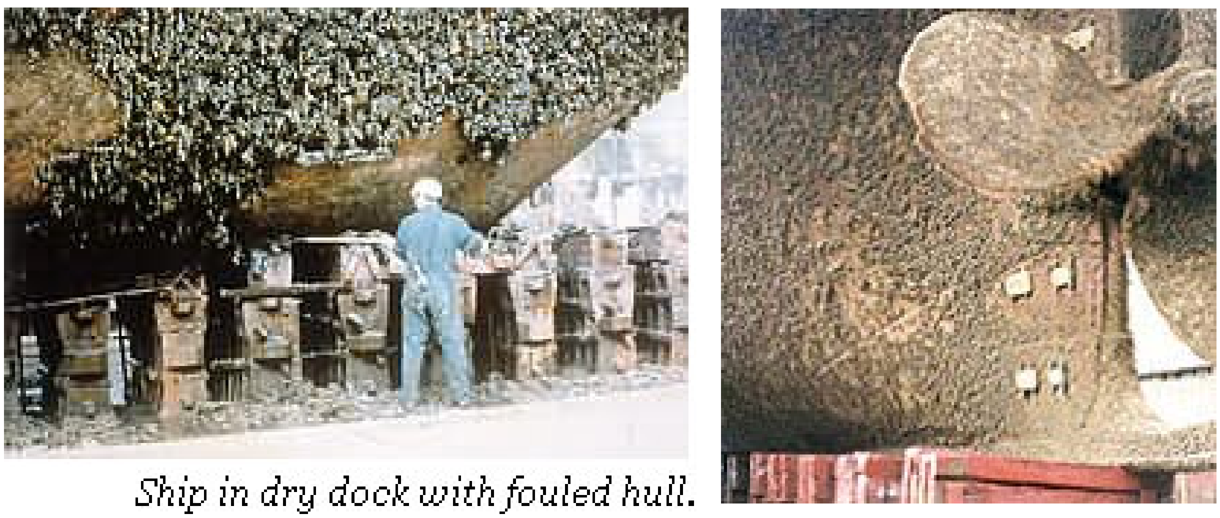

Figure 3: Reduced fouling with nanostructured materials [8,21].

BASF has developed a new material for organic-emitting diodes, also known as OLEDs. This is an organic semiconductor material consisting of very thin layers (5 to 150 nm). In addition to other advantages, OLEDs do not become hot when emitting light, which means less energy is lost in radiation than with a conventional light source. OLEDS use only half as much electricity. With organic photovoltaics, a nanometer layer of dye is encapsulated in solar cells in order to use the energy of sunlight to generate electricity. They have become more cost effective and have more and wide-ranging applications [8]. Green nanotechnology contains designing nanoproducts *for* the environment and *with* the environment in mind for the future developments.

3.2 Green Engineering

Green engineering is the conceptualization, design, and processes and products while minimizing pollution at the source and risk to human health and the environment. This new energy concept elaborates the idea that decisions to protect human health and environment have the greatest impact on our society. Green engineering describes how to accomplish sustainability through technology, education and science. The 12 principles of green engineering provide a guideline for scientists and engineers to design novel materials, systems, and processes that are beneficial to the environment and human health. These principles are as follows [9]:

1. ***Inherent Rather Than Circumstantial***
   Engineers and designers need to ensure that all materials and energy input and output are nonhazardous.
2. ***Prevention Instead of Treatment***
   It is better to prevent waste as much as possible than to treat waste after it is formed.
3. ***Design for Separation***
   Operations that involve purification and separation should consume less energy and materials.
4. ***Maximize Efficiency***
   Products, processes, and systems should be designed in such a way as to maximize mass, energy, space, and time-efficiency.
5. ***Output-Pulled Versus Input-Pushed***
   Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.
6. ***Conserve Complexity***
   Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.
7. ***Durability Rather Than Immortality***
   Targeted durability, not immortality, should be a design goal.
8. ***Meet Need, Minimize Excess***
   Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.
9. ***Minimize Material Diversity***
   Material diversity in multicomponent products should be minimized to promote disassembly and value retention.
10. ***Integrate Material and Energy Flows***
    The design of systems, products, and process must be interconnected with energy and materials flows.
11. ***Design for Commercial "Afterlife"***
    Products, processes, and systems should be designed for performance in a commercial "afterlife."
12. ***Renewable Rather than Depleting***
    Material and energy inputs should be renewable rather than depleting or going into waste.

The materials and energy that enter each life cycle stage of any process and product have their own life cycles. If a material is environmentally friendly but when used in combination with other materials becomes nonrenewable or hazardous, then the impact is shifted to another part of the overall life cycle. If a process or a product is energy-efficient but the fabrication process consumes more energy, then there is no net sustainability advantage. Engineers should consider both the entire life cycle of materials and energy input and then makes the process sustainable. The 12 principles of green engineering offer a framework for assessing the elements of design relevant to maximizing sustainability. Designers and engineers can utilize these principles as guidelines for designing products, processes, and systems that have a fundamental concept of sustainability [9].

3.3 Green Chemistry

Green Chemistry is a fundamental and necessary tool in accomplishing pollution prevention. Pollution prevention is an approach that involves preventing waste from being formed so that it does not have to be dealt with later on by treatment or disposal. More than 20 years, the chemistry community and, in particular, the chemical industry has made extensive efforts to reduce the risk associated with the manufacture and use of various chemicals. There have been innovative chemistry approaches to treating chemical waste and remediating hazardous waste sites. New monitoring and analytical tools have been developed for detecting contamination in air, water, and soils. New handling procedures and containment technologies have been developed to minimize exposure [10].

Green chemistry applies to the entire life cycle of a chemical product, comprising its design, fabrication and consumption. Green chemistry technologies provide a number of benefits, including the following [6]:

1. *Reduced waste*
2. *Safer products*
3. *Reduced use of energy and resources*
4. *Improved competitiveness of chemical manufacturers and their customers*

The goal of the green engineering program is to integrate risk-related concepts into chemical processes and products, and to utilize the available tools and methods to determine risks to human health or the environment. It also recognizes opportunities to reduce chemical hazards and exposure to raw materials, products, and waste by using alternative technologies and environmentally friendlier chemicals. Current engineering methods are to emphasize waste minimization rather than direct impact on human health and the environment.

5. CONCLUSIONS

The principles of sustainable nanotechnology and engineering outlined in this paper are not a final set of strategies. Engineers and scientists are constantly developing new materials and devices. Continuous changes in the global environment require new tools and principles in sustainable engineering, as well. However, the principles outlined in this paper can provide a guideline for further investigation in this field. The burgeoning field of nanotechnology will play a significant role in the near future in this field. The benefits of nanomaterials and nanoproducts are many, but at the same time, there are some unintended health and environmental issues to be considered. The hazardous effects of many nanomaterials and nanoproducts are still unknown; however, there is enough evidence to suggest that the exposure to nanomaterials poses the greatest risk to environment and human health. Thus, there is an urgent need to address the potential environmental and health hazards associated with nanomaterials and nanoproducts, and to use green nanomanufacturing and green nanotechnology principles that are less troublesome to the environment and health.

REFERENCES

1. M.A. Abraham and R. Sheldon, *Sustainability Science and Engine*ering, first edition, Elsevier, 2006.

2. D.T. Allen, K.S. Rosselot, *Pollution Prevention for Chemical Processes,* Wiley, New York, 1997, p. 434.
3. "Nanotechnology," retrieved August 2009 from website: http://www.gitam.edu/.
4. "Introduction to Nanotechnology," retrieved October 2009 from website: http://www.nanowerk.com/.
5. Rajive Dhingra, Sasikumar Naidu, Girish Upreti, and Rapinder Sawhney, "Sustainable Nanotechnology: Through Green Methods and Life-Cycle Thinking," *Sustainability*, vol. 2, 2010, pp. 3323-3338.
6. Approaches to Safe Nanotechnology, Managing the Health and Safety Concerns Associated with Engineered Nanomaterials, Department of Health and Human Services Centers for Control and Prevention National Institute for Occupational Safety and Health.
7. Hatice Sengül, Thomas L. Theis, and Siddhartha Ghosh, "Toward Nanoproducts: An Overview of Nanomanufacturing Methods," *Journal of Industrial Ecology*, vol. 12, no. 3, 2008, pp. 329-359.
8. http://www.basf.com/group/corporate/en/sustainability/dialogue/in-dialogue-with-politics/nanotechnology/environmentally-friendly, retrieved May 5, 2012.
9. Paul T. Anastas and Julie B. Zimmerman, "Design through the 12 Principles of Green Engineering," *Environmental Science & Technology*, March 1, 2003.
10. Paul T. Anastas and Tracy C. Wiliamson, *Green Chemistry: An Overview*, Chapter 1, 1996, pp. 1-17.
11. P.T. Anastas and J.C. Warner, *Green Chemistry: Theory and Practice*, Oxford University Press, Oxford, 1998.
12. M.A. Abraham, *Environmental Progress*, December 2004.
13. C. Hendrickson, M. Conway-Schempf, L. Lave, and F. McMichael, *Introduction to Green Design Initiative*, Carnegie-Melon University, Pittsburgh PA, 1999.
14. Judith Light Feather and Miguel F. Aznar, *Nanoscience Education, Workforce Training, and K-12 Resources*, CRC Press, 2011.
15. R. Asmatulu "Toxicity of Nanomaterials and Recent Developments in Lung Disease," Chapter 6 in *Bronchitis*, InTec, ed. P. Zobic, 2011, pp. 95-108.
16. R. Asmatulu, E. Asmatulu, and A. Yourdkhani "Toxicity of Nanomaterials and Recent Developments in the Protection Methods," SAMPE Fall Technical Conference, Wichita, KS, October 19–22, 2009, 12 pages.
17. http://www2.basf.us/businesses/plasticportal/Products/Ultradur/ktn_Ultradur_High_Speed_en.html, accessed in August 2, 2012.
18. http://iwww.plasticsportal.com/automotive/pdf/ultradur_high_speed.pdf, accessed in August 2, 2012.
19. Asmatulu, R. "Nanocoatings for Corrosion Protection of Aerospace Alloys" (Part 2), in *Corrosion Protection and Control using Nanomaterials*, Woodhead Publishing, ed. V.S. Saji and R. Cook, 2012.
20. Dhanasekaran, S.P., Kalla, D.K., Zhang, B., and Asmatulu, R. "Sustainability in Nanomanufacturing: Status and Vision for the Future," 2011 International Manufacturing Science and Engineering Conference, Corvallis, OR, June 4–7, 2011, 6 pages.
21. http://cqdjournal.com/Hot_Events/biofouling_7-22/7-22-InvSp/7-22-invsp.htm, accessed in August 2, 2012.
22. http://www.cdc.gov/niosh/docs/2009-125/pdfs/2009-125.pdf, accessed in August 2, 2012.

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