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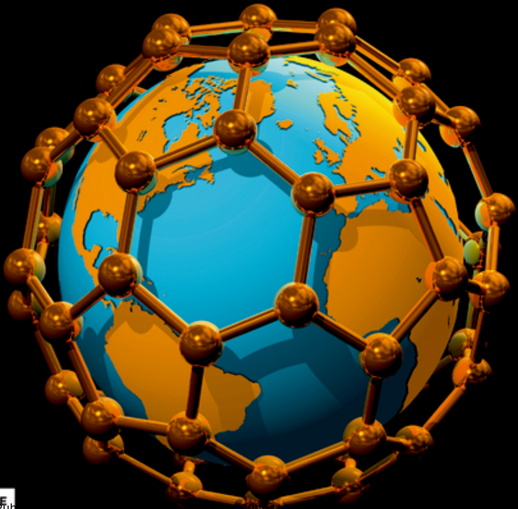
NANO-SAFETY

WHAT WE NEED TO KNOW TO PROTECT WORKERS



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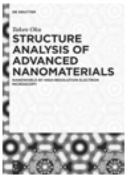

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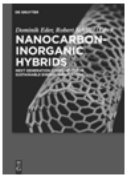

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Nano-Safety

What We Need to Know to Protect Workers

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Foreword

Nanotechnology, or more correctly the application of nanoscale science and engineering to material science, has been the focus of a major global R&D investment over the past 20 years. In the United Sates alone, the public investment has been over $ 23 Billion since 2000, with an equal investment in the private sector. To help organize its efforts in this vital area, the U.S. created the National Nanotechnology Initiative (NNI) in 2000 to help coordinate the activities of 20 federal agencies engaged in one or more aspects of the national strategy to promote the technology. Developing the scientific knowledge needed to address questions and concerns about the possible environmental, health, and safety impact of this new technology was recognized as a critical need early in the program. The fact that developing the science needed to support safe and responsible development of nanotechnology was listed in the first US Nanotechnology Strategic plan was very exciting to the practitioners, especially the occupational health and safety community. Delivering on the expectations set with that first plan have been a challenge, but good progress is being made.

As a PhD chemist, an occupational health professional, and a Board Certified Industrial Hygienist, I am excited about the diversity and promise of the output of nanotechnology, yet I am aware of the difficult science needed to answer key questions about the possible implications on human health and the environment. Many of the traditional precepts of safety and health have to be re-examined, if not redesigned to examine the potential impact on human health that this new and promising form of material science represents. If we do not meet the challenge of understanding the possible hazards; evaluating and quantifying any potential risk; and most importantly, developing solutions to manage any risk and support responsible development of this amazing technology, it is possible that ultimately we may not realize the many great benefits to society that are currently being explored.

I have had the privilege of managing the Nanotechnology Research Center at the National Institute for Occupational Safety and Health, NIOSH, for the past 10 years. My duties at NIOSH, coupled with the 16 years I spent in the private sector, have given me a unique opportunity to interact with some of the best scientists in every aspect of the current challenge. I am honored to work with some of the best minds in occupational safety and health and to interact with the thought leaders in nanoscale science and engineering as I promote a message of practical yet effective methods to evaluate and manage potential risks of nanotechnology. The health and safety and scientific communities have been very receptive to taking a precautionary approach with the technology and materials while it is still evolving, recognizing that high-quality science is being conducted in a concurrent fashion to develop very detailed answers to key health and safety questions. One of most encouraging things I have seen throughout this challenge is that we have all interested, and invested parties engaged in asking and addressing the health, safety, and environment questions out in advance of the

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technology; versus the old paradigm of reacting to incidents or disasters and then formulating solutions after-the-fact. This may well be one of the first proactive approach being taken to address key issues of a technology as it is being developed.

This strategy would not be possible without the active participation, collaboration, and support of scientists engaged in in the actual development of the technology. This is why I am so pleased to see the development of Nano-Safety: What we need to know to protect workers. Dr. Dominick Fazarro and colleagues has done a wonderful job of gathering up experts from a variety of technical areas to contribute their expert knowledge to this work. This reference takes a very pragmatic view of what is needed to educate students, researchers, faculty, and safety practitioners on the basic knowledge needed to approach this very complex issue. I am very happy to see the variety of topics this book develops, including areas usually not seen in ‘traditional’ safety reference, such as Ethics, Communication, Behavior, Reliability of Information, and evaluating competence of workers and safety professionals. I believe the reader will find this book to be a valuable addition to their resource library and, most importantly, a valuable tool for developing an effective strategy to keep students, researchers, faculty, engineers, line operators, and all other workers involved in the responsible development of nanotechnology safe and healthy.

Charles (Chuck) Geraci, Jr, PhD, CIH, FAIHA
Associate Director, National Institute for Occupational Safety and Health

Preface

This book is the culmination of more than eight years of effort. In 2006, the Nanomaterials Application Center at Texas State University was involved in evaluating nanotechnology for commercialization. One of the items that was raised was “safety.” At that time, there were concerns about the impact of nanomaterials on both people and the environment. There was a significant amount of work being done on toxicity, but it was focused on individual cases. A white paper was produced that listed elements required to ensure the safety and proper handling of nanotechnology.

An award by a government agency to develop any aspects of safety for nanotechnology came from Occupational Safety and Health Administration (OSHA) as a Susan Harwood award. It was awarded to Kristen Kulinowski at Rice University to develop an eight-hour course for practitioners. Texas State supported the Rice contract, with Walt Trybula as principle investigator (PI). The resultant effort was tested at a number of national conferences. The response from course participants indicated that the eight-hour course was preferred over a four-hour course. That course is available through OSHA.

Additional efforts followed from that contract at Texas State University. Several proposals were submitted to the National Science Foundation (NSF) over a three-year period. There was an NSF award made to Texas State in 2013, with Jitendra Tate as PI and Dominick Fazarro of UT Tyler and Craig Hanks of Texas State as co-PIs. The award was to develop nanotechnology safety education courses. One course was to be at an introductory level, and the other course was to include more advanced topics. Each course consisted of nine independent modules to be used for standalone insertion into existing courses. In the course of developing the contents of the courses, it was apparent that there was a need to consider ethical concerns in the courses. Judgment calls are required when working with materials with unknown properties, so the courses needed to include some basis for making decisions. Those decisions need to look at the impact on people and the environment. Inclusion of the topic of ethics was considered a necessity by the team. The material was developed, and tested with students at Texas State University and UT Tyler. UT Tyler offered complete courses, whereas Texas State courses were in modular form, enabling insertion of individual modules into a number of existing courses. The feedback from students and NSF evaluators provided the opportunity to tune the courses. This material is available from NSF. For this work, the team was honored by the National Academy of Engineering as having one of the 25 exemplary programs in engineering ethics.

After developing the courses, with successful response to the material, it was time to develop an educational book to be used to supplement the work on nanotechnology education. There was an outreach to leaders in the field to contribute chapters to the book. The editors are professionals who have contributed to this work.

This book has been two years in writing and proofing in order to ready it for publication. The content is structured to provide a logical flow from one topic to the next. The

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first chapter, “*The World of Nanotechnology*” by Barbara Foster, starts by examining the world of nanotechnology and safety. Nanotechnology is not the first technological development that might contain significant risks to both people and the environment. Proper planning enables the development of controls to ensure the safety of workers involved. In this first chapter, Barbara Forster discusses previous development of new technology and mentions how some of the controls were established. Chapter 2, “*The World of Engineering Nanomaterials*” by Eylem Asmatult, provides an overview of how the understanding and application of nanomaterials have evolved. Chapter 3, “*The Importance of Safety for Manufacturing Nanomaterials*” by W.S. Khan and R. Asmatulu, presents the involvement of safety with manufacturing and usage of nanomaterials. Chapter 4, “*Safety Approaches to Handling Engineered Nanomaterials*” by Jitendre S. Tate and Roger A. Hernandez, covers engineered nanomaterials and some of the possible sources of health hazards. Chapter 5, “*Certification: Validating Workers’ Competence in Nano-safety*” by Christie M. Sayes, addresses the need for training in safety and certification to ensure that safety is dominant in nanotechnology efforts. Chapter 6, “*Understanding the Implications of Nonomaterial Unknowns*” by Walt Trybula and Deb Newberry, covers the facts that the vast majority of nanomaterial properties are unknown and that their impact on people and the environment will not be known for some time. Chapter 7, “*What is Considered Reliable Information*” by Evelyn Hirt and Walt Trybula, addresses the fact that many sources of nano-safety information are not renewed on a regular basis and new regulations may change the existing recommendations. Consequently, there is a need to develop an understanding of reliable information sources. Chapter 8, “*Ethics and Communication: the Essence of Human Behavior*” by Craig Hanks, delves into the need for an ethical approach to nanotechnology safety, without which many questionable decisions might be made. Chapter 9, “*Behavior-Based Worker Safety for Engineered Nanomaterials*” by Christie M Sayes, Patrick Van Burkleo, and Grace V. Aquino, addresses the issue that worker training and the implementation of controls for the application and handling of nanomaterials need to be thorough and built on the need for safety. Chapter 10, “*The Future of Nanotechnology Safety*” by Dominick Fazarro, provides a hypothetical view of the future, where safety is properly incorporated into the world of nanotechnology, and highlights the possible mechanisms for ensuring safety.

This author and the editors thank all the people who have been involved in this effort and is pleased to see the publication of this book, which represents years of development as nanotechnology has grown. Our goal with this book is to provide a basis for additional learning as the field develops and matures. No one organization or source has all the answers, but we hope that we have provided the reader with a starting point to ensure that he or she is creating and working in an environment that can be considered safe.

30 April 2017 Walt Trybula

Contents

About the Editors

Dr Dominick Fazarro is an associate professor in the Department of Technology at the University of Texas at Tyler. Dr Fazarro has been researching nanotechnology safety for over ten years. He was a co-principle investigator on federally funded programs with the National Science Foundation (NSF) and Susan Harwood to address nanomaterial safety education and training. Dr Fazarro is recognized as a senior member by the IEEE Nanotechnology Council. He has published over 30 peer-reviewed articles, book chapters, and presentations on the topic of nanotechnology safety education. Dr Fazarro facilitated the development of an online nano-safety certificate program with a short course. In 2016, Dr Fazarro along with the grant team was recognized by the National Academy of Engineering Exemplars of Engineering Ethics Education.

Dr Craig Hanks is NEH Distinguished Teaching Professor of the Humanities and professor of philosophy at Texas State University. A winner of seven teaching awards, including the highest recognition at Texas State University and the University of Alabama in Huntsville, he has more than 20 years of experience teaching philosophy of technology, engineering ethics, and professional ethics. He has served Texas State on the Institutional Animal Care and Use Committee (IACUC) and the Institutional Review Board (IRB), which he chaired for three years. Dr Hanks was a visiting associate professor at the Stevens Institute of Technology, and has offered short courses and seminars on philosophy and ethics for teachers, from high school through to doctoral programs. He is an active member of the International Society for Philosophy and Technology, a member of the editorial board for Philosophy in the Contemporary World, and an editor for the book series Philosophy of Engineering and Technology (Springer).

Dr Jitendra S. Tate, associate professor of manufacturing engineering at Texas State University, has established safe handling practices for industrial (such as nanoclay) and engineered (such as carbon nanotubes) nanoparticles in his teaching and research on advanced polymer nanocomposites. His research areas include developing, manufacturing, and characterizing high-performance polymeric thermoplastics and thermoset nanocomposites for thermal protection systems (TPS), rocket ablatives, fire-retardant interior structures for mass transit and aircraft, lighter and damage-tolerant wind turbine blades, high temperature composites, replacement of traditional composites using biobased materials, sustainable composites from renewable resources, conductive polymers for 3-D printing, nanotechnology education, and nanotechnology safety. He is recipient of a prestigious national teaching award, the 2009 Dow Chemical Educator of the Year by the Society of Plastics Engineers' Composites Division. Dr Tate also served as principal investigator for the National Science Foundation/Nanotechnology Undergraduate Education (NSF-NUE) program "NanoTRA –

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Texas Regional Alliance to foster ‘Nanotechnology Environment, Health, and Safety Awareness’ in tomorrow’s engineering and technology leaders,” 2013–2015.

Walt Trybula, PhD, MBA, IEEE Fellow, and SPIE Fellow, is a director of the Trybula Foundation, Inc., and an adjunct professor in the Ingram School of Engineering at Texas State University–San Marcos. Dr Trybula is a technology futurist and has focused his activities on evaluating technology trends and applications in emerging key industries, with an emphasis on their impact on economic development and job creation.

Dr Trybula is active in disseminating information on the importance of the appropriate insertion of emerging technologies into the communities. He authored the State of Texas teaching module on “Nanotechnology and Economic Development” and has made presentations to numerous organizations, including the "Nanoelectronics, Photonics, and Nano-Safety"topic for the US Congressional Nano Caucus. He is an IEEE Distinguished Lecturer.

Dr Trybula has been involved in various aspects of nanotechnology since 1979. In 1996, his research at SEMATECH led to investigation of distortions in the single-digit nanometer range. Additional efforts in 2002 focused on the existence and impact of “nanobubbles” on the creation of leading-edge semiconductors. As the latter work was developing, his interest in the impact of nanotechnology on people and the environment increased. His white paper on a systematic approach to nano-safety was produced in 2007, with special emphasis not only on the effect on people and the environment but also on the development of educational programs to train future workers. He has been involved in early efforts in on-site industrial surveys on nanotechnology safety and the development of nano-safety educational materials.

A SEMATECH senior fellow, Dr Trybula spent 13 years working on leading-edge technologies. He is involved in the International Technology Roadmap for Semiconductors (ITRS) serving on the Litho Technical Working Group (TWG) and has chaired the US Modeling and Simulation TWG. In his role at SEMATECH, he was involved in the development of the Texas State Strategy on Advanced Technology and was a member of the nanotechnology committee of the Texas Workforce Commission Advanced Manufacturing Working Group. He was a member of the steering committee for the Texas Alliance for Nanoelectronics (TxAN) and co-chair of the Texas State Strategy on Advanced Technology Working Groups for both nanotechnology and MEMS.

Prior to his current assignments and SEMATECH, Dr Trybula had been with two start-up companies. He was president and founder of Ivy Systems, Incorporated, which is a Virginia electronics manufacturing automation company, and a director at Compunetics, which is a computer integrator. Prior to Ivy Systems, he was with the General Electric Company for 12 years, the last nine of which were on corporate staff as senior consultant in electronics manufacturing technology and product commercialization evaluation.

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Barbara Foster

1 The World of Nanotechnology

1.1 Introduction

The year was 1944. A 23-year-old chemist stood at a laboratory bench, in a top secret facility hidden in the New Mexican desert. His faced several challenges: First was the chemistry and metallurgy of refining the first nonmicroscopic quantities of plutonium for the war-crucial Manhattan Project. Second was keeping his laboratory safe from the unknown hazards of conducting research in the newly discovered realm of radioactivity.

A year later, he produced what he later called his other major “Manhattan Project” – me. Under my father’s tutelage, I grew up to become a high school chemistry teacher and my father’s early research exerted considerable influence. Laboratory safety was always job #1. For example, I became famous for unexpectedly standing in the front of the class during laboratory sessions and loudly counting, “1, 2, 3 . . . ” My students knew I was counting faces, looking carefully to see who was NOT wearing their safety goggles. During those years, the promise of broad peace-time use of the atom intrigued me and, as my career developed, both the impact and risks of the Atomic Age found their way into my curricula.

For the past 25 years, I have been a strategic consultant to the microscopy arena, helping companies identify and launch new technologies, many of which are used to image, characterize, and measure the nanoworld.

Why are these two historical notes important? First, as a “daughter of the Atomic Age,” I see many similarities between the promise, evolution, and risks of nuclear science and those of nanotechnology. Second, my current in-depth involvement in microscopy and “nanoscopy” literally gives me a unique view into the nanoworld. In that role, I have had an opportunity to work with many of the new microscopy techniques in atomic force, confocal, super-resolution and even light microscopy, allowing me to actively observe the nanoworld at work. From those perspectives, I share with you this overview of nanotechnology.

How does nanotechnology compare to those early days of atomic research? As in the early days of working with radioactive materials, there is much we do not know about the interaction between nanomaterials and the biome in general, and humans in particular. Walt Trybula and Deb Newbury discuss this very issue in Chapter 6 of this book, “Understanding the implications of nanomaterial unknowns.”

Early pioneers in radioactivity had dosimeters and Geiger counters, but what can be used to detect exposure to nanomaterials? Risk is measured by both exposure to the

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hazard and the dose. Although radiation is relatively easy to detect and measure, the new throng of nanoparticles makes developing selective nanosensors challenging.

Not only are the large numbers and variety of nanomaterials daunting, to add even further complexity, sometimes a small difference in structure produces a major shift in potential safety. Carbon nanotubes, described in greater detail in Section 1.3.1, are a good case in point. Observations suggest that if they have closed ends, they tend to orient themselves parallel to surfaces such as skin and are benign. However, if they have open ends, they tend to approach surfaces head on, potentially penetrating skin and causing havoc inside cells.

A second interesting comparison between radioactive materials and nanomaterials is the rate and extent of commercialization. In both research and commercialized products, there is potential for exposure during synthesis, modification, processing, characterization, and testing. Even now, 70 years after the Manhattan Project, radioactive materials remain largely in the purview of either the government or developers of nuclear power plants and nuclear medicine. In comparison, nanotechnology has moved aggressively into the mainstream. Within the last decade, it has undergone explosive commercialization across a broad landscape from energy to agriculture, golf clubs to computers, and medicine to food processing and water treatment. At the time of writing this chapter The Nanotech Industries Association [1] reports over 2000 member companies, and the Nanotech Inventory for Products Containing Nanomaterials [2] cites over 2300 entries.

As in the mid-1940s, we stand on the brink of a brave new world, with nanomaterials promising blazing leaps in technology. However, there is a great deal for us to learn about how best to use them safely and ethically. Contributions to this book were invited specifically to help you begin that investigation. In this chapter, we begin with the fundamentals: the technology, its applications, current directions in research, the market, and a glimpse of the future.

1.2 What Is Nanotechnology?

Long before nanotechnology and the science to investigate it came into existence, man unknowingly put the power of tiny particles to work, using colloidal gold to make the magnificent stained glass windows and goblets of the Middle Ages and the unique Wootz steel in Damascene swords.

The nanoworld is the world of the very small and is typically defined by structures and unique interactions that occur at the size range of 1–100 nm. For a quick size comparison, a nanometer is about 100,000th the diameter of an average human hair.

The concept of technology at the nanoscale was first hypothesized in the abstract by Dr Richard Feynman in his 1959 presentation to the annual meeting of the American Physical Society at the California Institute of Technology. In “There’s Plenty of Room at the Bottom,” [3] he began by posing the question, “How small can we write?”

More specifically, he asked, “Could we write the entire Encyclopedia Britannica on the head of a pin?” After explaining that we can actually write much smaller, he moved on to “How can we *read* what we have written?” It was the first conceptual step toward manipulating and controlling things at the nanoscale. The use of photolithography to print semiconductors was in its infancy [4] and, although the electron microscope had been invented, it would be decades before we had the high resolution electron microscopy and, eventually, atomic force microscopy needed to really “read” the nanoworld.

In 1972, Taniguchi coined the term “nanotechnology” to describe semiconductor processes such as thin film deposition and ion beam milling, which could exert control at the nanoscale. His definition was as follows: “‘Nano-technology’ mainly consists of the processing of, separation, consolidation, and deformation of materials by one atom or one molecule.” However, the term did not catch on until the 1980s. That period saw a convergence of thought and technology. Eric Drexler, who was unaware of Taniguchi’s prior use of the term, published his first paper on nanotechnology in 1981, followed in 1986 by his foundational work, *Engines of Creation* [5]. In 1984, Feynman updated his earlier presentation in “Tiny Machines.” [6] His slides show just how much the semiconductor industry has changed. In 1981, scanning tunneling microscopy (STM) was invented, giving the world not only a unique view into the nanoworld but enabling manipulation and measurement at that scale. In 1986, fullerenes were discovered and nanotech reached a tipping point. The race was on!

1.3 The Growing World of Nanomaterials

Interesting things happen to chemistry, physics, and biology at the nanoscale. Surface area increases millions of times. There are changes in hydrophobicity and hydrophilicity, strength, transparency, melting point, and the ability to conduct both heat and electricity. Gold is no longer gold, but red. Perhaps most amazing of all, materials have the ability to self-assemble. Today, nanomaterials come in all shapes and forms. Chapter 2, “The world of engineering nanomaterials” by Eylem Asmatulu, discusses this topic further, but here is a quick overview.

1.3.1 Carbon-Based Nanomaterials

A large number of nanomaterials are based on carbon. They exhibit exceptional strength, electrical conductivity, and heat resistance, which make them industrially interesting. These materials are allotropes (Figure 1.1). Although each is made of carbon, they have different internal structures that result in properties as different as those of pencil lead and diamonds. The ability to more reliably produce, characterize, and manipulate carbon nanomaterials has led to their growth, and this family now

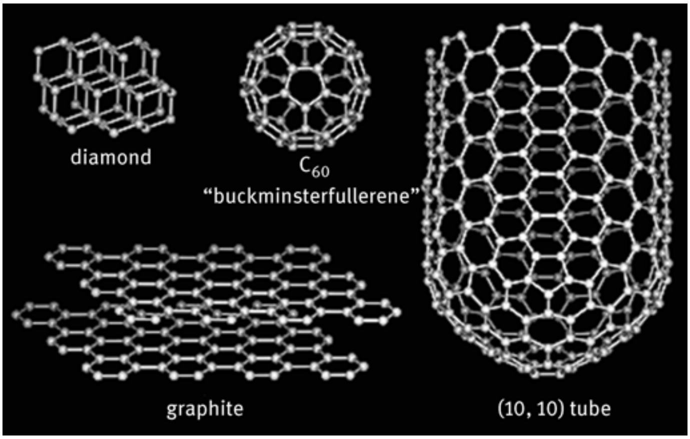


Fig. 1.1: Relationships between various allotropes of carbon [7].

includes the original two allotropes, conventional diamond and graphite, as well as nanocrystalline diamond, fullerenes (aka, buckyballs), and graphene.

Graphene [8] has sparked considerable interest. It is a two-dimensional (2-D) material comprised of single sheets of hexagonally bonded carbon only one atom thick; it is flexible and transparent, conducts electricity better than silver, conducts heat better than diamonds, and is stronger than steel. Ironically, this exotic material was discovered using rudimentary tools. In 2004, Andre Geim and Konstantin Novoselov (both at the University of Manchester, UK) used scotch tape to pull layers of graphene off a piece of graphite (essentially, pencil lead) until they achieved a layer one atom thick. Their efforts were quickly rewarded. Only six short years later, they received the Nobel Prize in Physics [9]. During those early years, growing even a single crystal of graphene for research purposes was a challenge. Today, graphene is available by the ton.

Structurally, graphene forms the building blocks for a number of other structures. Although not manufactured in this fashion, when a sheet of graphene is shaped into a ball, it generates a fullerene (bucky ball, C_{60}); rolled into a tube, it produces a single-walled carbon nanotube (SWCNT), with wall thickness of the order of 1–2 nm. Covering a SWCNT with one or more additional sheets of graphene produces double- or multi-walled CNTs (DWCNTs or MWCNTs, respectively). CNTs can also aggregate, forming nanohorns and nanobrushes [10], structures that are projected to have importance in new batteries and capacitors.

One of the latest products is wrinkled graphene. New research describes how bacteria are tucked under a blanket of graphene [11]. After heat and vacuum are applied, the graphene essentially shrink-wraps the bacteria, generating what the inventors term, "a new carbon allotrope: a half CNT linked to graphene." The resulting wrinkles are about 7 nm in height and exhibit anisotropic electrical properties along the length of the wrinkle versus across the wrinkle.

The question as to who actually discovered CNTs is a matter of hot debate that has intellectual property implications [12–14]. Nisha and Mahajan [15] point out that Mother Nature has been producing CNTs for eons and they can be found both in volcanic byproducts here on earth and in materials recovered from space.

Although carbon filaments and hollow fibers have been observed in the laboratory for over a century (Figure 1.2), it is widely reported that the first definitive images of CNTs were electron micrographs of MWCNTs, published in 1952 by Radushkevich and Lukyanovich in a Russian publication [16]. However, because it was published in Russian, it was not widely read. CNT research increased through the 1970s and 1980s, some of which resulted in patents. However, the concept did not gain much traction. Nisha and Mahajan propose a number of reasons for the lack of interest, including the fact that the CNTs were structurally imperfect and, as a result, displayed no interesting properties of commercial value. Further, they cite that early studies focused more on growth mechanisms rather than on discovering new carbon structures, and that researchers were limited by the then-available analytical tools.

In 1991, that scenario changed. Sumio Iijima of NEC developed a high-resolution tunneling electron microscopy and began actively researching a wide variety of carbon materials, which resulted in publication of a seminal paper on MWCNTs in *Nature* [17]. He later went on to image and describe SWCNTS. Because of the breadth and depth of his work, Iijima's research became the cornerstone of carbon nanostructure research and, as a result, he is often cited as the inventor of CNTs.

1.3.2 Colloidal-Based Nanomaterials

A second family of nanomaterials can be found in the colloidal world. Colloidal silver has been known since the mid-1880s, but is now enjoying vast new markets in nanotechnology. There are now nanosilver wipes, sponges, food storage materials, etc. Both nanosilver and nanogold are finding key applications in Raman spectroscopy on both substrates (surface-enhanced Raman spectroscopy, SERS) and atomic force microscopy probe tips (tip-enhance Raman spectroscopy, TERS).

1.3.3 Quantum Dots

Quantum dots [18] (QDs) form a third group of nanomaterials. These optoelectronic nanoparticles can be made of a variety of semiconductor materials, including silicon, cadmium selenide, cadmium sulfide, and indium arsenide. Their properties change as a function of both size and shape. As discussed in *Wikipedia*, "larger QDs (radius of 5–6 nm, for example) emit longer wavelengths resulting in emission colors such as orange or red. Smaller QDs (radius of 2–3 nm, for example) emit shorter wavelengths resulting in colors like blue and green, although the specific colors and sizes vary de-

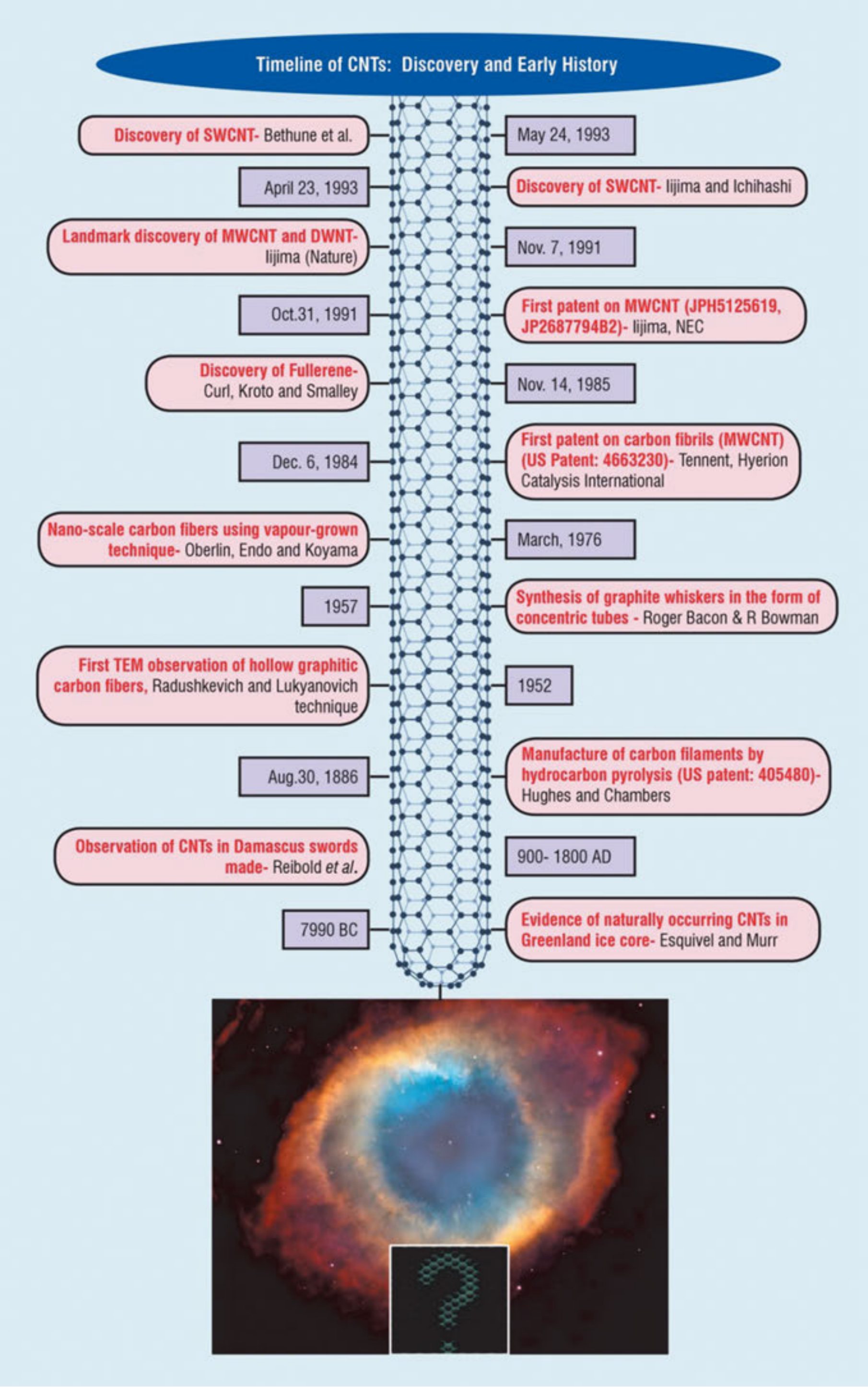
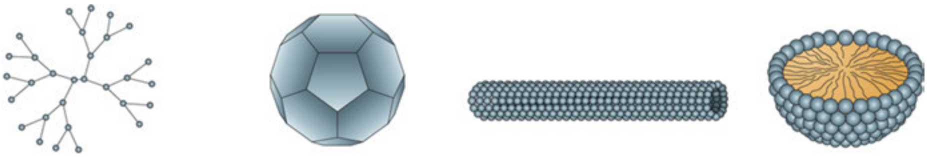


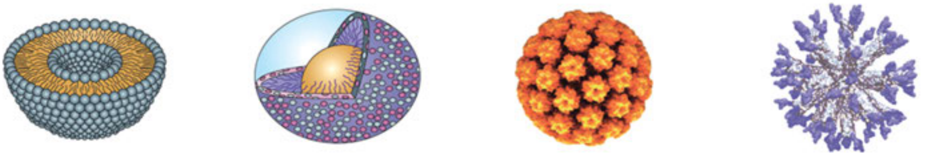
Fig. 1.2: The history of carbon nanotubes (Courtesy, Nisha and Mahajan).

pending on the exact composition of the QD.” This article goes on to describe their range of applications: “Because of their highly tunable properties, QDs are of wide interest. Potential applications include transistors, solar cells, LEDs, diode lasers and second-harmonic generation, quantum computing, and medical imaging [19]. Additionally, their small size allows QDs to be suspended in solution, which leads to possible uses in inkjet printing and spin-coating. These processing techniques result in less expensive and less time-consuming methods of semiconductor fabrication.” [20]

Because of their excellent photoelectric efficiency, QDs are being proposed for the next generation of solar cells. For example, normal solar cells convert each photon into an electron. In comparison, QDs can convert each photon into two electrons. In microscopy, their tunability and stability makes them an interesting substitute for more sensitive and degradable organic fluorophores. The same fluorescence makes them interesting candidates for electronic displays. For example, different sized QDs can be grouped to make the R-G-B dots that form a pixel.



(a) Dendrimer (b) Spherical fullerene (c) Cylindrical fullerene (d) Micelle



(e) Liposome (f) Oil-in-water emulsion (g) Virus-like particle (h) Synthetic virus-like particle

Size	< 5 nm	10–20 nm	50–100 nm	> 150 nm
Nanoparticle	Dendrimer	Polymer	DNA pollyplex	Liposome
Bioactivity	Partion like small molecules and filter through the kidney	Escape the vasculature, infiltrate the tissues and lymphatics like proteins	Penetrate the mucosal membranes and the skin and are taken up into cells.	Taken up mainly into phagocytic cells

(i)

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Fig. 1.3: Depictions of various nanotechnology topologies that can be applied to immunoregulation include nanoparticles (a–c), nanoemulsions (d–f), and virus-like particles (g–h).

1.3.4 Biologically Based Nanomaterials

As illustrated in Figure 1.3, there is a growing family of biological nanoparticles [21]. Although this particular image refers to immunoregulation, similar nanoparticles are being actively researched and developed to locate, diagnose, treat, and monitor many diseases. As discussed in the analysis of the market (Section 1.8), drug delivery ranks high in biological nanoparticle applications.

1.4 Instrumentation for Investigating Nanotechnology

Although other chapters in this book are more specific about methodology, a quick review of some of the techniques for imaging nanomaterials is useful here.

From the early days of nanotechnology, transmission electron microscopy (TEM) [22] has been a key technique for investigation, well suited because of its ability to image at the atomic and molecular level. TEM transmits an electron beam through the material of interest and is able to magnify 1000 to 1,000,000 times. The beam is preferentially absorbed by both the density of the material and its thickness, resulting in shifts in both amplitude (intensity) and phase that generate contrast and provide information about particle morphology and surface, thickness of surface coatings, and even atomic order.

Scanning electron microscopy (SEM), as the name implies, uses an electron beam to scan the surface. By using a variety of detectors and a range of electron voltages, images are created using either backscattered electrons or secondary electrons, revealing phases within the material and also the morphology and texture of the surface. SEM devices are often fitted with energy dispersive X-ray (EDX) detectors for elemental analysis and with diffracted backscattered electron detectors (EBSD) to examine crystallographic orientation. SEM can typically obtain magnifications ranging from several thousand to 30,000×. Desktop models that integrate optical microscopy with electron microscopy seamlessly bridge conventional optical magnifications of 20–1000×through SEM ranges of up to 20,000×. Furthermore, these instruments can combine brightfield or fluorescence in the optical range with SEM and EDS in the electron microscopy range.

Scanning probe microscopy (SPM) includes two families of technology: (1) STM and nearfield scanning optical microscopy (NSOM), which take advantage of nearfield effects, and (2) atomic force microscopy (AFM), which scans the surface with an atomically sharp tip. Depending on the application, the scans can be done with the tip in contact with the surface, hovering over the surface, or “hopping” or “tapping” across the surface. SPM offers over 40 different imaging modes, with contrast generated by changes in topography, phase, hardness, tacticity, various electrical parameters (voltage, capacitance, tunneling current), magnetism, etc. In addition to “images,” these modes can provide quantum mechanical testing. The latest iteration of these microscopes combines AFM with Raman spectroscopy. Raman has always been a challenge because of its weak signal. Raman at the nanoscale presents even more of a challenge. However, the signal can be boosted nearly a million-fold (enhanced Raman spectroscopy) by using materials such as gold and silver to enhance the electric field at the tip–sample interface. In conventional Raman, this goal is achieved by using special substrates to generate surface-enhanced Raman spectroscopy (SERS). In AFM, special tips coated with nanogold or similar materials are used, generating tip-enhanced Raman spectroscopy (TERS). Until recently, TERS was difficult to control experimentally. However, new hybrid instruments [23] have stabilized the AFM–spectrometer interface, facilitating the use of TERS in both research and more routine applications. Figure 1.4 shows a true AFM/Raman hyperspectral image, in which both the AFM image and the Raman signal were collected simultaneously from a single CNT. The ability to combine both molecular-level imaging with the power of chemical analysis in an easy-to-use system has powerful implications for nano-safety.

When it comes to the nanoworld, optical microscopy is not typically included in the analytical scheme. With a limit of resolution of about 250 nm, it does not seem to be a good fit; however, several approaches can be applied. Scanning white light interferometry (SWLI) and phase shifting interferometry (PSI) offer the ability to image nanoscale variations in step height and topography. Surface-enhanced ellipsometric contrast microscopy (SEEC) is a more recent entrant into the field, combining reflected light differential interference contrast with the use of special substrates. SEEC routinely images step heights of the order of a few nanometers.

Although imaging nanosteps in the *Z* plane has been available for over 35 years, using optical technology to break the 100 nm barrier in the *XY* plane has been more of a challenge. The past decade has seen the rise of a variety of super-resolution techniques, used primarily in the life sciences [24]. Some, like structured illumination microscopy (SIM), stimulated emission depletion (STED), and light-sheet microscopy

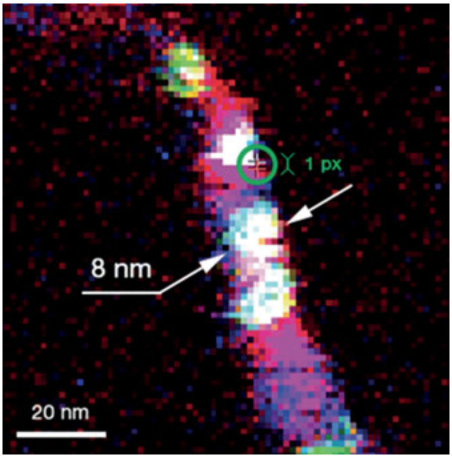


Fig. 1.4: Hyperspectral nanoscale Raman image of an isolated carbon nanotube. Raman resolution 8 nm; scan area 100 nm × 100 nm; scanned in 1.2 nm steps at 100 ms/pixel; scan time < 9 min. (Image courtesy of HORIBA and AIST-NT).

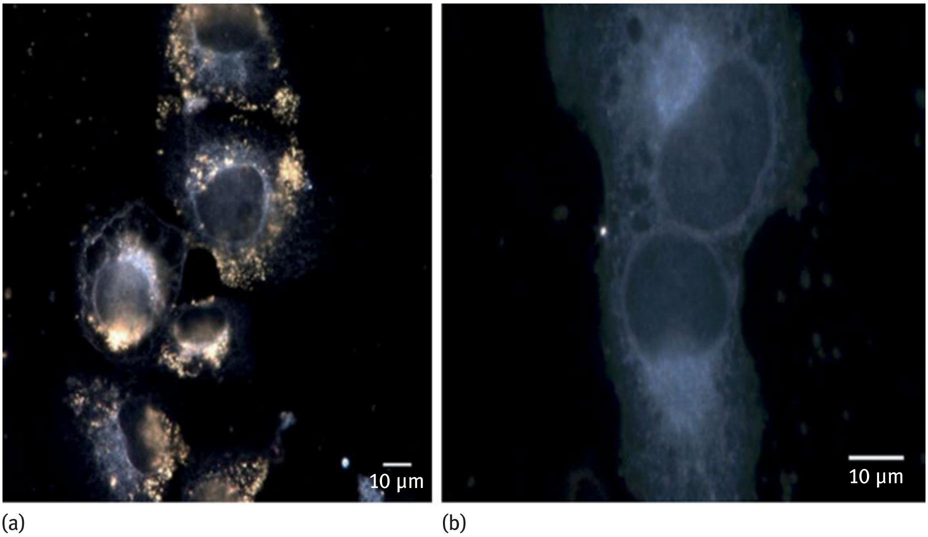


Fig. 1.5: Gold nanoparticles used as indicators in cancer cells: (a) Gold nanoparticles taken up by cancer cells. (b) Negative/control. (Image: Courtesy of CytoViva).

manipulate illumination to drop the conventional *XY* resolution to the 65–90 nm range. Others, like photoactivation localization microscopy (PALM) and stochastic optical reconstruction microscopy (STORM), both taking advantage of new photoswitchable probes, locate and map individual molecules. From those maps, it is possible to "image" structures and processes at resolutions on the order of approximately 20 nm. These instruments, however, typically fall in the $400,000–$800,000 range.

Another, elegantly simple solution comes from CytoViva and has applications in both life sciences and materials sciences. The device consists of modified light source and condenser system that readily retrofits to most current microscopes. It makes use of near-field effects to drop *XY* resolution to about 90 nm and detection below 50 nm (Figure 1.5) for under $20,000. It can also expand into a larger, hyperspectral imaging system (~$125,000).

1.5 Where Is Nanotechnology Today?

Today, nanotechnology is just beginning to hit its stride, with active education, research, and development on multiple fronts that are already making dramatic changes in how we live, what we wear, the food we eat, and how we manage resources such as energy and water.

For over a decade, industry observers have asked the question, "Can nanotechnology continue to exist as a separate entity or will it devolve back into the basic sciences of chemistry, physics, and biology/medicine?" As discussed in Section 1.8 on the nanotechnology market, there is ample evidence to suggest that nanotechnology has firmly established its own identity, both scientifically and commercially.

That said, nanotechnology is cutting edge and highly multidisciplinary, reaching across the scientific and informational spectrum from biology and medicine to materials science and semiconductors, to practical applications in energy generation/transmission/storage, agriculture, and water purification. It is also highly interdisciplinary. Consider, for example, the interplay between private enterprise, government, academia, and foundations across the globe, and across many disciplines, in this excerpt from the description of authors in a recent article on nanotechnology in food:

Materials Measurement Science Division at NIST; Center for Environmental & Human Toxicology; Department of Environmental and Global Health, University of Florida/Gainesville; Fulton Schools of Engineering, Arizona State; School of Pharmacy, University of Canberra, Australia; Therapeutic Research Unit, School of Medicine, University of Queensland, Brisbane Australia; ILSI Europe Novel Foods and Nanotechnology Task Force, Brussels, Belgium; Friends of the Earth, Washington, DC; Center for Risk Science Innovation and Application, ILSI Research Foundation, Washington; Department of Food Science, School of Environmental and Biological Sciences, and the Center for Gastrointestinal Physiology, New Jersey Institute for Food, Nutrition and Health, Rutgers, The State University of New Jersey/New Brunswick [25].

The bottom line is that a student or practitioner can enter nanotechnology through many gateways. Nanotechnology only requires that you bring to a sense of cooperation, team building, and the ability to think outside the box. Just choose a discipline, choose whether you would prefer research and/or commercialization, and nanotechnology will provide a pathway into the future. The next section details some of the more active application areas.

1.6 Applications

In 2005, as part of the process designed to assist UN agencies in achieving their millennium development goals (MDGs), the UN convened a special Task Force on Science, Technology, and Innovation to address specifically the potential of nanotechnology for sustainable development. Their findings were reviewed in an excellent *PlosMed* article, “Nanotechnology and the developing world.” [26] Although this research was conducted over a decade ago, the results provide an important perspective on the extensive real-life world of nanotechnology today.

The task force recruited 85 nanotechnology experts from around the world. Of those, 63 completed the three-round process, with 60% of that group representing developing countries and the other 40% representing developed countries. The question posed to them was: “Which do you think are the nanotechnologies most likely to benefit developing countries in the areas of water, agriculture, nutrition, health, energy, and the environment in the next 10 years?” They were asked, specifically, to evaluate their answers in terms of the following factors, which are still highly relevant in terms of assessing the potential for nanotechnology:

- *Impact*: How much difference will the technology make in improving water, agriculture, nutrition, health, energy, and the environment in developing countries?
- *Burden*: Will it address the most pressing needs?
- *Appropriateness*: Will it be affordable, robust, and adjustable to settings in developing countries, and will it be socially, culturally, and politically acceptable?
- *Feasibility*: Can it realistically be developed and deployed in a time frame of ten years?
- *Knowledge gap*: Does the technology advance quality of life by creating new knowledge?
- *Indirect benefits*: Does it address issues such as capacity building and income generation that have indirect, positive effects on developing countries?

Not only did the study identify the top ten key applications, it was able to prioritize the importance of each application niche and define relevant examples (Table 1.1). Priorities were derived by having each panelist rank their top 10 choices from the 13 key applications selected on the previous round. With 63 panelists and 13 choices, the maximum score any given application could receive was 819.

Tab. 1.1: Correlation between the top ten applications of nanotechnology for developing countries and the UN millennium development goals (MDGs) of 2005.

Ranking (score)	Applications	Examples	Comparison with MDGs
1 (766)*	Energy storage, production and conversion	Novel hydrogen storage systems based on carbon nanotubes and other lightweight nanomaterials Photovoltaic cells and organic light-emitting devices based on quantum dots Carbon nanotubes in composite film coatings for solar cells Nanocatalysts for hydrogen generation Hybrid protein–polymer biomimetic membranes	VII
2 (706)	Agricultural productivity enhancement	Nanoporous zeolites for slow release and efficient dosage of water and fertilizers for plants, and of nutrients and drugs for livestock Nanocapsules for herbicide delivery Nanosensors for soil quality and plant health monitoring Nanomagnets for removal of soil contaminants	I, IV, V, VII

Tab. 1.1: (Continued)

Ranking (score)	Applications	Examples	Comparison with MDGs
3 (682)	Water treatment and remediation	Nanomembranes for water purification, desalination, and detoxification Nanosensors for the detection of contaminants and pathogens Nanoporous zeolites, nanoporous polymers, and attapulgite clays for water purification Magnetic nanoparticles for water treatment and remediation TiO_2 nanoparticles for catalytic degradation of water pollutants	I, IV, V, VII
4 (606)	Disease diagnosis and screening	Nanoliter systems (lab-on-a-chip) Nanosensor arrays based on carbon nanotubes Quantum dots for disease diagnosis Antibody–dendrimer conjugates for diagnosis of HIV-1 and cancer Nanowire and nanobelt nanosensors for disease diagnosis	IV, V, VI
5 (558)	Drug delivery systems	Nanocapsules, liposomes, dendrimers, bucky balls, nanobiomagnets, and attapulgite clays for slow and sustained drug-release systems	IV, V, VI
6 (472)	Food processing and storage	Nanocomposites for plastic film coatings used in food packaging Antimicrobial nanoemulsions for applications in decontamination of food equipment, packaging, or food Nanotechnology-based antigen-detecting biosensors for identification of pathogen contamination	I, IV, V
7 (410)	Air pollution and remediation	TiO_2 nanoparticle-based photocatalytic degradation of air pollutants in self-cleaning systems Nanocataysts for more efficient, cheaper, and better controlled catalytic converters Nanosensors for detection of toxic materials and leaks Gas separation nanodevices	IV, V, VII
8 (366)	Construction	Nanomolecular structures to make asphalt and concrete more robust to water seepage Heat-resistant nanomaterials to block ultraviolet and infrared radiation Nanomaterials for cheaper and durable housing, surfaces, coatings, glues, concrete, and heat and light exclusion Self-cleaning surfaces (e.g., windows, mirrors, toilets) with bioactive coatings	VII

Tab. 1.1: (Continued)

Ranking (score)	Applications	Examples	Comparison with MDGs
9 (321)	Health monitoring	Nanotubes and nanoparticles for glucose, CO_2, and cholesterol sensors and for in-situ monitoring of homeostasis	IV, V, VI
10 (258)	Vector and pest detection and control	Nanosensors for pest detection Nanoparticles for new pesticides, insecticides, and insect repellents	IV, V, VI

There are a number of places to learn more about specific applications in nanotechnology. Here is a brief listing of some internet sites:

- www.nano.gov: Site for the US National Nanotechnology Initiative (NNI). See especially, “Big things from a tiny world” [27] and “Nanotechnology and energy: powerful things from a tiny world” [28] at http://www.nano.gov/node/734.
- www.Nanowerk.com: *Nanotechnology Spotlights*, especially some of their articles on food, energy, and water purification.
- www.AzoNano.com: Online publication for the nanocommunity.
- www.ACSNano.org: The American Chemical Society’s journal dedicated to nanoscience and nanotechnology.
- www.spie.org/newsroom/nanotechnology: SPIE’s nanotechnology newsroom.
- www.rdmag.com/topics/nanotechnology: *R&D magazine*’s section on topics in nanotechnology.

1.7 The Role of the Government in Promoting Nanotechnology

Governments across the globe actively support nanoscience and technology. Nanowerk.com lists 430 networks and initiatives [29].

In the USA, the nanotechnology efforts of 20 different agencies and departments are coordinated under the National Nanotechnology Initiative (NNI), 11 agencies of which are directly involved in science, engineering, R&D, and technology and the rest have “nanotechnology-related mission interests or regulatory responsibilities.” [30] Reflecting the current status of discipline, NNI is tasked with supporting both research and technology transfer. Initiated in 2001, it has budgeted nearly $24 billion for nanoscience and technology over its lifetime.

The President’s FY2017 budget allocates $1.4 billion in NNI funding [31]. Table 1.2 describes the allocation by agency, whereas Figure 1.6 shows the allocation by program component area (PCA). The current budget also stresses “greater focus on

Tab. 1.2: Allocation of the 2017 National Nanotechnology Initiative budget, by agency (dollars in million).

Agency	2015 Actual	2016 Estimated*	2017 Proposed
CPSC	2.0	2.0	4.0
DHS	28.4	21.0	1.5
DOC/NIST	83.6	79.5	81.8
DOD	143.0	133.8	131.3
DOE**	312.5	330.4	361.7
DOT/FHWA	0.8	1.5	1.5
EPA	15.1	13.9	15.3
DHHS (total)	385.8	405.0	404.4
FDA	10.8	12.0	11.4
NIH	364.0	382.0	382.0
NIOHS	11.0	11.0	6.1
NASA	14.3	11.0	6.1
NSF	489.8	415.1	414.9
USDA (total)	21.1	21.5	21.0
ARS	3.0	3.0	3.0
FS	4.6	4.5	4.0
NIFA	13.5	14.0	14.0
TOTAL***	1496.3	1434.7	1443.4

* 2016 numbers are based enacted levels and may shift as operating plans are finalized.
** Funding levels for DOE include the combined budgets of the Office of Science, the Office of Energy Efficiency and Renewable *Energy (DOE-EERE), the Office of Fossil Energy, and the Advanced Research Projects Agency for Energy (ARPA-E).
*** Totals may not add, due to rounding.

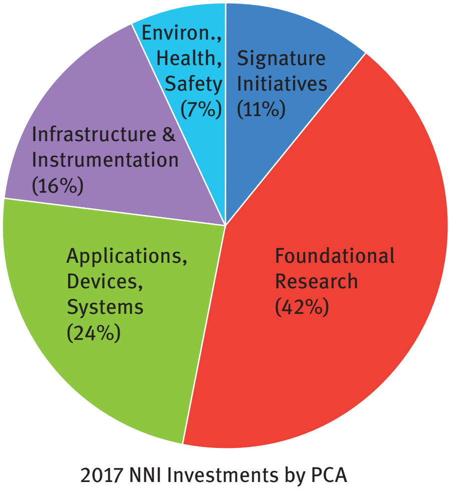


Fig. 1.6: Allocation of 2017 National Nanotechnology Initiative budget, by program component area (PCA).

promoting commercialization and increasing education and outreach efforts to the broader nanotechnology community."

In 2017, just as this book was going to press, a second major government effort came into effect, the National Microbiome Initiative (NMI), adding another $121 billion for 2016/2017. The stated role of NMI is, "Research to understand various biomes and the development of strategies to manage them and ensure their health." According to their definition, "Microbiomes are the communities of microorganisms that live on or in people, plants, soil, oceans, and the atmosphere. Microbiomes maintain healthy function of these diverse ecosystems, influencing human health, climate change, food security, and other factors. Dysfunctional microbiomes are associated with issues including human chronic diseases such as obesity, diabetes, and asthma; local ecological disruptions such as the hypoxic zone in the Gulf of Mexico; and reductions in agricultural productivity. Numerous industrial processes such as biofuel production and food processing depend on healthy microbial communities." [32]

The *ACSNano* press release and accompanying article on this program stressed the strong need for interdisciplinary research "that would create multimodal and multidimensional data sets, that would result in new interactions between medicine, agriculture, microbiology, oceanography, and atmospherics science." [33–35] For example, "multiplexed, multimodal sensor arrays will be needed to understand the chemical communication between organisms and in microbial communities. Synthetic biology will be used to manipulate microbiomes both for elucidating function and for modifying or correcting malfunctioning microbiomes."

On a global scale, there is also strong local government support, but a comprehensive discussion is outside the scope of this chapter. For insight into European efforts, search for "nanotechnology" in CORDIS [36] (Community Research and Development Information Service). For example, the search conducted for this chapter unearthed over 7300 projects!

1.8 The Nanotechnology Market

Sizing the nanotechnology market presents several challenges. To begin with, there is some debate as to whether nanotechnology is really a product-based industry or whether it is "simply, a set of enabling technologies that supports many existing industries (basically applying the 'nano' label to existing technologies – electronics, optics, composite materials, pharmaceuticals, etc.)." [37]

1.8.1 Is There Really a "Nanotechnology Market"?

The debate began with Cientifica's "Nanotechnology opportunity report" in 2003, which stated that "what exists… is a teeming collection of technologies and applications seeking each other." Recently, Tim Harper, one the report's authors, re-iterated his position that nanotechnology is still not really an industry [38].

Yet, when material was collected for this chapter, considerable evidence supported the position that nanotechnology was more than just an enabling technology. The rapid proliferation of technical journals and conferences dedicated specifically to nanotechnology and its subsets lends credence to its existence as a separate industrial sector.

Second, professionals in both research and development place significant value on nanotechnology, as evidenced by the 2016 "R&D global funding forecast." [39] This report includes the results of the study "Most important technologies by 2018." As shown in Figure 1.7, nanotechnology ties for first place and nanobiology is placed strongly in the middle of the pack.

A third factor is the participation rate. A number of sources describe the breadth of the nanolandscape. For example, the Project on Emerging Nanotechnology [40] (PEN) reports 1,200 companies, universities, government laboratories, and other organizations across all 50 US states (Figure 1.8). At www.nano.gov, NNI has an interactive map showing NNI centers and user facilities [41], as well as the nation's higher education nanotechnology degrees (from community college through to PhD programs).

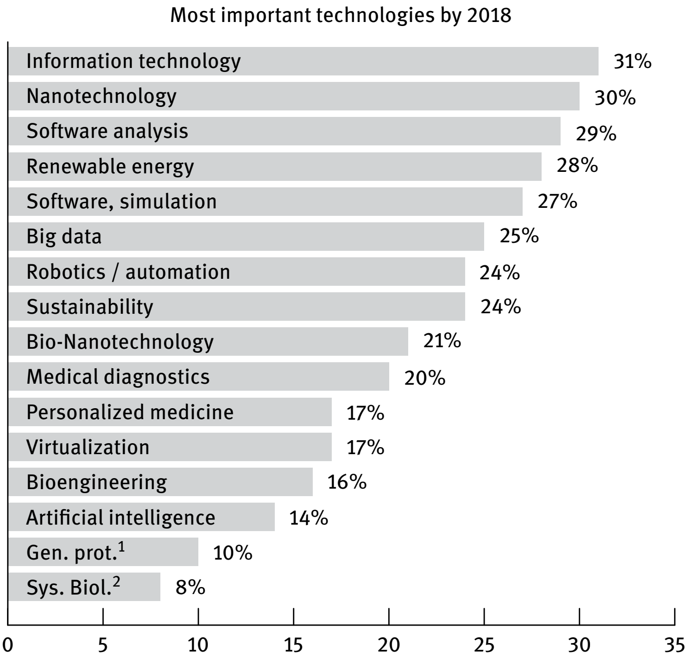


Fig. 1.7: Most important technologies by 2018, taken from the "2016 R&D global funding forecast." Data has been reformatted from the original alphabetical listing to a relative ranking. 1 Genetic proteins, 2 system biology.

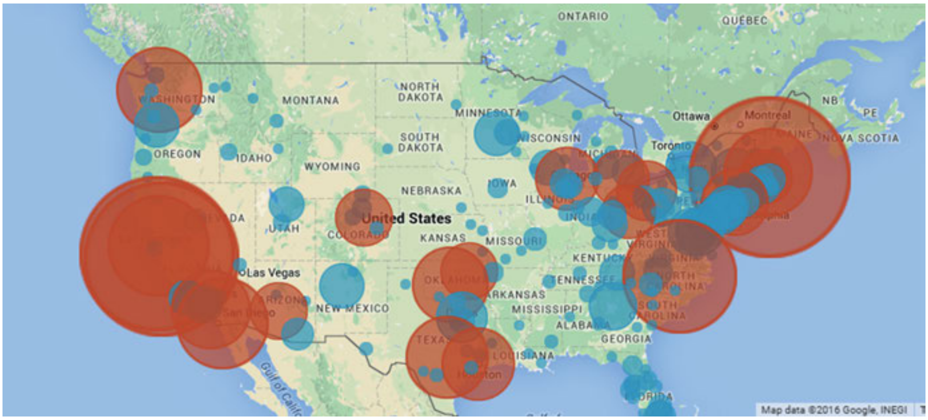


Fig. 1.8: US NanoMetro Map showing relative nanotechnology activities across the USA (PEN).

In 2005, PEN established the Consumer Product Inventory, [42] which now boasts over 1800 products. AzoNano's "Directory of nanosuppliers" [43] lists over 2000 companies, and Nanowerk, a major nanotechnology portal, [44] provides a global roll call, country-by-country (state-by-state for the USA) that includes both commercial and research nanoactivities. Nanowerk reports, "At the latest count, over 2100 companies from 48 countries are involved in nanotechnology research, manufacturing, or applications – a number that keeps growing at a considerable pace. With more than 1100 companies, the USA is home to roughly half of all nanotechnology firms. 670 companies are in Europe, 230 in Asia and 210 elsewhere in the world. Within Europe, Germany is represented with 211 companies, followed by the UK with 146 companies." [45]

Table 1.3 summarizes the nanoactivities listed in some of the current databases. Clearly, there is extensive activity and broad participation in both research and commercialization.

There is also the maturation and expansion of the industry itself to consider. Looking back through the lens of the past decade and a half is almost like looking at the Industrial Revolution in nineteenth century England from the *Starship Enterprise*. Nanotechnology commercialization has proceeded at a blazing pace. In 2003, graphene was not even a twinkle it its inventors' eyes. Today, it is not only commercially viable, but has already found its way into cell phone touch screens, smart clothing, new battery technology, and 3-D printing. Although nanosilver has been known since the 1880s, [46] it now provides antimicrobial activity in everything from cosmetics to sponges, wipes, and food storage containers. Silver nanowires are being developed for "use in solar cells, flexible displays for computers and consumer electronics, and future 'optoelectronic' circuits for sensors and information processing." [47] CNTs were an intellectual curiosity. Today, they are being produced reliably and reproducibly by the ton to provide lightweight superstrength in bicycle frames and golf clubs; coatings

Tab. 1.3: Survey of databases from nanowerk.com reveals that nanotechnology is far-reaching and active.

Nanomaterials	>2500
Nanotechnology companies and laboratories	2057
Universities departments, labs, and research groups	131
Government, industry, and private labs	291
Initiatives and networks (national & international)	430
Associations and societies	25
Services, intermediaries and “other”	197
Raw materials	292
Biomed and life sciences	275
Products, apps, instruments, and technologies	1208
Science and degree programs	300
BSc	67
MSc	155
PhD	48
Other – certifications, etc.	31
Conferences & events	>100

and films that can be radar absorbing or water resistant; new approaches to batteries, energy storage, and transmission; and advances in water purification.

Based on these observations, one can readily conclude that nanotechnology has matured sufficiently to be considered an industry.

1.8.2 What Is the Size of the Nanotechnology Market?

In 2013, NSF and the *National Nanotechnology Coordination Office* (*NNCO*) funded an independent study to determine the global revenue from nanoenabled products. The results were published in the LUX Research Report, an extract of which follows:

Governments, corporations, and private investors (venture capitalists) invested $18.5 billion in nanotechnology in 2012, increasing their spending 8% relative to 2010. The US contributed 36% of this amount. Corporations expanded spending by 21% over 2010, while governments and private investors reduced their investments by 5% and 10% respectively. The United States maintained its lead over all other governments, with $2.1 billion of federal and state funding in 2012. US corporations also led global spending on nanotechnology research and development, investing $4 billion in 2012, which was approximately $1 billion more than the next country, Japan. The revenue from nano-enabled products has continued to grow, from $339 billion in 2010 to $731 billion in 2012. This total is a slight decrease in our estimate relative to our last update on nano-enabled product revenues released in 2009. Our expanded forecast for nano-enabled products reveals the global value of nano-enabled products, nano-intermediates, and nanomaterials reaching $4.4 trillion by 2018 [48].

Tab. 1.4: Summary of nanotechnology market estimates from various sources.

Report	Published	Benchmark	$, billions	Projection	US$, billions	CAGR (%)
LUX Research	2014	2010	339	2018	4.4×10^3	n/a
BCC (WW)	Nov 2014	2013	22.9	2019	64.2	19.8
RNCOS	Dec 2015	2013		2022		16.5

The accompanying press release from NSF reported that the survey "shows global funding for emerging nanotechnology has increased by 40-to-45 percent per year for the last three years [2010–2013]." [49]

Data from this report has been quoted extensively, but there is a major flaw in the presentation of these findings, which has triggered extensive controversy. The report cites "nano-enabled" technology and "nano-intermediates". Why are these terms misleading? Consider the case of a car that has a nanocoating. The nanomaterial forms the coating on the car and should be counted in the category "nanomaterials." It would have a value of a few dollars. However, this report tallies the nanoenabled technology as the entire car, valued at thousands of dollars. A more reasonable approach is to size the market on the actual nanotechnology itself.

Table 1.4 summarizes the findings from four different nanotechnology global market reports, with the Lux report placed first, for comparison. Synopses of the other two reports, with clarifying/bridging text shown in square brackets, follow Table 1.4.

Clearly, the results vary dramatically. What guidelines can be used to best interpret these results? The critical caveat is "read carefully." The following questions should be asked:

- Is the report citing funding or revenue? The Lux report, for example, reports both.
- Is it discussing the actual nanocomponent/technology or the sales of products containing or enabled by nanotechnology? Calculations for the LUX report are based on nanoenabled products; the other two reports, on the nanotechnology itself.
- Which market sectors are included and which are not? For example, in discussing the global nanotechnology market, the BCC report does not include semiconductor manufacture, but does include the instrumentation used for semiconductor testing and measurement.

1.8.2.1 BCC Research, "Nanotechnology: A Realistic Market Assessment"

For the purposes of this report, BCC defined nanotechnology applications as "the creation and use of materials, devices, and systems through the manipulation of matter at scales of less than 100 nm."

"The global market for nanotechnology products was valued at $22.9 billion in 2013 and increased to about $26 billion in 2014. This market is expected to reach about

$64.2 billion by 2019, a compound annual growth rate (CAGR) of 19.8% from 2014 to 2019.

[The report included] nanomaterials (nanoparticles, nanotubes, nanostructured materials and nanocomposites), nanotools (nanolithography tools and scanning probe microscopes), and nanodevices (nanosensors and nanoelectronics).

[The report did not include nanoscale semiconductors, but did include] the tools used to create them. [It also excluded very high volume, materials that have been used long before nanotechnology came into existence such as] carbon black materials carbon black nanoparticles used to reinforce tires and other rubber products; photographic silver and dye nanoparticles; and activated carbon used for water filtration [because their data would] tend to swamp the newer nanomaterials in the analysis." [50]

1.8.2.2 RNCOS, "Global Nanotechnology Market Outlook 2022"

According to RNCOS, "The global nanotechnology market is expected to grow at a CAGR of around 17.5% during 2016–2022. [Its] impressive growth [is driven by] significant amounts of public and private investments in R&D [and] partnerships and strategic alliances between countries. At present, the biomedical industry is one of the largest sectors in which nano-enabled products have made major contributions, majorly in healthcare industry, with significant developments being done in other sectors like electronics and energy as well." [51]

1.8.3 Nanotechnology Market Sectors

Table 1.5 summarizes market projections from over a dozen different sector reports. Except for the smallest sectors, data were rounded to the nearest $0.1 billion. Because the market is changing so quickly, a significant effort was made to cite only data collected over the past three years (i.e., since 2013), with a preference for 2015/2016 research.

What conclusions can be drawn from this data? At first glance, it is tempting to add up the numbers and derive the potential market for 2020. However, several issues should be taken into consideration. Without making a considerable investment and purchasing all the reports (an average of about $4000–$6000 per report), the degree of overlap between reports cannot be ascertained. Some studies, like graphene in electronics and the drug delivery reports from BCC and TMR are very specific. Others, like the nanomaterials report, probably present data that significantly overlaps the information on polymer nanocomposites, CNTs, nanogold, and nanosilver. Still others, such as wearables and smart textiles, have an emphasis on nanotechnology but include other related markets.

Furthermore, although Table 1.5 covers a number of different perspectives, some sectors, such as the nanosemiconductor and nanoenergy markets, are either absent or represented tangentially.

It is possible to assess the relative sizes of these sectors. For example, nanomaterials, drug delivery, and wearable technology lead the field. We can also identify strong growth areas, including nanomaterials in general, graphene in electronics, drug delivery, wearables/smart textiles, and the internet of nanothings.

Several areas are not represented in this chart, the most noticeable being nanoenergy. Although no reports could be found in this area, review of some of the tables of contents of the included reports suggests that this sector is hidden within those reports, especially those covering graphene and CNTs.

Tab. 1.5: Summary of market report findings across multiple nanotechnology sectors.

Market	When	Beginning, $ billion	When	End, US$ billion	CAGR (%)	Notes
Nanomaterials	2016	5.5	2020	15.5	22.1	(1)
Carbon nanotubes	2015	2.3	2020	5.6	20	(2)
Graphene, 2-D structures, and carbon nanotubes	2016		2020	0.220	n/a	
Graphene/electronics	2013	0.06	2020	1.5	46.8	
Nanosilver	2013	0.7	2020	1.8	*15	
Nanogold			2020	4.8		
Polymer nanocomposites		2	2020	5.1	n/a	
Test equipment				0.9	5	
Environmental applications	2014	0.02	2020	0.04	10	(3)
Life sciences/nanoparticles (BCC)	2014	29.6	2019	*79.8*	22	
Life sciences/drug delivery (BCC)	2014	15.8	2019	*32.2*	21	(4)
Life sciences/drug delivery (Cientifica) (nanotechnology-enabled)			2021	*136*	40	(5)*
Life sciences/drug delivery (TMR)	2014	4.1	2023	*11.9*	13	
Wearables and smart textiles	2016		2022	70	132	
Internet of nanothings	2016	4.3	2020	9.7	23	

[1] The 2003 version of this report projected $35 billion for 2020; however, recent private communications report a value of $15.5 billion, with a CAGR for the period from 2016 to 2020 of 22.1% (based on research conducted in 2012).

[2] This report cites a 2009 market of $1.24 billion.

[3] This CAGR was calculated for the period from 2015 to 2020.

[4] This CAGR was calculated for the period from 2015 to 2023.

[5] This report cited numbers in terms of nanoenabled technologies, so was not included in this calculation.

* Calculated.

1.8.4 Report Synopses and Excerpts

This section gives synopses of each report cited above, with some quoted extracts. As with the reports above, clarifying/bridging text is shown in square brackets.

1.8.4.1 Nanomaterials

"World demand for nanomaterials will rise more than two-and-a-half times to $5.5 billion in 2016. Nanotubes, nanoclays, and quantum dots will be the fastest growing types. The energy storage and generation and construction markets will offer the best growth prospects. China, India and the USA will lead gains among countries." [52]

1.8.4.2 Carbon Nanotubes Market

"The global carbon nanotubes market size is estimated to grow from $ 2.26 billion in 2015 to reach $5.64 billion by 2020 at a CAGR of 20.1%." [53] Unmatched mechanical and transport properties are given as the key reasons for the surging demand for CNTs. In their article cited earlier, Nisha and Mahajan added a comment that the 2015 figure represents "an increase of 45% from the 2009 market estimate of ~$1.24 billion … due to the growing potential of CNTs in electronics, plastics and energy storage applications."

CNTs are used in various applications such as electronics and semiconductors, chemical and polymers, batteries and capacitors, energy, medical, composites, and aerospace and defense. The electronics and semiconductors application segment accounted for the largest market share of the overall CNT market in 2015. The electronics and semiconductors segment is followed by the application segments of advanced materials, chemicals and polymers, and batteries and capacitors. The aerospace and defense application is estimated to witness the highest CAGR between 2015 and 2020, in terms of volume.

The report categorizes the CNT market by type (MWCNTs and SWCNTs); by application (electronics and semiconductors, chemical and polymers, batteries and capacitors, energy, medical, composites, and aerospace and defense, among others); and by region (North America, Europe, Asia–Pacific, and rest of the world). The base year considered for the study was 2014 and the forecast period is for 2015–2020.

1.8.4.3 Graphene, 2-D materials, and Carbon Nanotubes

"Our latest up-to-date analysis shows that the graphene market will grow to $220 million … [and] reach 3800 tonnes per year by 2026.

[The market] will remain in a state of over-capacity until 2021, beyond which time new capacity will need to be installed. Furthermore, IDTechEx Research forecasts that nearly 90% of the market value will go to graphene platelets (versus sheets) in 2026.

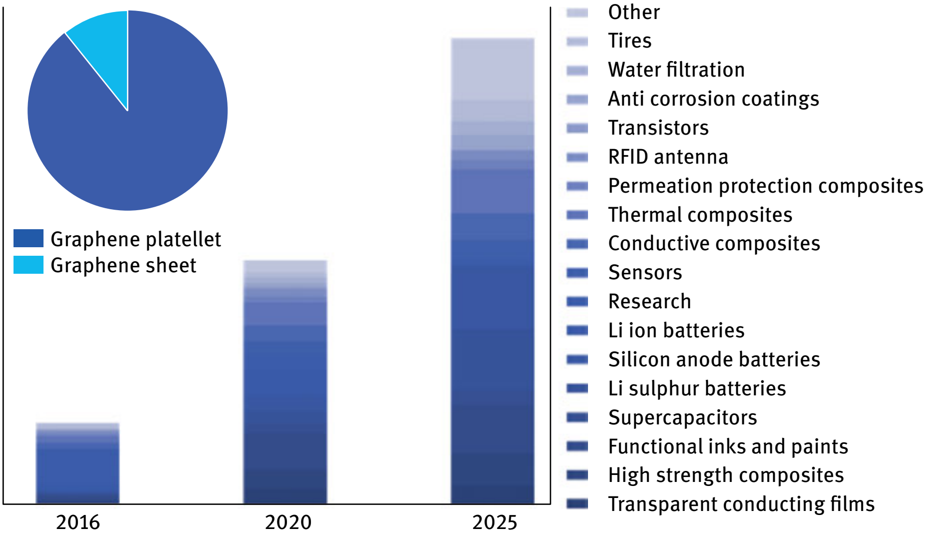


Fig. 1.9: Ten-year market projections split by application. Inset: market share of graphene platelets versus sheets in 2026, by value. Source: IDTechEx.

The market will be segmented across many applications, reflecting the diverse properties of graphene. … and project that the market for functional inks and coatings will make up 21% of the market by 2018. Ultimately however, energy storage and composites will grow to be the largest sectors, controlling 25% and 40% of the market in 2026, respectively.” [54]

Figure 1.9, taken from the IDTechEx report, depicts their projections for the graphene, 2-D, and CNT market through 2016. It is especially interesting that it also illustrates the transition from graphene platelets to graphene sheets over that time, as well as the applications for each form.

1.8.4.4 Graphene in Electronics

“The global graphene electronics market is expected to grow at a CAGR of 46.8% from 2014 to 2020 and reach $1,512.10 million by 2020; it was valued at $58.53 million in 2013. In terms of technology, the CVD (chemical vapor deposition) process accounted for the largest market share of 58% in 2013. The industry is witnessing a spree of other technology mapping methods such as graphite exfoliation, scotch tape method, synthesis on silicon carbide (SiC), and so on.” [55]

It is interesting to compare this study with the IDTechEx data. After extensive email conversations with the Graphene Council [56], which has access to multiple market research reports, it was determined that, as with the Lux report, the numbers from the “Graphene in electronics” report are based on nanoenabled technologies and nanointermediates.

1.8.4.5 Nanosilver

Two reports are cited concerning the market for nanosilver. The first is from Grand View Research.

"Electronics application was the largest end-use, accounting for over 35% of the nanosilver market in 2013 in application growth such as water and air purifiers, hair dryers, washing machines, socks, drugs, medical devices, and food packaging. Increasing application scope is expected to be a key driver for the nanosilver market over the forecast period. The nanosilver market finds opportunities in niche applications such as solar energy, food and beverages, pharmaceuticals and medical, which are expected to contribute to high demand." [57]

The second report is from Transparency Market Research.

"As electronic producers seek to pace up with the latest technologies, miniaturization will emerge at the fore as the latest trend in the industry. . . . Based on revenue, the global nanosilver market is expected to rise at a CAGR of 15.4% between 2014 and 2020. The market was valued at $682 million in 2013 and is expected to reach $1.8 billion by the end of 2020 [. . . with the volatility of nanosilver prices exerting a moderating effect].

Regionally, North America . . . [exhibits] the most lucrative prospects for nanosilver sales. . . holding a [global market] share of 41.8% in 2013 [212.8 tons], [expected] to rise to 484.8 tons by the end of 2020, exhibiting a CAGR of 12.9% during the period. [Healthcare will be the key driver]. [Asia–Pacific represents the second key area]. . . and is expected to rise at a CAGR of 13.5% between 2014 and 2020." [58]

In 2013, the two largest sectors were electronics (37.8%) and healthcare (27.6%). Major projected growth areas include food and beverages, the textile industry, and water treatment.

1.8.4.6 Nanogold

"[The] global gold nanoparticles market is expected to reach $4.86 billion by 2020. [At 50% of the total demand in 2013]. Medical and dentistry was the largest end-use segment. . . . Growing metal nanomaterial use in medical diagnostics and imaging, especially for drug delivery systems in cancer and tumor cell detection, is expected to drive gold nanoparticle demand over the forecast period.

[In 2013,] North America dominated the global gold nanoparticle market, accounting for over 30% of global volume. Increasing R&D spending by individual nanotechnology companies and universities, along with expanding medical diagnostics industry, are expected to be the major factors driving gold nanoparticle demand in the region. Asia–Pacific is estimated to witness the fastest growth at a CAGR of over 25% from 2014 to 2020. Growth of the nanomaterials industry in countries including China, Taiwan, South Korea, and Japan, along with emergence of these regions as electronic manufacturing hubs, is expected to fuel market growth over the next six years." [59]

1.8.4.7 Polymer Nanocomposites

"The polymer nanocomposites market in terms of value is expected to reach above $5,100 million by 2020, growing at a significant CAGR from 2014 to 2019.

Currently, Asia–Pacific is the largest consumer of polymer nanocomposites [with China leading in consumption].

Almost 80% of the total nanocomposites demand in 2014 was from packaging, electronics and semiconductor, and automotive industries. This was due to their physical properties such as gas, oxygen, water, etc. barrier properties, high mechanical strength, thermal stability, chemical stability, recyclability, dimensional stability, heat resistance, and good optical clarity (since particles are nanosize). A majority of consumer products that use nanocomposites packaging are in the beverage industry." [60]

1.8.4.8 Nanoparticle Test/Analysis Market

This report was especially interesting because it reviews much of the instrumentation used to analyze nanoparticles, including DLS, NTA, XRD, SMPS, CPC, and NSAM. The forecast period was 2015 to 2020.

"The market is expected to reach $91.1 million by 2020, at CAGR of 5.4% from 2015 to 2020. [Demand is fueled by] a number of factors such as increasing government spending on pharmaceutical R&D in emerging nations, rising focus on nanotechnology research, and continuous advancements in nanoparticle analysis technologies." [61]

1.8.4.9 Environmental Applications

"The global nanotechnology market for environmental applications reached $23.4 billion in 2014. This market is expected to reach about $25.7 billion by 2015 and $41.8 billion by 2020, registering a compound annual growth rate (CAGR) of 10.2% from 2015 to 2020." [62]

1.8.4.10 Nanotechnology Markets in Healthcare and Medicine (BCC)

This report is an excellent foundation article.

"The global market for nanoparticles in the life sciences is estimated at over $29.6 billion for 2014. This market is forecast to grow to more than $79.8 billion by 2019, to register a healthy compound annual growth rate (CAGR) of 22%. The biggest increase will come in the area of drug delivery systems.

Key applications areas include drug delivery, drugs and therapies, in vivo imaging, in vitro diagnostics, biomaterials, and active implants

To date, drug delivery has been the main near-term opportunity for medical nanotechnology. This market has an estimated value of $15.8 billion for 2014 and is forecast to grow to $44.5 billion by 2019, to register a significant CAGR of 23%. The drug development category, the second fastest-growing opportunity, was projected at nearly

$12.6 billion for 2014 and is expected to increase to $32.2 billion by 2019 at a 20.7% CAGR." [63]

1.8.4.11 Nanotechnology for Drug Delivery: Global Market for Nanocarriers (Cientifica)

Cientifica's report [64] views the market from the perspective of nanotechnology-enabled drug delivery.

"Nanocarriers will account for 40% of a $136 billion nanotechnology-enabled drug delivery market by 2021. We forecast the total market size in 2021 to be $136 billion, with a 60/40 split between nanocrystals and nanocarriers respectively, although developing new targeted delivery mechanisms may allow more value to be created for companies and entrepreneurs.

Of the 10 nanocarrier technologies studied, liposomes and gold nanocarriers account for 45% of the total addressable market. Liposomes will offer the largest addressable market ($15 billion) in 2021 while gold nanocarriers will see the highest compound annual growth rate (CAGR), 53.8%, in the next decade." [65]

1.8.4.12 Nanotechnology Drug Delivery Market (Transparency Market Research)

This report from TMR is specifically targeted to drug delivery.

"Advancement in nanotechnology has revolutionized the delivery of nanometer-range drug molecules. Rising prevalence of infectious diseases and cancer, significant nanotechnology research, and increasing demand for novel drug delivery systems are driving the nanotechnology market. However, unspecific regulatory guidelines for novel nanotechnolog-based drugs are expected to hamper market growth during the forecast period. The global nanotechnology drug delivery market was valued at $4.1 billion in 2014 and is anticipated to reach $11.9 billion by 2023, expanding at a CAGR of 12.5% from 2015 to 2023." [66]

1.8.4.13 Wearables and Smart Textiles

"Unlike today's 'wearables,' tomorrow's devices will be fully integrated into the garment through the use of conductive fibers, multilayer 3-D printed structures and two dimensional materials such as graphene. [Nanotechnology will be involved] from antibacterial silver nanoparticles to electrospun graphene fibers [.. and will] impact on sectors including wearables, apparel, home, military, technical, and medical textiles.

The market for wearables using smart textiles is forecast to grow at a CAGR of 132% between 2016 and 2022 representing a $70 billion market." [67]

1.8.4.14 Internet of Nanothings

"The Internet of Nano Things Market consists of nano things that are connected to the Internet, that is, anything, anytime, and anywhere. It consists of integrating sensors and devices into everyday objects that are connected to the Internet over fixed and wireless networks.

The Internet of Nano Things (IoNT) Market is expected to grow from $4.26 billion in 2016 to $9.69 billion by 2020, at an estimated compound annual growth rate (CAGR) of 22.81% from 2016 to 2020." [68]

1.9 The Challenge of Nanotechnology Safety

As discussed at the beginning of this chapter, nanotechnology, like radiation, presents unique safety challenges because you cannot see it, cannot smell it, cannot taste it, cannot feel it, and cannot hear it. But, unlike radiation, which comes in relatively few forms, nanotechnology presents dangers from an ever-growing panoply of different structures, forms, and chemical constitutions. The issue of open-ended versus closed CNTs was discussed in Section 1.3.1. In QDs, other hazards come from the materials in the semiconductor. Cadmium is a prime example. In the biological realm, the threat could come from the mutation of a virus used as a carrier. Each sector and material has its own risks and hazards, from air-borne particles to materials that are toxic on contact or through ingestion.

Even more than with radiation, there are many unknowns with far-reaching implications. That topic is addressed in greater detail by Walt Trybula and Deb Newberry in Chapter 6 of this book. Another challenge involves assessing which information is truly reliable, as discussed by Evelyn. Hirt and Walt Trybula in Chapter 7. For example, in writing this introductory chapter, a great deal of material surfaced from the 2005–2008 time period. The author had to weigh carefully whether concepts from that era still applied. Technology and tools have evolved considerably over the intervening decade. Similarly, the market analyses included in this chapter required a keen eye to assess which information was valid, which presented only part of a story, and which was overly enthusiastic. Those of you interested in pursuing nano-safety as a career will need to be well-grounded in science, technology, engineering, and math (STEM), but also exercise a healthy skepticism and organization of thought.

Clearly, nano-safety is very much on the mind of the US government. At a first level, multiple organizations, including OSHA, NIOSH, EPA, FDA, and CDC, are beginning to compile standards and methods that will be helpful in meeting these challenges. Second, through NNI, the government is establishing foundational research to focus specifically on nanotechnology-related environmental health and safety (EHS). In 2011, NNI developed the EHS Research Strategy, with a charter to coordinate, map, and implement all governmental EHS efforts in nanotechnology. The 2014 progress review [69] of that group outlines six core research areas, which provide the following framework:

- Nanomaterial measurement infrastructure
- Human exposure assessment

- Human health
- Environment
- Risk assessment and risk management methods
- Informatics and modeling

Industry has long been on-board, with companies adding EHS officers early in the commercialization process. [70]

1.10 The Crucial Need for Education and Certification

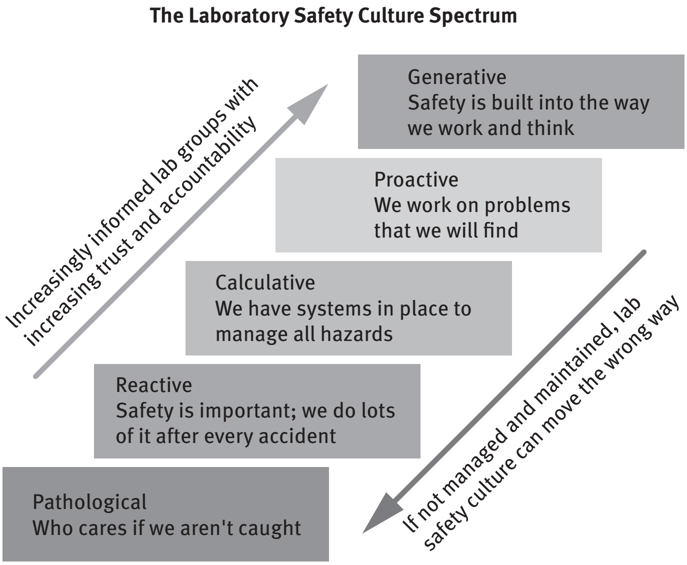
In April 2016, NNI's working group on Nanotechnology Environmental and Health Implications (NEHI) launched the webinar, "Applying a lab safety culture to nanotechnology: Educating the next generation." [71] The presentation summarizes both the need for a culture of safety in all areas of nanotechnology and for proper education and certification in this field. NEHI [72] encompasses 19 government agencies and collaborates extensively with industry and academia, both within the USA and abroad.

Kicking off the webinar, panelist Larry Gibbs, Associate Vice Provost for EHS at Stanford University discusses the "laboratory safety culture spectrum" (Figure 1.10), outlining the hierarchy of attitudes about safety, from the lackadaisical "pathological" to the attentive, proactive, culture-based "generative." An important point to take away: if safety consciousness and education are not managed properly and consistently, it is very easy for a facility to slide down this scale.

The second speaker, Dr Craig Merlic, Executive Director of the UC Center for Laboratory Safety and Associate Professor in UCLA's Department of Chemistry and Biochemistry, defines the "safety triad" (Figure 1.11), based on an institution's attitudes and commitment to safety, their formal protocols and procedures, and the staff's willingness to report honestly so that facility can learn from accidents and errors.

The last presenter is Lori Seiler, Global R&D EHS at Dow Chemical, who describes The Dow Lab Safety Academy (http://safety.dow.com), an online program developed in 2013. Since its inception, Academy lessons have been seen more than 250,000 times by more than 25,000 enrolled viewers. They have also provided services to >60 universities, >40 government agencies and national laboratories, and >100 companies in 10 countries.

At the Academy's core are four safety modules: (1) safety orientation and training; (2) specialized training; (3) how to plan, evaluate, and execute a safety culture; and (4) how to build a sustainable safety culture. Through these modules, the program trains the visitor in pretask planning, hazard awareness, how to build procedures and protocols, emergency planning, and the importance of leadership engagement, accountability, and ownership. All modules reinforce the message, "You are your own best safety advocate."



Gibbs: Adapted from Hudson, P. Safety Management and Safety Culture:
The Long, Hard and Winding Road (2001)

Fig. 1.10: Laboratory safety culture spectrum. (From the webinar "Applying a lab safety culture to nanotechnology: Educating the next generation").

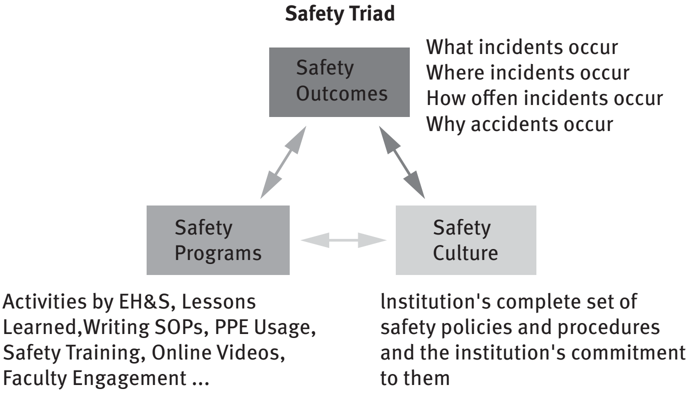


Fig. 1.11: The safety triad, demonstrating the impact of safety programs and cultures on safety outcomes. (From the webinar "Applying a lab safety culture to nanotechnology: Educating the next generation").

A number of programs have answered the call for education, training, and certification. An important resource is NanoHub (www.nano.gov/education-training), a searchable database of nanotechnology education resources.

One of the most extensive programs in the USA is Nano-Link (Nano-link.org). This NSF-funded project brings together 11 institutions throughout the Mid-West that provide workforce development, teacher training, and classroom resources. They also partner with local industries "to promote nanotechnology education at multiple grade levels by providing comprehensive resources for students and educators... supported by hands-on educator workshops and online content and activity kits." Nano-Link organizer, Deb Newbury, has also posted the following two key presentations on the website: [73]

- NCPN (National Career Pathways Network) 2012: A correlation study between emerging technology concepts and job requirements
- NSTA 2015: What is Nano-Link?

METPHAST [74] (Midwest Emerging Technologies Public Health and Safety Training) is also part of Nano-Link. Funded by the National Institute of Environmental Health Sciences Superfund Research Program, METPHAST is a multi-institutional collaboration between the University of Minnesota/School of Public Health, the University of Iowa College of Public Health, and Dakota County Technical College. The group has constructed 20 web-based modules on nano-safety, which are available for public use.

The International Association of Nanotechnology Training Programs (IANT) [75] also provides professional courses and certification in both nano-safety and clean technology.

Oxford University's Department of Continuing Education (UK) has also taken an online approach, offering a series of postgraduate part-time courses, online courses, and training in nanotechnology and nanomedicine [76].

For more formalized degree programs, NNI (www.nano.gov) provides the US Technology Resource, an interactive map that shows the locations of higher education degree programs, and a link to Penn State's Nanotechnology Applications and Career Knowledge Center (NACK) for the development of community college programs.

Although all of these programs feed into professional education and certification in nanotechnology, the need for education begins earlier and more broadly, with STEM (educational programs in science, technology, engineering, and math) and in community outreach. For STEM, Nano-Infusion (another component of Nano-Link) offers a collection of modules, including 10 min demos and 20 or 50 min experiments. They provide the supplies (no charge), training, and support, as well as a "nano-geek" T-shirt. Important components of the package are excellent online videos that demonstrate each activity.

In support of career education, Arizona University's Nanotechnology Cluster K-20 provides nanotechnology scientists who educate students at all levels on "intricacies and careers in nanotechnology." Everyone can learn more about nanotechnology during NanoDays [77], a nationwide week-long festival held each year during the last week in March/first week in April at more than 250 science museums, children's museums, research centers, and universities.

1.11 The Future

The future of nanotechnology is limited only by our imaginations. The NNI has a special, evolving list of nanotechnology signature initiatives (NSIs) that "spotlight topical areas that exhibit particular promise, existing effort, and significant opportunity, and that bridge across multiple Federal agencies." [78]

1.11.1 Nanotechnology Signature Initiatives

Here is the current list and the charter for each initiative.

1.11.1.1 Nanotechnology for Solar Energy Collection and Conversion: Contributing to Energy Solutions for the Future

Enhancing understanding of energy conversion and storage phenomena at the nanoscale, improving nanoscale characterization of electronic properties relevant to solar energy, and utilization of the unique physical phenomena that occur on the nanoscale to help overcome current performance barriers and substantially improve the collection and conversion of solar energy. This NSI has three thrust areas: (1) improving photovoltaic solar electricity generation; (2) improving solar thermal energy generation and conversion; and (3) improving solar-to-fuel conversions.

1.11.1.2 Sustainable Nanomanufacturing: Creating the Industries of the Future

Establishing manufacturing technologies for economic and sustainable integration of nanoscale building blocks into complex, large-scale systems by supporting product, tool, and process design informed by and adhering to the overall constraints of safety, sustainability, and scalability. This NSI specifically focuses at this time on high-performance structural carbon-based nanomaterials, optical metamaterials, and cellulosic nanomaterials. The nanomanufacturing NSI has two thrust areas: (1) design of scalable and sustainable nanomaterials, components, devices, and processes; and (2) nanomanufacturing measurement technologies.

1.11.1.3 Nanoelectronics for 2020 and Beyond

Discovery and use of novel nanoscale fabrication processes and innovative concepts to produce revolutionary materials, devices, systems, and architectures to advance the field of nanoelectronics. The nanoelectronics NSI has five thrust areas: (1) exploring new or alternative "state variables" for computing; (2) merging nanophotonics with nanoelectronics; (3) exploring carbon-based nanoelectronics; (4) exploiting nanoscale processes and phenomena for quantum information science; and (5) expanding the national nanoelectronics research and manufacturing infrastructure network.

1.11.1.4 Nanotechnology Knowledge Infrastructure: Enabling National Leadership in Sustainable Design

This NSI has four thrust areas that focus efforts on cooperative interdependent development of (1) a diverse collaborative community; (2) an agile modeling network coupling experimental basic research, modeling, and applications development; (3) a sustainable cyber-toolbox for nanomaterials design; and (4) a robust digital nanotechnology data and information infrastructure.

1.11.1.5 Nanotechnology for Sensors and Sensors for Nanotechnology: Improving and Protecting Health, Safety, and the Environment

The two thrust areas for this NSI are (1) to develop and promote adoption of new technologies that employ nanoscale materials and features to overcome technical barriers associated with conventional sensors; and (2) to develop methods and devices to detect and identify engineered nanomaterials (ENMs) across their life cycles in order to assess their potential impact on human health and the environment.

1.11.2 Future Research Projects

On the commercial front, here are some thought-provoking excerpts from future research projects actually in progress.

1.11.2.1 Origami Robots

"Ido Bachelet of Bar-Ilan University in Israel and colleagues describe a set of 'DNA origami robots' that, when mixed in various combinations, function as biological logic circuits, capable of responding to the presence or absence of various molecular triggers.

These 'robots,' aren't robots in the sense of Wall-E. They're DNA molecules that fold into complex and intricate shapes. Upon receiving the proper signals, they change shape, producing a measurable output.

The robots were made in several forms. Some are 'effectors' capable of releasing a 'payload,' while others act as positive or negative regulators that modify the effectors' behavior. When combined in specific stoichiometric ratios and combinations, these robots can mimic the behavior of any of seven discrete ‘logic gates’: AND, OR, XOR, NAND, NOT, CNOT, and a ‘half-adder.’” [79]

1.11.2.2 Programmable Food

“Researchers at US food giant Kraft have developed a colorless, tasteless liquid in the lab that consumers will design after you’ve bought it. You’ll decide what color and flavor you’d like the drink to be, and what nutrients it will have in it, once you get home. You’ll zap the product with a correctly tuned microwave transmitter. This will activate nano-capsules – each one about 2000 times smaller than the width of a hair – containing the necessary chemicals for your choice of drink: green-hued, blackcurrant-flavoured with a touch of caffeine and omega-3 oil, say.” [80]

1.11.2.3 Flexible Electronics

“The novel device operates on magnetoresistive random access memory (MRAM), which uses a magnesium oxide (MgO)-based magnetic tunnel junction (MTJ) to store data. MRAM outperforms conventional random access memory (RAM) computer chips in many aspects, including the ability to retain data after a power supply is cut off, high processing speed, and low power consumption.” [81]

1.11.2.4 Self-assembling Microchips

“Microchips, for example, use meticulously patterned templates to produce the nanoscale structures that process and store information. Through self-assembly, however, these structures can spontaneously form without that exhaustive preliminary patterning. And now, self-assembly can generate multiple distinct patterns, greatly increasing the complexity of nanostructures that can be formed in a single step.” [82]

1.11.2.5 Flexible, Transparent Cell Phones and Solar Cells, and Ultrafast Computers and Internet

In a quick, four-minute video, Dr Frank Koppens of the Institute of Photonic Sciences/ Nano-optoelectronics research group describes the structure of graphene, one of the most promising and rapidly emerging nanomaterials. He also outlines its applications, including future smart phones that are flexible and transparent; new types of circuitry for ultrafast processing in ultrafast phones, computers, and the internet; and flexible transparent solar cells that could be mounted on windows.

Using Lego bricks, he demonstrates how quantum dots, which are excellent light absorbers, might be mounted on a graphene substrate to make ultrasensitive, flexible, transparent photosensors that could be used, for example, as night vision cameras for cars. Finally, he describes a new generation of computers in which light runs through very tiny circuits that can be manipulated at the nanoscale [83].

1.11.2.6 More Food, Less Energy, Less Water

This article describes how zinc nanoparticles can activate enzymes in plants without the need to use inefficient fertilizers, which are applied by spraying or in irrigation.

"When we made these enzymes more active, the plants took up nearly 11% more phosphorus than was naturally present in the soil, without receiving any conventional phosphorous fertilization. The plants that we treated with zinc nanoparticles increased their biomass (growth) by 27% and produced 6% more beans than plants that we grew using typical farm practices but no fertilizer." The authors also pointed out that this "nanofertilizer also has the potential to increase plants' nutritional value." [84]

1.11.2.7 Personalized Medicine

"Cancer and neurodegenerative diseases like Alzheimer's and Parkinson's are all able to be better treated if detected early. Unfortunately, this is not always the case as symptoms may not appear until these diseases are well established. To help counteract this problem, scientists at the National Nanotechnology Laboratory (LNNano) in Brazil have created a biosensor capable of rapidly detecting molecules specifically linked to various cancers and neurological diseases.

Essentially a nanometer-size, single-layer organic transistor mounted on a glass slide, the new biosensor contains a reduced form of a peptide (a short chain amino acids; also referred to as 'small proteins') known as glutathione (GSH). This substance, when exposed to the enzyme glutathione S-transferase (GST) – associated with Parkinson's, Alzheimer's, breast cancer and a number of other diseases – creates a reaction that is detected by the transistor." [85]

1.11.2.8 Energy

"Blue energy in the form of ocean waves offers an enormous energy resource. However, it has yet to be fully exploited in order to make it available for the use of mankind. Blue energy harvesting is a challenging task as the kinetic energy from ocean waves is irregular in amplitude and is at low frequencies. Though electromagnetic generators (EMGs) are well-known for harvesting mechanical kinetic energies, they have a crucial limitation for blue energy conversion. Indeed, the output voltage of EMGs can be impractically low at the low frequencies of ocean waves. In contrast, triboelectric nanogenerators (TENGs) are highly suitable for blue energy harvesting as they can effectively harvest mechanical energies from low frequencies (<1 Hz) to relatively high frequencies (~kHz) and are also low-cost, lightweight, and easy to fabricate. Several important steps have been taken by Wang's group to develop TENG technology for blue energy harvesting. In this Perspective, we describe some of the recent progress and also address concerns related to durable packaging of TENGs in consideration of harsh marine environments and power management for an efficient power transfer and distribution for commercial applications." [86]

1.12 Questions for Contemplation

- From where you are now, describe two different pathways for you to support nanosafety.
- Nanotechnology: is it really a science of its own or is it merely an extension of chemistry, physics, and biology? State your position and defend it.
- Download a research report on a specific sector of the nanotechnology market and evaluate the quality of the data. Determine whether it is citing funding or revenue numbers, which sectors it is really including, and whether or not the data are a true reflection of a specific nanotechnology or are based on nanoenabled technologies and nanointermediates.
- Define a project you think should be commercialized and map out the safety hurdles you perceive in moving from concept to full commercialization.
- Describe how technology transfer from your local school, college, or university, can contribute to commercialization of a nanotechnology project.
- Discuss what you perceive as the greatest hurdle to an attitude of safety in nanotechnology.

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Eylem Asmatulu

2 The World of Engineering Nanomaterials

2.1 Introduction

2.1.1 How Did Engineering Nanomaterials Evolve?

The first introduction to nanotechnology began with American physicist Richard Feynman stating in a speech at an American Physical Society meeting at Caltech in 1959, “There is plenty of room at the bottom” [1]. Feynman specified that new processes could be developed at smaller scales for the manipulation of atoms and molecules, using new tools to investigate the behavior of materials at those smaller scales. Scaling changes the magnitude of many physical phenomena such as gravity (which become less significant) and surface tension and van der Waals attraction (which become more significant) [2].

A scientist at Tokyo University of Science, Norio Taniguchi, was the first to use the term “nanotechnology” in a 1974 conference. He described an example of semiconductor processes, such as ion beam milling and thin-film coating, showing characteristic control at the nanoscale [1]. He described it this way: “‘Nano-technology’ mainly consists of the processing of separation, consolidation, and deformation of materials by one atom or one molecule.” In 1981, the American engineer Eric Drexler published his first paper on nanotechnology. Furthermore, Drexler was credited with the development of molecular nanotechnology, leading to manufacture of nanosystems machinery. In the 1980s, Zurich scientists at IBM invented scanning tunneling microscopy (STM). This invention was followed by the invention of atomic force microscopy (AFM), which allowed scientists to see materials for the first-time at near the atomic level. Figure 2.1 shows an example of images at the nanoscale, obtained using AFM and STM.

In the 1980s, the accessibility of supercomputers enhanced many activities, including modeling and simulation, atomic scale visualization and characterization, and experimental synthesis activities, which in turn encouraged nanoscale research activities. Another innovation came in 1985 with the discovery of fullerenes (buckyballs), which are perfectly spherical and have 60 carbon atoms. A significant achievement was made in 1990 when a team of physicists wrote the word “IBM” using 35 xenon atoms. The earlier discovery of buckyballs pioneered new discoveries such as carbon nanotubes (CNTs) in 1991. Applications involving CNTs are growing because of their extraordinary thermal, mechanical, and electrical properties. CNT characteristics that make them promising in nanotechnology are that they are 100 times stronger than steel and six times lighter in weight. Along the same lines, new studies on semiconductors and nanocatalysts have led to many new developments for quantum dots

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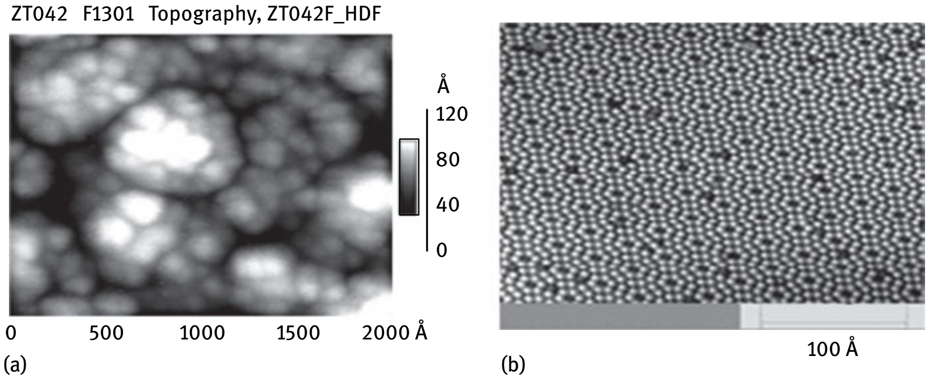

Fig. 2.1: Images taken at the nanoscale: (a) AFM image of $ZnSnO_4$/glass showing grains smaller than 100 Å, and (b) STM image of Si (111) 7 × 7 reconstruction. Source: National Renewable Energy Laboratory (NREL), 2017 [3].

(QDs), which have properties between those of bulk semiconductors and discrete molecules. All of these innovations encouraged industrialized nations to form new nanotechnology initiatives in the early 2000s, which in turn has led to a global increase in nanotechnology activities. Working with both academia and industry, the US Interagency Working Group on Nanotechnology (IWGN), established by the Office of Science and Technology Policy (OSTP), created the US National Nanotechnology Initiative (NNI) to support more advanced studies in this field [1].

Today, the major focus of research around the world is to study nanoscale properties, synthesis of different materials, characterization techniques, safety concerns, and applications to make useful devices and processes, as well as gain economic benefit from these unique materials. Although nanomaterials offer limitless possibilities, they carry new challenges for detecting and handling potential safety and health hazards to scientists, engineers, students, and consumers. Based on their core components, nanomaterials can take the form of nanotubes, nanoparticles, nanowires, nanofibers, nanowhiskers, nanofilms, and nanocomposites. Even well-known bulk materials can react differently both health-wise and in the environment when they are nanosized. Because the variety of nanomaterials is enormous, there are no exact rules and regulations for many of them [1–4]. There is growing awareness of the importance of educating future engineers and scientists about this developing field, in addition to addressing the safety and health aspects [1]. This chapter provides up-to-date information on engineering controls and safe work practices to be followed when working with nanomaterials in research and teaching laboratories [4].

2.2 Stabilization of Nanomaterial Shape

2.2.1 Surfactants

Most nanoparticles are insoluble in water and have high binding affinities to each another, so stabilizing agents are necessary to reduce agglomeration and increase aqueous dispersion of nanoparticles. Many cationic, anionic, nonionic, and amphoteric surfactants have been used for stabilizing nanomaterials in the aqueous phase. However, some of these surfactants have strong cytotoxicity effects on health and the environment. For example, cetyl trimethylammonium bromide (CTAB) has been used for synthesizing and stabilizing gold nanorods, but has a strong detergent effect that seriously increases nanorod cytotoxicity in many biological applications. Use of sodium dodecyl sulfate (SDS) and sodium dodecylbenzenesulfonates (SDBS) surfactants for CNT dispersion also causes significant toxic effects compared with other alternatives. Thus, surfactant selection for dispersion of nanoparticles must be considered cautiously, and proper research should be performed to compare surfactant toxicity levels for different nanomaterials [5]. Some polymeric materials can be used to stabilize nanomaterials through a steric stabilization process. Manipulating surface changes and adding coagulants can significantly stabilize nanomaterials in liquid suspensions.

2.2.2 Nanomaterial Shape and Stabilization

2.2.2.1 Stabilization of CNTs

CNTs can be produced using various chemical and physical methods [6]. Aggregation is a challenge for most nanomaterial applications and weakens the distinct properties of the individual CNTs. As a result of strong van der Waals attraction, single-wall carbon nanotubes (SWCNTs) pack into crystalline ropes that aggregate into tangled networks, which are very difficult to separate under normal conditions. A simple procedure described for dispersing as-produced nanotube powder in aqueous solutions involves gum Arabic and a washing detergent. Because of physical adsorption of the polymer, a stable dispersion of full-length, well-separated, individual nanotubes can be formed in a single phase [7]. Nitric acid and sulfuric acid stabilizations can also be used for the same purpose.

2.2.2.2 Stabilization of Nanofibers

Nanofibers with an average diameter average 10–500 nm can be produced using various polymeric precursors (e.g., polyacrylonitrile, polyvinylchloride, and polystyrene) via an electrospinning technique. Some nanofibers have been stabilized at temperatures of 250–280 °C for 1–3 h, followed by carbonization at 1000 °C, resulting in the fabrication of carbon nanofibers (CNFs). Characterization techniques to obtain information about the morphology, thermal properties, and chemical structures of nanofibers include scanning electron microscopy (SEM), transmission electron microscopy (TEM), differential scanning calorimetry (DSC), Fourier transform infrared spectroscopy (FTIR), glass transition temperature, X-ray diffraction (XRD), and X-ray photoelectron spectroscopy (XPS) [8]. To stabilize individual nanofibers in water, similar techniques can be applied with CNT procedures.

2.2.2.3 Stabilization of Nanowhiskers

A number of different nanowhiskers have been developed and characterized for different industrial applications. Cellulosic nanowhiskers can be sterically prepared using hydrochloric acid hydrolysis of cotton powders and subsequent surface grafting of monomethoxy poly(ethylene glycol) (mPEG) [9]. Based on the structures and elemental distributions of nanowhiskers, steric techniques can be utilized to stabilize the nanowhiskers for a number of days, or even weeks. The dispersion process allows nanowhiskers to mix well with the matrix materials and create high-performance, mechanically robust nanostructured materials for various industrial applications, such as aircraft, manufacturing, energy conversion, and electronics [6, 10].

2.2.2.4 Stabilization of Nanorods

Nanorods can be produced using a wet chemical precipitation process and stabilized using a variety of surfactants and coagulants. Stable aqueous dispersions of citrate-stabilized gold nanorods (Cit-GNRs) have been made by surfactant exchange from CTAB-stabilized GNRs, utilizing polystyrenesulfonate (PSS) as a detergent. To monitor the surfactant exchange process, FTIR, surface-enhanced Raman scattering (SERS), and XPS techniques are usually chosen. Cit-GNRs are perfectly stable at low ionic strength and are relatively conducive to further ligand exchange without any loss of dispersion stability in a solution [11]. These stable nanorods can be employed in design and manufacture of bio- and nanosensors, nanocomposite layers, electric probes, and agents for targeted drug delivery [6].

2.2.2.5 Stabilization of Nanospheres

Nanospheres are another set of newly developed nanostructured materials and are made in different ceramic and polymeric forms, such as silica nanospheres. The difficulty with silica nanospheres is aggregation, which often occurs at low pH and at neutral and high pHs in a high-salt medium. Modifying the silicate surface with trihydroxysilyl propionic acid can overcome this issue. In experimental studies, 5 g of 3-(triethoxy silyl) propionitrile and 4.2 g of KOH were mixed and heated to a boiling temperature while stirring on a hot plate. The heat was then adjusted to maintain a steady reflux of water in the condenser tube. At the end of 24 h, refluxing ammonia gas was released. Using a rotary evaporator at below 60 °C, the carboxylic acid derivate was saved, and excess water and ether were removed. The resulting transparent solution was diluted to 10 mL and analyzed by FTIR. It was concluded that 2.4 M 3-trihydroxysily propionic acid and the modified nanospheres were significantly stabilized against aggregation, even under physiological salt concentrations [12].

2.2.2.6 Stabilization of Magnetic Nanoparticles

Most magnetic nanoparticles (MNPs) correspond to iron-based nanoparticles (e.g., superparamagnetic iron oxides [SPIONs], zero-valent iron, core–shell Fe/Au, or Fe_xO_y/Au nanoparticles and ferrites); a smaller number correspond to magnesium oxide, nickel, and cobalt nanoparticles. Magnetic nanoparticles can be stabilized in nonaqueous solvents or water for short or long periods of time. MNPs are usually dispersed through functionalization by water-soluble compounds (e.g., sulfonic acid disodium salts, porphyrins, soluble polymers, citric acids, tetramethylammonium hydroxide, and calixarenes) after fabrication using chemical coprecipitation, thermal decomposition, microwave heating, and ultrasonication techniques. To increase MNP dispersion rates, polyols are frequently used. MNP stabilization in solutions can be achieved with the help of monomeric, inorganic, and polymeric compounds [13].

2.2.2.7 Stabilization of Nanoflakes

Nanoflakes, such as phosphorene, graphene, and boron nitrate, have been produced and functionalized for various industrial and technological purposes. Phosphorene has been gaining considerable attention because of its robust direct-band gap and high-charge mobility features in semiconductor applications. Phosphorene is a two-dimensional (2-D) semiconductor and allotrope of phosphorus. The first time that phosphorene was isolated by using a mechanical exfoliation process was in 2014. Today, phosphorene can be produced by mechanical or liquid exfoliation; however, direct epitaxial phosphorene growth is a challenge that significantly delays mass production and application of phosphorene nanoflakes. The stability of a nanoscale cluster or flake on a substrate is crucial in epitaxial growth. The stability of phosphorene nanoflakes is strongly reliant on the strength of interaction between the substrate and the nanoflake. For instance, strong interaction (0.75 eV/P atom) with the Cu(III) substrate breaks down the phosphorene nanoflakes, whereas weak interaction (0.063 eV/P atom) with hexagonal boron nitride (h-BN) substrate fails to stabilize its 2-D structure. Substrates with a moderate interaction (about 0.35 eV/P atom) could stabilize the 2-D structures of the nanoflake on a realistic time scale [14, 15].

2.3 Classification and Labeling of Nanomaterials

2.3.1 What Are Nanomaterials?

Nanosized particles can be found in nature. They include volcanic ash, automobile exhaust gas, cosmic dust, fire dust, windblown fine particles, and ocean mist. They can also be created from a variety of sources, such as metallic, polymeric, semiconductor, ceramic, and composite particulates, which are all man-made. To be considered a nanomaterial, one dimension of the material should be less than 100 nm, to which is attributed exclusive chemical, biological, physical, and physicochemical properties over bulk particles. The smallest size that the human eye can see is about 0.01 mm (~10 μm), so nanosized particles cannot be seen with the naked eye, even with a conventional microscope; instead, SEM, STM, TEM, and AFM techniques must be employed [16, 17]. Figure 2.2 shows a comparison of microscopic organisms and devices at the nanoscale [17].

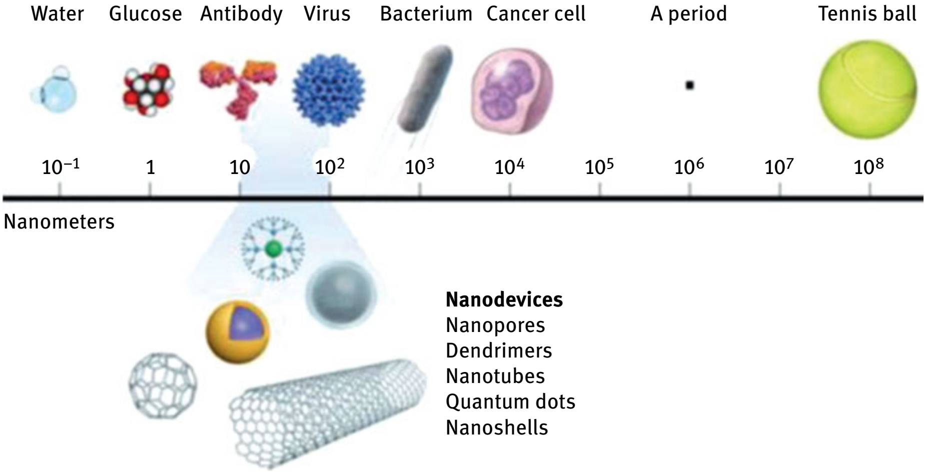

Fig. 2.2: Comparison of microscopic organisms and devices at the nanoscale [17].

2.3.2 Types of Nanoparticles

A number of different nanomaterials are used in a wide variety of applications in science, technology, defense, and medicine [18]. Nanoparticles fall into three major categories: naturally occurring, incidental, and engineered. Human beings have been generating nanoparticles accidentally or intentionally long before they could see them using high-magnification electron microscopes.

2.3.2.1 Naturally Occurring Nanomaterials

Naturally occurring nanomaterials include volcanic ash, exhaust gas, cosmic dust, fire dust, windblown fine particles, ocean mist, mineral composites, and biological entities (e.g., viruses). The action of waves on rocks eventually reduces the rock surface. Some of the particles created by wave action are nanosized.

2.3.2.2 Incidental Nanoparticles

Incidental nanoparticles are the byproducts of human activity, have poorly controlled shapes and sizes, and may cause disease and environmental concerns. Many common daily sources contain incidental nanoparticles, such as cooking smoke, diesel exhaust, and welding fumes. Furthermore, incidental nanoparticles are emitted during activities such as sandblasting, waterjet cutting, crushing and grinding, metallurgical coke manufacturing, mining and blasting, and oil refining. Table 2.1 shows some of the incidental nanoparticles occurring from daily activities and their possible health effects [19].

Tab. 2.1: Possible health effects cause by incidental nanoparticles [20].

Source of incidental nanoparticles	Possible health effects
Diesel and other exhaust	Cancer and respiratory disease
Cooking smoke	Pneumonia, chronic respiratory disease, and even lung cancer
Welding fumes	Metal fume fever, infertility, benign pneumoconiosis
Industrial effluents	Asthma, atherosclerosis, chronic obstructive pulmonary disease
Waterjet cutting	Silicosis, respiratory disease
Sandblasting	Silicosis, respiratory disease
Crushers and fine grinders	Silicosis, respiratory disease

2.3.2.3 Engineered Nanoparticles

Engineered nanoparticles consist of any manufactured particles with precise nanoscale dimensions, shapes, and compositions. At least one dimension of these nanoparticles is in the range of 1–100 nm. Examples of this category include different metals and alloys, QDs, buckyballs/fullerenes, graphene, CNTs, sunscreen pigments, nanocapsules, nanofilms, nanocomposites, nanofibers, and nanowires [20]. Engineered nanoparticles can be simple or complex and are easily obtained with different chemical compositions, such as a gold core covered in a shell of silica and coated with specific antibodies and polymers [19].

2.3.2.3.1 Dimensions

It is necessary to classify nanomaterials on the basis of the number of dimensions, because their shape (morphology) plays an important role in their toxicity. Classification of nanomaterials is dependent on the number of dimensions in the nanoscale range (<100 nm). One-dimensional nanomaterials (e.g., coatings, thin films, and multilayers) have one dimension at the nanometer scale. In 2-D nanomaterials (e.g., fibers, tubes, and wires), two dimensions are at the nanoscale. Three-dimensional nanomaterials (e.g., quantum dots, hollow spheres, and box-shaped graphene) have all three dimensions <100 nm [21].

2.3.2.3.2 Morphology

Flatness, sphericity, and aspect ratio are the morphological characteristics of nanomaterials. Overall classification is into high- and low-aspect ratio particles. Figure 2.3 shows the classification of nanostructure materials according to dimensions, morphology, composition, agglomeration, and uniformity states. High-aspect-ratio nanoparticles contain nanotubes and nanowires in various shapes, such as zigzags, belts, helices, and nanowires of various diameters and lengths. Low-aspect ratio nanoparticles contain spherical, oval, cubic, helical, prism, or pillar shapes. These nanoparticles may exist as powders, suspension, or colloids.

2.3.2.3.3 Phase Compositions

Nanoparticles can be made from a single component material or a composite of several materials. Single-phase solids include crystals, amorphous particles, and layers. Multiphase solids can be matrix composites or coated particles. Multiphase systems include colloids, aerogels, and ferrofluids.

2.3.2.3.4 Nanoparticle Uniformity and Agglomeration

Nanoparticles can occur as dispersed aerosols, suspended colloids, or in an agglomerate state (Figure 2.3) as a result of their chemistry and electromagnetic properties. For instance, magnetic nanoparticles have a tendency to cluster under a magnetic field, forming an agglomerate state if their surfaces are not coated with a nonmagnetic material. Furthermore, nanoparticle agglomeration, size, and surface reactivity, along with shape and size, need to be considered when choosing health and environmental regulations for new materials [20].

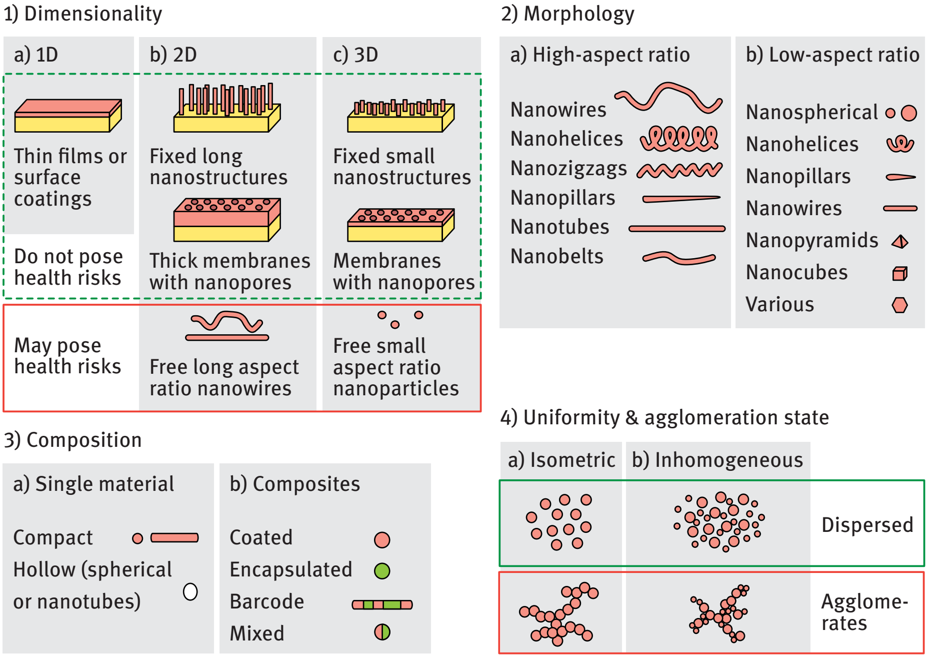

Fig. 2.3: Classification of nanostructured materials on the basis of dimensions, morphology, composition, uniformity, and agglomeration state. Source: Pipal et al. (2014) [22].

2.3.3 Labeling of Nanomaterials

2.3.3.1 Nanoproducts in the Market

The Woodrow Wilson Center set up a project on emerging nanotechnologies (PEN), which is a foundation program that analyzes consumer nanoproducts. The PEN's consumer products inventory (CPI) offers a complete list of nanoproducts. As of 2014, the nanotechnology CPI contained 1814 products or product lines. Consumer nanoproducts have a wide range of applications (e.g., sporting goods, clothing, personal care products, and medicine) as well as contributions to faster and stronger cars and planes, more powerful computers and satellites, better micro- and nanochips, and longer lasting batteries [23]. Although some of the nanoproducts available on the market are completely free of health concerns, the safety of remaining products is still unknown. Exposure to nanomaterials can occur during the experimentation, production, transportation, and consumption of nanoproducts. Examples of exposure to a nanoproduct include using aerosol sprays, applying sunscreen body lotion, taking medicine, or consuming supplements that contains nanomaterials.

2.3.3.2 Nanomaterial Labeling in the USA: Present Status

The USA regulates labeling on many types of consumer products, although none of the regulations require product labeling to indicate the existence of nanomaterials or the use of nanotechnologies. Even though nanomaterial labeling should be required for a variety of products, currently this requirement has only been considered for food and cosmetic products.

2.3.3.2.1 Food Labeling

The primary responsibility of the US Food and Drug Administration (FDA) is to focus on food safety in the USA, which relies on the multiple legal authorities that govern food, food ingredients, and dietary supplements. The FDA follows the Federal Food, Drug, and Cosmetic Act (FFDCA), and other laws governing the evaluation and approval of new food and color additives before they can be marketed. The FDA also focuses on postmarket regulatory tools, including labeling, to ensure product safety for other food ingredients and dietary supplements. These labels should be carefully designed with the exact details of the ingredients, and should not be misleading to consumers and agencies. To date, the FDA has not provided clear guidance for all nanomaterials used in consumer products (regarding benefits and the risk of nanomaterials) and their labeling. However, in 2007, the FDA published a Nanotechnology Task Force report on labeling, which discussed whether all food products containing nanomaterials should disclose details on their labels [24].

2.3.3.2.2 Cosmetic Labeling

The US cosmetics laws and regulations do not require nanotechnology-specific labeling of cosmetics. Similar to the situation for food, the FDA regulates cosmetic labeling, which mainly relies on FFDCA and FPLA laws. For some color additives, there are a few exceptions for premarket notification, but not for postmarket tools, including labeling and monitoring. The FFDCA mandates that agencies and manufacturers eliminate adulterated and misbranded products from the market, through legal action if necessary. If the product labeling fails to include the required information, the cosmetic product is misbranded. Cosmetic labeling should include the materials in the cosmetics and avoid false or misleading information. According to FDA regulations, labels should consist of a list of ingredients and include all relevant warnings for consumers. The manufacturers perform some safety analysis, but are not required to share their findings with the FDA. Improperly labeled products must bear a warning label, informing consumers that the cosmetics company substantiates the safety of their ingredients and/or cosmetic products.

To date, US regulators and legislators have not specified a real need to introducing comprehensive nanomaterial labeling for many cosmetic products currently available on the market. In 2007, although the FDA considered the labeling of nanomaterials for food and cosmetic products, it was not recommended. This decision was mainly because of a lack of understanding of the risks of nanomaterials. Since 2007, many agencies and manufacturers have not considered comprehensive nanomaterial labeling on products associated with nanomaterials.

For a number of reasons, consumer labeling of nanomaterials has become a serious issue from many public perspectives. According to PEN (Woodrow Wilson Center), more than 1814 nanoproducts exist on the market. Recently, calls have been rising for mandatory consumer labeling of nanomaterials. In the USA, there is no general labeling requirement for many nanomaterials; however, some specific rules governing product labeling in the food and cosmetics area should apply to nanomaterials and nanoenabled products [24].

2.4 Toxicity of Nanomaterials

2.4.1 Particle Size

Surface area substantially increases with a reduction in the size of nanoparticles. Increased surface area allows some additional chemical interactions to take place at the nanosurface, which in turn can increase reactivity and toxicity effects. Nanosized particles can easily pass through the cell membrane and interact with DNA structures to cause damage. Compared with the same materials containing larger particles, materials containing nanosized particles (<100 nm) can cause greater adverse health effects, such as inflammation, chronic respiratory illnesses, and cancer [20].

2.4.2 Surface Chemistry

It has been reported that aggregated nanoparticles are less toxic than individual nanoparticles because their relative surface area is drastically reduced. Surface chemistry determines the aggregation levels of nanomaterials in dry and wet conditions. Surface chemistry also determines the wetting properties and surface characteristics, which control some specific chemical reactions that remain active or passive for surface-controlled nanomaterial growth.

2.4.3 Surface Charges

Surface charge densities of nanomaterials predominantly affect toxicity levels, so high surface charge densities can result in higher cytotoxic effects than those with low charge densities. Particles with positive or negative high surface charges remain in suspended form for a longer period of time than those particles with low surface charge. Particles with high surface charges can create additional damage to cells and surrounding tissue because they react more intensely with cell membranes [20]. Zeta potential is the electrostatic property that measures the colloidal stability of nanomaterial samples in liquid suspension. This is closely associated with the particle surface charge and severely influences the aggregation state. Nanoscale colloids having a low zeta potential tend to aggregate, which can be better for reducing toxicity levels. The resultant aggregation can be observed using particle size and concentration measurements due to the enlarged size of aggregates [25].

2.4.4 Surface Area

Nanoparticles have a larger surface area and higher particle number per unit mass than microparticles. Because material in nanoparticulate form offers a greater surface area for chemical reactions, reactivity with the surrounding tissue is also greater. According to Driscoll (1996) [48] and Oberdörster (2001) [49], surface area plays a major role and is highly associated with particle-caused adverse health effects [26]. Oxidative stress occurs as the result of free radicals produced by nanoparticles in the human body. Inflammation, cell destruction, and genotoxicity can occur as a result of biological oxidative stress. The particle surface of free radicals can activate the redox cycle and improve particle toxicity levels. As particle size decreases, the number of atoms/molecules on the surface increases, in turn increasing interactions with the surrounding tissues and environment. This means an increased chance of additional chemical reactivity of a particle and, thus, production of reactive oxygen species (ROS) and free radicals. ROS-induced oxidative stress is the original mechanism of nanomaterial toxicity, which can cause DNA damage, cell membrane disruption, cell leakage, and interference with cell signaling. ROS have also been determined in the secondary toxicity effects of nanomaterials, which cause oxidation of proteins and the release of hazardous components [25].

2.5 Exposure Assessment

2.5.1 Exposure Limit for Nanoparticles

Because of their unique physical, chemical, physicochemical, and biological properties, nanomaterials are appealing materials for the twenty-first century. However, the available information on possible environmental and health effects for some of these nanomaterials is limited. Therefore, the National Institute for Occupational Safety and Health (NIOSH) has provided some endorsements for limiting worker exposure to nanoparticles through standard practices, which includes respiratory protection and other safe laboratory practices. The NIOSH recommended exposure limits (RELs) for some forms of engineered nanoparticles are mainly related to their masses, but also to the special chemical and physical properties of nanoparticles, such as shape, surface energy, surface area, and reactivity [27].

The occupational exposure limit (OEL) is one of the main tools used for preventing occupational disease from specific exposure. Providing risk managers and health authorities with a quantitative health basis can be good work practice for measuring the effectiveness of nanomaterial safety procedures (use of engineering controls and other general laboratory guidance) [28]. Thus, OELs for many nanomaterials can be useful in decreasing the health risk from those materials for workers who are exposed to nanoparticles.

Several new nanomaterials are developed every year and enter the market. Currently, no regulatory standards for specific nanomaterials have been established in the USA. An REL has been recommended via NIOSH to the Occupational Safety and Health Administration (OSHA) for use as an acceptable exposure limit [29]. More recently, NIOSH has stated that the recommended exposure limit for titanium dioxide (TiO_2) is 2.4 mg/m^3 for a fine compound and 0.3 mg/m^3 for an ultrafine compound (including engineered nanoscale material), assuming time-weighted average (TWA) concentrations for up to 10 h per day during a 40-h work week (Table 2.2) [30, 31]. Another statement by NIOSH is that worker exposure should be limited to no more than 1 $\mu g/m^3$ for nanotubes and nanofibers [30, 31].

Without any governmental direction on exposure limits, some of the manufacturers producing nanomaterials have established suggested OELs for their nanoproducts. For example, the Bayer company has developed its own OEL of 0.05 mg/m^3 for Baytubes® (multiwalled CNTs) [45]. For Nanocyl CNTs, the no-effect concentration in air was estimated to be 2.5 $\mu g/m^3$ for an 8-h/day exposure, which may offer protection for workers [28, 29, 46].

Similarly, the European legislation REACH requires a manufacturer-driven derived no-effect level (DNEL) for material they bring to market (ECHA, 2010) [50]. DNELs can be used to create acceptable exposure limits for workers [47]. Table 2.2 reviews the general efforts to derive a mass-based OEL or DNEL for numerous nanoparticles. Table 2.2 also demonstrates the large differences for CNTs with a “similar” identity.

Because of limited information about exposure limits for all nanomaterials and their products, employers and researchers should minimize worker exposure to nanomaterials by using hazard control measures and other best available practices. The following information and practices should be adopted in the work environment:

- The worker/researcher should assume that all nanoparticles are hazardous.
- To reduce their inhalation, hazardous nanoparticles should be handled in solution to prevent the generation of dust/aerosols.
- The recommended exposure limit should be minimized for the potential risk of adverse lung effects in workers who are possibly exposed at this concentration over an extended period of time.
- Health surveillance and medical screening modules should be implemented to help detect early signs of respiratory disease in workers.

Tab. 2.2: Proposed occupational exposure limits (OELs) and derived no-effect levels (DNELs) for engineered nanoparticles.

Materials	Duration	OEL or REL (mg/m^3)	DNEL (mg/m^3)	Source
MWCNT (Baytubes®)	8-h TWA	0.05	–	Pauluhn (2010) [32]
MWCNT (10–20 nm/5–15 μm). Scenario NOAEC pulmonary effects	Short-term inhalation		201	Stone et al. (2010) [33]
MWCNT (10–20 nm/5–15 μm). Scenario NOAEC pulmonary effects	Chronic inhalation		33.5	Stone et al. (2010) [33]
MWCNT (10–20 nm/5–15 μm). Scenario LOAEC immune effects	Short-term inhalation		4	Stone et al. (2010) [33]
MWCNT (10–20 nm/5–15 μm). Scenario LOAEC immune effects	Chronic inhalation		0.67	Stone et al. (2010) [33]
MWCNT (Nanocyl)	8-h TWA	0.0025		Nanocyl (2009) [34]
CNT (SWCNT and MWCNT)	8-h TWA	0.007		NIOSH (2010) [35]
CNTs or CNFs	8-h TWA	0.001		NIOSH (2013) [36]
Fullerenes	Short-term inhalation		44.4	Stone et al. (2010) [33]
Fullerenes	Chronic inhalation		0.27	Stone et al. (2010) [33]
Fullerene		~ 0.8		Shinohara et al. (2009) [37]
Ag (18–19 nm)	DNEL-lung scenario 1		0.33	Stone et al. (2010) [33]
Ag (18–19 nm)	DNEL-lung scenario 2		0.098	Stone et al. (2010) [33]
Ag (18–19 nm)	DNEL-liver		0.67	Stone et al. (2010) [33]
TiO_2	0.1 risk level particles\100 nm	0.1		NIOSH (2005) [38]
TiO_2 (21 nm)	Chronic inhalation		17	Stone et al. (2010) [33]
TiO_2 (10–100 nm; REL)	TiO_2 (10–100 nm; REL)	0.3		NIOSH (2011) [30]
TiO_2 >100 nm	TWA 10 h per day/40 days	2.4		NIOSH (2011) [30]
TiO_2 P25 (primary size 21 nm)	TWA 8 h a day, 1.5 days a week	1.2		Hanai et al. (2009) [39]

Tab. 2.2: (Continued)

Materials	**Duration**	**OEL or REL (mg/m^3)**	**DNEL (mg/m^3)**	**Source**
General	0.004% risk level	Mass-based OEL 15		OECD (2008) [40]
General dust		3		BAuA (2009) [41]
Photocopier toner	Tolerable risk	0.6		BAuA (2008) [42]
Photocopier toner	2009 acceptable risk	0.06		BAuA (2008) [42]
Photocopier toner	2018 acceptable risk	0.006		BAuA (2008) [42]
Biopersistent granular materials (metal oxides, others)	Density >6000 kg/m^3	20,000 $particles/cm^3$		IFA (2009) [43]
Biopersistent granular materials	Density <6000 kg/m^3	40,000 $particles/cm^3$		IFA (2009) [43]
CNTs	Exposure risk ratio for asbestos	0.01 $fibers/cm^3$		IFA (2009) [43]
Nanoscale liquid		Mass-based OEL		IFA (2009) [43]
Fibrous	3 : 1; length 75,000 nm	0.01 $fibers/cm^3$		BSI (2007) [44]
CMAR		Mass-based OEL 10		BSI (2007) [44]
Insoluble	Not fibrous	Mass-based OEL 15		BSI (2007) [44]
Insoluble	Not fibrous	Mass-based OEL 10		BSI (2007) [44]
MWCNT	Bayer product only	0.05		Bayer (2010) [45]
MWCNT	Nanocyl product only	0.0025		Nanocyl (2009) [34]

CMAR carcinogenic, mutagenic, asthmagenic, and reproductive toxicants; TWA time-weighted average; CMF carbon nanofiber; CNT carbon nanotube; SWCNT single-wall CNT; MWCNT multiwall CNT; NOAEC no-observed adverse effect concentration; LOAEC lowest observed adverse effect concentration; REL recommended exposure limit. 8-h TWA 8-hour time weighted average.
Source: Adapted from Broekhuizen et al. (2012) [47].

- Employers must understand the risks of hazardous nanoparticle exposure and implement measures to keep all workers safe.
- Knowing how to characterize nanomaterials and processes provides clues for protection.
- To minimize and manage exposure to nanomaterials, engineering controls and personal protective equipment are the best techniques for protecting workers.

- Training programs for workers about potential hazards are crucial, and workers should have knowledge about the proper use of administrative controls, engineering controls, and safe work practices.
- Researchers must be familiar with analytical instruments and methods used to measure nanomaterial exposure levels.
- Quantitative and qualitative measurements of nanomaterial exposure are both essential for protecting workers in the workplace.

2.5.2 Exposure Monitoring

Currently, it is not clear which metrics related to the exposure to diverse nanomaterials are the most important from health, environment, and safety perspectives. Considering air contaminants, the mass-based metric has been used for characterizing toxicological effects of nanomaterials. The actual measurement of aerosolized particles that contain primary nanoparticles and agglomerates plays an important role in detecting nanomaterial emissions and evaluating control systems through field surveys. For convenience, the measurement devices used to evaluate controls in the workplace should be portable, robust, and reliable. Information about available instruments and techniques for nanoparticle monitoring has been discussed in technical reports and is summarized in Table 2.3 [36].

Tab. 2.3: Instruments and techniques for monitoring nanoparticle emissions in nanomanufacturing workplaces and laboratories.

Metric	Instrument	Remarks
Aerosol concentration	CPC	Real-time measurement. Typical concentration range of up to 400,000 particles/cm^3 for stand-alone models with coincidence correlation; 1,000,000 particles/cm^3 for hand-held models
	DMPS	SMPS often uses a radioactive source. FMPS uses electrometer-based sensors. Concentration range from 100–107 particles/cm^3 at 5.6 nm and 1–105 particles/cm^3 at 560 nm
Surface area	Diffusion charger	Needs an appropriate inlet preseparator for nanoparticle measurement. Total active surface area concentration up to 1000 μm^2/cm^3
	ELPI	Real-time size-selective detection of active surface area concentration. Range of 2×10^4 to 6.9×10^7 particles/cm^3 depending on size range/stage
Mass	Size-selective static sampler	Low-pressure cascade impactors. Micro-orifice impactors
	TEOM	EPA standard reference equivalent method

Tab. 2.3: (Continued)

Metric	Instrument	Remarks
Aerosol concentration by calculation	ELPI	–
Surface area by calculation	DMPS	–
DMPS and ELPI used in parallel		Surface area is estimated by difference in measured aerodynamic and mobility diameters
Mass by calculation	ELPI	Calculated by assumed or known particle charge and density
	DMPS	Calculated by assumed or known particle charge and density

CPC condensation particle counter; DMPS differential mobility particle sizer; SMPS scanning mobility particle sizer; FMPS fast mobility particle sizer; ELPI electric low-pressure impactor; TEOM tapered element oscillating microbalance [36]

2.6 Conclusions

There have been enormous developments in various nanomaterials (e.g., nanotubes, nanowires, nanoparticles, nanofibers, nanowires, nanocomposites, and nanofilms), as well as in fabrication, characterization, stabilization, and commercial application worldwide. Although nanomaterials of various sizes, shapes, and structures have been produced and utilized in different consumer products, the health and environmental concerns about these nanomaterials have not been studied in detail, which creates considerable public concern. To minimize this concern, new study programs should be developed for each nanomaterial, and health and environmental concerns must be evaluated prior to industrial application of the nanomaterials. Furthermore, educational seminars, workshops, and conferences should be conducted at different universities and research centers worldwide for the awareness of students, engineers, scientists, and employees working in these fields.

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3 The Importance of Safety for Manufacturing Nanomaterials

3.1 Rapid Growth of Nanotechnology

Nanotechnology is a wide interdisciplinary field of research, development, and industrial activity that has grown rapidly worldwide over the past few years [1–3]. This field entails physics, chemistry, biology, material science, engineering and electronic processing, composites, applications, and concepts in which the defining characteristic is the size or dimension [3]. This field involves the manufacturing, processing, imaging, and application of materials that are in the size range of 1 to 100 nm. The term “nanotechnology” was first introduced in 1974 by a Japanese engineer, Norio Taniguchi. The name implies a new technology that can control materials beyond the micrometer scale [4]. To quote K. E. Drexler, “Nanotechnology is the principle of manipulation of the structure of matter at the molecular level. It entails the ability to build molecular systems with atom-by-atom precision, yielding a variety of nanomachines” [5]. Nanotechnology has the potential to change our standard of living. Some of its applications are energy storage and production, information technology, medicine, manufacturing, food and water purification, instrumentation, and environmental uses. Several nanotechnology-based products are already available on the market, including electronic components, nanopaints, storage devices, stain-free fabrics, cutting boards, socks, and medical components. The most common nanomaterials used in consumer products are carbon nanotubes (CNTs), nanoscale metal oxides (titanium dioxide, zinc oxide), nanosilver, nanosilica, and nanogold [1–5].

Commercialization of nanotechnology has the potential to affect the health and safety of workers involved in research, the general public, customers, and the environment [1]. This emerging field has the potential for great economic expansion and is growing rapidly in various disciplines. A key aspect of this science of manipulating matter at the atomic/molecular scale is the creation of new materials at the nanoscale that have different properties compared with their bulk counterparts. For example, graphite, which is a form of carbon, is used extensively in pencils; however, when synthesized into CNTs, it becomes 100 times as strong as steel. Research in nanotechnology continues to expand around the globe and, in a few years, this field will assume a $1 trillion economy. The National Science Foundation has estimated that by 2015, nanotechnology will have a $1 trillion impact on the global economy and will employ two million workers, about one million of whom will be in the USA [1].

The commercialization of nanotechnology is important; however, a complete understanding of the hazardous effects of nanoparticles/nanomaterials on human

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health and the environment is not available because there has not been sufficient research in nanotechnology to answer all questions pertaining to those two areas. Furthermore, safety and health-related technologies and best industrial practices have not been imposed to protect the well-being of workers during the lifecycle of nanobased products. Safety concerns also apply to workers in nonmanufacturing enterprises, the environment, and consumers [1]. The application of nanotechnology in the medical industry for the prevention, detection, and treatment of occupational diseases (e.g., musculoskeletal disorders and pulmonary diseases) associated with exposure to nanoproducts will cost considerable sums of money. The exact cost of healthcare in this area is unknown in the long term. With the advancements in nanotechnology, new challenges such waste management, safety, and health risks to workers could arise in the future [2]. Progress in nanotechnology is still at mid-stage; however, it has the potential for an outstanding future in terms of improving quality of life and advancing the capabilities of materials, processes, and products in a wide range of industrial and domestic applications. Without substantial progress in establishing methodologies and relevant technologies in the workplace and laboratories, the workforce could be in great danger as a result of the unknown possible adverse health hazards of nanomaterials and nanoproducts [1].

Furthermore, airborne nanoparticles in the environment and the impact of exposure to nanoparticles must be strongly considered [1]. A strategy to deal with these issues must include the following: (i) comprehensive guidelines for health, safety, and protection throughout the life cycle of nanoproducts; (ii) research programs and focus groups to establish guidelines for the health and safety of the workforce and general public, and find ways to protect the environment from the adverse effects of nanotechnology and nanoproducts; (iii) a national research agenda related to strategy and planning for the application of nanotechnology in the biomedical industry and its long-term effects; and (iv) dissemination of the latest research findings on the life cycle of nanoproducts.

3.2 Nanotechnology Involvement

3.2.1 Scope of Nanotechnology

Nanotechnology comprises the following four areas [3]: nanofabrication, nanomedicine, nanometrology, and nanomaterials/nanoparticles. Nanofabrication is the design and manufacture of devices and systems with dimensions in nanometers. Nanomedicine is the application of nanotechnology in the medical industry. This area ranges from the medical application of nanoparticles/nanomaterials in nanobiosensors as well as the possible application of molecular nanotechnology and nanobiotechnology. Nanometrology is concerned with the science of measurement at the nanoscale. Particles having an aerodynamic diameter of less than 100 nm are regarded as true nanoparticles [6]. Nanoparticles with novel physicochemical properties are used to improve the functionality of commercial and consumer goods [6]. Examples of such products are paints, sunglasses, sunscreen, cosmetics, building materials, clothing, electronics, solar cells, industrial lubricants, semiconductors, advanced tires, and fuel cells [6].Titanium dioxides are used in paints, and zinc oxides are used in sunscreen products. Nanoparticles provide great benefits in almost all sectors. However, the properties of particles that are scientifically and commercially exploitable could be the basis of some adverse health and environmental effects. There is a growing need to identify those nanoparticles with excellent commercial potential, evaluate techniques for their manufacture, conduct hazard assessments of those materials, and analyze their exposure assessments. Currently, limited information is available on human exposure and the environmental effects of nanomaterials.

Nanotechnology will continue to grow, with more and more applications emerging globally in the near future. Thousands of workers may be potentially exposed to engineered nanoparticles as a result of the recent acceleration in their manufacture and application. Research on the toxicity of engineered nanoparticles has demonstrated greater biological activity of nanoparticles compared with large particles of the same material composition. Laboratory tests have reported significant toxicity in animals exposed to nanomaterials. Determining the kind of adverse health effects that nanomaterials pose to human health in the workplace is a crucial issue.

Nanomanufacturing is the bridge between the innovation and discovery of nanoscience and real-world nanotechnology products. Through nanomanufacturing, the potential of technological innovations across a spectrum of products will ultimately affect all industrial sectors in the near future. Nanomanufacturing is the fabrication of nanoscale building blocks (nanomaterials, nanostructures) into higher-order structures, such as nanosystems and nanodevices, and integrating these into larger structures and systems. Nanotechnology is generally considered a technology that uses the “bottom-up” approach for creating materials, devices, and systems, in contrast to the traditional “top-down” approach [4]. The manufacture of nanocomponents and nanoproducts involves a wide variety of synthesis technologies [7]. These techniques can be classified on the basis of approach (top-down or bottom-up) and the nature of the synthesis (wet or dry).

A top-down approach for nanomanufacturing involves the creation of nanoproducts and nanocomponents using bulk material as a starting block. Examples of such techniques are lithography and etching [7]. Lithography is a process that allows the patterning of a required design onto the starting material. This technique is used to produce miniaturization of electronic components such as computer chips, CDs, and DVDs. Etching is a process used to create a precision surface and the attrition of metals to create metal nanoparticles [7].

In the bottom-up approach, nanocomponents are built up from the atomic/molecular level. An example of this kind of approach is found in nature; cells use enzymes to produce DNA by binding molecules together to make the final structure.

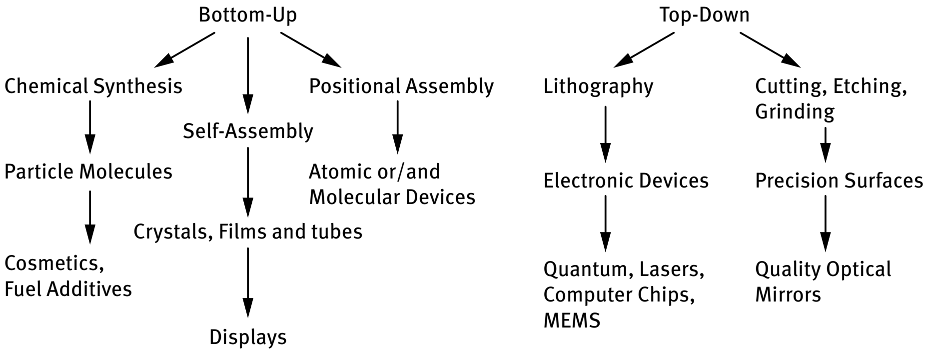

Fig. 3.1: Bottom-up and top-down techniques used in nanomanufacturing [1].

Other examples of this approach are self-assembly and chemical synthesis. Cosmetics, additives in fuel, and atomic/molecular devices are examples of products manufactured using the bottom-up approach. Figure 3.1 illustrates some of the types of materials and products used in the bottom-up and top-down approaches [1].

The primary requirements in nanomanufacturing are that the manufacture involves a dimensional scale of 1–100 nm, and that the processes and resulting nanostructures exploit the physical phenomena unique to that scale. Nanomanufacturing begins with nanoscale building blocks, such as quantum dots, buckyballs, nanotubes, and nanowires, and their production in volume. Nanoscale building blocks are then integrated into nanostructures. In turn, nanostructures are used to manufacture nanodevices, which are used to form nanosubsystems, which are then integrated into nanosystems. From here, nanosystems form useful products that are inserted into large-scale systems and platforms such as cell phones, power grids, and airplanes.

3.2.2 Nanotechnology Education and Research Programs

Educational and research programs in nanotechnology are greatly needed in order to determine the impacts of nanotechnology products, as well as occupational and environmental health and safety (OEHS) issues. The following two perspectives should be considered, as shown in Figure 3.2 [1]:

- Protection of an individual's safety and health throughout the life cycle of nanoproducts.
- Application of new technology for the prevention and detection/treatment of occupational and environmental maladies/diseases.

Figure 3.3 shows the nanoproduct life cycle, which mainly consists of nanomanufacturing (processing, materials handling, manufacturing, environment, and supply chain), nanoproducts (customer and industry use), and after-use (disposal and dis-

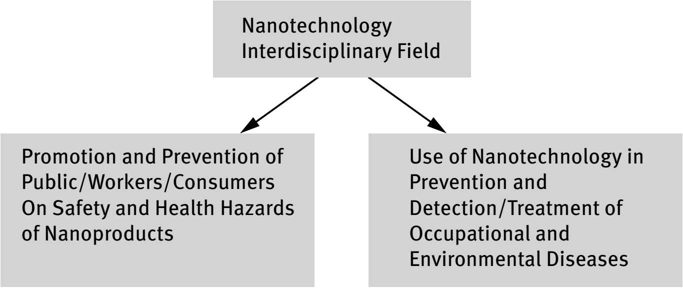

Fig. 3.2: Objectives of nanotechnology from an occupational and environmental health and safety point of view [1].

Fig. 3.3: Life cycle of nanoproducts [1].

charge). Universities, research centers, government institutions, and private companies should be involved in every step of nanoproduct production. An education program should address issues such as training the workforce in handling nanobased products, as well as finding solutions to minimize waste and exposure to nanomaterials, nanoparticles, and nanoproducts, thus creating an atmosphere of awareness of the hazardous effects of nanomaterials in the workforce.

Education Program: An educational program should consist of four major steps [1]:

- Determine the potential health hazards associated with exposure to nanomaterials/nanoproducts by reviewing the literature available regarding this issue.
- Derive qualitative and quantitative exposure estimates associated with nanomanufacturing by reviewing the literature regarding exposure to nanomaterials, international exposure standards, and current technologies to minimize airborne nanoparticles; develop promotion and protection intervention for workforce well-being, and apply this learning.
- Address the issue of safety and potential health hazards in nanomanufacturing enterprises in all manufacturing sectors, and educate the workforce on safety and health hazard issues associated with exposure to nanomaterials.
- Identify issues related to safety and health hazards associated with the exposure of the general public and consumers of nanoproducts to nanomaterials. Although nanotechnology is expected to increase life expectancy and enhance product capability, many uncertainties are still associated with the exposure of the environ-

ment to nanoproducts, and related health issues. An educational program would be designed to address these issues.

Research Program: A research program aimed at protecting the workforce from the hazardous effects of nanomaterials and nanodevices would have two main objectives [1]:

- Provide a platform for the exchange of ideas and research outcomes on the hazardous effects of nanomaterials on the environment and human health. The aim would be to develop a national agenda for assessing the impact of nanotechnology on occupational health, along with the life cycle of nanoproducts and their disposal techniques.
- Provide a platform for the exchange of ideas and research outcomes on the use of nanotechnology for the prevention, early detection, and treatment of specific diseases associated with exposure to nanoproducts.

3.3 Nanostructured Materials

Nanostructured materials are products of nanotechnology and have enormous potential in various fields of materials science, engineering, technology, and biomedical science [8]. Nanostructured materials can exhibit outstanding physical and chemical properties due to their quantum size, high surface area, high aspect ratio, few defects, and macroquantum tunnel effects [8]. The rapid growth of nanotechnology suggests that it will not take long before a wide variety of new electronic, pharmaceutical, and other industrial uses for nanostructured materials are found [9]. Such rapid proliferation of nanotechnology has prompted great concern over the safety and environmental effects of nanostructured materials [9].

Nanotechnology has revolutionized our society. Nanomaterials are being used in almost all industries, and their usage is increasing in an ever-growing number of products and applications. Such rapid advancement of nanomaterials has stimulated the demand for safety assessment with respect to both human health and the environment. The potential advantages of these materials are too numerous to count, and industries have great expectations, but there are many unanswered questions regarding the safety of workers and potential hazards to humans and the environment following exposure to nanomaterials. It is very difficult to classify these nonhomogeneous materials because they exist in various forms, and their impact on human health and the environment is still unknown. There are some daunting analytical problems associated with characterizing nanomaterials into different categories, assessing exposure to these materials, and elucidating their potential pathways. Lack of such information related to nanomaterial exposure is impeding the potential risk assessment and life cycle assessment (LCA) of nanomaterials. Some LCA methods are being used by researchers to assess the potential hazardous impact of nanomaterials, but the assessment is still in its early stages and information is limited.

3.3.1 Nanoparticles

Nanoparticles are the end products of a variety of chemical, physical, and biological processes [10]. A nanomaterial is a substance with at least one dimension less than 100 nm and can take many different forms, such as particles, wires, tubes, rods, and spheres. Nanoparticle products include quantum dots, iron oxides, titanium dioxides, aluminum oxides, cerium oxides, zinc oxides, silicon dioxides, gold nanoparticles, dendrimers, and some layered structures. Recently, there has been rapid growth in the development of new nanoparticles. One edition of the *Journal of Material Chemistry* included 47 papers on the development of nanoparticles [9]. Table 3.1 shows the main categories of nanoparticles according to their morphologies, applications, and composition [9].

Tab. 3.1: Different categories of nanoparticles available on the market [9].

Nanostructures	Materials
Fullerenes	Carbon
Nanotubes	Carbon, boron nitride
Nanowires	Metals, semiconductors, oxides, sulfides, nitrides
Nanocrystals	Insulators, semiconductors, metals
Quantum dots	Magnetic materials
Other nanoparticles	Iron, zinc, titanium and ceramic oxides, metals/alloys, composites, polymers, etc.

3.3.1.1 Fullerenes

Fullerenes are a naturally occurring form of carbon, discovered in 1985 [9]. They are a series of carbon molecules that form either a closed hollow sphere (buckyballs) or a cylinder (nanotube). Fullerenes are similar in structure to graphite, which is composed of a sheet of hexagonal rings that form a three-dimensional structure [9]. Fullerenes are produced by laser ablation of graphite in a helium atmosphere [9]. The smallest structure is a cage-like molecule composed of 60 carbon atoms (C_{60}) joined together by single and double bonds to form a hollow sphere with 12 pentagonal and 20 hexagonal faces. Other techniques used to produce fullerenes are the combustion of hydrocarbon, thermal and nonthermal plasma pyrolysis of coal and hydrocarbons, and thermal decomposition of hydrocarbon [9].

3.3.1.2 Carbon Nanotubes

Carbon nanotubes (CNTs) were first discovered by Iijima in 1991 in Japan using an arc-discharge method. CNTs are a special form of fullerene, consisting of concentric layers of graphite (multiwalled CNTs, MWCNTs). However, nanotubes composed of a single layer (single-walled CNTs, SWCNTs) were discovered during analysis of ash from a synthesis reactor. CNTs are similar in structure to C_{60} (buckyballs), but they are elongated to form a tubular structure [9]. A SWCNT has a diameter of 0.6–5 nm, whereas a MWCNT has an inner diameter of 1.5–15 nm and an outer diameter of 2.5–50 nm. CNTs can be produced in various aspect ratios and varying lengths, depending on the processing technique [9]. CNTs possess outstanding mechanical, thermal, and electrical properties [11]. Their mechanical strength is 150 GPa, thermal conductivity is 1500–300 W/m K, and electrical conductivity is as high as 10^4 S/cm [11]. CNTs are 100 times stronger than steel, and their thermal conductivity is 4–5 times higher than that of most metals. They are potentially one of the strongest materials known to date [9].

3.3.1.3 Nanowires

Nanowires are nanostructures composed of either conducting or semiconducting nanoparticles with diameters of 1–100 nm and large aspect ratios. Nanowires are used as interconnectors in nanodevices [9]. At the nanoscale, quantum effects become predominant; therefore, these wires are also known as “quantum wires.” Various types of conducting and semiconducting nanowires have been fabricated, including nickel, gold, platinum, silicon, and, recently, gallium nitride (GaN). However, some insulating nanowires, including zinc oxide (ZnO), stannic oxide (SnO_2), silica (silicon dioxide, SiO_2), and titanium dioxide (TiO_2), have also been produced.

3.3.1.4 Quantum Dots

Quantum dots are very tiny particles or nanocrystals of semiconductor materials, metal oxides, or assemblies of metals. They have diameters of 2–10 nm and exhibit novel optical, electronic, magnetic, and catalytic properties [9]. The unusual properties of quantum dots are the result of the high surface-to-volume ratios of these particles. Quantum dots are neither an extended solid structure nor a single molecular entity [9]. Various techniques are available to produce them; however, the wet chemical colloidal process is the most common technique [9]. Scientists have applied quantum dots in solar cells, light-emitting diodes (LEDs), transistors, and medical imaging.

3.3.1.5 Metallic Nanoparticles

A nanoparticle is the basic component of a nanostructured material. Generally, the size of a nanoparticle is in the range of 1–100 nm. The term “metallic nanoparticle” is used to describe nanosized metal with dimensions (length, thickness, or width) in this range. Metallic nanoparticles exhibit different physical and chemical properties from their bulk counterparts, and some of these properties might prove attractive in industrial applications [28]. Nanoparticles possess some unique features, such as high surface area-to-volume ratio, large surface energy, quantum confinement, and short-range ordering. Commercially available metallic nanoparticles include Ag, Au, Pt, ZnO, and metal oxides such as CuO, SiO_2, TiO_2, alumina (Al_2O_3), and iron oxides (Fe_3O_4, and Fe_2O_3).

3.3.1.6 Carbon Black

Carbon black is produced by the incomplete combustion of fossil fuels. Generally, anthropogenic combustion produces a wide variety of particles, including some ultrafine particles that are compatible with the definition of nanoparticles [12]. These particles are referred to as carbon black and are the result of the incomplete combustion of heavy petroleum products. Carbon black is used as reinforcing material in automobile tires and rubber products, paints, and color pigments. The particle size for carbon black is in the range of 10–300 nm [12].

3.3.1.7 Dendrimers

Dendrimers are highly branched, monodispersed macromolecules with a star-like appearance and nanosized dimensions. Dendrimers have three components: a central core, an interior structure (branches), and an exterior surface with functional groups. By varying these three components, dendrimers of different shapes and sizes can be produced. Their structure greatly impacts their physical and chemical properties. Dendrimers are an ideal candidate for applications in biology, engineering, and material science.

3.3.1.8 Nanocomposites

Nanocomposites are materials to which nanosized filler components are added to improve the properties of the resulting materials. Nanocomposites are composed of two or more distinct constituents or phases having different physical and chemical properties and separated by a distinct interface. Their many unique properties are not depicted by any of the constituents. The constituent that is generally present in greater quantity is called the matrix. The constituent that is embedded into the matrix material to improve the mechanical properties of nanocomposites is called the reinforcement (or nanomaterial). Reinforcement is generally in the form of nanosized filler material. Generally, nanocomposites show anisotropy (properties are directionally dependent) because of the distinct properties of the constituents and inhomogeneous distribution of the reinforcement.

3.3.1.9 Nanoclays

Nanoclays, a modified form of layered mineral silicates, are a class of organic–inorganic hybrid material [13]. Depending upon the chemical composition and morphology of the particles, nanoclays can be categorized into many classes, such as montmorillonite, bentonite, kaolinite, hectorite, and halloysite. These materials are finding a wide range of applications in polymer nanocomposites, absorbents for toxic gas emissions, drug delivery carriers, rheological modified inks, fire-retardant materials, paints, and greases [13]. “Layered silicate” is a generic term referring to synthesized layered silicates (montmorillonite, laponite, and hectorite) and natural clays [13]. Montmorillonite is the most common nanoclay used in many materials applications. The plate-like montmorillonite consists of a 1-nm thick aluminum silicate surface layer modified with cations having dimensions (length and width) of hundreds of nanometers [13]. Nanoclays are naturally occurring materials that contain nanosized particles within the mined material.

3.3.1.10 Nanocrystals

Nanocrystals are crystalline particles having nanometer dimensions. Nanocrystals are the building blocks of nanotechnology. Their properties can be changed by controlling the methods of synthesis. They can be incorporated into electronic devices such as LEDs for energy-efficient lighting, and are being used in filtration to refine crude oil into diesel fuel. Nanocrystals are also finding application in many other areas, such as solar cells, catalysts, and sensors.

3.4 Toxicity of Nanomaterials

Nanomaterials can come in contact with the vascular endothelium and cause cardiovascular damage [14]. Generally, nanomaterials enter the human body via inhalation, dermal, or oral routes. Some researchers have found that nanomaterials can promote DNA damage. Previous studies have shown that nanoparticles can cause some level of damage to cells. Silver nanoparticles are more toxic, and endothelial cells are more susceptible than bulk silver materials when exposed to silver nanoparticles. Titanium dioxide nanoparticles are less toxic than silver particles. Nanomaterials possess unique toxic properties due to their physicochemical characteristics and nanosize features [14]. Some nontoxic microparticles become toxic when they are reduced to the nanoscale. Nanomaterials are more toxic than bulk materials of the same chemical composition.

Nanoparticles are very reactive and possess catalytic properties as a result of their high surface area-to-volume ratio. They have access to transport mechanisms that are not possible for large structures, thus bypassing all biological barriers and penetrating into the interior of cells [14]. Therefore, significant attention has been paid to nanoparticle toxicity, because the impact of many nanomaterials on human health is not yet known. There is considerable concern regarding the toxicity of nanomaterials and the methods of toxicity assessment. Toxicity evaluation of nanomaterials provides some insights into the adverse effects of nanomaterials and helps in developing a database that can provide useful information for assessment of potential risk and risk-management issues [14].

The latest studies show that the potential genotoxic, oxidative, and cytotoxic effects at the cellular level, as well as respiratory, neurotoxic, cardiovascular, dermal, and immunological effects, can be caused by exposure to different nanomaterials [14–16]. To determine the toxicity of nanomaterials, both in vitro and animal studies are being used. Generally, an in vitro assay consists of subcellular systems, cellular systems, individual cells, and tissues. Although in vitro data is not a substitute for whole-animal studies, it helps establish a platform for further assessment of the potential risk of the hazardous effects of nanomaterials [16]. The results of in vitro studies can be extrapolated to human health. Toxicity data from in vitro studies can be used to screen acute hazards and possible mechanisms of compound interactions with animals or humans. Advancement in toxicity testing aims at the characterization, uptake, and mechanisms of toxicity of nanomaterials in all types of cells. After characterization, the interactions of nanomaterials with cells can be determined by biochemical assay and microscopy. Viability testing, combined with studies of nanomaterial morphology and the generation of oxidative stress, is helpful in elucidating the toxicity mechanism. These tests provide useful information for determining how the size of nanomaterials, their chemical composition, and their functionalization contribute to toxicity [16].

3.4.1 Toxicity of Carbon-Based Nanomaterials

The most widely used nanomaterials are based on carbon and include fullerenes, SWCNTs, MWCNTs, carbon black, and graphene. Some studies have demonstrated the pulmonary toxicity of SWCNTs in rats [17]. It has also been determined that SWCNTs cause dose-dependent interstitial granulomas and pulmonary injuries and are more toxic than quartz. Basic approaches generally used to determine the toxicity of carbon nanomaterials include the following [17]:

- Assay for inhibition of mitochondrial dehydrogenase activity
- Phagocytic response to latex beads
- Transmission electron microscopy (TEM)

3.4.1.1 Assay for Inhibition of Mitochondrial Dehydrogenase Activity

Assay for inhibition of mitochondrial dehydrogenase activity is a common method in cytotoxicity testing. Alveolar macrophage (AM) cells are the first line of immunological defense against nanoparticles in the lungs [17]. For this test, adult pathogen-free healthy pigs are chosen and AM cells obtained using the bronchoalveolar lavage medical procedure [17]. AM cells are isolated from the lung lavage fluid and then suspended in RPMI (Roswell Park Memorial Institute) 1640 medium containing 10% FBS (fetal bovine serum). The macrophages are plated at a specified density of viable cells per well, in a coaster in order to attach the plastic matrix. Afterwards, the medium is removed and a fresh cell monolayer is exposed to the nanomaterial [17]. The cytotoxicity of nanomaterials is determined by the MTT colorimetric assay. This assay is used for quantification of cell death and cell lysis and is based on the measurement of lactate dehydrogenase (LDH) activity released from damaged cells into the supernatant. After exposing AM cells to the nanomaterial, phosphate buffered saline (PBS) is added to each sample. Incubation for a specified period of time results in dark formazan crystals. These crystals are dissolved in HCl–2-propanol and then centrifuged to remove any traces of particles. The supernatant is re-aliquoted into a new well plate, and the absorbance recorded using a Biorad Microplate Reader [17]. Four steps must be performed for calculating the percentage cytotoxicity, as follows [18]:

- *Background control*: Provides information about the LDH activity contained in the medium.
- *Low control*: Provides information about the LDH activity released from untreated cells.
- *High control*: Provides information about the maximum release of LDH activity from cells.
- *Experimental value*: Provides information about the LDH activity released from treated cells.

To determine the percentage cytotoxicity, the average absorbance values of triplicate samples are subtracted from each absorbance value obtained for the background control. The resulting values are then substituted into the following equation [18]:

$$\text{Percentage cytotoxicity} = \frac{\text{Experimental value} - \text{low control}}{\text{High control} - \text{low control}} \times 100 \qquad (3.1)$$

3.4.1.2 Phagocytic Response to Latex Beads

This technique is used to demonstrate the immunological function of the alveolar macrophage [17]. The phagocytic ability of isolated primary AM cells exposed to carbon nanomaterials can be assessed by measuring their ability to phagocytose colloidal gold latex breads. After exposing AM cells to various doses of nanomaterials, they are transferred to fresh medium containing latex breads. Beads that are not phagocytosed are removed from the medium and washed with PBS solution. Then, cells are tested under a fluorescent microscope. The adhered particles and phagocytized particles can be counted separately by adjusting the focal length in the microscope [17].

After microscopic observation, cells are harvested and investigated using a flow cytometer. From the plot of forward scatter versus side scatter, the AMs can be extracted and cells isolated. Then, free particles can be distinguished on the basis of granularity and size [17]. The phagocytic ability can be expressed as the geometric mean of the fluorescent intensity of the phagocytized beads compared with that of total beads [17].

3.4.1.3 Observation Using Electron Microscopy

Electron microscopy is a well-known technique for nanoimaging particles of a small size to show their morphology, and material features [19]. Many studies depend upon TEM for information on particle size, shape, morphology, and aggregation. TEM is generally used for imaging metallic samples; however, energy-filtered TEM (EFTEM) can be used to image nonmetallic samples [19]. Structural alteration of AM cells induced by nanomaterials is generally observed by TEM. AM cells are harvested using a cell scraper, washed with PBS solutions, and prefixed with glutaraldehyde [17]. After washing, the AMs are postfixed with osmium tetroxide and again washed with a cacodylate buffer. The cells are then analyzed with TEM after dehydration, ultrathin sectioning, and staining with uranyl acetate and lead citrate [17].

3.4.2 Toxicity of Metal-Based Nanomaterials

Nanoparticles can cause harmful effects on tissues and organs, as well as at the cellular, subcellular, and protein levels in the body, as a result of their abnormal physiochemical properties [23]. Metal nanoparticles have attracted significant attention because of their wide range of applications in medical, consumer, industrial, and military sectors. As the particle size decreases, some metal nanoparticles exhibit toxicity even though the same material is inert in its bulk form (e.g., Au, Ag, and Pt). Metal nanoparticles interact with enzymes and proteins, and also interfere with the antioxidant defense mechanism, resulting in generation of reactive oxygen species, initiation of the inflammatory response, and perturbation and destruction of mitochondria, causing apoptosis [23].

To investigate the health consequences of exposure to metal nanoparticles, an in vitro system is generally used to predict effects at the cellular level. Toxicity testing of nanomaterials is used for characterization, uptake, and the mechanism of toxicity in a variety of cell types. After successful characterization of nanomaterials, the interaction of nanomaterials with cells can be studied with the help of biochemical assays and microscopy techniques. Results of microscopy observation, viability testing, and the generation of oxidative stress can help in elucidating the mechanism of toxicity.

Silver is not normally found in sufficiently high concentrations to pose a real threat to humans and the environment; however, nanosilver particles have surface and physical properties that could pose a threat to both [24]. The release of toxic silver ions from nanosilver particles is of great concern. Such particles exhibit high toxicity as a result of the activity of free silver ions released from nanoparticles. Silver nanoparticles can cause chromosomal aberrations and DNA damage. Some studies have shown that silver nanoparticles can enter into cells and cause cellular damage [24]. Many in vitro studies have been conducted on the adverse effects of silver nanoparticles with a size of 1–100 nm. The uptake of silver nanoparticles by different cells has been reported in many in vitro studies. Most related publications show reduced cell viability after exposure to silver nanoparticles. Some in vitro studies show glutathione depletion, mitochondrial derivations, and damage to cell membranes. Exposure of human peripheral blood mononuclear cells to nanosilver causes inhibition of phytohemagglutinin (PHA)-induced proliferation [24]. The toxicity of silver nanoparticles is higher than that of most carbon-based nanomaterials and many metal nanoparticles [16]. The toxicity of silver nanoparticles increases with a decrease in size and increase in concentration, as a result of oxidative stress. Research studies have shown that C18-4 germ line stem cells are more sensitive to 15 nm silver nanomaterials than are BRL 3A liver cells and CRL-2192 alveolar macrophages, after 24 hours of exposure to 15 nm silver nanoparticles [16].

A large number of other metal nanoparticles have been screened to determine their toxicities using assays that reveal LDA leakage through the plasma membrane [16]. The LDA release of BRL 3A rat liver cells was determined after 24 h exposure to different nanoparticles, showing that exposure to microparticles of cadmium oxide increased membrane leakage [18]. Silver nanoparticles exhibited higher LDH leakage at concentrations of 150 μg/mL than metal oxide nanoparticles. The evaluation of nanomaterial uptake into cells is useful in determining the toxicity of nanomaterials [16] and can be monitored using fluorescent microscopy, flow cytometry, and fluorescence-activated cell sorting. Some advanced techniques such as ultrahigh-resolution light microscopy and wet imaging under a high vacuum are also being used, in addition to TEM observation on thin films [16].

Titanium dioxide nanoparticles are commonly used because of their photocatalytic properties, availability, and low cost [25]. Some studies show biokinetic activity of TiO_2 nanoparticles both in vitro and in vivo. However, it is difficult to compare results because TiO_2 exists in different crystalline phases, sizes, and shapes. Some studies indicate that it can be readily uptaken by A549 cells (carcinomic human alveolar basal epithelial cells) in vitro. However, absorption through the differentiated Caco-2 monolayer system (human epithelial colorectal adenocarcinoma cells) and in an in vivo oral study was low [25].

3.5 In Vitro Assessments of Nanomaterial Toxicity

The significant expansion of technological and commercial interest in nanomaterials has stimulated the field of nanotechnology. Around 1,500 consumer products of nanotechnology are available on the market [19, 26]. The global market requires tons of raw nanomaterials, ranging from nanoscale metals and metal oxide particles to carbon-based nanomaterials [19]. This robust manufacturing and consumer usage produces many sources that release nanomaterials into the environment, water, food supplies, ecosystem, and other routes of entry into the human body [19]. When a material's dimensions approach the nanoscale, certain properties such as capillary force, melting point, optical characteristics, conductivity, surface energy, magnetism, electron affinity, polarization ability, reactivity, and ionization potential can become scale-dependent [19, 27].

This section outlines the methods generally used to assess the surface and bulk properties and biological reactivity of nanomaterials in a model system in an in vitro system. These assays are significant in order to characterize nanomaterial applications in biotechnology, ecosystems, biomedicine, and cytotoxicity screening. There is no consensus about the risk, toxicity, hazards, and environmental effects of almost all nanomaterials. At present, the tools available to determine the pharmacological and toxicological characteristics of nanomaterials are too primitive to provide much information [19].

3.5.1 Detection of Surface Contamination

Surface contaminants can be detected by many widely used techniques, such as time-of-flight secondary ion mass spectroscopy (ToF-SIMS), X-ray photoelectron spectroscopy (XPS), X-ray fluorescence (XRF), energy-dispersive X-ray analysis (EDX), and surface-enhanced Raman spectroscopy (SERS) [19].

ToF-SIMS is a surface analytical technique that focuses a pulsed beam of primary ions onto a sample surface, producing secondary ions in a sputtering process. Analyzing these secondary ions provides information about the molecular and elemental species present on the surface of the sample [19]. XPS is a widely used surface analysis technique, whereby a sample is irradiated with a beam of X-rays under an ultrahigh vacuum. The kinetic energy and number of electrons that escape from the top surface of the sample are analyzed [19]. XRF is a technique in which X-rays or gamma rays are bombarded onto a sample. The emission of secondary fluorescent X-rays photons yields quantification of all elements present in the sample [19]. EDX irradiates the sample with X-rays and measures the energy (wavelength) and intensity of the X-rays emitted from the sample to determine the composition of the sample. This technique scans only 5 μm on the top of the sample; however; it can provide an entire spectrum simultaneously. SERS is a surface-sensitive technique in which an intense laser beam is focused on the surface. Localized surface plasmons are excited due to the vibration on the sample surface and leave the sample with a different frequency [19]. The energy change reflects the chemical composition of the sample surface.

3.5.2 Particle Sizing and Aggregation

Nanomaterials possess a very high surface and low diameter, so all physical, chemical, physicochemical, and biological properties blend together because of their small size. Thus, nanoparticle sizing is a crucial aspect of precharacterization [19]. Moreover, because of the high dispersion and high surface energy of nanoparticles, aggregation is an issue when handling nanoparticles experimentally. At the nanoscale, aggregation is extremely difficult to avoid. Several properties such as colloidal stability, homogeneity, optical and electronic features, and cell uptake are adversely affected by aggregation. Widely used techniques for characterization include scanning electron microscopy (SEM), TEM, dynamic light scattering (DLS), optical spectroscopy, and fluorescence polarization [19].

3.5.2.1 Transmission Electron Microscopy

TEM is a well-known technique for micro- and nanosized imaging of material features, particle size distribution, surface morphology, and aggregation [19]. Imaging of particles by TEM provides sizing information through direct electron imaging, but it is usually used for metallic samples. However, EFTEM can be used for imaging nonmetallic samples. TEM uses electrons as a “light source” for transmission through the specimen. Electrons interact with the specimen as they pass through and form an image, both inside and out. The image is magnified and focused onto a fluorescent screen or a detector. The information obtained by TEM for solution aggregation may be inconclusive and should be confirmed by other techniques such as zeta-potential spectrophotometry and gel electrophoresis [19]. Many samples, upon drying, produce aggregation as a result of increased ionic strength and surface tension. TEM analysis cannot control the effects of surface tension. Information obtained by TEM in ex situ conditions may not necessarily be a true representative of in situ aggregation states because preparation of a nanoparticle solution for TEM imaging requires sample desiccation [19].

3.5.2.2 Scanning Electron Microscopy

SEM uses electrons to impinge on the surface of a specimen. The electrons interact with the atoms on the surface of specimen, producing signals that can be detected and contain information about the specimen’s surface features and composition. SEM requires a high vacuum and a dried specimen, which causes some experimental uncertainty and the inability to produce in situ characteristics accurately [19]. However, modern SEM can scan and image the specimen in hydrated conditions under a high vacuum.

3.5.2.3 Optical Spectroscopy

Optical spectroscopy is the measurement of the interaction of light with the specimen. Some metallic nanoparticles display size-dependent absorption and scattering of incident light through excitation of the metal's plasmon band electrons by incident photons or through scattering of incident photons [19]. Free electrons and electronic coupling of metal lattice energies and excitation interband energies are essential for plasmon excitation. These requirements are found in a few metals, such as lead, mercury, tin, cadmium, and gold. In most metals, the plasma frequency is in the ultraviolet region of the electromagnetic spectrum. Some metals such as gold and copper have interband transitions in the visible range of the electromagnetism spectrum, resulting in the absorption of specific light energies (color), thereby yielding the color of interest [19].

Other metal and metal oxides display plasmon in a nonvisible region, thereby making plasmon excitation and detection extremely difficult. Metal oxide formation and intrinsic surface metal lattice mismatch generally distort the energy interband coupling. Furthermore, the free-electron phenomenon diminishes the plasmon coupling effects in most metals, except those that are oxide-free (noble metals) [19]. Shifts in surface plasmon band excitation take place in metal as a result of adsorbate binding, which causes changes in the surface interband electronic states. Thick surface-stabilizing layers and surface oxide can prevent other adsorbate electronics. Gold and silver nanoparticles are generally sized by measuring the extinction wavelength of incident light [19]. Plasmon absorbance decreases in intensity and red-shifts to higher optical wavelengths as the average particle diameter increases. This results in characteristic plasmonic peaks for each size of metal nanoparticles. Likewise, adsorption of contaminants, stabilizing layers, and DNA on the nanoparticle surface red-shift the extinction wavelength by a few nanometers. This shift indicates particle aggregation. Gold colloidal solutions change in color from red to blue, thus indicating particle aggregation [19].

Optical spectroscopy has been used in a wide variety of analytical techniques. The method can selectively detect and identify a large number of substances and serve as an important tool in the pharmaceutical and chemical industries. Recently, optical spectroscopy has been used to detect and identify engineered nanomaterials.

3.5.2.4 Dynamic Light Scattering

Particle size can also be determined by measuring changes in the intensity of light scattered from a solution. This technique is generally called dynamic light scattering (DLS) but is also known as photon correlation spectroscopy (PCS). Applications of this technique are the characterization of particles, molecules, and emulsions in solution.

In this technique, a beam of monochromatic light strikes a solution containing spherical particles. Brownian motion of the particles causes a Doppler shift, changing the wavelength of the incoming light [20]. Brownian motion of the particles in suspension causes light to be scattered at different intensities; thus, by analyzing the fluctuation in intensity, it is possible to measure particle size distribution, particle motion in solution, and the diffusion coefficient of the particles [20]. This technique is cost-effective, automatized, and easy to operate.

3.5.2.5 Fluorescence Polarization

Fluorescence polarization (FP) is based on the fact that a fluorescent molecule in solution is excited by a plane-polarized light and emits polarized fluorescent light back into a fixed plane if the molecules remain stationary during excitation and emission [21]. Molecules rotate and tumble, and the planes into which light is emitted can be different from the excitation plane. The polarization of a molecule is related to the molecule's rotational relaxation time (molecule rotation through an angle of 68.5°). The rotational relaxation time depends on absolute temperature, molecule volume, gas constant, and viscosity [21]. Recently, time-resolved fluorescence polarization anisotropy (TRFPA) has been used in nanosystems for measuring particle size. The fluorescence polarization decay time is related to particle size in accordance with the Stokes–Einstein–Debye rotational equation for particle motion. With this method, particles having a size of 1–10 nm can be measured with 0.1 nm resolution [19].

3.5.2.6 Other Techniques

Several other techniques are available for quantifying the sizing of nanomaterials, as follows [19]:

- X-ray diffraction (XRD) is used to differentiate between crystalline and noncrystalline samples.
- Multiangle laser light scattering is an analytical technique for finding the absolute molar mass, size, and structure of macromolecules and particles in solutions. This technique is used in combination with ultraviolet-visible spectroscopy and field-flow fractionation for particle sizing.
- Small-angle X-ray scattering and small-angle neutron scattering are used for studying particle size and shape.
- Inductively coupled plasma–mass spectroscopy (ICP-MS) is a type of mass spectroscopy that is used to measure/detect metals and several nonmetals.
- Inductively coupled plasma–atomic emission spectroscopy (ICP-AES) is used for the detection of trace metals.

3.6 Nano-safety

The National Institute for Occupational Safety and Health (NIOSH) is a US federal agency mainly is responsible for supervising research and preventing work-related injuries and illnesses. NIOSH is also responsible for protecting workers from injuries and illness in the workplace in the future, which is important because the applications of nanotechnology are advancing rapidly [2, 22]. Nanotechnology has a wide range of applications, with some unknown safety and health risks. Because nanotechnology is a new field and the potential risk and hazardous effects of nanomaterials are unknown, precautionary measures must be taken [2, 22]. There are many concerns and uncertainties related to the use of engineered nanomaterials and whether their exotic properties pose any adverse threat to human health and the environment. The data currently available to determine the adverse effects of engineered nanomaterials is not adequate to predict their harmful effects [2, 28].

The applications of nanotechnology are very broad, and continued evaluation of potential health hazards as the result of exposure to nanomaterials is important to ensure their safe handling. Some studies have shown that the physicochemical properties of nanomaterials can have harmful effects in the biological system [2, 22]. Initial studies of animals and humans exposed to engineered nanomaterials can provide a platform for ascertaining their harmful effects on human health and the environment. Some research studies using rodents and cell cultures have shown that the toxicity of nanomaterials is relatively higher than that of their bulk counterparts. Nanomaterials have a high surface area, high aspect ratio, high porosity, and quantum size effects. These factors have a great influence on the properties of nanomaterials. Researchers are currently engaged in nanotechnology research, but more studies are needed in order to estimate the harmful effects of nanomaterials on the human biological system. Available data on the toxicity of large particles can provide fundamental knowledge for estimating the possible adverse effects that may occur from exposure to nanomaterials. However, this information is preliminary and may not be enough to provide proper protection against nanomaterials. NIOSH has published the following summary as part of their program to minimize workplace exposure to nanomaterials [2, 22].

- Nanomaterials have the potential to enter the human body through the respiratory system if they are airborne, come in contact with the skin, or are ingested. Studies on humans and animals have shown that airborne nanoparticles can be inhaled and deposited in the respiratory tract. Nanomaterials can enter the blood stream and translocate to other organs in the body.
- Studies on rats show that nanoparticles are more formidable than their bulk counterparts of the same composition and may cause pulmonary inflammation and lung tumors.
- Studies in animals, cell cultures, and cell-free systems have indicated that changes in chemical composition, size of particles, and crystal structure can significantly affect oxidant generation capacity and cytotoxicity.

- Studies in workers exposed to aerosols have shown harmful lung effects, including lung function disorder and fibrotic lung disease.
- More research is needed on the adverse effects of nanomaterials.

3.6.1 Potential Safety Issues

To date, research on nanomaterials relative to their risk of fire and explosion is inconclusive. Some studies have shown that nanomaterials pose catalytic effects and explosion hazards because of their nanosize and exotic properties. Powders from nanomaterials pose higher risk of fire and explosion than bulk-size materials of the same chemical composition because of their uncommon properties. When the material size is reduced to the nanoscale, electrons lose their freedom, which results in discrete energy states. The energy of electrons is not enough to break this confinement and, as a result, abnormal properties are observed. Decreasing the particle size of combustible materials to the nanoscale can increase the chances of spontaneous and quick combustion and cause a higher combustion rate. Some nanomaterials may initiate catalytic reactions because of their chemical composition and structure. Nanomaterials and nanostructured porous materials are used as catalysts for increasing the rate of reactions [2, 22].

3.6.2 Exposure Assessment and Characterization

It is still unknown what techniques should be used to measure and monitor the mechanisms underlying the toxicity of nanomaterials and what methods should be used to accurately predict exposure to nanomaterials in the workplace. Recent studies have shown that bulk chemistry is less important than size, shape, surface area, and surface chemistry for some nanomaterials. Techniques used for measuring nanoscale aerosols vary in complexity, but are capable of providing some useful information for evaluating occupational exposure to nanomaterials with respect to size, shape, morphology, surface area, composition, and concentration. It is very important to conduct background nanoscale particle measurements before production and processing. Personal sampling should be used to ensure representation of the exposure of workers to nanomaterials. However, a real-time exposure measurement is more helpful in evaluating the need for control systems and work practices [2, 22].

3.6.3 Precautionary Measures

Because the information currently available to predict the hazardous effects of nanomaterials is inadequate, taking measures to protect workers is highly prudent. The control of airborne exposure to nanoscale aerosols can be achieved by using a wide variety of engineering control systems, similar to those used to minimize exposure to traditional aerosols [2, 22]. The following points should be taken into account:

- Studies have shown that particle size is the key factor in causing hazardous effects in humans. Nanoparticles deposited in the human body can move quickly into organs. Research in nanotechnology is in the preliminary stages; therefore, no international standards are available to dictate what kind of clothing, gloves, and eye protection are best suited for handling nanomaterials.
- Seminars, workshops, and risk management programs must be organized in workplaces where workers are exposed to nanomaterials. These workshops and seminars should include the followings aspects:
  - Evaluation of the hazardous effects posed by nanomaterials based on their physical, chemical, and biological properties.
  - Evaluation of workforce jobs related to the handling/fabrication of nanomaterials in order to determine the potential for exposure.
  - Training and education of workers to use nanomaterials properly.
  - Installation of exhaust ventilation in areas where exposure to nanomaterials exists.
  - Compliance with general safety rules and regulations in the workplace.
  - Provision of appropriate personal protection equipment to workers.
  - Systematic evaluation of all control systems to ensure they are working properly.
  - Evaluation of the sources of error in handling nanomaterials.
- Control techniques such as source enclosure and exhaust ventilation systems can help in capturing airborne nanoparticles. Well-designed ventilation systems with high efficiency particulate air (HEPA) filters are now available for removing nanoparticles.
- Good work practice can help to minimize the potential hazard of nanomaterials. This includes using HEPA filters, washing hands, changing clothes daily, and preventing food consumption and beverages in places where nanomaterials are fabricated and handled.
- Isolating the sources of nanomaterials, including nanofiber and nanoparticle fabrication, from workers must be done in a closed environment or inside a fume hood. A high-efficiency ventilation system with nanoscale filters can successfully remove nanomaterials. It is generally recommended that all nanoparticles be handled in a fume hood or in an enclosed environment.
- Respirators may be necessary when conventional control cannot adequately control exposure to nanomaterials. A specially designed and NIOSH-certified respirator can be useful for protecting workers from inhalation of nanomaterials.

3.7 Conclusions

Nanomanufacturing involves the synthesis of nanostructured materials, their impact on human health and the environment, and a life cycle assessment of nanostructured materials. The development of new synthesis techniques has invigorated the rapid emergence of a wide variety of nanoscale consumer products. Engineered nanomaterials are being used in almost all industries, and their usage is likely to increase for a wide variety of products. Such rapid advancement of nanomaterials has initiated the need for safety assessment with respect to both human health and the environment. The potential advantages of nanomaterials are numerous, and industries have great expectations, but there are many unanswered questions regarding the safety of workers and potential hazards to humans and the environment. The risks associated with nanomanufacturing and the use of some nanomaterials are still unclear. However, scientists are gathering data and relevant information in order to establish a database for assessing the risks and harmful effects of the synthesis and use of nanomaterials. Life cycle assessment is a comprehensive approach for documenting the impact of nanomaterial synthesis, processing, and production, using a well-defined and documented methodology. Until the hazardous effects of nanomaterials are known, precautionary measures must be taken, such as employing an advanced control system and using good work practices.

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4 Safety Approaches to Handling Engineered Nanomaterials

4.1 Introduction

Nanoparticles, according to the ASTM standard E2456, are a subclassification of ultrafine particles having two or three dimensions ranging from 1 to 100 nm [1]. Engineered nanomaterials can be defined as an engineered structure having at least one external dimension between 1 and 100 nm. Nanomaterials incorporate nanoparticles and are being used in many different industries for products that include electronics, sporting goods, medicine, clothing, and many more [26]. The research and development of nanomaterials has surpassed knowledge of their health and environmental effects. This has resulted in a need for additional safe handling guidelines, regulations, and risk assessment procedures for workers in research laboratories and manufacturing facilities that work with and are exposed to nanomaterials [8]. The purpose of this article is to provide information and guidelines for workers who use nanomaterials in an occupational setting in the hope of, if suggestions are followed, improving worker safety, producing safer products, and providing insight into the steps being taken to minimize risks and impose regulatory standards.

4.2 Potential Health Concerns

There has been worldwide outcry for a halt on nanomaterial research and production until procedures are set in place that can guarantee worker safety [26]. As a particle is reduced in size, the way it interacts with its environment can change. Because of the atypical physiochemical properties seen with engineered nanomaterials, limited information is available on what effects these particles can have on biological cells, especially with long-term exposure [38].

Cytotoxicity, the ability to be toxic to cells, is commonly referred to when discussing potential health concerns related to nanomaterials. Properties such as surface chemistry, aspect ratio, and agglomeration state can all have diverse and adverse effects on living cells, depending on the type of nanomaterial and degree of exposure [26, 48]. Epidemiological, in vivo, and in vitro studies are ways to research and collect data on nanoparticle cytotoxicity. Studies performed by the Institute of Condensed Matter Physics in Switzerland concluded that, in general, carbon-based nanomaterials (the most common types used industrially) lead to cell proliferation inhibition and eventually cell death [20]. An in vitro study from the Department of Metallurgical and

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Materials Engineering at the University of Texas at El Paso found that a combination of carbon nanotube (CNT) aggregates and carbon black was just as cytotoxic as asbestos, whereas silver aggregates were found to be even more cytotoxic [38, 41].

However, many products containing engineered nanomaterials are being produced before the hazards have been fully assessed. This is worrisome for both the workers who manufacture these engineered nanomaterial products and for the end consumer [38]. Skin products such as creams and sun block use titanium dioxide (TiO_2) as an ultraviolet ray blocking agent. In its bulk form, TiO_2 is considered to be harmless, but information on the long term effects at the nanoscale is lacking or inconsistent [38, 40]. A number of studies on the cytotoxic effects of silicone oxide (SiO_2) have shown that it can cause cell death via apoptosis, but do not agree on the direct cause of cell death [11, 43, 46]. Other studies focusing on multiwall carbon nanotubes (MWCNTs) saw similar results, where cell damage or death was evident, but the exact cause was not unanimously agreed on [3, 13]. One study even reported that CNTs were not toxic [7].

Inconsistent results like these that reveal the gaps in information related to nanomaterials and demonstrate the need for standardized methods for handling nanomaterials in an occupational environment to ensure worker safety.

4.3 Proactive Measures to Examine Precautions

Before a standard set of regulations can be put into effect, it is important to know the practices currently in use throughout different industries to have a better understanding of where the improvements in nanomaterial safety knowledge should be made [8].

Many surveys have been conducted over the years, examining how different companies handle and assess nanomaterials. One survey, focusing on nanomaterial risk and safety issues in German and Swiss industries, asked 40 companies a series of questions about the kinds of nanomaterials they use in their products, and how, if at all, they assess these hazards. Some of these questions included: “What are the mean particle diameter and the particle size distribution of the nanoparticulate material (NPM) in your product?”, “Have you evaluated the possible uptake of the NPM by the following organisms (aquatic, soil, humans, other organisms) during the different stages of the product life cycle?”, and “Does your company conduct risk assessments where NPMs are involved?”. The results concluded that 26 of the 40 companies surveyed did not have any nanomaterial risk assessment procedures in place (Helland, et al., 2008).

A second survey, published in 2012, asked 78 companies in 14 countries how they perceived the risks related to different types of nanomaterials (CNTs, quantum dots, metal oxides, heavy metals, dry powders, and other carbonaceous materials). The study found that 22% and 40% of participants admitted that they do not know the risks of CNTs and quantum dots, respectively. An average of 28% of companies believed that there was little to no risk involved with any of the nanomaterials described in the survey, while 44% reported moderate to high risks associated with each nanomaterial. On average, almost one-third of participants reported that they did not have any information on the risks of any of the nanomaterials [9].

4.4 Assessment of Engineered Nanomaterials

As with any material, it is good practice for a worker to know what kind of material he or she is working with, and how to handle it. If there is little or no knowledge available about the material, then the material should be considered hazardous and be treated as such. To prevent a lack of knowledge, it is highly recommended to preemptively collect as much useful information on a material as possible. Suppliers often provide a safety data sheet (SDS), which may include some, but not all of the information needed about a material. However, this information may only represent the material on the macroscale, not the nanoscale, and properties can change when particle size is reduced. In this event, additional research should be conducted in order to protect not only the workers, but also anyone who may come in contact with the material at any point during its life cycle. This information includes, but is not limited to the following [4, 17, 47]:

- Chemical composition
- Commercial and technical names
- Current safety data sheets (SDS) and technical data sheets (TDS)
- Hazard and toxicity levels
- Material dustiness
- Material substitutions
- Particle size distribution
- Presence of nanomaterials and identification
- Proportions of nanomaterials
- Solubility

4.4.1 Hazard Assessment

Nanoparticles can exhibit changes in their physical, chemical, and mechanical properties compared with the same material in bulk form. Two key reasons for this alteration are surface effects and quantum effects [38]. Surface effects cause the smooth scaling of properties as a result of the fraction of atoms at the surface. Quantum effects display discontinuous behavior as a result of quantum confinement effects in materials with delocalized electrons [5]. It is important to know which properties of a material will change when brought to the nanoscale, and what resulting actions are required if nanoparticles are present in the working environment.

Studies on the toxicity of single-walled carbon nanotubes (SWCNTs) on mice have shown that the physical and chemical properties of nanoparticles can cause serious health issues [22, 44]. These properties include the following [2, 4]:

- Agglomeration state
- Chemical composition
- Crystal structure
- Impurities and/or contaminants
- Nanomaterial shape
- Particle size and distribution
- Physical properties
- Porosity
- Reactivity
- Solubility
- Surface area

4.4.2 Hazardous Communication

It is the responsibility of the employer to communicate information regarding any and all possibilities of hazardous exposure to employees who are likely to come into contact with engineered nanomaterials. This list, which has been derived from the ASTM standard guide *Handling Unbound Engineered Nanoscale Particles in Occupational Settings*, explains the type of information employers must communicate to workers with respect to either normal or emergency conditions, as follows [2]:

- Any known and potential physical, health, and safety hazards related to engineered nanomaterials
- Which processes in the work environment come in contact with engineered nanomaterials
- How to determine the presence of engineered nanomaterials in the work environment by visual appearance, odor, etc.
- Procedures on exposure minimization including engineering and administrative controls, personal protective equipment, and emergency procedures

4.4.3 Exposure Assessment

So far, there are no general occupational exposure limits that are primarily concerned with airborne exposure of unbound engineered nanoparticles. There are, however, designated occupational exposure limits for nuisance particles that can be used as a reference for particles of similar physical and/or chemical composition. However, these limits do not necessarily take particle size into account and may be inaccurate for nanosized particles. [31].

When assessing exposure, it is important to understand how nanoparticles can enter the body. There are five types of exposure route:
- Dermal
- Ingestion
- Inhalation
- Injection
- Ocular

Inhalation, ingestion, and dermal are the three most common and most discussed methods of exposure, as they typically deal with airborne particles. Inhalation is the most common and most studied of the three routes [21].

Engineered nanoparticles bound in a solid matrix, such as nanocomposites, pose little to no exposure risk while being handled. There may be a possibility of exposure if these nanocomposites are machined or burnt, unbinding the nanoparticles from the matrix in the form of airborne dust. This can lead to inhalation, ingestion, dermal, or ocular exposure. Nanoparticles bound in a liquid matrix, such as resins, pose an even higher risk of exposure. Physical contact with nanoparticles suspended in a liquid matrix can result in dermal exposure, and inhalation and ingestion exposure is possible if the particles become aerosolized [2].

When working with nanoparticles, it is best to use the manipulation methods in the order shown in Figure 4.1, from least to most favorable.

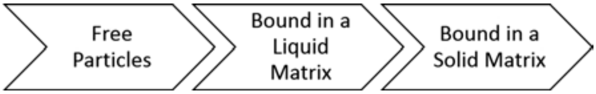


Fig. 4.1: Nanoparticle manipulation method precedence.

To properly assess exposure, a facility should keep records of any processes involving engineered nanomaterials [32]. These processes can include the following:
- All other activities performed during the life cycle of an engineered nanomaterial
- Maintenance
- Manufacturing processes
- Material handling
- Material receiving/shipping
- Storage
- Waste management

4.5 Characterization of Engineered Nanomaterials

Characterization can be defined as determination of the physical and chemical properties of a material. These properties can include size, shape, atomic structure, and solubility [34]. According to the standard ISO/TS 12901-1, the most commonly used engineered nanomaterials include fullerenes, CNTs, carbon black, quantum dots, and metals and metal oxides [17].

4.5.1 Fullerenes

Fullerenes are comprised completely of carbon. They take on a hollow sphere shape and form hexagonal carbon ring structures, similar to graphite. Pentagonal and heptagonal rings are also possible, allowing three-dimensional structures. A common form of fullerene is Buckminsterfullerene (Buckyball). Because they are based on carbon, fullerenes are electrically conductive. Under the right conditions, they can behave as semiconductors, conductors, or superconductors. Fullerenes have the ability to contain other materials and substances inside and also to absorb free radicals. They are chemically inert and relatively harmless to humans [16, 17].

4.5.2 Carbon Nanotubes

CNTs, a type of fullerene, are another commonly used nanomaterial and can be classified into three categories: SWCNTs, double-walled CNTs, and MWCNTs [17]. SWCNTs consist of sheets of hexagonal ring-structured graphene sheets rolled into a cylinder along a lattice vector. CNTs can be relatively long, ranging from 1 to 100 µm, with diameters of 1–2 nm for SWCNTs and over 100 nm for MWCNTs. This high aspect ratio results in excellent electrical conductivity and applications in plastic and composite materials. Conductivity can be increased or decreased on the basis of the CNT's diameter, chirality, and the angle between hexagons and tube axis [4, 29]. According to a study of the cytotoxicity of CNTs on human cells, refined SWCNTs caused the most severe cell damage compared with other types of nanomaterials tested. The cytotoxity of CNTs was thought to be a result of their surface area and surface chemistry. The difference between refined and unrefined SWCNTs is that refined SWCNTs do not possess catalytic transition metals such as iron or cobalt [22, 44]. Even a miniscule amount of refined SWCNTs (25 µg/mL) increased cellular apoptosis/necrosis compared with 0.06 mg/mL of unrefined SWCNTs.

4.5.3 Carbon Black

A common nanomaterial used in industrial settings is carbon black. Carbon black, known for its electrical conductivity, relatively high surface area-to-volume ratio, high tinting strength, and ability to absorb ultraviolet light, can be classified into five subcategories: furnace black, thermal black, acetylene black, channel black, and lamp black. Those categories can be further divided according to particle grade and size [6, 14]. Generally, carbon black contains more than 97% elemental carbon arranged in an aciniform structure (grape cluster). A common practice is to incorperate carbon black as an antistatic agent filler in plastic and elastomer products, because of its electrical conductivity. Almost 90% of carbon black is used as filler in rubber products, most notable in tires. About 9% of carbon black is used as a pigment in paints, inks, and resins for newspapers, inkjet printers, and automobiles, respectively. The other 1% is utilized in countless applications throughout various industries [15, 23]. According to a study on high-priority carcinogens, carbon black may be carcinogenic to humans. This conclusion came after a series of trials performed on animals and a few tests conducted on humans [14, 27].

4.5.4 Quantum Dots

Quantum dots, with their core–shell structure, are composed of semiconductor nanocrystals and range in diameter from 2 to 10 nm [4, 17]. The core and shell of a quantum dot are usually made up of two different combinations of elements. The core is typically composed of two elements from groups 2B and 6A, groups 3A and 5A, or groups 4A and 6A. In most cases, the shell is made of zinc sulfide [45]. Semiconductor quantum dots possess photophysical properties related to their size. During excitation, a desired wavelength of light can be achieved by altering the particle size. This is especially useful for in vitro diagnostics, therapeutics, imaging, and optical devices [25]. However, the use of quantum dots is limited because of cytotoxicity concerns regarding the nature of their semiconductor elements and outer chemical coatings, which can succumb to oxidation or ultraviolet damage in biological systems [39].

4.5.5 Metals and Metal Oxides

A wide category of engineered nanoparticles includes metals and metal oxides. There is no set definition on the size and shape of these nanoparticles, because they can consist of several different types of metals and alloys [17]. Commonly used metal nanoparticles are TiO_2, gold, and silver. The small size of these particles typically results in different properties of the material compared with their macroscopic counterparts. For example, the color of gold nanoparticles changes as the particle size increases or decreases [24]. Although it has not been concluded that metal oxide nanoparticles are always more toxic than metal oxide microparticles, copper oxide nanoparticles have been found to be highly toxic compared with copper oxide microparticles [31]. TiO_2, a commonly used component in sunscreens, is categorized as a possible carcinogen on the basis of sufficient studies on animals and an inadequate number of studies on humans [14]. In light of this, cytotoxicity is still a concern with metal nanoparticles, but most applications use these nanoparticles in sizes too large for dermal penetration. Typical applications of metals and metal oxides can include cosmetics, coating, pigments, and composites [4, 12].

4.6 Control Preferences

When it comes to handling nanoparticles, nanomaterials, and hazardous materials in general, it is important to understand how to minimize worker exposure. Figure 4.2 shows a standardized hierarchy of exposure control that should be implemented to ensure worker safety. The chart displays different exposure control methods ranked from first method of action (top) to last resort (bottom) [17, 31, 47].

The six exposure control methods involve the following actions:

1. *Elimination*: Removing any hazardous materials entirely from a process or workplace.
2. *Substitution*: Replacing hazardous materials with ones that pose less risk to workers.
3. *Isolation*: Isolating a process or machine in an area where hazardous materials can be used without causing harm to workers.
4. *Engineering controls*: Altering a process or work environment to reduce exposure.
5. *Administrative controls*: Implementing safety precautions and good housekeeping.

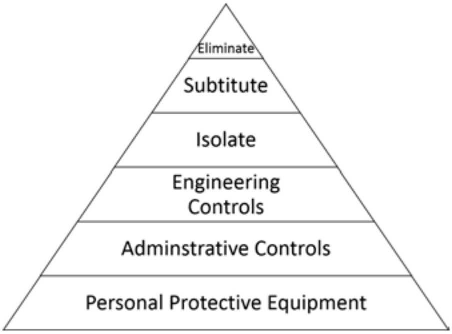


Fig. 4.2: Exposure control hierarchy.

6. *Personal protective equipment* (PPE): Wearing equipment to protect against hazardous materials.

4.6.1 Elimination

If a hazardous material is not absolutely necessary, it should be avoided whenever possible. Completely removing hazardous materials from a process may not always be an option. In this case, substitution is the next step [31, 32].

4.6.2 Substitution

Replacing hazardous materials such as toxic chemicals and nanoparticles with less hazardous materials is an excellent way to protect workers from exposure. However, this only works if the new less hazardous materials can perform the same functions as the previous materials. If not isolation may be necessary [31, 32].

4.6.3 Isolation

In situations where there is no other choice but to use a hazardous material in a process, isolating that process should be considered. An example of this would be placing a machine, such as a sonicator used for nanoparticles, into an isolated room where particles and exhaust can be contained, and workers outside are free from exposure [31, 32].

4.6.4 Engineering Controls

To reduce the amount of exposure, changes in a process or the workplace may be required. These changes can include containing a process in a separate environment (isolation) and/or installing a ventilation system such as the following [10]:

- General exhaust ventilation
    - General ventilation for a workplace.
    - Usually provided by a heating, ventilation, and air conditioning (HVAC) system.
    - Should be placed as close to the source of contamination as possible.
    - Exhaust should not contaminate any areas of air intake or be recirculated back into the work environment.
- Local exhaust ventilation
    - Contains contaminates in a small area or completely encloses them.
    - Includes chemical fume hoods, ventilated enclosures, and snorkel hoods.

- Exhaust is funneled into an air cleaner or filtered before being released into the open air.
- HEPA (high-efficiency particulate air) filters should be used on any exhaust ventilation where engineered nanomaterials are to be handled.

These ventilation systems should employ negative pressure to ensure adequate protection. Glove boxes and other sealed enclosures offer a higher level of protection than less pressurized enclosures such as ventilated hoods and snorkel hoods [31, 32].

4.6.5 Administrative Controls

Worker safety is the responsibility of both the employee and employer, working in tandem to ensure proper safety conditions are met and maintained in the work environment. In general, administrative controls are used to limit worker exposure to hazardous materials and promote worker safety [2]. Proper hand-washing facilities should be provided to workers along with basic hygienic information such as washing hands after coming into contact with engineered nanomaterials and before consuming food or drink [37]. In addition, employers should reduce how long workers are exposed to engineered nanomaterials by regulating working hours and implementing shifts to rotate workers. Typically, general workplace administrative controls can be applied to an environment containing engineered nanomaterials, provided the following additional precautionary measures and practices required for such environments are also implemented:

- *Housekeeping*: General good housekeeping should be practiced in any workplace. Keep work areas clean and clear of debris, regularly clean work surfaces, replace any tools or equipment to their original storage location, etc. In the case of a work environment where engineered nanomaterials are handled, ensure all equipment (including glassware, tools, and ventilation equipment) is vacuumed with a HEPA filter and/or cleaned and wiped on a regular basis (minimum at the end of each shift). Dry sweeping and using compressed air to clean up nanoparticle dust should be prohibited. These procedures can also fall under the category of work practices [10, 31].
- *Work practices*: Another step in promoting worker safety is employing good work practices. To do so, both employer and employee must have an understanding of the potential hazards posed by engineered nanomaterials and other hazardous materials. The Occupational Safety and Health Admin istration (OSHA) has prepared a list of work practices (Table 4.1) that pertain to both management and workers to ensure proper worker safety. Other administrative controls can fall under the category of work practices, such as housekeeping and training [29, 32].
- *Signs/labels/storage*: Areas where engineered nanomaterials are present should be posted with a hazard sign stating such. This includes isolated work areas, ex-

Tab. 4.1: Good work practices for management and workers according to OSHA.

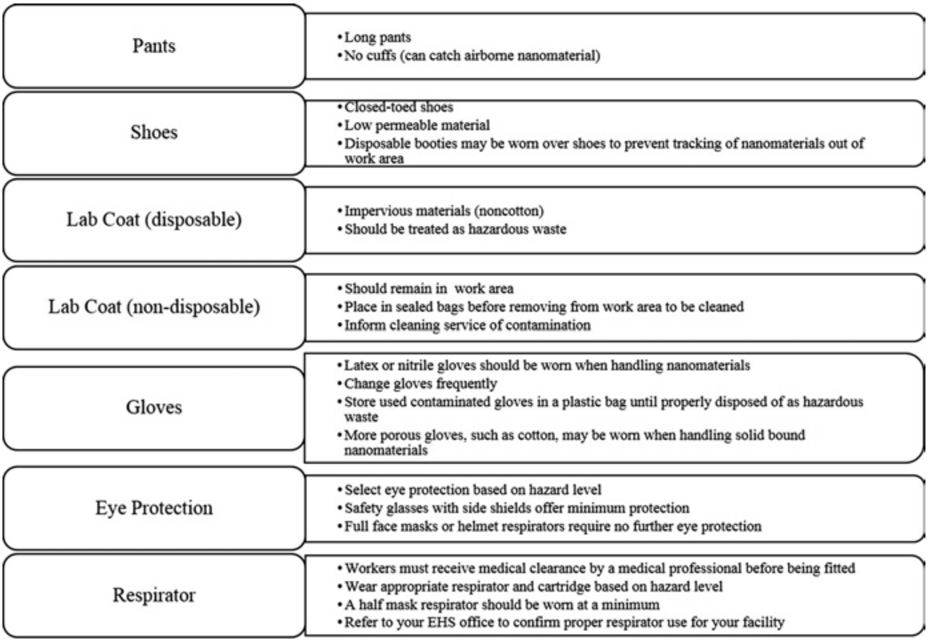
Management	Workers
Provide education to workers on safe handling of nanomaterials to reduce the possibility of exposure	Avoid working with nanomaterials in a free particle state in open air conditions
Provide information to workers on any hazardous properties of materials being handled and how to prevent exposure	Store dispersible nanomaterials in tightly sealed containers when possible (both liquid suspended and dry particles)
Encourage workers to use sanitary facilities to wash their hands before leaving the workplace, smoking, or consuming food or drink	Clean work areas and equipment at the end of each shift, at the minimum. Avoid dry sweeping or compressed air. Vacuum using a HEPA filter or use wet wiping methods
Provide additional control measures to ensure that nanomaterials do not leave designated work areas (decontamination facilities, buffer areas, etc.)	Waste material must be disposed of in compliance with any and all federal, state, and local regulations
Provide showering and changing facilities for workers to prevent contamination of other areas caused by clothing and skin transfer of nanomaterials	Food and beverages should not be stored or consumed in areas where nanomaterials are handled or stored

haust ventilation areas, and any other places in the work environment where engineered nanomaterials are handled. Signs should also indicate what type of PPE is required to enter the area. Storage areas for engineered nanomaterials should also have proper signage to indicate hazardous materials. According to the “OSHA Hazard Communication Standard, 29 CRF 1910.1200”, employers must label all hazardous chemicals and materials in the work environment [31]. When storing engineered nanomaterials, appropriate labels must be implemented to indicate contents and material form (liquid, powder, aerosol, nanoparticulate, etc.). Contact information for a facility’s environmental health and safety officer, or other appropriate representative, should be provided on the label in case of container breakage. Secondary containers must also be labeled appropriately [10].

- *Training*: Any worker who is required to handle engineered nanomaterials must receive proper training on all hazards and risks involved. OSHA requires that, at a minimum, workers be trained on detecting chemicals in the work environment, any hazards associated with the chemicals, and methods to avoid exposure [37]. Additional training should incorporate explanations of relevant safety data sheets and labeling systems, proper engineered nanomaterial handling and storage procedures, proper PPE usage, proper methods for cleaning surfaces contaminated with engineered nanomaterial, and proper waste disposal for engineered nanomaterial [2, 17].

4.6.6 Personal Protective Equipment

When engineering and administrative controls are incapable of providing a work environment safe from exposure, the final step is to employ the use of PPE. Employers must provide the necessary PPE to the appropriate workers, and provide education and training on how to use it properly. Figure 4.3 lists different types of PPE along with appropriate annotations for proper usage, disposal, etc. [28, 32].



Pants	• Long pants • No cuffs (can catch airborne nanomaterial)
Shoes	• Closed-toed shoes • Low permeable material • Disposable booties may be worn over shoes to prevent tracking of nanomaterials out of work area
Lab Coat (disposable)	• Impervious materials (noncotton) • Should be treated as hazardous waste
Lab Coat (non-disposable)	• Should remain in work area • Place in sealed bags before removing from work area to be cleaned • Inform cleaning service of contamination
Gloves	• Latex or nitrile gloves should be worn when handling nanomaterials • Change gloves frequently • Store used contaminated gloves in a plastic bag until properly disposed of as hazardous waste • More porous gloves, such as cotton, may be worn when handling solid bound nanomaterials
Eye Protection	• Select eye protection based on hazard level • Safety glasses with side shields offer minimum protection • Full face masks or helmet respirators require no further eye protection
Respirator	• Workers must receive medical clearance by a medical professional before being fitted • Wear appropriate respirator and cartridge based on hazard level • A half mask respirator should be worn at a minimum • Refer to your EHS office to confirm proper respirator use for your facility

Fig. 4.3: Proper personal protective equipment for a nanomaterial-contaminated work environment.

4.7 Management of Engineered Nanomaterials

Engineered nanomaterials should be always be considered hazardous. For this reason, waste disposal, spills, and releases should be strictly regulated. Most regulations typically refer to any engineered nanomaterials that are not bound in a solid matrix, or bound in a solid matrix but present the risk of breaking free when contacted with air or water. This includes engineered nanomaterials bound in a liquid matrix, and PPE and cleaning wipes contaminated with engineered nanomaterials. The disposal of engineered nanomaterials should follow any existing federal, state, or local regulations [10].

4.7.1 Waste Disposal

As with any hazardous material, engineered nanomaterials should have their own designated disposal area. Engineered nanomaterials should not, under any circumstances, be placed in regular trash containers or poured down the drain. Any engineered nanomaterial waste should be properly stored in a small sealed container with appropriate labels indicating the type of waste, the form it is in, and any known properties related to the material. The label should also explicitly state that the container is holding nanomaterials [2, 10, 32]. Larger containers are not preferred, because failures of large containers are much more difficult to clean up compared with smaller containers. This is especially true with more dispersible forms of nanomaterial waste [17]. Any other loose forms of contaminated waste, such as PPE, wipes, gloves, etc., should be placed in a sealable container or re-sealable plastic bag and stored in a fume hood or other well-ventilated area. Once the container or bag is full, it should be double-bagged, appropriately labeled, and properly sealed before being removed from the fume hood. Waste containers should then be properly disposed of in accordance with the facility's standard procedures [29].

4.7.2 Management of Spills

In the event of a nanomaterial spill, spill kits should be available on hand. According to OSHA, spill kits should contain at the minimum [31] the following items:

- Adsorbent material
- Barricade tape
- Elastomeric respirator with filters
- Nitrile or latex gloves
- Sealable plastic bags
- Spray bottle with deionized water
- Vacuum with HEPA filter
- Walk-off mat
- Wipes

The type of spill determines the type of procedure needed for cleanup. When assessing a spill, determine how large an area has been contaminated. Block off this area using barricade tape or other means of entry restriction. If the spill is minor (less than a few grams of nanomaterial) it may be cleaned by trained personnel in the work area. If the spill is more significant (more than a few grams of nanomaterial), then restrict any entry to the area and contact the environmental health and safety office for further instructions [4, 32].

For liquid spills, such as nanomaterials suspended in a liquid matrix, standard hazardous material cleanup procedures should be followed. These are based on the type of material and its known hazards. Additionally, extra steps should be taken to ensure complete removal of any nanomaterials. To minimize air currents moving across the spill position barriers around the area. Place an absorbent walk-off mat at the exit point of the contaminated area to prevent nanomaterials from being tracked out. Vacuum up any excess nanomaterial with a HEPA-filtered vacuum cleaner. Once the area is clear, treat any contaminated cleaning materials as hazardous waste and dispose of them properly [10, 29].

For dry materials, like powders, similar procedures to liquid spills can be followed. Place a sticky walk-off mat at the exit point of the contaminated area. Use wet wipes to clean small dry spills, then dispose of the wipes as hazardous waste. For larger dry spills, contact the environmental health and safety office (EHS). If EHS gives the OK, vacuum the spill using a HEPA-filtered vacuum cleaner, otherwise wait for further instructions. Do not dry sweep nanomaterials because this can cause airborne dispersion. This includes broom and compressed air sweeping [2, 10].

4.8 Overview of National and International Associations that Adopted the Handling and Use of Nanomaterials

4.8.1 British Standards Institution

In 2008 the British Standards Institution (BSI) published a guidance consisting of nine documents covering information regarding terminology for medical, health, and personal care applications of nanotechnologies, the bio–nano interface, nanoscale measurement and instrumentation, carbon nanostructures, nanofabrication, nanomaterials, a guide for specifying manufactured nanomaterials, and a guide to safe handling and disposal of manufactured nanomaterials. These nine documents were developed by a wide variety of experts from industry, academia, government, and professional organizations. These documents are a part of the UK's contemporary work to develop standards for a field that is still relatively new [4].

4.8.2 Health and Safety Executive

The UK Health and Safety Executive (HSE; hereafter referred to as "the Executive") was founded under the Health and Safety at Work, etc. Act of 1974 along with the Health and Safety Commission. As of 2007 the Health and Safety Commission has delegated its responsibilities to the Executive. The duties of the Executive, granted by the Safety at Work, etc. Act of 1974, include:

- "to assist and encourage persons concerned with matters relevant to those purposes to further those purposes"

- “make such arrangements as it considers appropriate for the carrying out of research and the publication of the results of research and the provision of training and information, and encourage research and the provision of training and information by others”
- “make such arrangements as it considers appropriate to secure that the following persons are provided with an information and advisory service on matters relevant to those purposes and are kept informed of and are adequately advised on such matters:
  i. government departments
  ii. local authorities
  iii. employers
  iv. employees
  v. organizations representing employers or employees
  vi. other persons concerned with matters relevant to the general purposes of this Part”

The Executive also proposes regulations to, and advises, the Secretary of State based on research and the publication of the results of research carried out on behalf of the Safety at Work Act.

The HSE endorses the UK Nanosafety Group. The group has published guidance for research and development for managers, advisors, employers, and users of nanomaterials. The guidance covers multiple nanomaterials such as fibers, powders, tubes and wires, as well as aggregates. The goal of the UK Nanosafety Group is to promote precautionary strategy to minimize the risk of exposure to nanoparticles. The group co-hosted an international conference on working safely with nanomaterials at the Royal College of Physicians to further spread nano-safety awareness [32].

4.8.3 International Organization for Standardization

The International Organization for Standardization (ISO) began in 1946 when delegates from 25 countries met in London with the goal of creating an international organization “to facilitate the international coordination and unification of industrial standards.” The organization began operation the following year. ISO is now a network of national standards bodies, with 162 member countries, a central secretariat that is based in Switzerland, and 150 full-time employees.

The function of ISO is to develop standards with the help of a variety of experts from all over the world. Each group of experts develops standards based on requirements in their respective sectors. ISO has over 19,500 standards touching nearly all aspects of life, such as air, water and soil quality, emissions of gases and radiation, and environmental aspects of products. These standards contribute to efforts to preserve the environment and protect the health of people around the world [18].

Beginning in 2005 ISO began researching and developing nanotechnology and deriving standards based on those results. Standardization in the field of nanotechnologies includes 86 published ISO standards pertaining to understanding and control of matter and processes at the nanoscale, and using various properties of nanomaterials that differ from the properties of individual atoms, molecules, and bulk matter, to create better materials, devices, and systems that feature the new properties. Specific tasks for ISO include developing standards for “terminology and nomenclature; metrology and instrumentation, including specifications for reference materials; test methodologies; modeling and simulations; and science-based health, safety, and environmental practices.” There are currently 34 countries involved in ISO’s nanotechnology research [19].

4.8.4 Organisation for Economic Co-operation and Development

The Organisation for European Economic Co-operation (OEEC) was created in 1948 and was designed to run the Marshall Plan to reconstruct Europe’s damaged infrastructure after World War II. The OEEC helped countries realize that their economies were interdependent, which brought with it a new era of cooperation that was able to transform Europe. Once other nations around the world saw the success of the OEEC, they realized the need for an organization like this on the world stage. In 1960, representatives from Canada and the USA joined OEEC members in signing the new Convention on the Organisation for Economic Co-operation and Development (OECD). The OECD began operations on 30 September 1961, when the Convention entered into force. Since then, the number of OECD member countries has grown to 34. These countries work together in identifying problems, analyzing those problems, and then promoting policies to solve them. Since the OECD was created, some countries have seen their national wealth double or even triple. Countries that were only minor players on the world stage, such as Brazil and India, are now key partners of OECD and contribute to its work [36].

For over 40 years the OECD has had a pivotal role in the safe use of chemicals and the protection of human health and the environment. As part of its response to emerging issues, the OECD launched the “sponsorship programme for the testing of manufactured nanomaterials” in 2006 to improve approaches for hazard, exposure, and risk assessment for manufactured nanomaterials. The OECD complemented the testing program by developing guidance documents on exposure measurement (including sampling techniques and protocols) and mitigation. These documents address exposure at the workplace, exposure to consumers, and exposure to the environment. The OECD has been vital in analyzing risk assessment strategies for manufactured nanomaterials. It is also analyzing whether current waste management practices are adequate for nanomaterial waste [35].

4.8.5 US National Institute for Occupational Safety and Health

The National Institute for Occupational Safety and Health (NIOSH) was established under section 22 of the Occupational Safety and Health Act of 1970 as a part of the Centers for Disease Control and Prevention. The duties of the organization under the OSHA Act are the following:

- “develop recommendations for health and safety standards”
- “develop information on safe levels of exposure to toxic materials and harmful physical agents and substances”
- “conduct research on new safety and health problems”. NIOSH may also “conduct on-site investigations (Health Hazard Evaluations) to determine the toxicity of materials used in workplaces”
- “fund research by other agencies or private organizations through grants, contracts, and other arrangements.”

The mission of NIOSH is to produce scientific knowledge and provide practical solutions for reducing the risk of workplace injury and death. NIOSH employs over 1300 people from multiple fields, including medicine, industrial hygiene, epidemiology, psychology, chemistry, statistics, and many branches of engineering. Headquartered in Washington, D.C. and Atlanta, Georgia, NIOSH has eight laboratories across the country in which they conduct research on the many emerging problems that are arising from dramatic changes in the twenty-first century workplace and workforce [33].

In 2004 NIOSH established the NIOSH Nanotechnology Research Center (NTRC). The purpose of the NTRC is to accelerate progress in research on the application of nanoparticles and nanomaterials in occupational safety and health and the implications of nanoparticles and nanomaterials for work-related injury and illness. The NTRC consists of NIOSH scientists from various disciplines who are responsible for developing and guiding NIOSH scientific and organizational plans in nanotechnology health research. One year after creating the NTRC, NIOSH drafted the “Strategic plan for NIOSH nanotechnology research: filling the knowledge gaps.” The plan called for a concerted effort to identify and address the knowledge gaps of nanotechnology. The four main goals for the NIOSH nanotechnology research are as follows [30]:

- “understand and prevent work-related injuries and illnesses potentially caused by nanoparticles and nanomaterials”
- “conduct research to prevent work-related injuries and illnesses by applying nanotechnology products”
- “promote healthy workplaces through interventions, recommendations, and capacity building”
- “enhance global workplace safety and health through national and international collaborations on nanotechnology”

4.8.6 Safe Work Australia

Safe Work Australia (SWA) was established by the Safe Work Australia Act 2008. It began operating as an independent Australian Government statutory agency in 2009. SWA mainly consists of members who represent the Commonwealth, the States, the Territories, workers, and employers. SWA's primary responsibility is to lead development of policy to improve occupational health and safety and workers' compensation arrangements in Australia. The key functions of SWA as set out in the Safe Work Australia Act of 2008 are as follows:

a. "develop national policy relating to occupational health and safety and workers' compensation"
b. "prepare a model Act and model regulations relating to occupational health and safety and, if necessary, revise them"
c. "prepare model codes of practice relating to occupational health and safety and, if necessary, revise them"
d. "prepare other material relating to occupational health and safety and, if necessary, revise that material"
e. "develop a policy, for approval by WRMC, dealing with the compliance and enforcement of the Australian laws that adopt the approved model occupational health and safety legislation, to ensure that a nationally consistent approach is taken to compliance and enforcement"
f. "monitor the adoption by the Commonwealth, states and territories"
g. "collect, analyse and publish data or other information relating to occupational health and safety and workers' compensation in order to inform the development or evaluation of policies in relation to those matters"
h. "conduct and publish research relating to occupational health and safety and workers' compensation in order to inform the development or evaluation of policies in relation to those matters"
i. "revise and further develop the National Occupational Health and Safety Strategy 2002–2012 released by WRMC on 24 May 2002, as amended from time to time"
j. "develop and promote national strategies to raise awareness of occupational health and safety and workers' compensation"
k. "develop proposals relating to harmonising workers' compensation arrangements across the Commonwealth, states and territories, and workers' compensation arrangements for employers with workers in more than one of those jurisdictions"
l. "advise WRMC on matters relating to occupational health and safety or workers' compensation"
m. "liaise with other countries or international organisations on matters relating to occupational health and safety or workers' compensation"
n. "perform such other functions that are conferred on it by WRMC"

In January of 2010 SWA published a work health and safety assessment tool for handling engineered nanomaterials. The assessment tool is to be used to document practices and procedures, and also as a tool for work health and safety regulators when visiting nanotechnology organizations. The assessment tool provides a checklist of nanomaterials and how they are being used, controls in place to prevent exposure, information available to businesses, organizations, or laboratories, and characteristics of the business that is manufacturing, supplying, or using nanotechnology. This tool plays a vital role in helping manufacturing facilities document their use of engineered nanomaterials, and in helping regulators check whether proper precautions are being taken when handling these nanomaterials [42].

4.9 Concluding Remarks

In modern times, engineered nanoparticles are increasingly being found in consumer and industrial products due to their extensively researched material improvement advantages. While a rich understanding of how materials can be affected by their incorporation has been developed, knowledge of their impact to the environment and human health is indefinite. Scientists do not agree on their toxicity to the human body, with stances taken from benign to imminent death. Even though health impacts of the bulk material may be well documented, when transitioning into the nanoscale things begin to drastically change. Nanoparticles can be absorbed into the body in ways that their macro-sized parents cannot be. Simply having skin exposed to particles may allow for absorption and distribution throughout the body. Seeing as exposure to these materials may pose large risks to factory workers and handlers of these substances, it is of importance for employers to communicate the signs, dangers, and safe handling procedures to their employees. Further, hazardous communication is made more difficult by the insufficient knowledge of things like exposure limits and processing variables. Based on a German and Swiss survey, it was shown that over half of all companies do not have any nanomaterial risk assessments in place. If risks are known, they can and should be managed by one of the six control preferences – elimination, substitution, isolation, engineering controls, administrative controls, and personal protective equipment. Finally, environmental impact of nanomaterials should be evaluated so proper disposal methods can be set in place.

4.10 Questions for Contemplation

- Define characterization.
- What are the six exposure control methods, listed from most effective to least effective?
- Should an employee use a large container or a small container to dispose of engineered nanomaterial waste? Why?
- What should an employee do with loose forms of contaminated waste such as PPE, wipes, or gloves?
- How should an employee clean up a small amount of dry nanoparticles that have been spilled?
- Why may a particle become cytotoxic after its size is reduced to the nanoscale?
- What is material dustiness? Describe a scenario where it is beneficial and a scenario where it is negative to have a dusty material.

The following will need further reading and they are open-ended research questions.

- With the emergence of nanomaterials, research is beginning to take consumption products such as lotions, probiotics, and vitamins to the nanoscale. Pick a consumption product that interests you and research the advantages and disadvantages of reducing its substance to the nanoscale. Focus on its production processes, biological interactions, and environmental impact.
- Pick a product that you use on a daily basis and imagine if it had nanoparticles incorporated in it (maybe it already does!). Describe multiple ways that these nanoparticles could pose hazards to the workers who made it, you as a consumer, and the environment after disposal.
- Write about an animal that has been or is being affected by nanomaterial contamination. Discuss how the contamination occurs, the results of the contamination, and what you think could be done to reduce or stop the problem.
- Write a 500 word essay explaining methods currently being used to recover nanomaterial waste from the environment.
- Research current recycling methods of nanoparticle infused materials and write a 1-page report on your findings.

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5 Certification: Validating Workers' Competence in Nano-safety

5.1 Introduction

Worker safety training tools are needed in the workforce today [1]. Traditionally, the Occupational Safety and Health Administration (OSHA) has adopted the role and responsibility for developing, directing, overseeing, managing, and ensuring implementation of training for workers in the USA. Training materials should assist those in the industry to identify, reduce, and eliminate nanotechnology-related hazards and improve workplace health and safety [2, 3].

A successful nano-safety training tool requires a method to assess the trainee's comprehension of the content. Certification refers to the confirmation that a person or organization understands the specific technical content and serves as a way to accomplish this goal [4]. Some form of external review, education, assessment, or audit often provides this confirmation. This chapter offers a proposal on what a worker safety training certification program might include in order to ensure that employees and employers, in collaboration, can create a healthy workplace environment in the nanotechnology industry.

Training and certification in nanotechnology safety should include the following modules:

1. Introduction to nanotechnology: Defining terminology, describing benefits, highlighting challenges
2. Occupational and environmental safety and health (OESH) life cycle paradigm: Designating occupational and environmental health issues specific to nanotechnology
3. Nanotechnology regulations and related standards: Explaining US Environmental Protection Agency (EPA), Food and Drug Administration (FDA), OSHA, and Consumer Product Safety Commission (CPSC) regulations, regulatory requirements, and standards

For further reading on module 1, see Chapter 1 of this book and *Introduction to Nanotechnology* [5]. For further reading on module 2, see Chapter 3 of this book and *Nanotechnology: Health and Environmental Risks* [6]. For information on module 3, see Chapter 6 of this book and the webpages of the EPA (https://www3.epa.gov/), FDA (http://www.fda.gov/), OSHA (http://www.osha.com/), and CPSC (http://www.cpsc.gov/).

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5.2 Definition of Nanotechnology for Training and Certification

The first module of a nanotechnology worker safety certification course offers training in subjects relevant to nanomaterial structure, stability, and functional characteristics. Its goal is to provide a broad overview of nanotechnology and nanomaterials from the viewpoint of a variety of stakeholders, such as research, industry, manufacturing, commerce, and regulatory environments. The topics should include terminology and descriptions, benefits and uses, and challenges and risks.

There are several definitions of the term "nanomaterial" used in domestic and international agencies [7–9]. The most universal definition states "materials of which at least one dimension is sized between 1 and 100 nm and for which has at least one unique physical or chemical property." In the USA, nanomaterial is generally defined as "any particle, substance, or material that has been engineered, purposefully produced and purposefully designed to be a nanoscale material and to have one or more dimensions in the nanoscale." In Europe, the common definition includes "a natural, incidental, or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1 to 100 nm." In China, the working definition of nanomaterial is "a material which has a structure in the three-dimensional space in at least one dimension in the nanometer scale (1 to 100 nm) range of geometric dimensions or constituted by the nanostructure unit and a material with special properties." In Japan, the term nanomaterial "refers to, among solid materials manufactured using elements, etc. As a raw material, a nano-object with at least one of the three dimensions of approximately 1 to 100 nm and a nanostructured material composed of nano-objects including matter composed of aggregated/agglomerated nano-objects."

5.3 Occupational and Environmental Health and Safety Management

A nanotechnology certification course should offer training in risk management and occupational and environmental health and safety (OEHS) models. Once these models are defined, the course training material should describe how trainees could enhance safety within the nanomaterial environment in which they work. The goal of this module is to provide a broad overview of the risk management and safety concepts that govern current good practices in nanotechnology and nanomaterial handling. Disciplines included in this training could include risk science (e.g., assessment, management, and communication), life cycle analysis, industrial hygiene, and medical surveillance.

According to the American Industrial Hygiene Association (AIHA) (https://www.aiha.org/), "industrial hygiene (IH) is a science and art devoted to the anticipation, recognition, evaluation, prevention, and control of those environmental factors or stresses arising in or from the workplace which may cause sickness, impaired health and well being, or significant discomfort among workers or among citizens of the community." Within the technology community, industrial hygiene professionals are responsible for examining the work environment and identifying any hazards and potential dangers, recommending safety improvement, leading research efforts to provide data on unsafe conditions in the workplace, proposing tools and techniques to anticipate and control unsafe conditions, providing training and educational material to workers about job-related risks, collaborating with government officials in the development of safety regulations, and ensuring worker compliance related to safety in the workplace [10]. Even though these tasks were not developed specifically for nanotechnology, each of these activities can be applied to nano-safety in the work environment.

A risk management model, as it pertains to the nanotechnology workplace, can be defined as the assessment of exposure to engineered nanomaterials and hazards of that exposure unique to an occupational worker or cohort of workers in conjunction with the recommendation and governance of procedures designed to minimize adverse impact [11]. In June of 2007, the Environmental Defense Fund and The DuPont Company collaborated and produced the "Nano Risk Framework" [12]. The document "describes a 'framework' for ensuring the responsible development of nanoscale materials. It establishes a process that can be widely used by companies and other organizations." The following six iterative steps allow new information to be incorporated, even after the steps have been implemented within a company or institution:

- Step 1 describes the nanomaterial and its application in industry or commerce.
- Step 2 is data-rich and defines the process to develop the nanomaterial's physical and chemical properties, its hazards, and its associated exposures throughout the material's life.
- Step 3 involves the evaluation of risks based on information gained from step 1 and 2, specifically, information such as identity and characteristics, the amount of material being generated, and probability of scientific, regulatory, business, health, and environment risks.
- Step 4 is the risk assessment.
- Step 5 is risk management.
- Step 6 is the prompt to review, revise, and adapt new information as it is developed in the company or institution's efforts in nanotechnology research and development.

Figure 5.1 depicts the steps of the framework and its iterative nature.

An OEHS model is a management process established within a company or institution that is concerned with the safety, health, and welfare of people engaged in the workplace or other work environment [13]. This model varies among industries, but

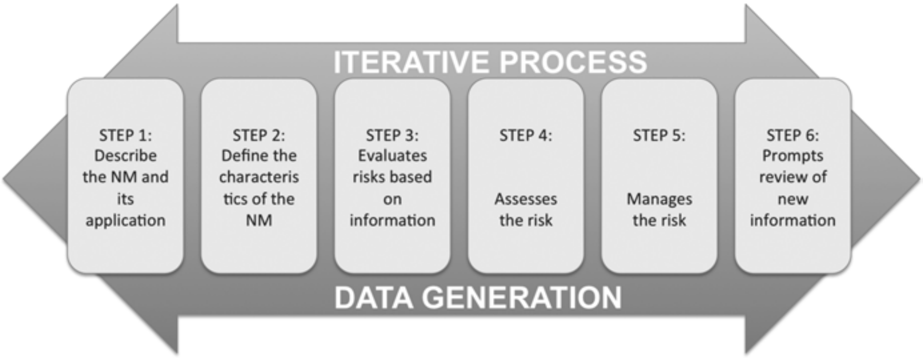

Fig. 5.1: The nanorisk framework developed by the Environmental Defense Fund and The DuPont Company in 2007.

the basic components include the following five stages: anticipate, recognize, evaluate, control, and confirm. In the "anticipate" stage of the management process, the nanomaterial is identified and categorized. Information about its biological affects after exposure is collected and banded based on a hazard code. Some characteristics documented include the dustiness of the sample and potential exposure pathway based on its use.

After the materials have been identified and categorized, the OEHS management process can recognize anticipated biological or chemical hazards associated with each sample. The "recognize" stage involves documenting the production and handling steps and describing worker activities that might result in occupational and environmental exposure.

The next stage involves evaluation of nanomaterial health hazards. This is necessary to determine the best control procedures (i.e., implementing engineering control, personal protective equipment, or both). The evaluation includes an assessment of the effectiveness of these controls by validating the level of containment. Data gained from these continuous evaluations promotes an iterative process, whereby changes in control can be implemented without loss in material production [14].

After evaluating the OEHS management processes, the available data should be reviewed and adjustments should be made in order to control occupational and environmental exposures. This step in the management paradigm serves to match the "level of control" with the "hazard banding schemes" employed. The level of control consists of matching the recommended personal protective equipment and engineering controls used by workers to assure that exposures are minimized. Engineering controls are designed to eliminate exposure to a hazard through the use or substitution of engineered machinery, equipment, tools, or process [15].

The last stage in the OEHS management model is confirmation. The confirmation process involves developing testing methods to measure real-time exposure and to create a medical management system that assures the absence of harm to workers. This process is repeated each time a significant change in the work environment occurs because any variation in environment also impacts potential exposures to new or existing hazards. Figure 5.2 depicts the five stages in the OEHS management cycle.

There are several reasons why workplaces need an OEHS management model. First, the program demonstrates the commitment of employers to the health and safety of employees; in other words, it outlines employer and employee accountability and responsibility. Second, an effective program shows that safety performance and business performance are compatible in the workplace. Third, an implemented OEHS program sets safe work practices and procedures to follow to prevent worker illness or injury.

Occupational hazards and risks in the workplace can be controlled by a variety of methods, such as the precautionary principle, segregation of working staff members, mandatory yearly safety training, and quarterly equipment maintenance and process evaluation [16]. Arguably, the most effective risk management model requires a shared understanding of the nanomaterial of interest followed by the application of assessments and controls to achieve an appropriate balance between safety and productivity. Regardless of the method used, risks in the workplace are foreseeable and manageable.

5.4 Anticipating Hazards in Nanotechnology

Anticipating hazards in the nanotechnology workplace requires a thorough knowledge of the nanomaterial through physicochemical characterization, its toxicological profile, information of hazard banding for the material or its chemical components, a human health risk assessment, and an ecological or environmental risk as-

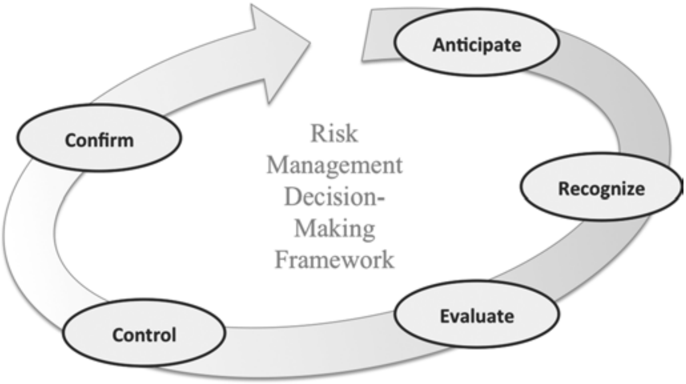

Fig. 5.2: The occupational, environmental, health and safety (OEHS) management model.

sessment [11]. Trainees should gain an understanding of the role that toxicology has in determining the hazards associated with nanomaterials present in the workplace, be familiar with categorizing and banding specific nanomaterials of interest according to their ability to cause adverse health affects, and identify the recommended exposure limits for various classes of nanomaterials.

Because most occupational and industrial health professionals are experts in the fundamentals of exposure assessment and exposure containment, they are also trained to anticipate the unique physical, chemical, and toxicological characteristics associated with nanomaterial manufacturing operations. Thus, a "cradle-to-grave" approach to developing a successful OEHS management model is possible. Trainees should be able to provide knowledge in each of the following areas: toxicology, industrial hygiene, and medical management. These knowledgeable individuals are able to streamline the compliance process by anticipating details of their OEHS needs well in advance of assessment, thus minimizing potential hazards and risks.

The US National Institute for Occupational Safety and Health (NIOSH) is a federal institute with two distinct responsibilities in preventing worker illnesses and injuries: conducting research and making recommendations. Specific to anticipating exposures in nanotechnology-related workplaces, aerosolization of particles on the nanoscale is the greatest concern to workers, employers, and regulators alike. To that end, NIOSH recommends the following graded approach to assessing, measuring, and anticipating aerosol exposure [17]:

- Step 1 is to screen the area and process using particle counters and size analyzers.
- Step 2 is to collect samples at source using filter-based sample collection for electron microscopy and elemental analysis.
- Step 3 is to collect personal samples, also using filter-based sample collection for electron microscopy and elemental analysis.
- Step 4 is to use less portable equipment and more sensitive aerosol sizing equipment for additional analytical analyses and particle quantification.

Health banding provides a tool for hygienists carrying out exposure risk assessment and risk management in the workplace [18]. This type of banding or categorization is a logical system of classifying a nanomaterial of interest. Each material is placed into a health band based upon its ability to cause harm. The data utilized for deriving this assessment are acquired from a professional review of current toxicological literature. By providing the relative hazard bands for the substances under review, the health band serves the working community in the qualitative aspects of risk management.

5.5 Recognizing Hazards in Nanotechnology

An OEHS management program is the basis for all health and safety activities in a workplace. Simply put, it is the "master plan" designed to recognize and identify hazards before they cause accidents or illness; it also explains how to respond to emergencies. This program, however, is not meant to be performed only in workplaces that manufacture the raw nanomaterial of interest, but also in all workplaces along the entire life cycle of the nanoenabled product (including manufacturing, distribution, formulation, use, and end-of-life), as shown in Figure 5.3.

Recognizing potential hazards in the nanotechnology workplace requires anticipating illnesses and injuries as well as asking workers and employers a series of behavioral questions. These questions should cover a wide range of elements such as, but not limited to, basic questions of the OEHS program concerning hazard evaluation, exposure containment, communication, and education. The following list provides example questions appropriate for an OEHS manager or trained staff to recognize gaps in nanotechnology safety:

1. Is there a demonstrated commitment to OEHS?
2. Do OEHS initiatives have both technical staff and senior management participation?
3. Does information exists relative to environmental fate and health effects?
4. Is appropriate technology implemented to minimize exposure?
5. Are facilities in place to contain and control exposures?
6. Are worker exposures continuously monitored and controlled?
7. Are exposure and medical monitoring results communicated?
8. Is training at the appropriate levels available and provided?
9. Are safety data sheets and tech transfer information available?
10. Is the appropriate selection of personal protective equipment available to all employees?

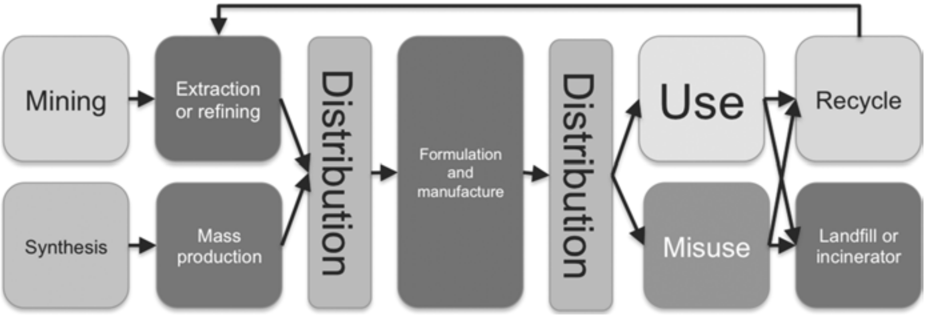

Fig. 5.3: Recognizing potential hazards should be considered along the entire life cycle of the nanoenabled product.

5.6 Evaluating Hazards in Nanotechnology

Although anticipation and recognition are fundamental to understanding the hazards in nanotechnology workplaces, evaluation is key to defining whether a hazard event exists and if so, to what extent. Following the assignment of health bands and cataloguing the nanomaterial(s) of interest, the OEHS management model can be used to support investigative work to evaluate the potential for exposures.

Evaluation includes determining an acceptable exposure level (AEL) for each nanomaterial. Once determined, a "surrogate" is selected and the workplace processes are simulated with this nonhazardous material. Based on the results of this effort, adjustments are made and nanomaterial handling can begin.

Three unwritten laws of systems engineering are used to evaluate the safety of a workplace [19]. First, there is an understanding that everything interacts with everything else and the impacts of those interactions ripple throughout the system and should not be ignored. Second, every particle, vapor, fume, liquid droplet, or other aerosol goes somewhere, and if it leaves one place, then it will deposit somewhere else. Third, one should never become so enamored with a new design decision that the consequences are not thoroughly thought through.

Containment is a large part of the evaluation stage and can be described as the action(s) of preventing a hazard from expanding into other work areas [20]. In the workplace, this takes on significant proportions, particularly in nanotechnology laboratory environments, and should be considered in building design, process management, and research and development project work. Validation is the second large component of the evaluation stage and often refers to establishing documented evidence that a process or system, when operated within established parameters, can contain nanomaterials effectively and reproducibly. Used together, containment and validation provide the necessary information needed to evaluate an injury or illness in the workplace and prevent the injury or illness from happening again.

5.7 Controlling Hazards in Nanotechnology

Nanotechnology workplace assessment of activities should utilize the recognition and evaluation stages to generate recommendations for control. In other words, changes in infrastructure, institutional processes, or worker behavior can be made in order to control the conditions that exceed AELs. This level of control is generally achieved through a series of well-established industrial hygiene control solutions such as ambient air dilution, ventilation, respiratory protection, isolation of nanomaterials, and other well-established techniques. Because the OEHS management model is specifically designed for nanotechnology workplaces, control recommendations can be novel, but are only implemented as necessary to achieve compliancy requirements [21].

Controlling the hazards in a nanotechnology workplace requires identifying all of the nanomaterial handling processes. Once these processes have been identified, a control banding matrix can be laid out and implemented. Control banding is a method used to manage workplace risks by matching a control measure (such as ventilation, engineering controls, containment, or personal protective equipment) to a range or "band" of potential hazards (such as skin irritation, carcinogenic, eye damage). Control banding is most effective in controlling exposure to the nanomaterial of interest [22, 23]. The hierarchy of actions for controlling nanomaterial exposure in the workplace is shown in Figure 5.4.

Elimination and substitution: These are the least practical control approaches because they require avoiding the use of nanotechnology in the workplace. Although there are reasons for eliminating the nanomaterial content from a product (such as high probably of nanoparticles being released into the environment; marginal added benefits and unacceptable unknown risks; or health complaints from users of the product that might be associated with the nanoscale component), this is not the preferred control measure in the nanotechnology industry because the nanoscale component can add many benefits to the product, such as increased biodistribution in pharmaceutical applications or efficient catalytic conversation in petroleum applications [24–27]. Furthermore, there is data to suggest that nanoparticles quickly aggregate, transform, or disintegrate once placed in environmental matrices.

Modification: Modifying the way a worker handles a nanomaterial of interest is a more acceptable way of controlling exposure. For instance, is there a process that could be adopted to reduce airborne nanoparticles? Yes, nanoparticles can be provided and worked in a "wet state" to reduce the risks of inhalation exposure [28].

Containment and ventilation: A glovebox is a type of containment system that serves to keep airborne nanoparticles inside a contained space during processing. Manufactur-

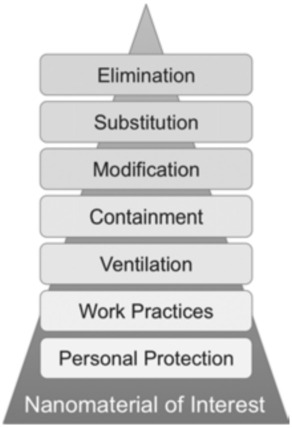

Fig. 5.4: The hierarchy of controlling a nanomaterial exposure. Elimination is the first line of defense, and personal protection is the last.

ing facilities and research laboratories also use fume hoods, vacuum systems, clean rooms, laminar flow ventilation tables, and biosafety cabinets as means of controlling nanomaterial exposure [28]. However, each one of the containment solutions eventually needs to be opened to remove the product and waste or to clean and maintain the unit. Cautious work practices are needed to minimize and/or eliminate exposure during these specific activities.

Personal protection: NIOSH recommends wearing hand, eye, and lung protection when working with nanomaterials [21]. There is limited data indicating penetration of the skin by these materials, but cuts in the skin may offer an easier path to internalization and the circulatory system. Disposable nitrile gloves are the most widely used because they provide protection against a wide range of chemicals. Using safety glasses for eye protection is also necessary. Goggles prevent splashes from getting into the eyes much better than safety glasses. Respirators are used to prevent nanomaterial exposure to the lungs [29]. The different types of respirators can be divided on the basis of facial coverage (i.e., full-face or half-face). Full-face respirators have a major design advantage in that they go across the forehead. Building a respirator that goes across the forehead is much less problematic than trying to cover the bridge of the nose where there is much greater human variation. Not surprisingly, the greatest leakage occurs at the bridge of the nose.

5.8 Confirming Hazards in Nanotechnology

Unique to most operations is the use of confirmation in managing OEHS. This process involves reassessing conditions following either a change in process or an upgrade in control. Because of the unique characteristics of nanomaterial manufacturing, even the slightest variance can result in exceeding the already established AEL. To manage this, the workplace must have a system of ongoing testing to confirm whether exposure potentials have changed [30]. This testing might include scheduling worksite assessments or establishing a process for continuous detection. Either way, the use of confirmation brings current occupational health knowledge and good practice to the OEHS management model.

Monitoring is a large component of the confirmation stage. Nanomaterial monitoring can be classified as area, personal, or biological. Area monitoring is used to measure nanomaterial concentration levels in ambient air prior to, during, and after a process or event is conducted [30]. Area monitoring can be used to establish background concentrations, trigger alarms in the event of elevated concentrations, and monitor long-term changes in air quality. Wipe sampling is another form of area monitoring, but can also be used for personal monitoring. Instead of sampling a known volume of air, a known surface area (such as a countertop, instrument knob, patch of skin, or laboratory coat) is wiped. A new sample area should be wiped and used for each analysis to reduce the likelihood of cross-contamination. Biological monitoring measures the nanomaterial, metabolites, or biomolecules (such as enzymes or cytokines) in the blood, urine, or exhaled breath [31].

Biological monitoring can also be used as a metric for exposure. This type of monitoring confirms that the previous stages of anticipating, recognizing, evaluating, and controlling are not only being conducted, but also are reducing the uncertainty inherent in traditional exposure and risk assessments. Measuring the nanomaterial, metabolites, or biomolecules in blood, urine, or exhaled breath eliminates much of the uncertainty in estimating risk because internal dose and response is directly available. Monitoring is a valuable tool for assessing human exposure to nanomaterials of interest, with measurements divided into biomarkers of exposure, effect, and susceptibility. Furthermore, biological monitoring provides unequivocal evidence of exposure when utilized as part of an occupational exposure assessment [31, 32].

5.9 Conclusions

In conclusion, validating worker competence in health and safety in the nanotechnology workplace is a crucial component of the emerging field of nano-safety science. Training and certification in nanotechnology safety should include an introduction to nanotechnology, explanation of the OEHS management model, and a list of available nanotechnology regulations and related standards. Both technical staff and senior management in an organization using nanomaterials should be able to anticipate, recognize, evaluate, and control hazards in the workplace. In addition, workers should be able to confirm containment and reduced exposure along all phases of the nanomaterial product life cycle.

5.10 Questions for Contemplation

- What are the three most critical components needed in a successful and effective nano-safety certification class?
- List the five components to a traditional Occupational, Environmental, Health and Safety (OEHS) Management Method.
- What term is used to describe the first line of defense against nanomaterial-related occupational exposure? What is used as the last line of defense against nanomaterial-related occupational exposure?

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6 Understanding the Implications of Nanomaterial Unknowns

6.1 Introduction

Upon reading the title to this chapter, the obvious question that occurs is, “How can we understand what is unknown?” The answer is that we cannot immediately, or probably even within the time required to act, make a considered decision. However, doing nothing is totally unacceptable and probably exposes the researcher, developer, manufacturer, and others involved to litigation. This chapter discusses some situations where exact compliance is impossible, how to address risk avoidance, and how to prepare for the completely unexpected.

It is *impossible* to address all possible situations involving nanomaterials. Why? There are a number of reasons, but first consider the volume of possible materials that need to be investigated. Based on work done under an Occupational Safety and Health Administration (OSHA) Susan Harwood Grant [1], it is estimated that there are between 10^{200} and 10^{900} different materials and combination of materials that need to be investigated. To put that number into perspective, if the properties of one material per second had been determined since the creation of the universe, the total number of materials and combinations investigated would be less than 10^{18}! It is acknowledged that some of those materials and combinations may be immediately qualified as “undesirable,” but the number of possible test candidate remains extensive.

Consequently, procedures must be developed for addressing situations where the material properties are unknown. This is not unlike firefighters moving into a fire of unknown cause, yet a general set of protocols does exist. For example, in the case of safely dealing with an accidental spill of nanomaterials, there are certain general steps that can be taken, depending upon whether the nanomaterial is a liquid spill, solid substance spill, or airborne contamination. Current efforts in nanotechnology safety (nano-safety) education are addressing the training of students and workers to handle these situations properly [2].

This chapter builds on this previous work and focuses on developing an understanding of why these efforts are needed to ensure the application of safety in the development and application of nanotechnology. It is not only unacceptable to do nothing to address the needs of nanotechnology safety for people and the environment, it also opens organizations to potential litigation both now and in the future.

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6.2 Background on Nanotechnology Safety Programs

By 2017, there had been only two contracts awarded and completed that focused on nanotechnology safety and the related education efforts. There is an ongoing METPHAST program addressing health and safety in nanotechnology and emerging technology. A certification in nanotechnology safety by the Association of Technology, Management, and Applied Engineering (ATMAE) started in 2016. Many individual efforts have considered the issue of safety in handling nanomaterials, but very few have moved beyond the specific concerns related to a nanomaterial of interest. In many cases, concern developed only after many people had become involved in the research, development, and application of the particular nanomaterial. A representative example is the case of carbon nanotubes (CNTs). CNTs were being used in Toyota bumpers to replace the metal that was then commonly employed. The result was a stronger but lighter material that helped improve vehicle mileage. Other applications included tennis racquets and baseball bats. Stronger, lighter products improved the performance of the users. This seemed to be a great new material. However, a question arose about the potential toxicity of CNTs. The shape of a CNT (a narrow, straight tube) is noticeably similar to most forms of asbestos, which is considered highly detrimental to lungs if inhaled. Although CNTs are considerably shorter, the issue was raised about their possible effects. A number of toxicity studies were carried out to evaluate the potential dangers, but only after there were several applications and many participants involved in the use of CNTs

In the mid-2000s, there were some efforts to address the education of workers on the handling of nanomaterials. This was precipitated by the release of a guideline by the US Occupational Safety and Health Administration's (OSHA) on the proper disposal of broken compact fluorescent light bulbs, which contain microgram amounts of mercury. However, there were larger amounts of unknown nanomaterials being employed in the absence of guidelines.

In 2010, a team from Rice University led by Kristen Kulinowski (with Texas State University as a subcontractor) was awarded an OSHA Susan Harwood Training Grant to develop and implement training modules on the safe handling of nanomaterials. The target participants were workers with the primary responsibility for safety in small-to-medium chemical companies.

The result was an 8-h, seven-module training course that was validated at presentations during national meetings of experts. The modules were titled:

1. Introduction to nanotechnology and nanomaterials
2. What workers need to know about nanomaterial toxicology
3. Assessing exposure to nanomaterials in the workplace
4. Controlling exposure to nanomaterials
5. Risk management approaches for nanomaterial workplaces
6. Regulations and standards relevant to nanomaterial workplaces
7. Tools and resources for further study

The intended audience for this course was people who already had a background in workplace safety but not in aspects of nanomaterials.

In 2012, a National Science Foundation award was given to Texas State University (Jitendra Tate as principal investigator) and University of Texas at Tyler (Dominick Fazarro as principal investigator) to develop two nanotechnology safety education courses. A development team was formed, which included Craig Hanks of Texas State, Robert McClean of Texas State, Satyajit Dutta of Texas State, and the first author of this chapter. A primary issue that faces education of students (or current employees) about the use of any emerging technology is to develop an appreciation for the potential impact of the technology – both benefits and risks. As Professor Hanks stated in an abstract: “New knowledge, new techniques, materials, systems, and devices have brought new industries, new social forms, and new ethical challenges. One important aspect of technological societies is the intentional pursuit of change, of new technologies. This requires that responsible engineers have heightened awareness of the health and safety risks, ethical and social considerations, and environmental and humanitarian implications of their work” [3].

Each of the two courses included nine modules, which were designed to be offered either as a complete course or as modules that could be extracted and inserted into existing courses. The ability to add courses to a curriculum based on current student credit loading is not always possible, but often module insertion is. The courses were developed, tested, enhanced, and re-tested. The complete courses were offered at UT Tyler and the modular selection employed at Texas State University.

The curriculum of the first course, *Introduction to Nanotechnology Safety*, consisted of the following modules:

1. What is nanotechnology and nano-ethics
2. Ethics of science and technology
3. Societal impacts
4. Ethical methods and processes
5. Nanomaterials and manufacturing
6. Environmental sustainability
7. Nanotechnology in health and medicine
8. Military and national security implications
9. Nanotechnology issues in the near future

Referring to the primary issue mentioned above, it was determined that ethics, societal aspects, and environmental considerations needed to be introduced early in the course. When working on materials with unknown properties, many aspects of the development and production need to be considered with thoughtful and diligent consideration of potential impacts, which may not be obvious until years after the initial applications.

The second course, *Principles of Risk Management for Nanoscale Materials*, contained the following modules:

1. Overview of occupational health and safety
2. Applications of nanotechnology
3. Assessing nanotechnology health risks
4. Sustainable nanotechnology development
5. Environmental risk assessment
6. Ethical and legal aspects of nanotechnology
7. Developing a risk management program
8. Results of case studies and research projects
9. Hands-on experience in the Texas State Composites and Plastics Lab (designed specifically for handling nanomaterials).

As with the first module, the inclusion of ethics and environmental considerations was a significant part of the educational effort.

The driving force behind this work was to provide an educated populace that neither fears nanotechnology nor assumes that there are no dangers. One can look back at the development of the asbestos situation. If there had been knowledge of the dangers of asbestos to people, would the widespread application of the material have taken place? Would it even have been considered? We do not want a reoccurrence because of a lack of understanding.

The third program was developed by the University of Minnesota. With funding from the National Institute of Environmental Health Sciences Superfund Research Program, the Midwest Emerging Technologies Public Health and Safety Training (METPHAST) Program develops and disseminates web-based modules to educate and train a variety of learners about health and safety issues associated with emerging technologies. This is a multi-institutional collaboration between the University of Minnesota School of Public Health, the University of Iowa College of Public Health, and Dakota County Technical College.

The METPHAST Program's central objective for the current three-year funding period is to develop a comprehensive array of focused, web-based modules about nanotechnology health and safety that can be used flexibly by instructors to create academic courses, continuing education initiatives, and individual lessons that serve the unique needs of different learners. This objective is being met by developing 20 1-h, web-based modules and supplemental hands-on activities to train students and professionals to work safely with engineered nanomaterials.

The content can be presented by two academic courses. The first, *Introduction to Occupational Hygiene* is a single-credit, semester-long course that uses five modules and accompanying activities to introduce students in science and engineering to occupational health and safety. This course was piloted in the spring semester of 2016. The second course, *Nanotechnology Health and Safety* is a three-credit, semester-long course that uses 15 modules and accompanying activities to provide in-depth training to occupational health and safety students and science and engineering students regarding nanotechnology health and safety.

The content is also intended for use by continuing education students and is arranged in the following sequence of six units:

1. Awareness-level training for industrial hygiene professionals
2. Operational-level training for industrial hygiene professionals
3. Awareness-level training for other occupational health and safety specialists
4. Operational-level training for other occupational health and safety specialists
5. Awareness-level training for nanotechnology professionals
6. Operational-level training for nanotechnology professionals

6.3 What are Nanomaterial Unknowns?

Working with materials at the nanoscale is an embryonic technology with numerous unknown factors. Compounding this is the fact that many aspects of the nanomaterials involved must be considered. This list of characteristics is extensive and some of them are discussed in this section.

Current government efforts are trying to provide specific quantification for what constitutes a "nanomaterial." The majority of cases employ size as the determining factor. That size is 100 nm and smaller. Many things that are perceived as constants in the world actually change as the size of the material approaches the atomic scale.

As has been the case for centuries, there are things that are known at the current time that were unknown only a short time before. For example, consider gold. Gold is a precious material that has been employed for many centuries. People working with gold are aware that its melting point is 1064.18 °C. Although that is true for the bulk material, as the size of the gold nanoparticles decreases below 50 nm, the melting point starts to lower and drops significantly as particle size approaches 1 nm. Silver is another commonly employed material. As its size decreases to the 20 nm range, the silver nanomaterial is able to kill bacteria. The nanomaterial is employed in certain situations to prevent the development of bacterial colonies. Unlike antibiotics, bacteria "seem" not to build a resistance to the silver-based material. A problem arises because, although silver nanomaterials can kill bacteria, it does not distinguish between "good" bacteria and "bad" bacteria, which calls into question its use as an antibacterial material in some instances.

CNTs are nanoscale carbon particles that exhibit strength while being lightweight. Combination of CNTs and polymers results in a material stronger than steel but much lighter. The material has been used for lightweight automotive bumpers, resulting in better vehicle mileage. Some may ask, however, about the lifetime of the bumper and what happens when the car and associated materials are recycled or treated as waste. In another case, one form of a single-walled CNT is conductive, whereas a slightly different orientation of the crystalline structure results in a semiconductor-type material, resulting in different applications that may have different advantages and disadvantages for material use. One of the characteristics of the nanoscale is exemplified by a slightly different form of carbon. Graphene is an extremely strong sheet of carbon atoms. It is often referred to as a two-dimensional material because it can be only one atomic layer thick. Graphene is, simply stated, a CNT unrolled, but it has some totally different properties

The above examples show that the properties of materials at the nanoscale are different from those at the bulk (macro) level. The discovery continues and “new” properties of nanomaterials are continually being found. Therefore, the assessment of any system involving nanomaterials should be made with the acknowledgement that more will be discovered as the work progresses. The following is a list of some of the properties that need to be considered:

- *Size*: Aluminum nanoparticles become highly reactive in the range of 30 nm, which has led to their application in certain types of rocket fuel.
- *Shape*: CNTs come in single-walled and multiwalled configurations, which have different properties. Unrolled CNTs (graphene) have further differences in properties.
- *Length*: There is concern in the medical profession that CNTs in excess of 5 µm long, and definitely over 20 µm, may cause similar reactions as asbestos.
- *Thickness*: The properties of graphene change as the number of atomic layers increase.
- *Temperature*: The melting point of gold and most metals starts decreasing as the nanomaterial size decreases below 50 nm.
- *Purity*: Graphene has significant electrical properties and is being evaluated for use in future electronic devices. Add hydrogen to the graphene and it becomes an insulator.
- *Electrical properties*: At dimensions below 50 nm, copper conductivity is dependent on the crystal orientation and grain boundaries of the nanomaterial.
- *Color*: Gold is known as a yellow material, but the color of a suspension is dependent on the size of the particles in solution. The red color in stained glass windows is the result of a particular size of gold nanoparticle introduced into the glass during manufacture. This characteristic was employed during the Middle Ages.
- *Distribution*: The nanomaterial may change behavior depending on the half-width of its distribution. Unfortunately, equipment to measure large distributions quickly and accurately is not currently available.
- *Very small size*: In the range of 1 nm, gold is a semiconductor. For both silver and platinum, particles of thirteen atoms have a magnetic moment. This is a new and unexpected property of these metals.
- *Aging*: There have been some indications that exposure to environmental conditions may cause some nanomaterial properties to be modified.
- *Equipment calibration*: Equipment changes over time. When measuring properties of nanomaterials, even slight changes in equipment calibration can result in significant changes in the results.

- *Equipment design*: Modifying (improving) portions of the measuring apparatus can result in inconsistencies in measurement.
- *Atomic level shape*: Cerium oxide particles of less than 10 nm tends to take of the shape of a truncated octahedron with {100} and {111} faces; however, above 10 nm, the structure shifts toward a {111} octahedron [4].
- *Multiple material states*: Materials in the nanorealm are unique and different. Hochella [5] showed that transition metals can exist in five different states that are dependent on the item that the metal interacts with. The five states are hydrated atom; metal complexed in a small protein; metal adsorbed to the surface of a 1 nm mineral particle; metal adsorbed to the surface of a 20 nm particle; and metal adsorbed to the surface of a 200 nm particle.

As can been seen from the above list, there are many possible influencing factors that can change the properties of a nanomaterial, resulting in a complex assessment. There is insufficient data available to classify all nanomaterials and guarantee that there are no hidden dangers.

6.4 Impact on the public

In most cases, the general population receives information from news sources. These sources provide descriptions of current and past events. Broadcast, print, and web media need to capture the audience's attention. How is this done? Usually, it is an unusual event, such as a surprising success or tragedy. Although there are also numerous other stories in the published media, they are not normally within the purview of the audience.

The assumption that must be made is that the first the public will hear about and become interested in a subject like nanotechnology is when there is some sort of sensational event – either positive or negative – or something interesting within the book and film industry. For example, nanotechnology-based discoveries that increase knowledge about diseases and aging often cause an increase in nanotechnology interest among the public. Similarly, written material and movies such as Spiderman and Spy Kids can cause an upsurge of interest in science in general and nanoscience in particular.

Of course, not all awareness is based on positive occurrences. Negative occurrences typically involve some issue of nanomaterial toxicity.

One such occurrence made the headlines in 2009. Reuters News Service reported on 9 August 2009 that seven women (in China) became ill and two later died after working with paint containing nanoparticles. They all had insufficient protection from the material (based on a 2008 study). The Chinese researchers who did the original investigation indicated that the five surviving women suffered permanent lung damage. The claim was that this was the first case documenting health effects of nanotechnology in humans [6]. Clearly, this initial reporting presented the “risk” of nanomaterial use.

A further analysis was performed. A US government expert said that the study was more a demonstration of industrial hazards than any evidence that nanoparticles pose more of a risk than other chemicals. The women who became sick were spraying a paste containing nanoparticles in a very small, unventilated room, and wore gauze masks only occasionally. Toxicology findings from the lungs of the two women who died told the true story. The paste they were spraying accumulated and hardened in their lungs. There was a 30 nm nanoparticle in the center of a larger area of hardened paste, so the incident was described as a nanoparticle incident. More accurately, it was a failure of proper industrial protection for workers. But, it was originally reported as a nanomaterial incident. It is important to be able to provide facts that include not only the materials involved, but also aspects of human involvement and protection methodologies.

This process requires an effort to educate the public. Two separate areas must be addressed. The first is an understanding of the health hazards of nanoparticles. Understanding the hazard and degree of that hazard involve the material aspects and the method of nanoparticle introduction to the system. The following discussion assumes the human body as the “system.” From what we understand today, nanoparticles can enter the body intentionally or unintentionally though inhalation, swallowing, and skin penetration. Obviously, nanomaterials can be injected through medical procedures, but that is an intentional action. The effects of the different modes of nanoparticle introduction are as follows:

- Inhalation can create a pulmonary inflammation. A persistent inflammation may cause a reaction that could lead to diseases such as cancer or fibrosis.
- Swallowing or ingestion can permit the nanoparticles to transfer to other body organs by way of the gastrointestinal tract. The effects are still being studied.
- Penetration through the skin (dermal exposure) may cause harmful effects locally within the skin. Material can also be absorbed through the skin and circulated by the bloodstream. This can occur for particles in the 1 µm (1000 nm) range, so nanoparticles have no problem penetrating the skin. Again, medical research requires specific particles and a long duration to determine the effects of most nanoparticles.

The second area that must be addressed within the public arena is consideration of possible causes and issues with nanomaterials. These are areas of concern for the general public. The following list describes eleven of these areas of concern:

- Toxicity of materials in many cases is known and there are industrial safety precautions that are observed in industry. These existing precautions can be adapted for dealing with smaller sizes.
- Chemical dangers are also usually known and steps are taken to prevent occurrences; if something occurs, steps are taken to control the situation.

- Fire is a danger in many ways. The containment of a fire is dependent upon the type of fire. The overall approach does not change because of particle size.
- Explosion can be a size-related issue. As mentioned previously, aluminum becomes extremely reactive at smaller sizes. The need to contain the particles and prevent exposure to air (oxygen) is crucial. This is a known issue and can be controlled by proper procedures.
- Nanoparticles in the form of free-floating dust are a concern. Inhaling the substance can be an issue because the material could be toxic or could cause some unwanted internal reaction. This is one reason that breathing masks are strongly recommended for situations that could involve exposure to dust.
- Electrostatic properties of materials in dust can enable the nanomaterial to cling to garments and be transferred outside the containment area.
- Size can be segregated into three categories. Nanomaterials less than 8 nm are normally considered of minimal impact, because current thinking is that these particles pass through the biological system of a person with minimal interactions. Particles in the range of 8–20 nm are a greater concern because the nanomaterial has different properties from the bulk properties and has enough surface atoms exposed to be reactive. Over 20 nm, the nanomaterials may have an impact and this area is being addressed. Much of the needed information is still not available.
- Shape is a concern. As mentioned earlier, the straight shape of CNTs has been likened to the shape of asbestos. Because the needle-like shape of asbestos enhances its ability to penetrate into and accumulate in lungs, similar shapes have been considered dangerous. The one type of asbestos that is curved is not a capable of penetrating into lungs, but is still considered part of the asbestos family and classified as dangerous.
- Volume is a measure of the total amount involved and provides an estimate of the magnitude of the issue.
- Density of the material is important because some of the heavier elements tend to concentrate in certain parts of the body and may continue to accumulate over time.
- Concentration is important. There are levels of exposure where different materials become a concern. Some nanomaterials can be toxic to certain organisms at levels of a few parts per million or even lower.

The combination of all the factors listed above determines whether a hazard is present, but also impacts the degree of the hazard and how critical it is.

The public also needs to be aware that nanoparticles are created in nature. Forest fires and volcanic activity create nanoparticles. Even photochemical-based nucleation creates nanoparticles. Human activity creates nanoparticles. Welding can generate quantities of nanoparticles. Diesel exhaust, if untreated, creates nanoparticles. Even home gas cooking can create nanoparticles. Nanoparticles are the result of a variety of biological, chemical, and physical processes, some of which are commonplace.

The general public will have concerns if there are problems or issues with various materials. In some cases, there will be opposition to manufacturing that uses these materials in areas near populated neighborhoods. It is important to have adequate controls on all aspects of the application of nanotechnology and to ensure that workers are trained in the proper handling of these materials.

6.5 Risk Avoidance

There are always potential problems with any endeavor. The important objective is to proceed in a manner that will minimize the risks associated with a program or project. Risk is a combination of the probability of a harmful occurrence versus the severity of possible harm. Any large project has a risk analysis associated with it. Building a large building or a long bridge has the potential for a number of severely harmful or even deadly incidents. The goal is to minimize the incidents. The Golden Gate Bridge had a number of incidents that resulted in 11 workers dying. This number was considered low compared with other projects at that time. The "low" number was the result of extreme safety measures [7].

At present, there is insufficient data to create a classification of *all* nanomaterials that can guarantee there will be no hidden dangers or other surprises. The lack of information means that any risk assessment must proceed along the lines of identifying potential hazards and minimizing the risk. In many ways, this approach is similar to the training received by firefighting personnel. They are taught basic emergency analysis procedures and how to approach a situation in which the combustible material and other items are unknown.

The most efficient method of avoiding potential risk from nanomaterials is to control exposure to the materials. The first measure is to contain the process with controlled enclosures. This can range from a completely controlled facility to individual gloveboxes. Regardless of the method, there is a need to control ventilation, both local and general. The usage of high-efficiency particulate air (HEPA) filters to clean air before being returned to the workplace or exhausted is recommended. For particularly high exposure areas, supplied-air respirators or filtering respirators that are properly fitted for the individual must be employed.

Nanoparticles can cling to clothing. Consequently, protective equipment items such as clean room garments are a wise investment. In situations where fully protective garments are required, there will normally be an airlock that has forced air streams to loosen any adhering nanoparticles, which are swept into a HEPA filtering system. Garments require a specialized cleaning process to remove potential residues. For situations with less potential for exposure, more traditional chemical laboratory garments can be used.

In all cases, there must be controls to reduce potential ingestion of nanomaterials. This starts with strict usage of gloves while handling nanoparticles. A face mask prevents accidental hand to mouth touching. It is also important that workers understand the need for hand washing before eating and/or drinking.

With the concerns raised in the last few paragraphs, it becomes obvious that worker training is a necessity. There should be a series of documented training sessions, and testing to indicate an understanding of the necessary precautions. Many facilities are now capturing the baseline health of each worker as he/she starts employment in the nanomaterials sector.

Ideally, an organization has instruments that measure potential contaminants and keep an ongoing record of the results. One company that has an excellent control system found an abnormal reading in airborne particle count. Fortunately, they also had on ongoing baseline outside their facility. The incident turned out to be caused by a very high pollen count in the area. There should also be a defined process regarding who has access to the nanomaterial secure storage areas and the frequency and times of access.

With precautions taken to minimize the risks to people and the environment in the manufacture and usage of nanomaterials, decisions need to be taken on the application of nanomaterials. This is a much more difficult situation because application of nanoparticles can take many forms. Developing a gold nanoparticle that is attached to a virus (for capture by a cancer cell to kill the cancer) has a limited probability of large quantities of the nanoparticle getting into the environment. A more difficult application decision involves the use of quantum dots (semiconductor nanoparticles). Application of certain types of quantum dots can reduce the demand for generated electricity. View screens, televisions, monitors, etc. use a significant amount of energy because they are normally on continuously. These same screens manufactured with quantum dots for the viewing area can reduce the power required by more than 50%. The reduced demand results in a reduction in pollution created by the source of power generation. The potential problem is the release of quantum dots into the environment. They are initially harmless; however, over time they may separate into their constituent elements, which could be toxic.

In spite of all the preparations and all the evaluations, there will be insufficient information to make a completely informed decision. Consequently, it is necessary to provide a means of making the best decision with imperfect knowledge. This is why there needs to be a focus on and understanding of ethics.

6.6 Ethics

Working with emerging technologies means working with uncertainty. Making choices that may take years to develop issues requires the inclusion of ethical choices. This is not an area that one normally associates with emerging technologies. Ethics impacts every industry and nanomaterial applications, and use is not exempt. To understand the need for ethics, one needs to look no further than the recent Volkswagen scandal on “fudging” the emissions test results. Researchers at West Virginia University analyzed diesel emissions of vehicles from BMW and Volkswagen under a $50,000 grant from the International Council on Clean Transportation. The objective of the grant was to test the clean diesel cars outside a laboratory environment. Diesel emissions contain both carbon monoxide and NO_x, which have serious detrimental health effects. The approach employed by BMW and other manufacturers to reduce/eliminate the NOx is to add a selective catalytic reduction system, which involves injecting urea into the exhaust. The resultant reaction turns the NO_x into nitrogen and oxygen. This is effective but requires adding a storage tank for the urea, along with the associated parts required for the system to work. The Volkswagen development was based on research from Toyota in the mid-1990s that “periodically” used extra fuel to convert stored NO_x into nitrogen and oxygen. The extra fuel reduced the fuel efficiency of the vehicle. By fine-tuning the engine, they claimed they could meet emissions requirements and still deliver mileage and performance [8].

The tests of the Volkswagen clean diesel cars found discrepancies that were 15 to 35 times worse than the Volkswagen published data [9]. The other cars tested met the manufacturers’ published results. Eventually, this published data led to investigation by the California Air Resources Board (CARB). Both the CARB and the EPA raised the question of the large discrepancy directly with Volkswagen. The initial response by the company was that the differences were the result of a technical issue rather than deliberate falsification. When the EPA threatened that it would not approve the 2016 clean diesel cars for sale in the USA, Volkswagen admitted that they had inserted a device to provide low emissions at the engine conditions employed to certify meeting environmental regulations. However, to provide the performance advertised, the emissions increased during typical highway driving. This is currently an ongoing problem for Volkswagen, with numerous lawsuits by consumers and government regulators.

There are many more examples of problems caused by not having the background to consider the ethics of a situation. With nanotechnology and the development of manufactured nanomaterials, there are many more unknowns than with conventional technology, which implies that greater understanding and consideration are required in assessing the potential impact on individuals, society, and the environment. Consequently, ethics must be a part of any project concerned with advanced usage of nanotechnology.

Technology development tends to increase in speed and not move toward an equilibrium. Technology creates new concepts and new applications, and opens even more opportunities for new actions and new goals. Progress is always moving on and creating changes and challenges as it develops. There are many examples of changes in technology and associated challenges. Semiconductors started as a replacement for vacuum tube switches. This evolved into integrated circuits and then microprocessors (computers). The evolution of the cell phone into today’s “smart” phone is another example.

As mentioned in Section 6.2, ethics education is an important focus of overall education on nanotechnology development and application. All emergent technology exists beyond current understanding and consensus. Understanding the ethical implications should provide an understanding of the impact on the subsequent development of laws and regulations.

6.7 Government Pressure to Create Facts

When there is a concern raised by voters, elected officials like to respond to their concerns. Politicians are not normally scientists or technologists. They react to the concerns being expressed. One example of this occurred in 2006. There was concern in the city of Berkeley, California that research in nanotechnology could be dangerous and harmful to citizens of the city. The city council passed an ordinance that all materials employed in nanotechnology research must have a material safety data sheet (MSDS) listing the characteristics of the material being employed, including demonstrated potentially harmful effects. At the time this was passed, CNTs were a particularly active focus of research.

The issue that arose was the lack of MSDS information on CNTs. The researchers needed the materials, but the information was nonexistent. Research into the material properties was the reason for bringing the material into the area. This created an interesting loop. You cannot do research on the material because the material properties are not available. You cannot determine the material properties because you cannot bring the material into the research laboratories to test them. Obviously, no research would be done.

In many cases, it is acceptable and permissible to employ closely related materials and their properties to quantify the probable characteristics of the material under question. In the case described, and per my understanding, the MSDS for graphite was employed as a substitute for the nonexistent MSDS for CNTs. Both are forms of carbon and exist at relative small dimensions. This satisfied the regulatory requirement for a document in cases where an exact document does not exist.

In this case, the city council (government) required information that did not exist and would not permit experimentation to develop the data without having the data beforehand. Obviously, this was not possible. The government is trying to create facts that do not exist. The best you can hope for is a close approximation.

The characteristics of laws, regulation, and codes include (1) promoting minimal standards of conduct with the aim of ensuring safety; (2) providing lists of allowable and prohibited actions, with considerably more emphasis on the latter; and, (3) providing sanctioning and punishment for failure to meet the standards required [10].

The development of laws, regulations, and codes always follows the implementation of technology. Technology development is a high risk opportunity. There are many more failures than survivors, and the number of “winners” is a relatively small percentage of the total. Consider the relative life cycles of regulations and companies. The typical time needed to obtain approval for a drug ranges from 7 to 10 years. This includes phases of testing and evaluation. Some negative results are almost immediate. If that time scale is applied to testing the impact of a product going to market, and compared with the typical 18-month duration of a large number of startup companies, it is clear that the product is developed, out in the market, and the company out of business before their product has been fully evaluated.

Because nanotechnology has been in development and application for a number of years, there are web sites that can be used to review nanotechnology-related regulations and guidelines. The following sites are from the US government:

- National Nanotechnology Initiative (NNI): http://www.nano.gov
- Occupational Safety and Health Administration (OSHA): http://www.osha.gov/dsg/nanotechnology/nanotechnology.html
- National Institute for Occupational Safety and Health (NIOSH): http://www.cdc.gov/niosh/topics/nanotech/default.html
- National Institute of Environmental Health Sciences (NIEHS): http://z-prox.appspot.com/tools.niehs.nih.gov/wetp/public/hasl_get_blob.cfm?ID=9094
- Environmental Protection Agency (EPA): http://www.epa.gov/oppt/nano/
- EPA: http://www.epa.gov/pesticides/about/intheworks/nanotechnology.htm
- Food and Drug Administation (FDA): http://www.fda.gov/ScienceResearch/SpecialTopics/Nanotechnology/
- National Institutes of Health (NIH): http://www.nih.gov/research-training/nanotechnology-nih

6.8 There Is No Place for Politics or Opinions

Scientific efforts need to be based on fact and not on the approach that generates the most federally funded research dollars or the most supporting opinions on mass media, or even on a scientific theory that warns of impending crisis. When making decisions that have far-reaching effects, it is imperative to have all the facts.

The ubiquitous internet, with its various sources of information, provides the opportunity to select information that may not always be accurate. Edward Muzio provides an interesting example of the possible quality of information [11]. His commentary discusses a mathematical problem presented on a web post. The problem contained a series of mathematical operations on numbers and included parentheses. With an engineering background, he enjoys solving problems and then checking other answers. What stunned him when he completed the problem and reviewed other people's answers was that was one person stated: "The answer is either 50 or 56. It depends on how you do the problem." Mathematics is exact. There is no place for opinions. As Muzio stated: "To say that a mathematical equation is subject to a personal approach is to say that opinions are equivalent to facts. . . . It is simply not true. And being unable to differentiate your opinions from the factual reality in which they exist is, well, dangerous." This is true in mathematics and is true in science. We need accurate data and resultant facts. There is a current tendency to overlook that requirement.

In a newspaper commentary, Charles Krauthammer provided examples of accepted science that was later discarded or proven inaccurate [12]. One example is the federal government's 1980 warning of the bad effects of saturated fats. Public activists managed to persuade food companies to switch to trans-unsaturated fatty acids (trans fats). Now, the FDA has determined that trans fats are unsafe and has ordered them removed from food. A second example is the medical "standard" that the average human temperature is 98.6 °F. In 1992, three researchers carried out a study and found that the average temperature is 98.2 °F. In the time from the original effort to 1992, which was 114 years, what had changed? Equipment capability? Methodology? Sample population? There is no means to determine an answer.

In an excerpt from his novel *State of Fear*, Michael Crichton presents an interesting historical case [13]. "Imagine that there is a new scientific theory that warns of an impending crisis, and points to a way out. This theory quickly draws support from leading scientists, politicians, and celebrities around the world. Research is funded by distinguished philanthropies, and carried out at prestigious universities. The crisis is reported frequently in the media. The science is taught in college and high school classrooms."

This is not about global warming. Chrichton goes on to provide a list of the prominent people who supported the efforts a century ago. Major institutions performed research, and the efforts were supported by the National Academy of Science, the American Medical Association, and the National Research Council. "The research, legislation, and molding of public opinion surrounding the theory went on for almost half a century. Those opposing the theory were shouted down and called reactionary, blind to reality, or just plain ignorant."

The theory was eugenics, which postulated that a crisis in the gene pool was developing that was leading to deterioration of the human race. "The 'superior' human beings were not breeding as fast as the inferior ones, which included foreigners, immigrants, Jews, degenerates, the unfit, and the 'feeble minded.'" The human disaster that built through the 1920s and 1930s culminated in the concentration camps of World War II. After that, no one was or ever had been an Eugenicist.

What permitted the evolution of this "theory"? There was no rigorous definition of was meant by the terms. Worse is the fact that gene theory was barely understood. Without precise definition, people developed their own "definition." Furthering the cause was the absence of push-back from the scientific community. The effort of this eugenics theory was an enabler for additional research funding.

In early 2016, another method was employed to create scientific "fact." Senator Sheldon Whitehouse, in his 98th weekly US Senate speech, called for the government to employ the Racketeer Influenced and Corrupt Organizations (RICO) Act against organizations that are in disagreement with climate change theory [14]. In September 2015, 20 climate scientists sent a letter to President Obama and Attorney General Loretta Lynch suggesting that these officials investigate, using RICO laws, climate warming naysayers [15]. In effect, the climate scientists were asking the government to fine and/or jail other researchers who disagree with the climate scientists' positions. Unfortunately, the threat of government lawsuits creates an environment hostile to independent investigation.

In his conclusion, Crichton references Alston Chase's comment: "when the search for truth is confused with political advocacy, the pursuit of knowledge is reduced to the quest for power." What is needed is the development of knowledge that is disinterested and honest. That is the scientific method.

The scientific method is a methodology for examining phenomena, developing concepts (hypotheses), testing them, analyzing the results, and proving or modifying the hypothesis as required. This process could start with the simple question of whether a nanomaterial is toxic or not. (In this case, consider the potential impact of CNTs on lung tissue.) The next stage is information gathering and analysis. (Asbestos is dangerous and five of its six types are needle-shaped. CNTs are needle-shaped.) With this information, one can develop an initial hypothesis predicting the outcome. (The needle shape of CNTs is harmful to tissue found in human lungs.) Probably the most difficult step is to test the hypothesis through experimental procedures that others can duplicate and obtain similar results. (The first test might be something very simple to enable observation/measurement of the reaction of tissue to CNTs.) The next stage is to analyze the resultant data. Based on the analysis, conclusions about the accuracy of the hypothesis can be made.

At this point, changes in the hypothesis can be made and new experiments run. Finally, a comprehensive report is developed and submitted for publication in a peer-reviewed authoritative journal. Before being accepted, the submission is reviewed by three or four experts in the field. Recommendations from these experts provide guidance on the accuracy of the overall research, thoroughness of the work, and completeness of the submission. Publication of the work provides sufficient details for other researchers to duplicate the initial work and obtain similar results.

Peer review is an integral part of the process. The three or four experts review the submission for details of the research, the hypothesis, and the experimental means of testing the hypothesis. Completeness of the experimental details and the logic behind the conclusions from the findings are considered. The reviewers may recommend changes, modifications, and additional information before accepting the work for publication. They can also reject the work because of insufficient completeness of the submitted documents. Historically, this has been the value of going through the work to have papers published. Unfortunately, there are pressures that can compromise the peer review process [16].

With all the potential means of subverting the accepted scientific process, how is it possible to trust published data? The most reliable sources are still the respected publications. However, it has become necessary to evaluate the information more closely and observe any potential "strange" occurrences that are incorporated into the work.

6.9 Summary

The material presented in this chapter should leave the impression that the effort required to obtain accurate information about new developments in nanotechnology is challenging. There are many possible dimensions to the application of nanotechnology that we have only begun to explore. With the lack of exact information, it becomes necessary to prepare for working with materials that are not really understood. Consequently, it is the researchers' obligation to learn as much as possible about the material and its potential effects, and prepare for the possibility of surprising findings that require some type of preventative action. To be prepared, the focus should be on maintaining and sustaining an environment that is friendly to both people and the environment.

6.10 Questions for Contemplation

- Why is a broad classification that anything under 100nm is nanomaterials misleading?
- Provide some ways in which nanomaterials are totally different from their bulk materials.
- What precautions need to be taken in a laboratory environment?
- Describe some of the bulk material properties changes, if any, as size decreaes.
- Explain how and why Risk Avoidance applies to nanomatierlas.
- Where are the best sources of the latest information?

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7 What Is Considered Reliable Information?

7.1 Introduction

In this chapter, we address two complementary aspects of communicating information related to all things “nano.” The first of these is the general concept of reliable information and its compatible concept of objective evidence. The second aspect is the overuse and sometimes conflicting use of the modifier and short form or prefix “nano.” How these two complementary aspects of communicating information are employed can complicate the usability of information, especially when considering the use of available research and the impacts of nanotechnology on worker safety and health.

The expectation of information reliability, sometimes referred to as data integrity, is always impacted by the user’s (reader’s) expected level of rigor and requirement that the information/data is consistent with their purpose or intended end-use of the information. Possible negative impacts or losses attributable to unreliable information/data can be quite diverse, but can include human injury, environmental damage, reduction in public safety, work-activity/project failure, financial loss, and reputation loss. As the severity or likelihood of these negative impacts or losses increases, the expected level of rigor applied to the information/data increases to manage/mitigate the assessed risk associated with its intended use (within acceptable limits). In this context, the core attributes of reliable information are that the information is trustworthy and that the use of any information/results presented can be depended on to be readily available, consistent, and accurate (i.e., perform consistently under stated conditions).

The concept of objective evidence prevails across many disciplines (e.g., legal, business, scientific, engineering, quality control). In all these disciplines, the core attributes of objective evidence are that it refers to information (documented statement or record) based on facts, either quantitative or qualitative, that can be verified (proven) by an objective means (based on observation, analytical tools, measurements, tests, or other forms of research). By its very nature, objective evidence (even if completely unbiased) is information that is frequently open to discourse by those familiar with the field or topic (e.g., in peer-reviewed journals) because it can be examined and evaluated by someone other than the one who presented the information.

Throughout history, the concept of open discourse, or peer review, has been a crucial concept in the distribution and sharing of scientific and technical information and a key factor in establishing sources of reliable information. Enterprises now operate in a global landscape that is highly influenced by the internet and big data. This impacts

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the communication and usability of information. For example, the internet has been a boon to information/data publication and availability, but the quality and reliability of that information/data varies widely. Although many information sources found on the internet and elsewhere continue to utilize peer review and encourage open discourse, this practice can no longer can be assumed by the user of information, unless some form of objective evidence associated with the reliability of the information/data is made available. Similarly, not all information/data on the internet is kept up to date or remains available over time. In other words, information/data found on the internet is best characterized as "consumers beware."

Usage of the modifier and short form or prefix "nano" has evolved over time, changing from its original usage as a measurement modifier (i.e., denoting a factor of 10^{-9}) to its current common usage as an informal short form of nanotechnology, with several iterations between. When reviewing information about nano-safety or any other endeavor associated with nanotechnology, how certain can you be that the usage of "nano" or nanotechnology-related terms is comparable from one source to another? One way to look at this is the observation that David Owen [1] applied to the reproduction and communication of information: "Copying is the engine of civilization: culture is behavior duplicated. The oldest copier invented by people is language, by which an idea of yours becomes an idea of mine." We must consider whether the use of "nano" or other nanotechnology-related term constitutes a comparable idea or information whose language-usage may impact or affect the understanding of available research and its applicability. This is especially important when it comes to consideration of the impact of nanotechnology on worker safety and health.

7.2 Background on the Use of "nano"

As mentioned, the use of "nano" has evolved over time. In this section, we address some attributes to consider in interpreting the use of "nano" when determining information usage and reliability. Consistency of usage when nanotechnology and its short form "nano" first emerged was more linked to the concept of small (i.e.„ a factor of 10^{-9} compared with the original size of the item) than the attributes we associate with nanotechnology and its associated terminology today. Sometimes, in those early days, "nano" was employed as a buzz-word to grab attention when writing grant proposals or pursuing contracts. In some cases, that usage bore little or no relationship to the current standard usage of nanotechnology-related terminology, as documented in the International Electrotechnical Commission (IEC) and International Organization for Standardization (ISO) standards.

This was further complicated by liability issues that began to develop associated with "nano" materials, components, products, and processes. For example, at one time, only one insurance company in the USA would provide insurance for nanotechnology efforts. The significance of consistency of usage of "nano" began to drive a need for standard usage of the terminology associated with nanotechnology to support interpreting and litigating liability issues. Liability issues also drove the motivation to begin creating guidelines and regulations for the use and creation of "nano" materials, components, products, and processes. This also resulted in "nano" often being eliminated and "emerging tech" or something similar being incorporated into everything from proposals to technical papers. This reduced the motivation to use "nano" as a buzz-word to grab attention.

Prior to the emergence of nanotechnology standards, guidelines, and regulations, one of the most useful differentiations was that "nano" not only referred to size reduction but also incorporated phenomena intrinsic to the nanoscale that result in things like extraordinary mechanical properties and unique electrical properties that are a function of the nanoscale. In other words, nanotechnology is an enabling technology that impacts electronic and computing, materials and manufacturing, health, medicine, energy, transportation, etc.

An example of phenomena intrinsic to the nanoscale is the memristor, one of the fundamental passive components along with the resistor, capacitor, and inductor. The memristor, a contraction of "memory resistor" was first theorized by Leon Chua in 1971 and was long considered an esoteric curiosity because no one had managed to build one. However, in 2008, advances in research yielded the physical reality of this missing nonlinear two-terminal passive electrical component. The memristot was first produced by a team at Hewlett-Packard (HP) Labs and announced in *Nature* [2]. Presentations that year by R. Stanley Williams, a member of the HP team, emphasized that the enabling technology for this device is driven by scale. According to Williams [3]:

> It turns out that the influence of memristance obeys an inverse square law: memristance is a million times as important at the nanometer scale as it is at the micrometer scale, and it's essentially unobservable at the millimeter scale and larger. As we build smaller and smaller devices, memristance is becoming more noticeable and in some cases dominant. That's what accounts for all those strange results researchers have described. Memristance has been hidden in plain sight all along. But in spite of all the clues, our finding the memristor was completely serendipitous.

Currently, standards are being established and maintained, such as those by an ISO/TC229 and IEC/TC113 joint working group on terminology and nomenclature (JWG1). JWG1 is working on the creation and maintenance of standards to assist in the usage of terminology associated with nanotechnology, such as those in the 80004 joint ISO/IEC Vocabulary Series. For example, as of June 2017, some under development and maintenance are:

- ISO/TS 80004-1:2015 *Nanotechnologies – Vocabulary – Part 1: Core terms*
- ISO/TS 80004-2:2015 *Nanotechnologies – Vocabulary – Part 2: Nano-objects* (replaces ISO/TS 27687:2008)
- ISO/TS 80004-3:2010 *Nanotechnologies – Vocabulary – Part 3: Carbon nano-objects*

- ISO/TS 80004-4:2011 *Nanotechnologies – Vocabulary – Part 4: Nanostructured materials*
- ISO/TS 80004-5:2011 *Nanotechnologies – Vocabulary – Part 5: Nano/bio interface*
- ISO/TS 80004-6:2013 *Nanotechnologies – Vocabulary – Part 6: Nano-object characterization*
- ISO/TS 80004-7:2011 *Nanotechnologies – Vocabulary – Part 7: Diagnostics and therapeutics for healthcare*
- ISO/TS 80004-8:2013 *Nanotechnologies – Vocabulary – Part 8: Nanomanufacturing processes*
- ISO/TS 80004-9: 2017 *Nanotechnologies – Vocabulary – Part 9: Nano-enabled electrotechnical products and systems*
- ISO/TS 80004-10:yyyy Nanotechnologies – *Vocabulary– Part 10: Nano-enabled photonic components and systems* (under development)
- ISO/TS 80004-11:2017 Nanotechnologies – *Vocabulary– Part 11: Nanolayer, nanocoating, nanofilms and related terms*
- ISO/TS 80004-12:2016 *Nanotechnologies – Vocabulary– Part 12: Quantum phenomena in nanotechnologies*
- ISO/TS 80004-13:yyyy *Nanotechnologies – Vocabulary– Part 13: Graphene and other two-dimensional materials* (under development)

For example, ISO/TS 80004-9 includes definitions for “nano-enabled device,” “nano-ink,” “nanoscale device,” “luminescent nanomaterial,” etc.

These standards are supported by other ISO standards that support terminology and nomenclature development. Such standards will further the ability to communicate and evaluate information related to all things “nano.”

So what should you take away about the use of “nano” in terminology used for nanotechnologies and their applications?

- Ideally, a source includes a definition of “nano” terminology and its uses or cites a technical standard, guideline, or regulation defining the “nano” terminology they are using.
- Do not assume that all sources of information use the term “nano” or nanotechnology-related terms in a comparable way. Check the context of the use of the term “nano” within a source and then compare that context with the context used in other sources you plan to use.
- When publishing information, be sure to establish the context of your usage of “nano” or nanotechnology-related terms.

7.3 Information “Fact and Fiction” – the Dangers

Nano-safety, especially as it applies to products and to worker safety and health, requires consideration of many factors. These factors include knowledge of effects, understanding of particle behavior, toxic effects (depending on the application), residual impact on the environment, etc. To achieve nano-safety, the ability to communicate reliable information/data supported by objective evidence is essential. This communication is the foundation for developing alliances to investigate issues and provide direction for the solution to any existing or potential problems. Communication is supported by addressing known nano-safety issues in a systematic manner to ensure that root causes are identified and investigated in an effort to develop effective methodologies to manage or mitigate existing situations and prevent foreseeable potential nano-safety issues. The rest of this section describes some examples of implied dangers that have resulted when information “fact and fiction” impacted various situations, resulting in incidents or near misses being described as nanotechnology-related.

7.3.1 Questionable Correlations in Chinese Workers’ Deaths

One of the first widely reported “nano” incidents involved the death of Chinese workers. Reuters News Service reported on 19 August 2009 that seven women workers became ill and two later died from nanomaterials after working with epoxy containing nanoparticles [4a, 4b, 4c]. The facts turned out to very different, based on research work done in the UK by Ken Donaldson to find the real cause [5]. Chinese researchers reported that seven young Chinese women suffered permanent lung damage and two of them died after working for months using nanoparticles without proper protection in a paint factory.

The women who became sick were spraying a paste containing nanoparticles in a very small, unventilated room, and wore gauze masks only occasionally. In addition, the exhaust equipment was broken and had not been repaired for over six months. Autopsies on the two women who died indicated that their lungs were coated with a material that had a 30 nm particle in its center. A US government expert said that the study was more a demonstration of industrial hazards than any evidence that nanoparticles pose more of a risk than other chemicals [6]. The UK toxicologist indicated that the symptoms were more typical of chemical exposure [5]. However, the headlines had stated that the women died from nanomaterials.

7.3.2 Questionable Identification of “nano” Specific Dangers

A DuPont report published in 2004 indicated that medical testing demonstrated that nanoparticles of coal dust are harmful to human lungs [7]. This report only confirms what miners have known for years, which is that coal dust (any type) is extremely detrimental to health if it enters the lungs. The report did indicate that there was some evidence that the nanoscale variety might be more harmful. Because coal dust is known to be deadly, publishing a report that highlights “nano” contributes a small amount of information, but permits sensational headlines that make “nano” in general look dangerous.

7.3.3 Questionable Correlation of Carbon Nanotubes to Asbestos

A similarity in the shape of carbon nanotubes (CNTs) to asbestos has created a concern based on correlation. Asbestos is known to cause serious health problem. In fact, there are many lawyers advertising on broadcast media for people or relatives of people with mesothelioma, which keeps reminding people of the dangers of asbestos. The similarity between the needle-like physical shapes of asbestos and CNTs is a starting place for raising alarm about the dangers of CNTs. To further complicate the issue, The University of Florida published research in 2008 [8a, 8b] describing an experiment to evaluate the effect of CNTs on rat intestine. The experimental results indicated that there were lesions that had characteristic signs that were very similar to those seen in tests with asbestos (i.e., mesothelioma). The press picked up on these results and promoted the premise that CNTs cause similar health issues to those caused by asbestos. Unfortunately, two issues were not understood by reporters. The first is that the CNTs used were specially made to be ten times longer than typical manufactured CNTs. This extended length made the experimental CNTs roughly the same size as asbestos. The second fact is that the quantity (concentration) employed in the experiment was extremely high. Extreme doses do not represent typical situations and cause abnormal experimental results; therefore, the results are not universally transferable to other applications or useful for comparison analyses. Context matters, and understanding context is one driving factor for citing references when publishing or discussing research findings

For more clarity on the appreciation of the importance of “context matters,” think of it this way: People have died as a result of consuming too much drinking (potable) water. Potable water can be safely consumed in moderation. Is it proper to suggest that the general drinking of potable water is a universal health hazard just because consuming too much of it can lead to death?

7.3.4 Issues with Nanosilver Particles

Not all information available is necessarily slanted in a particular direction. A number of studies have raised some very serious questions about nanosilver. It is known that nanosilver particles in the range of 20–30 nm have the ability to inhibit bacterial infection [9]. As a result, nanosilver is effective in fighting bacterial infection and has been used in bandages. The issue is that the nanosilver does not decide that it will kill only “bad” bacteria; it will attack any bacteria. This becomes especially problematic if the nanosilver is not properly handled and enters the environment, where it can have a negative impact on some microorganisms. Some microorganisms have susceptibility to concentrations of parts per billion, at which point nanosilver causes a 50% fatality rate. However, some chronic toxicity studies on fruit flies exposed to the 50% toxicity levels showed that offspring were resistant to the previously determined 50% fatality level [10].

This case demonstrates the validity of presenting and documenting all variables, potential risks, and impacts that are associated with a particular material application to establish the reliability of the information for potential users of the information. It also demonstrates a fair and balanced approach to discussing (documenting) key information in support of establishing objective evidence on a particular set of findings.

7.3.5 Overgeneralization of Human Contact with Nanomaterials

Nano-titanium oxide has been in the headlines many times during the past ten years. There was a claim that the presence of nanoparticles of titanium oxide in sunscreen was dangerous and could cause significant harm [11a, 11b]. Although it is an overgeneralization, nanoparticles of titanium oxide are capable of causing significant damage. As a result of its widespread usage, nanoparticles of titanium oxide can enter the human body through the mouth, skin, respiratory track, or other ways. The issue is that these particles can enter the blood stream and settle in the liver, where they can cause inflammation. A significant amount of research that supports this conclusion is available from various industries and has been summarized by the National Institutes of Health [12]. This literature emphasizes that the issue is the accumulation of material when this form of titanium oxide is used over time or in high concentrations.

The fact is that heavy metals ingested/absorbed by humans tend to be retained by the body. This presents an interesting challenge. For example, some cancer treatments employ gold nanoparticles attached to cells that are designed to be attracted to cancer cells. This application has two important features. First, the gold nanomaterial can be seen with medical imaging equipment and, thus, identify the locations of cancerous cells. Second, when the gold nanomaterial is attached to the cancer cells, an infrared light source can be employed to heat the gold to a very high temperature, which kills the cancer. These gold nanoparticles do accumulate in the body as do the titanium oxide nanoparticles mentioned above.

The key question to consider is: What are the risks versus rewards for using a nanomaterial that is known to accumulate and be retained within the human body?

Normally, it is possible to read through many articles published by reputable organizations. The long-term sources of reliable information tend to be enterprises such as government organizations, standards/regulatory bodies, or other organizations whose funded long-term organizational mission includes supporting the generation and maintenance of information on nanotechnology-related research, applications, and impacts. When organizational or activity (e.g., research) funding dries up (e.g., loss of government grants), the internet sites once relied on for information become outdated quickly and possibly cease to exist.

7.3.6 Impacts of Litigation on Fact Finding and Misleading Correlations

There are often headlines in the news that such-and-such a company settled out of court by paying extremely large financial settlements for damages caused by their product. Paying these amounts does not prove guilt or even cause in these cases. Lawsuits require extra time by corporate management, including lawyers. It often gets to the point that it is less expensive in both time and money to “settle” and get on with their real business rather than fight the lawsuit. This is especially true in a jury trial where the “victim” appears to be a helpless, poor individual who was “victimized” by a ruthless company. The following example is from early 2016.

Johnson & Johnson were awarded a jury verdict requiring them to pay $73 million to the family of a woman who died of cancer, which was claimed to be caused by the material in the Johnson & Johnson talc-based Baby Powder [13a, 13b]. The jury found Johnson & Johnson liable for fraud, negligence, and conspiracy. The case has created concern regarding the safety of using talcum powder. Both Baby Powder and Shower to Shower products are made of talc. Talc is a mineral rock that contains magnesium, silicon, and oxygen, although some forms can contain asbestos [14a, 14b]. Everyone knows asbestos is a potential carcinogen. As pointed out in an article [15], both talc and asbestos are categorized as silicates, containing both silicon and oxygen. To further complicate the situation, pictures of talc and talc with asbestos (long needle-like filaments) are widely available. Talc with asbestos has the potential to be an issue. However, asbestos has been removed from all talc products since the 1970s. In addition, the victim was not sure which talc products she had used and even whether they were manufactured by Johnson & Johnson.

The caution that this incident brings is twofold. First, the jury award is not final and, even if it is settled without contest, there is no proof that the talc was responsible for the woman’s death from cancer. A number of reports in the available literature indicate there *might* be a link, although the probability is very low. Second, the rapid reporting of an announcement like this will stay on the web, regardless of the final outcome. This implies that, as more and more articles, blogs, etc. are developed, it will be harder and harder to find accurate information.

7.3.7 Sources with Conflicting Information

Even government sources may have opposing views. An example of this occurred in 2008 when two offices within the US Environmental Protection Agency (EPA) were providing different information [19]:

Manufacturers of nanoengineered products are getting frustrated by the uncertainties about the regulatory definitions of chemicals, materials, and products made with nanotechnologies. The US Environmental Protection Agency's Office of Pesticide Programs (OPP) has come out with its definition of a 'nanoscale material': 'an ingredient that contains particles that have been intentionally produced to have at least one dimension that measures between approximately 1 and 100 nanometers,' along with a new policy stating that an active or inert ingredient will be considered new if it is nanoscale. But the size-based focus of that definition is different from the one used by the EPA's Office of Pollution Prevention and Toxics (OPPT), which says size alone does not determine whether or not a chemical is new, and therefore subject to review under the Toxic Substances Control Act (TSCA).

This example demonstrates the need to review specifications and regulations constantly. Initially, the EPA established a limit on the concentration of nanosilver. The limits were based on mature fish survival. As of 2016, the EPA has since changed the limits to reflect survival of the more fragile embryos. In addition to the changing evaluation, results have been published [16] that demonstrate that the properties of the nanosilver changes over time. Furthermore, the flies that were subjected to testing and survived unharmed evolved to become immune to the effects of silver nanoparticles [17]. Although this seems unusual, one of the authors (Trybula) has seen similar effects with other nanomaterials [18].

7.3.8 Separating 'Fact and Fiction'

It is important to remember that there is no absolute source of totally reliable information. The vast number of possible nanoparticles (a low estimate is 10^{200} different particles) makes it impossible to provide an exact answer to every situation.

With the usage of "nano" or nanotechnology-related terms in applications covering an increasing spectrum of uses, it is necessary to evaluate the relevant and most current information from reliable sources. This challenge is addressed in the next section.

7.4 Validity and Availability of Information Sources

One constraint on this discussion of the validity and availability of information sources is the assumption that books, in print or electronic, are readily identifiable and sourced via an internet search. At the time of publication of this book, the tradition of sound peer and editorial review of books published by nonvanity publishers and the publishers' reputation in the publishing industry can still be used as an indicator of the reliability of the information they present. Therefore, this section approaches this topic from the broader perspective of information sources and how information is disseminated.

With enterprises now operating in a global landscape, what is the impact of using information sources that are highly influenced not only by their validity, but also by their availability via the internet? As discussed previously, information/data found on the internet is best characterized as “consumers beware.” It is up to the consumer of the information or data to apply critical thinking to objectively analyze and evaluate the source to form a judgement on the reliability of the information/data. On a positive note, more information is being made available over time by reputable institutions, professional societies, standards bodies, regulatory bodies, and government entities.

On a cautionary note, in addition to information reliability and integrity, not all information on the internet is appropriately maintained. The inherent cost of originating, reviewing, and maintaining information (including data) on the internet can result in sites that are shut down, or still exist but the information is no longer maintained or updated. This is one of the reasons why some internet sites and social media outlets supplement their income by accepting advertising or grant/agency funding to support continued operation. For example, the International Council on Nanotechnology (ICON), a group concerned with the risks and uses of nanotechnology, was highly respected as a source of reliable information and collaboration, but no longer exists. This is probably because the grant funding that supported ICON became unavailable. Similarly, the Center for Biological and Environmental Nanotechnology (CBEN), formerly a department at Rice University, has a webpage that is still running to provide resources to those who still need access to them; however, none of the listed programs are open for application. It is not predicable whether CBEN will ever become active again or whether the information on its website will ever be transferred to another host and maintenance of the information/data resumed.

For these reasons, we have selected the following sample of resources and publications from enterprises/organizations and entities that should have the necessary viable financial model to support the long-term creation, review, maintenance, and retention of reliable information/data in support of research and consideration of the impacts of nanotechnologies on worker safety and health.

7.4.1 Professional Societies: Resources and Publications

- American Chemical Society
  - American Chemical Society Chemical & Engineering News, *Nanofocus*, http://pubs.acs.org/cen/nanofocus/
  - *Nano Letters*, http://pubs.acs.org/journals/nalefd/index.html
- American Society of Mechanical Engineers

  - Nanotechnology Institute, https://www.asme.org/engineering-topics/nanotechnology?cm_re=Engineering%20Topics-_-Left%20Navigation-_-Nanotechnology
- American Vacuum Society
  - Nanometer Scale S&T Division, https://www.avs.org/Divisions/nstd
- Institute of Electrical and Electronics Engineers, Inc. (IEEE)
  - IEEE *Xplore* digital library, http://ieeexplore.ieee.org/Xplore/guesthome.jsp, Provides access to millions of documents including research articles, standards, transactions, eBooks, and conference publications including but not limited to:
    IEEE Journal of Biomedical and Health Informatics (https://www.ieee.org/membership-catalog/productdetail/showProductDetailPage.html?product=PER171-ELE)
    IEEE Life Sciences Letters (https://www.ieee.org/membership-catalog/productdetail/showProductDetailPage.html?product=ONL351
    IEEE Transactions on NanoBioscience (https://www.ieee.org/membership-catalog/productdetail/showProductDetailPage.html?product=PER191-ELE)
    IEEE Nanotechnology Express (https://www.ieee.org/membership-catalog/productdetail/showProductDetailPage.html?product=ONL350)
    IEEE Nanotechnology Magazine (https://www.ieee.org/membership-catalog/productdetail/showProductDetailPage.html?product=PER209-ELE)
    IEEE Transactions on Nanotechnology (https://www.ieee.org/membership-catalog/productdetail/showProductDetailPage.html?product=PER192-ELE)
    IEEE Pulse: A Magazine published by the IEEE Engineering in Medicine and Biology Society (https://www.ieee.org/membership-catalog/productdetail/showProductDetailPage.html?product=PER309-PRT)
    IEEE Journal of Translational Engineering in Health and Medicine (https://www.ieee.org/membership-catalog/productdetail/showProductDetailPage.html?product=ONL264)
  - IEEE Nanotechnology Council, http://sites.ieee.org/nanotech/
  - http://www.TryNano.org, Established as a resource for anyone interested in learning about Nanoscience and Nanotechnology.
- Materials Research Society
  - Nanotechnology Initiative, http://www.mrs.org/home/
- The Institute of Engineering and Technology (IET)
  - *The Journal of Engineering*, http://digital-library.theiet.org/content/journals/joe/, Publishing articles covering a broad spectrum of engineering subjects, including micro and nanotechnology
- The Institute of Physics
  - *Nanotechnology*, http://www.iop.org/EJ/journal/0957-4484

7.4.2 Government-Sponsored Publications and Resources

- http://us-eu.org/. Joint effort between the USA and Europe on environmental health and safety (EHS).
- http://ec.europa.eu/research/industrial_technologies/nano-in-healthcare_en.html. Nano in health care, sponsored by the European Commission.
- United Kingdom
  - http://www.hse.gov.uk/nanotechnology/. UK organization for “nano” effects.
  - http://www.safenano.org/. Established as a Centre of Excellence in Nanosafety in 2006 at the UK’s Institute of Occupational Medicine (IOM).
- US Department of Energy (DOE)
  - DOE N 456.1, *The Safe Handling of Unbound Engineered Nanoparticles* (canceled by DOE O 456.1), https://www.directives.doe.gov/directives/0456.1-CNotice/view.
  - DOE O 456.1 Admin Chg 1, *The Safe Handling of Unbound Engineered Nanoparticles*, https://www.directives.doe.gov/directives-documents/400-series/0456.1-BOrder-admchg1.
  - DOE P 456.1, *Secretarial Policy Statement on Nanoscale Safety*, https://www.directives.doe.gov/directives-documents/400-series/0456.1-APolicy.
  - *Approach to Nanomaterial ES&H*, DOE Nanoscale Science Research Centers, http://science.energy.gov/bes/research/national-nanotechnology-initiative/nanomaterials-es-and-h/.
- US National Institute for Occupational Safety and Health (NIOSH)
  - *Approaches to Safety Nanotechnology*, http://www.cdc.gov/niosh/docs/2009-125/.
- US National Nanotechnology Initiative, http://www.nano.gov/.
- US State of North Carolina
  - https://ncsu.edu/nano/health-safety/, *Requirement to Review Safety Information Prior to Use of Engineered Nanomaterial at NC State*. This worker safety and health North Carolina State website includes the six-step *Safety Orientation Checklist* that must be used by their researchers before using nanomaterials and a listing of other nano-safety documents and nano-safety websites. The incorporation of enterprise requirements for research on this website improves the probability that the site will be maintained.

7.4.3 Other Information Resources

- *The Journal of Nanoparticle Research*, Springer, http://link.springer.com/journal/11051

- https://www.cosmeticseurope.eu/safety-and-science-cosmetics-europe/products-and-ingredients/nanotechnology-.html, Cosmetics Europe – nanotechnology.
- http://www.nanoretox.eu/. Addresses potential risks to human health and the environment.
- http://nano-safety.org/. The Trybula Foundation's website addressing safety in nanotechnology.
- http://www.nanosafetycluster.eu/. European effort to improve cooperation.
- http://www.nhecd-fp7.eu/index.php?id=515. Creation of a critical and commented database on the health, safety and environmental impact of nanoparticles.
- http://www.qualitynano.eu/. European funded effort to provide quality in nanosafety testing.
- http://www.rmit.edu.au/about/our-education/academic-schools/health-and-biomedical-sciences/research/research-areas/medical-sciences/nanosafe-australia/. Australian toxicologists and risk assessors.
- http://www.who.int/occupational_health/topics/nanotechnologies/en/. World Health Organization guidelines.

7.5 Summary and Observations

The goals of the chapter are to present the general concept of reliable information and its compatible concept of objective evidence, and to address "nano" terminology. Although there are reliable sources of information, the pressures of budget continue to reduce and change the number of established, active resources and sources of information. The positive side is that there are many new sources maintained by enterprises (e.g., government sponsored efforts) and other entities. Unfortunately, nanotechnology is a dynamic field with constant changes, which results in many sites being slightly behind in information. In addition, many site purport to have scientific rigor, but in fact are merely "wishful thinking" by the authors. Success in obtaining the latest details requires investigative searches for new developments. Some of the established sources of reliable information (including internet sites) are provided in this chapter. These can be starting points, but further investigation is always beneficial and prudent in order to obtain the latest reliable information.

7.6 Questions for Contemplation

- Where are the standards for nanotechnolog and nano materials located?
- Describe the roles of Governmnet agencies in nanotechnology.
- What are sources of "Fake"information about technology?
- What can be done to maintain existing sources of nanotechnology information?

- How can one find the latest, accurate information?
- What steps need to be taken within an organziation to ensure accurate and most recent information is available?

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8 Ethics and Communication: The Essence of Human Behavior

8.1 Introduction

The increasing evolution of nanotechnology and its resulting insertion into all aspects of everyday life and into life-making decisions (e.g., cancer remediation) provides challenges for the technology practitioner. Making potentially life-altering decisions without being able to know the potential impact on people and the environment necessitates some type of guidance. With products being developed and promoted over a short development period, even though full testing and evaluations may take decades, there is a need for some guidance. Understanding and applying ethics to situations enable some rational form of decision making.

A good engineer or technician[1] wants to do the best for clients and employers. Each also wants to do well for other stakeholders. What does it mean to be a good engineer, to be a good nanotechnologist? Clearly, one of the first and most important considerations is technical knowledge and skill. But, is that enough? Is it sufficient to have well-honed skills and have the most up-to-date information?

Although knowledge and skill are necessary, they alone are not enough to make a good engineer or technician, any more than knowledge and skill alone are sufficient to make a good physician or a good musician. A person might use knowledge and skill in the service of evil, or more likely fail to be sufficiently aware of the various responsibilities and virtues that are characteristic of engineering practice. Being a good engineer also requires meeting the standards and expectations of the profession, as set by governments and professional organizations. Professional codes of conduct, beginning with the Hippocratic Oath [1], establish rules and ideals to govern the conduct of members of the profession. Additionally, being a good engineer or technician requires effective communication with many parties, and failures to communicate effectively have important safety and ethical implications. Furthermore, safety, ethics, and communication concerning nanotechnology are made even more complex by the amount of uncertainty surrounding cutting edge technologies.

In engineering and technology, as in the other professions, neither knowledge and skill, nor staying within the bounds of law and regulation are sufficient to make one a good practitioner. As demonstrated during the Nuremburg Trials [2], by the Tuskegee Experiments [3], by the Kansas City Hyatt Regency walkway collapse [4], by the Chal-

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[1] For the purposes of this chapter, we will use the term “technologist” to refer to those who work with nanotechnology, including developers, researchers, technicians, and producers.

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lenger explosion [5], by Rachel Carson's *Silent Spring* and the ill-effects of DTD [6], and many other cases, engineering and technology also have ethical and communicative dimensions that go beyond following law and regulation and the skillful application of up-to-date knowledge. Even routine interactions and applications involve ethical considerations, because every stakeholder encounter involves the technologists' ethical duties, such as benefiting the client or employer and minimizing harm, and each encounter requires effective communication. Similarly, every technological decision engages the values of those involved, including clients, employers, regulators, and members of impacted communities. Being aware of these values and factoring them into decision making reflects ethical sensitivity and skill. It is only by also attending to the ethical and communicative dimensions of technology that one becomes a good technologist. In other words, a good technologist is a good communicator who is also ethically aware [7].

What does it mean to be ethically aware and to be an effective communicator? More specifically, what does it mean to be ethically aware about nanotechnology, and how does ethical awareness inform research, development, production, distribution, and use? Fortunately, we have over 2,500 years of thinking about ethics and communication that can inform these questions. In this chapter, we will (a) explain more about why knowledge and skill are not enough; (b) examine the relevance of major ethical traditions to technology; and (c) consider some of the communicative responsibilities of technologists working with emerging technologies. Each of these considerations sheds light on some important aspects of technical practice [8]. It is important to remember that dealing well with questions of ethics or communication is not merely a matter of applying any one theory to a situation, but rather "[w]hat matters is that the appropriated concept illuminates issues and provides conceptual resources useful in resolving practical difficulties." [9]

8.2 The Challenge of Ethics for Emerging Technologies

One of the central characteristics of contemporary technological society is the ceaseless and intentional search for innovation. This is a fundamental change from earlier, pre-industrial periods of human history, in which the human attitude toward technology was largely either preservative (to continue existing techniques) or to treat technology as something other, magical, or divine [10]. Contemporary residents of technologically advanced societies understand technology as a human product, and systematically seek to change existing technologies and create new ones. The development of new technologies aims to provide new material objects, new forms of efficient action, and thus allows new forms of social organization [11]. New technologies present not only new means for completing existing tasks, but create new possibilities and thus new goals for human activity. This means that we have ever-new products, techniques, and goals, which consequently change individual lives, communities, nations, the international community, and nature itself. This also means that the presence of technology and constant change, intentionally sought, has come to be expected as the natural state of human existence, a taken-for-granted background condition. Additionally, new technologies have a power and a range of impacts – both spatially and temporally – greater than at any time in history, and also create situations of both great knowledge and great uncertainty [12].

Engineers, as architects of this new world, produce products and processes that impact the lives of all people in various, differential, and often unexpected ways. Engineers and scientists [13] thus have responsibilities beyond developing and utilizing technical skills and knowledge. Consider, for example, nanomaterials. The past decade has seen a rapid growth in the development and use of nanomaterials in everyday objects (cosmetics and socks) and specialized items (wind turbine blades and geological sensors). Without some clear and intentional attention to ethical concerns, engineers (similar to other professionals) and the institutions within which they work, tend to focus on efficient performance and minimizing cost [14], or might avoid exploring nanomaterials out of caution. Realizing the full potential of this new technology demands guidance beyond the technical.

One reason to attend to ethical and social concerns is to mitigate criticism and resistance, such as happened in the case of genetic research, genetic engineering, genetically modified foods, and reproductive technologies in Europe and the USA during the 1970s to 1990s [15]. Another reason is that engineers and technologists have special responsibilities because of the role they play in developing and deploying new technologies [16]. A further reason is that accreditation requirements mandate that students develop "an understanding of professional and ethical responsibility." [17] Additionally, as we shall review below, emerging technologies are researched, developed, and often deployed before there is any social consensus about the wisdom of those technologies. A final reason, and perhaps the most important one, is that engineers and technologists are more than that; they are also citizens, parents, children, neighbors, and so on. Therefore, students and practitioners have many interests beyond the technical aspects of their work, many values beyond just avoiding harm [18].

8.3 What Does It Take to Be a Good Professional?

No one wants to be bad at a chosen profession. Who would seek work as a department manager, a director, or an elected official, with the aim to do the job poorly? No one. Rather, we desire to be good at what we do – to be a good manager, a good leader, a good director. We all want to be good professionals, but taken further, it seems reasonable to claim that we also want to be good parents, good siblings, good partners, good friends, and so on. Therefore, although our focus in this article is on professional lives, the ideas discussed are more broadly applicable. As noted at a recent workshop at the National Academies of Engineering, ethics is foundational to being a good professional, to being a good engineer [19].

What does it take, then, to be a good professional? Part of the answer is obvious; it requires knowledge and skill. One of the distinguishing characteristics of professional roles is that they require specialized knowledge. Beyond specialized knowledge, professional roles necessitate the development of skill sets in order to translate knowledge into action. Often, these skill sets are also specialized. For instance, public managers might pursue professional education through a Certified Public Manager program or a Masters in Public Administration, whereas attorneys attend law school and then continuing legal education. The National Society of Professional Engineers maintains a list of licensing requirements for PEs in each of the 50 states [20]. Most states require continuing education to maintain PE status, with many requiring regular ethics training. Some skills are generalized and necessary in most professions, such as skill in prioritizing tasks, but a surgeon or chef needs skills in cutting that a manager of a public agency typically does not. Engineers are particularly adept at using heuristic-based methods of problem solving [21]. A good professional is knowledgeable, and can deploy that knowledge skillfully and appropriately. This last is particularly important. To use knowledge and skill appropriately is to use them in the manner of an ethically mature and responsible person.

There are certain qualities or skills that characterize an ethically mature and responsible person [22, 23], a person who works not only to avoid problems but also to promote improved well-being [24]. The following four qualities should be encouraged in technologists and engineers:

- *Ethical sensitivity*: Awareness of the ethical dimensions of a situation, action, or institution.
- *Ethical judgement*: Capacity to evaluate the relevant ethical and factual decisions, to consult relevant sources of guidance, and to reach a decision about the best course of action.
- *Ethical motivation*: Desire to follow the decided course of action.
- *Ethical character*: Self-discipline to follow the decided course of action.

8.4 Technical and Procedural Knowledge and Skill Are Necessary, but not Enough

Although technical and procedural knowledge and skills are necessary to be a good engineer or technologist, they are not enough [25]. Not only might knowledge and skill be inadequate to the task (as when an issue arises due to a new technology), but knowledge and skill can also be used for bad ends.

Knowing how to do something does not tell us whether it should be done. If we always do what is right, then we need no rules and no laws. However, as we all know, humans sometimes act badly, and thus human societies and organizations benefit from the guidance of rules and laws. As noted by the great twentieth century Spanish writer José Ortega y Gasset, "Law is born from despair of human nature." [26] In a democratic social order, it is likely that bad actions are more often the result of a lack of knowledge, bad habits, and/or inattention than of outright maliciousness.

There are many possible reasons for bad actions, and many contexts in which they can occur. The following list outlines three situations:

A Sometimes people use knowledge and skills for selfish reasons, for private gain for themselves or friends and family, and not for the good of clients, employers, or the community. Sometimes this prioritizing of self-interest can lead to bad actions.

B And/or, people may use knowledge and skill for improper or bad ends because of a lack of guidance.

C And/or, sometimes rules exist, but they are bad or unjust rules. They may be unjust in the context of a generally unjust regime (authoritarian regimes have laws and courts, and so on) or be unjust laws or regulations within a democratic society, as existed in the USA under the former Jim Crow laws.

Having rules is a typical response to "A" and "B." Rules can provide guidance and alert us to inappropriate selfishness in our own actions and in the actions of others. But, as we shall see in the next section, following the rules, even good ones, is not enough. As "C" points out, the rules may be wrong, and thus we need criteria for evaluating whether a rule is a good one or not.

8.5 Guidance from Rules Is Necessary, but Compliance Is not Enough

When faced with a question about what to do in a situation of uncertainty, individuals seek guidance, often in the form of rules. Rules take many forms. Some are formalized, such as the rules of chess. Others are formalized, but in practice have many variations, such as the rules of Monopoly. Yet others are formalized and have interpretation built into their application, such as the strike-zone in baseball. Many rules are informal, such as habits of applauding or not between movements of a classical music performance. Rules offer guidance about when and how to act, as well as when and how to make use of the knowledge and skills we have. The rules also tell us which knowledge and skills are relevant to the context in question. In this context, we are concerned with the rules that are relevant to work as a technologist. These rules are found in laws, regulations, and codes of ethics or conduct. Examples of the latter are professional codes, such as the *Code of Ethics* of the American Society for Public Administration, or institutional codes, such as the *Code of Conduct for EPA Staff* or the *Code of Conduct of the International Federation of Red Cross and Red Crescent Movement*. All of these (laws, regulations, codes) are types of rules. Codes of ethics sometimes have the standing of law (as in the case of state ethics codes for state employees). Additionally, laws are often justified by reference to the value or goods they promote or protect within a society [27].

Rules serve many purposes for the professional, [28] including the following:

- Informing clients, the public, other professionals, and practitioners of standards for behavior and decisions.
- Defining and promoting the image of a profession or institution, both internally and to the public.
- Providing support for practitioners.
- Serving as inspiration and guidance.
- Regulating behavior.
- Standardizing professional practice.
- Communicating expectations to professionals, clients, citizens, and government.

Law, regulation, and professional codes thus all provide some guidance to the safe and ethical development and use of new technologies. For technologies that are used in a variety of contexts by a variety of persons, “many of the ethical issues have already been identified by society.” [29] In such a situation, we find increasingly complex and useful guidance to action codified in laws and regulations that represent an emergent social wisdom. This wisdom is arrived at through deliberation, trial and error, failures and successes, and through political, economic, and value debates [30]. Codes of ethics also are updated in response to technological changes. Professionals and society depend on the guidance of law, regulation, and codes to deal responsibly with existing technologies. The agreed-upon wisdom and guidance found in these rules can help practitioners avoid or resolve ethical problems.

However, rules are not the same as ethics, and following rules is not the same as acting ethically (even if it is generally an ethically good thing to follow just and good rules). Rules tend to provide guidance in reaching minimal standards and in avoiding some wrong. However, to be an ethical professional requires more, it also includes working to create a flourishing and vibrant situation, which is more than merely avoiding wrong [31]. For example, suppose someone works in an election office. The rules help that person avoid doing explicit wrong by unlawfully excluding anyone and thereby decreasing the number of eligible and interested voters who participate. Ethics might also require that the person encourages more people to vote and promotes more active participation, because that is a good for a democracy. In this context, a fuller understanding of the ethical responsibilities of a professional points toward courses of action beyond avoiding violations of law. The following chart offers a brief comparison of rules, regulations, and codes with ethics.

A focus on rules, although necessary, can leave us with the idea that if we follow the rules we have done enough. This is sometimes referred to as an “ethic of technical compliance,” a term coined by University of Miami Law Professor William Widen in

Laws, Regulations, and Codes	**Ethics**
Minimal standards	Aim at maximizing good, rather than minimal standards
Cover a limited range of previously encountered cases	Provides tools for evaluating new cases
Breaking a law or regulation can lead to criminal or financial penalties	Can evaluate whether laws or regulations are just
Breaking codes can result in loss of a license or job	Ethical failings are judged by individual conscience or by the community
Rest upon ethical principles and values, but do not evaluate those principles and values	Discussion, questioning, and evaluating ethical assumptions in order to obtain better understanding

his 2003 examination of the Enron case [32]. The ethic of technical compliance takes two forms. First, it can be articulated in the idea that if a person follows the rules, then that is enough. Of course, the rules may not be comprehensive, may be outdated, or may fail in subtlety or complexity. Even if they are generally good rules, they are likely to direct us only toward avoiding a wrong, not toward achieving a good. Remember the example above; we are technically compliant with the rules of work as a voting official if we do not unlawfully exclude anyone. But, if we believe this is all that is required (i.e., avoiding a wrong), then we do not do anything to increase democratic participation. The second sense of the ethic of technical compliance is when someone follows a narrow and technically correct reading of the rules, but does not act beyond that narrow understanding. This is commonly found within large organizations, and is a long-recognized characteristic of bureaucracies. Returning to the above example, if a voting official recognizes that more could, and perhaps should, be done to facilitate participation but does nothing to make that happen because increased participation is not required by a narrow understanding of the job, or because the inertia of the organization is to continue what is already done and not rock the boat, then technical compliance occurs but the ethical good is missed.

Nanotechnology, like all new and emerging technologies, is creating possibilities and questions beyond established social consensus or ethical analysis. This places significant pressure on developers, researchers, and users to make thoughtful and morally responsible decisions. Faced with this sort of situation, where science and technology are operating at the limits of policy and ethics, an ethic of technical compliance is especially problematic. It is not possible to rely on existing guidance when none exists. Those who work with emerging technologies, such as nanotechnology, are among the most ethically important actors in contemporary society, holding both the possibility of great harm and the promise of barely imagined possibilities and benefits.

In his 1953 novel, *The Long Goodbye*, Raymond Chandler noted, “The law isn’t justice. It’s a very imperfect mechanism. If you press exactly the right buttons and are also lucky, justice may show up in the answer. A mechanism is all the law was ever intended to be." Although it is necessary to have rules to provide guidance, and to help us guard against selfish motives, following the rules is not enough.

8.6 Considering Ethical Frameworks

After these preliminary considerations about the importance and limitations of having good rules and laws for guidance, how should an ethically responsible technologist act? How is an ethically responsible engineer to know what is the right, or better, course of action? Remember the four qualities and skills that we identified earlier as characterizing ethically responsible professionals. Two of these are *ethical sensitivity*, being able to identify an ethical issue or ethically problematic situation, and *ethical judgment*, being able to evaluate a situation or issue and reach a reasonable and defensible determination about an ethically appropriate course of action. Ethical frameworks help us identify the ethically relevant aspects of a situation (ethical sensitivity) and guide deliberation and evaluation (ethical judgement). Consideration of ethical frameworks can also help us think about how we can be morally good people, about our moral character, and thus point us toward a third essential characteristic – ethical character.

In the next three sections of this chapter, we examine the three most influential ethical frameworks in contemporary considerations of professional ethics. These frameworks originated over 2,000 years ago, in ancient Greece, and continue to influence law, policy, regulation, and individual behavior. These three frameworks help us consider different aspects of ethical decisions and actions; the character of the individuals and organizations involved (virtue ethics), the quality of the reasons given and the processes used, the value of persons (deontology), and the importance of balancing risk and benefit in the outcome (utilitarianism).

8.6.1 Deontology and Kant: Autonomy and Respect for Persons

The ethical approach of deontology focuses on fulfilling one's duties or obligations. The most important thinker in the deontological tradition is the German philosopher Immanuel Kant. Kant's moral philosophy is central to research ethics, medical ethics (both in clinical practice and in research), and professional ethics more generally. Deontology is an ethical approach concerned with acting righty and for the right reasons, with recognizing and fulfilling one's moral duty, with acting according to good reasons, and with respecting persons. According to Kant, a good act is one that arises from a motive of duty and is rationally justifiable. When acting from duty, the agent is not concerned with personal desires, inclinations, or happiness, and therefore produces good actions that are neither influenced by external demands nor predicated on the outcomes they produce. Deontology focuses on the reasons or ethical motivations for action.

For Kant, the supreme principle of morality is what he calls the “categorical imperative,” which he distinguishes from hypothetical imperatives. These latter imperatives tell us what we need to do in order to achieve a particular goal. For instance, if you want to lower your cholesterol levels, then you need to eat healthier foods. Technical codes can function as hypothetical imperatives. They tell us what to do in order to achieve a certain desired goal – how to keep a boiler from exploding, or a bridge from failing. Unlike categorical imperatives, hypothetical ones are commanded as means to a particularly desired end. For Kant, moral imperatives must be independent of our desires or interests, therefore hypothetical commands might be instrumentally good but they are not moral because they are not done for their own sake. Much of what we do as members of large organizations, as members of work teams, as employees, or as consultants is similarly instrumentally good; it is good in a particular context with respect to particular goals.

According to Kant, what motivates one to act from duty is the internal logic of the proposed action or, in Kantian terms, the maxim. This is evident in the first formulation of Kant’s categorical imperative, “Act only on that maxim through which you can at the same time will that it should become a universal law.” Thus, good actions are those that a rational person could will as a universal law. In other words, the right action is one that follows an implicit rule that it would be rational to follow in every similar situation. Exceptions to the rule are then disallowed, because if everybody acted according to the exception, the rule would become inconsistent.

Kant’s most famous example of a violation of the categorical imperative is that of telling a lie. A good example can be found in the history of medicine. Consider that empirical data from the 1950s to 1960s documented that clinical practice commonly involved lying to patients. An article published in 1953 showed that 69% of physicians never told, or usually did not tell, their patients that they had cancer [33]; another study published in 1961 revealed that 90% of physicians did not tell patients they had cancer [34]. This is in keeping with the fact that, for much of the twentieth century, the predominant principles in medical ethics were paternalism and beneficence. Because professionals posses specialized knowledge and skills, any professional might face the temptation to lie to a client while believing it is in the client’s interest. But, is this so? Is it ever justifiable to lie in a professional context? The deontological framework can help us think about this matter.

Lying takes many forms but, at its essence, it is any communication that knowingly intends to deceive another. This includes what ethicists call lying by omission, through not saying something. Suppose an engineer knows of a possible risk, such as the possible risks of inhaling carbon nanotubes. If the engineer is in a situation where he or she believes the risks are low and that others are not capable of rationally evaluating risk, it might be tempting to avoid talking about the uncertainty that accompanies new technology. This can be especially true when a professional believes there is a benefit that justifies the risk, and fears that the client might not take the risk. In these cases, a professional might want to bring the best outcome for the client, even if it means not identifying or explaining the risks. Not communicating about risks with those who might be impacted is a form of lying, and one that is not ethically supportable. As we will see below, such lying also fails to respect other people and violates their right to make choices about their own lives.

To lie to a client violates the categorical imperative because a person of sound reason cannot wish this act to be a universal law. No reasonable person desires to lie always, or to be lied to always. This is true for Kant, not because of the problems it would create for the world if we all regularly lied; that would be a pragmatic influence on action. Rather, for Kant, lying is unacceptable because willing it to be a universal law would mean that everyone would be lying all the time. This creates a conflict with the very idea of truth-telling and lying, and makes each impossible. Because the maxim of lying creates a logical conflict in its formulation, a rational person cannot accept it as a universal law.

Key to Kant's idea of ethical motivation is the role of reasoning. The physician who lies to a patient might justify the lie by saying that it was the only way to get the patient to do what he needed to for his health. This provides incentive for a lie, but it should not be mistaken for a reason [35]. Neither should it be mistaken for a ethical motive. In Kant's formulation, a good act has a reason that can be universally justified and that motivates the rational person to act from duty and against personal inclination and desire when these lead away from rational and ethical action. Consider the part of the Software Engineering Code of Ethics that specifies that software engineers will "not knowingly use software that is obtained or retained either illegally or unethically." [36] This provision states a clear rule that allows no exceptions, and it specifies a proper course of action even if that action is not in the apparent best interest of an individual. Suppose you know that a coworker has access to a pirated piece of software or code that would help you complete a project, saving money and time. It might be tempting to use that code, but clearly not allowed by following the code of ethics.

Beyond the emphasis on identifying and adhering to rational rules, Kant's central contribution to professional ethics lies in his emphasis on individual autonomy and rights. His ethics is an ethics of respect for persons. People are rational agents and, as such, are never to be treated as mere means but always as ends in themselves. This is an idea well delineated in medical ethics, perhaps more so than in other areas of science and technology ethics. Respect for persons means that professional paternalism – making decisions for another – is unethical when faced with a person capable of making decisions about her or his life or goals. This idea is firmly established in clinical and research bioethics, in the prioritization of autonomy, and in practices of obtaining informed consent. It should also be central to all professional ethics, including the practice of engineering [37]. Obtaining informed consent is a way to ensure that people are treated as ends and that the proposed action (i.e., treatment, diagnostic procedure, enrolling as a research subject, how a new bridge will impact a community, whether a new nanomaterial should be used for cookware or clothing, and so on) is compatible with an end the patient or client has set. This is the case even when the goals and values of the patient or client are not those of the professional(s) or even of the majority of patients or clients [38].

This was not always the case, as the above-cited evidence concerning lying to patients shows. Beginning with the Nuremburg Code [39] and continuing through the World Medical Association Declaration of Helsinki [40], respect for patient autonomy has been established as a one of the key principles in bioethics [41], and clinical practice reflects this change in patients' status. One marker of this change is data concerning whether or not patients are told that they have cancer. Unlike the customary practice two decades earlier, a study published in 1979 showed that 97% of physicians reported routine disclosure of such diagnoses [42]. This finding reflects advances in several areas, such as the ability of clinicians to provide better care to patients with cancer. It also represents an increased recognition of the need for doctors to respect the values of their patients by providing them with the necessary information to make good decisions, as well as the increased dialogue between doctors and philosophers that began in 1970 [43]. It is also a step away from the unjustified paternalism of the past, which continues to characterize the practices of many professions and professionals.

Of course, respecting the autonomy of clients should not be understood as simply giving information and then letting the clients fend for themselves. On the contrary, it requires that professionals foster autonomous decision making by disclosing information about clients' conditions and goals in appropriate ways, about reasonable alternatives for managing or achieving them, and about the benefits and risks of these alternatives. Further, clients should be free to select among these alternatives, and they should not be substantially controlled in either their process of decision making or in their final decision [44]. Moreover, professionals also enhance autonomous decision making by being aware of, and respecting, the values and desires of their individual clients as well as by helping clients to overcome their sense of dependence.

8.6.2 The Pursuit of Happiness: Utilitarian Ethics

Attending to the goals that a client has set considers individual preference and desire, and in some ways is consistent with some aspects of utilitarian theories of ethics that demand that the agent act in ways that maximize the good. Contrary to deontological theories, however, utilitarianism requires that in evaluating the rightness or wrongness of an action or practice we look at its consequences rather than at the ethical motives or ethical character of the agent.

The most influential formulation of utilitarianism is found in the works of nineteenth century British philosophers Jeremy Bentham and John Stuart Mill. Although their theories are not exactly alike, both agreed that the purpose of morality was to promote human welfare. The basic principle of utilitarianism is what Mill called the "principle of utility." According to this principle, actions are right when they maximize pleasure and minimize pain [45]. The individual agent who is weighing two possible actions to decide which course to pursue must ask which act will produce the most happiness or pleasure. For example, weighing the benefits and risks is one way that an individual might go about deciding whether to consent to a medical procedure.

Utilitarian theorists understand the desirable outcome as the situation that produces the maximal balance of happiness over unhappiness. This means balancing costs and benefits for all affected, and seeking to increase pleasure or happiness and minimize suffering for the greatest number. Contemporary Utilitarians call our attention to the often neglected portion of the process – relieving or avoiding suffering, especially unnecessary suffering [46]. They argue that one of the most important of human interests is avoiding pain.

Importantly, utilitarianism is not a defense of crude self-interest. The point is not to maximize one's own happiness at the expense of other people's happiness, but to give equal and impartial consideration to the interests of all affected parties. Thus, when making decisions about how to proceed, one must not allow one's own happiness to weigh more heavily that the happiness of others. Similarly, when evaluating the consequences of a particular course of action, both indirect and long-term consequences, and not just direct and short-term outcomes, must be taken into account. Utilitarianism is, thus, a form of cost–benefit analysis, and requires a type of reasoning familiar to most people in technologically advanced societies.

Utilitarian ethics is often employed in considerations of the allocation of resources, such as in determinations of healthcare policy. Cost–benefit analyses of resource allocation are an example. This follows the goal of the original utilitarian thinkers – to develop a social ethic. Clinicians take up the utilitarian focus on outcome and apply it to the individual patient and family. In this way, clinical ethics sets a goal of maximizing happiness for individuals, who must define happiness in their own terms and are expected to consent to or decline interventions based on that definition.

Utilitarianism is also used every day in engineering and technology. Utilitarianism is present every time a cost–benefit analysis is performed. Utilitarianism is a powerful and important ethical perspective. However, the goal of maximizing happiness presents some problems.

One problem with attempts to maximize happiness is that when confronted with a new situation, or one that is especially puzzling, people can be at a loss. Utilitarianism recognizes this, and proposes that the way out is to consult those persons with appropriate knowledge and experience to serve as guides to ethical judgement. Thus, in medicine, ethics consultations can help patients and physicians understand and evaluate the various choices they face. Unlike the Kantian approach, which aims for a universally correct answer, this approach aims to provide the best answer we can have at the time of the decision.

In a professional setting, the combination of Kantian ethics, with its focus on the autonomous individual, and utilitarian ethics, in which the right action is the one that maximizes happiness and minimizes suffering, illustrates how appropriating concepts from more than one theoretical approach can help address clinical situations. Professionals should respect clients' decisions, and those decisions are often guided by subjective evaluations of happiness and suffering. We might also consider the convergence of the two approaches around the matter of confidentiality of personal information. The deontological approach would value clients having control over their life and goals, including information about their lives, and thus respect for persons requires confidentiality. The utilitarian approach would argue that clients are more likely to seek advice and services, thus maximizing a good, if they can expect confidentiality [47]. Thus, both views argue that we should respect the privacy and confidentiality of clients, but point out different reasons for doing so.

8.6.3 Virtue: Character and Practice

Virtue ethics is sometimes characterized as more descriptive of professional practice and as having more in common with the practice of an ethical professional provider than deontology or utilitarianism [48]. Virtues are aspects of the character of a person put into practice. For instance, loyalty, fidelity, compassion, and benevolence are some of the virtues associated with health care practitioners. Importantly, however, virtues are both these inner states and modes of acting and can only be cultivated and realized in practice through nurturing virtuous relations with other persons. We can learn and develop virtues as we learn to play a musical instrument, or play a sport, or cook, or fly a plane; we need understanding and practice. Thus, the virtues of good technologists are not only their inner values, but also their relations with clients, employers, families, communities, and other practitioners.

Contrary to deontological and utilitarian theories that focus on evaluating moral actions, virtue ethics focuses on the ethical character of the agents who perform the actions. The point is not simply to determine what action to perform, but what kind of person to be, how to become a virtuous person.

Some virtues are necessary for moral action in general; others are special responsibilities for some, such as those in a profession [49]. For example, everyone with enough understanding of the world to appreciate its dangers can recognize that some degree of courage is required to do almost anything. Courage is needed by those who travel (to fly in an airplane or ride on a bus), by patients (to submit to medical tests or surgery), by physicians (to treat patients with communicable diseases), and by engineers who develop and produce new ways of doing things. We certainly want professionals, like everyone else, to be courageous people. Yet, without some special justification, there is no reason to count courage as a special feature of professionalism. Yet, the duty to consider the public good can demand that courage require more of technologists than of others. Alternatively, although sympathy is a virtue for all, it is especially applicable to physicians, whereas the virtue of prudence (thoughtfulness and avoidance of unnecessary risks) might be especially important for engineers [50].

Virtue ethics began with Aristotle [51]. One of the best contemporary accounts of how the virtues can work in modern society is that of Alasdair MacIntyre, who describes the virtues as socially embedded and as developed in relation to a practice that has a social history and goods internal to it [52]. He defines a practice as "… any coherent and complex form of socially established cooperative human activity through which goods internal to that form of activity are realized." [53] In the performance of these functions, activities, and attitudes one tries to achieve those standards of excellence that are appropriate to that form of activity.

When we apply MacIntyre's concept of practice to engineering, we can define engineering as the total set of skills and attitudes that are applied in the context of a particular goal or project, with the intention of providing good services or products (the goal) to another (person, community, organization). Noteworthy in this definition is the goal-oriented character of engineering practice. Whatever engineers do, for the ethically responsible engineer it must always be related to the final goal. The goal of technology is the improvement of human life, and thus implies care for persons and communities. Virtue theory understands good care in the broad meaning of the word, that is, focused on the physical as well as the psychological, relational, social, and moral.

Importantly relevant to the practice of engineering are the notion of internal goods and the focus on the social and historical nature of practice. Goods are internal to a practice in two senses: (1) the goods can only be described in terms of the practice, and (2) they can only be acquired and recognized by engaging in the practice and having the associated experiences.

Unlike Kantian duty, internal goods cannot be abstracted from the particular experience and made into external rules. In the example of lying to a client, the Kantian analysis requires that professionals disengage from their experience and form a rule abstracted from the particular experience that can be applied in all situations that involve lying. In contrast to this, a description of the technologist's experience in a similar situation with a particular client exposes the values that are at stake.

Moreover, in virtue ethics, acts are best understood not in relation to abstract implicit principles of action, but as a socially embedded activity that takes on a narrative form with a past, present, and future. In committing to working with and developing technology, the technologist's decisions and actions are understood as part of a narrative history, a story. Action becomes intelligible only within a story in which "[w]e place the agent's intentions … in causal and temporal order with reference to their role in his or her history." [54] Just as is the case for technologists, the decisions and actions of clients, consumers, and other stakeholders can be understood as part of a narrative, and are thus only intelligible by reference to this history [55]. Rights and individualist notions of autonomy are not sufficient to sustain a caring and empathetic practice [56]. Furthermore, attention to the stakeholder's narrative history in its full context can help us better realize Kantian values such as autonomy [57].

Because understanding and committing to the goods internal to the practice of making, developing, and using technology requires one to take up the practice and engage with others who are involved in the practice and to contemplate the historical basis of current practice, practitioner's ethical character should be nurtured in order that they become virtuous technologists who are inclined to act as they should [58]. Cultivating relational virtues such as openness and responsiveness allows the technologist to realize the goods internal to the caring practice of science and technology, which include attending to and prioritizing the needs of the stakeholder as those needs become apparent [59].

Related to the consideration of narrative is the challenge of engineering practice in a situation of cultural and value diversity. Culturally based values and views have important implications for human well being and professional practice in terms of how professionals, clients, consumers, and other stakeholders think and behave, and in terms of what they expect [60]. We know that in engineering and technology there are important differences in culturally based values and views between clients and customers and the technologists from whom they seek assistance or expertise [61]. How technology professionals think about and approach these issues has very real consequences for customers, clients, and communities because, if cultural differences are ignored or poorly addressed, they can result in conflict, decreased satisfaction, and problems with analysis, development, distribution and compliance, and even contribute to social inequalities [62]. We have also the example from architecture of how the design and construction of buildings helped shape the war in Syria [63]. We can do better. Evidence indicates that approaching cultural differences with sensitivity and skill can lead to better understanding [64] and better outcomes [65].

The goal of scientific and technological development is helping people and making the world better in some respect [66], but what that means is not always immediately evident. Consider an example from medicine. Suppose a patient refuses recommended care, be it evaluation or treatment [67]. Such cases bring into focus the complex relationship between respecting autonomy and fulfilling one's duty to advance the health of the patient. A physician might think treatment is the best course of action, and would select it, whereas the patient might refuse for reasons, such as religious belief, that the physician does not share. In approaching these decisions, it is necessary to be attentive to the specific beliefs and cultural backgrounds of patients [68].

Some authors have proposed "cultural humility" as an essential quality of scientists and technologists practicing in a multicultural world [69]. Cultural humility begins with self-awareness, self-reflection, and self-critique. It requires an open and respectful attitude toward diversity, and it recognizes the legitimacy of alternative ways of thinking and being. Cultural humility involves a willingness to learn about the unique perspectives of individual clients, consumers, and partners and the communities they come from; it also allows for the possibility that technicians themselves might grow and change as a result of appreciating others in this way. This means that engineers and other technicians can develop ethical sensitivity by cultivating a deep respect for others as partners in complex, dynamic relationships [70].

8.7 Communication and Ethics

Good engineering and technical practice requires good communication. In fact, good communication is not separable from good ethics. Ethical values are transmitted through explicit and implicit communication, and clear communication respects many ethical norms, including valuing truth-telling and respect for the listener. Ethical values may be explicitly and clearly communicated, what scholars call "espoused values." Alternatively, they may be implicit and communicated through practices, actions, habits, policies, and so on [72].

One unavoidable characteristic of working with emerging technologies is the experimental nature of the work. We often have some level of uncertainty about materials, outcomes, uses, likely benefits, and possible risks [72]. For these reasons, the development and deployment of technologies, especially new technologies, can usefully be thought of as an experimental process. Thinking about engineering and technical work in this way highlights some of the ways that ethical values and communication intersect.

Engineering introduces new products and processes that change – sometimes slightly and sometimes quite significantly – individual lives, patterns of life and work, ways of interacting (Facebook and online dating, for instance), economies and political institutions, and the natural world. This is done in situations of significant uncertainty about process and outcomes, and typically without much feedback (except through market mechanisms) from people whose lives will be changed.

Engineers should seek to provide good, clear, and full information about new processes and products and strive to bring affected parties into the conversation as early as possible. This requires managerial buy-in and, in some instances, placing ethical obligations over proprietary interests. Thus, engineers have great responsibility to stay broadly informed about the history of engineering and similar projects, about current contexts and the implications of their work, and about public feedback. The obligation to provide information places a *positive duty*, a duty not only to avoid harm or error, but also to take action to promote an ethically good outcome. In this case, the positive duty on engineers is to communicate actively about their work, beyond packaging inserts, user manuals, or product labels.

Espoused values can be defined as "the values a person or organization expresses or publishes in some manner" [73]. The espoused values of an organization are often articulated in various documents, goal and value statements, and policies. One of the best places to look for the explicit espoused values of any organization is the mission or goal statement. Development and dissemination of these documents is a standard and widespread practice, so much so that the work that these texts perform is at risk of being overlooked. These statements serve multiple functions. They can be used to motive and inspire, as in Patagonia's mission statement, "Build the best product, cause no unnecessary harm, use business to inspire and implement solutions to the environmental crisis." They can also telegraph expectations and provide cues regarding current/future desired behavior, as in Google's post-2015 statement that the organization's mission is to "organize the world's information and make it universally accessible and useful." Interestingly, this statement was a significant revision from the values espoused in Google's pre-2015 motto "don't be evil."

Organizations espouse values in documents other than mission or goal statements. Ethics statements and codes of conduct are also important instances of written articulations of the ethical expectations and values of an organization and provide guidance for its members/employees [74]. Although over 75% of US-based businesses now have codes of conduct/ethics [75], they are a relatively recent phenomenon, with most being written since 1970 [76]. These statements speak simultaneously to internal and external audiences. Internal to the organization, they play both instrumental and constitutive roles by articulating the ethical values and norms expected for individuals and for the organization. Externally, they help those who might interact with the organization to know what sorts of behavior it is reasonable to expect. Ethics statements also serve a publicity function and a legitimating function insofar as they communicate the ethical aspirations and values of an organization [77]. Some scholars view codes of conduct/ethics cynically, arguing that these statements primarily serve to coerce and/or control organizational members while enhancing and/or protecting the organization's external status [78].

Ethical values are communicated in what an organization or individual says and in what an organization does. Values are enacted and communicated through actions taken. These actions might be consistent with expressed values, as when Staples worked with HP to reduce e-waste from all sources, in keeping with their increased corporate emphasis on sustainability. Another example is the recognition of Marriott in 2016, for the tenth straight year, as one of the world's most ethical companies by The Ethisphere Institute in keeping with it's claim that "How we do business is as important as the business we do" [79]. Conversely, actions might not be consistent with espoused claims, as when the 2010 explosion of BP's Deep Water Horizon oil drilling platform and subsequent oil spill in the Gulf of Mexico stood in stark contradiction to BP's explicit goal of being an innovative and environmentally friendly energy company [80].

The actions taken have both material and symbolic impact. The material impact of the action can support or contradict the relevant explicit value. The action taken communicates either that the organization or person is a consistent actor or that, in reality, the person or organization follows a quite different value from that stated. Some argue that the values implicit in the actions taken are the actual values, and the explicit but not enacted values are thus articulations of self-deception or bad faith [81]. According to this view, whatever an organization or individual does, the impact of its actions should be the focus of analysis for identifying the values of the organization.

Ethical values are also enacted and communicated in practice. A practice is comprised of shared understandings, rules, and acceptable ends that are inherently tied to context, such that all factors are mutually defined through the relationships [82]. Put differently, ethical values may emerge in a dynamic performance of saying and doing [83]. For example, there are 759 full members of the Association for the Advancement of Sustainability in Higher Education (AASHE). One of the strategies advocated for reducing energy consumption and the carbon footprint on residential campuses was to supply drying racks in residence halls. Doing so is a practice likely to be consistent with espoused sustainability goals at member colleges and universities. However, none of those factors (values statements, membership in a relevant organization, and material practices), singly or together, can ensure that students use the drying racks. For humans to act in a particular way, especially if those actions run counter to existing norms of behavior or demand more emotional, psychological, mental, or moral effort than other options, requires either a particular individual character or an organizational culture that supports the action in question. As we know, at least since Aristotle, the actions of individuals and the character of the culture they comprise are inextricable intertwined.

Finally, talking about ethics – about values, expectations, and behaviors – encourages ethical sensitivity and helps develop ethical skills. Considerable research suggests that courses in ethics help raise awareness of ethical issues and encourage more responsible and critical thinking, and better action [84].

Two of the great challenges of emerging technologies are (i) creating organizations, workplaces, corporations, professional societies, agencies, and schools that encourage clear and timely communication and high ethical standards; and(ii) nurturing and supporting individual practitioners who work according to good principles of ethics and communication.

8.8 Final Remarks

Ethical theories provide a framework to help us determine what is right and wrong, good and bad. They provide a set of standards that allows us to evaluate particular actions or the characters of people. Although the theories presented here are competing ethical theories, and although a critical evaluation of their tenets can bring to the forefront some serious concerns about each theory, they can be helpful in guiding professional practice. As mentioned earlier, the usefulness and importance of these approaches is not predicated on a simpleminded adherence to any one theory in a professional situation. However, together with awareness of the principles of good communication practices, ethical theories can help us reflect on what is important and valuable [85], communicate with others [86], and think about how best to achieve the ends of science and technology.

8.9 Questions for Contemplation

- Define “ethical sensitivity.” Why is it important? Give an example of when ethical sensitivity is important in the development, manufacture, or use of new technologies.
- Define “ethical motivation.” Why is it important? Give an example of when ethical motivation is important in the development, manufacture, or use of new technologies.
- Define “ethical judgment.” Why is it important? Give an example of when ethical judgment is important in the development, manufacture, or use of new technologies.
- Define “ethical character.” Why is it important? Give an example of when ethical character is important in the development, manufacture, or use of new technologies.
- What are “espoused values?” How are they important to ethical communication?
- What does it mean to say “goods are internal to a practice?” Give an example from technology or engineering.
- Which ethical framework is most concerned with maximizing outcomes, or consequences?
- Which ethical framework is most concerned with ethical character?
- Which ethical framework is best for evaluating ethical motivation?
- Why are technical knowledge and skill alone insufficient to be an ethically responsible technologist?
- Explain why new technologies create new ethical concerns and challenges.

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9 Behavior-Based Worker Safety for Engineered Nanomaterials

9.1 Introduction

Engineered nanomaterials, including dry powders, composites or adhered films, and particle suspensions in solvents, offer unique advantages when incorporated into products [1]. The manufacture of these novel products uses techniques such as lithography and printing, milling and grinding, epitaxy, self-assembly, and sol–gel [2]. The term “nanopowder” is used to describe engineered particles that are nanometers in length. By convention, synthesized, produced, and manufactured nanopowders are defined as having at least one dimension less than 100 nm. Some of the unique advantages of so-called “nanoenabled” products are that the materials are stronger, lighter, more durable, more reactive, more sieve-like, or better electrical conductors than the bulk material (National Nanotechnology Institute, http://www.nano.gov/you/nanotechnology-benefits). However, the attractive benefits of nanomaterials are also associated with some significant risks to occupational workers involved in various stages of the nanoenabled product life or life cycle [3, 4].

When handling dry powders, distinct safety protocols must be followed because the material has increased surface-to-volume ratio and increased surface reactivity. For example, powder explosions are common and often result in serious injury and loss of life [5]. Exposure to airborne particles has been shown to induce adverse effects within humans. Pulmonary (i.e., lung) effects are especially worrisome if particles are inhaled chronically [6]. Exposure to composites, adhered films, and particle suspensions are generally regarded as less risky occupational exposures, but dermal effects have been reported after close contact with these types of nanosystems [7–10].

The extent of toxicological effects is not fully understood for each of the engineered nanomaterials being studied today [11, 12]. To complicate matters further, the resulting adverse pathology is sometimes not observed immediately. Because of this, illnesses may develop years after the initial exposure, making it very difficult to determine a cause–effect relationship between exposure and onset of disease. This chapter proposes some guidelines for the safe handling of engineered nanomaterials and nanoenabled products. These guidelines can help prevent exposure and development of exposure-related illnesses in an occupational setting. With increased mindfulness of the risks associated with dry powders, composites, adhered films, and particle suspensions in solvents, improved behavior-based worker safety for engineered nanomaterials can be achieved.

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9.2 Traditional Behavior-Based Worker Safety

Nanotechnology embodies the application of science and behavior to real world problems, because both research and development are needed to successfully launch a product or process enabled by nanomaterials [13]. However, the risks to workers associated with the development of these technologies must be met with adequate and evolving safety measures and regulations [3]. One of these safety regulations is a program known as "behavior-based safety" (BBS). BBS is conventionally defined as "the process that creates a safety partnership between management and employees that continually focuses people's attentions and actions on their daily safety behavior" [14]. This definition applies to the nanotechnology industry, in that communication between workers at research and development facilities, as well as comprehensive understanding of the technology, are crucial for safety in the workplace.

Developing a behavior plan should be inclusive of company culture, the past experiences of employees, and the physiological state of workers. In nanoscience research, it is evitable that workers are exposed to engineered nanomaterials such as aerosols or suspensions. Therefore, companies should provide adequate personal protective equipment (PPE) and engineering controls to mitigate exposure and decrease health risks. Furthermore, nanoparticles have been found to exacerbate the condition of an already unhealthy individual [15]. If a person has chronic lung disease, such as chronic obstructive pulmonary disease (COPD), then inhalation of nanoparticles could inhibit the healing process by increasing inflammation and defensive immune responses [16].

The best practices in worker safety follow a prescribed path that is accepted or adapted by most industries working in material science and engineering [17]. The following six tasks are completed by the local occupational health practitioner in an effort to educate, assess, and improve workplace safety:

1. Identify hazardous issues within the workspace as a whole.
2. Identify hazardous issues associated with an individual's task.
3. Create a forum to engage in open conversations to educate and discuss hazardous issues.
4. Draft a priority list of improvements, with respect to time and resources.
5. Assess the results of the implemented improvements.
6. Advocate for good housekeeping in the working environment.

When applying these tasks to a nanomaterial-specific workplace, the basic practices remain the same, but the following considerations should be added:

1. Involve all parties in the workplace, including administration.
2. Form an advisory committee knowledgeable of the nanomaterial literature.
3. Maintain proper labeling, packaging, and marking of each nanomaterial component.

4. Increased training in spontaneous combustion situations.
5. Increased use of personal protective equipment, including frequent changing of gloves and other body coverings.

9.3 The ABC Model as applied to Nanotechnology in the Workplace

One specific type of BBS program is the “ABC” model [18, 19]. ABC is the acronym for antecedent–behavior–consequence, where “A” stands for antecedent, which is a thing or event that existed before or logically precedes another. “B” stands for behavior, meaning the way in which a person acts in response to a particular situation or stimulus. “C” stands for consequence, which is a result or effect of an action or condition. The ABC model is designed to collect data and allow workplace safety analyses. It is an assessment tool used to gather information that should evolve into a positive behavior support plan (Figure 9.1).

In the nanotechnology workplace, the antecedent may not be directly observable. Nanomaterials are small and cannot be seen by the naked eye; therefore, observing a spill or a leak in a production system may not be obvious. The most commonly recommended behavior practice in nanotechnology workplaces is the use of PPE [20]. In the nanotechnology workplace, the results of safe behavior include an increase in business success and improved morale; whereas the consequences of misbehavior or

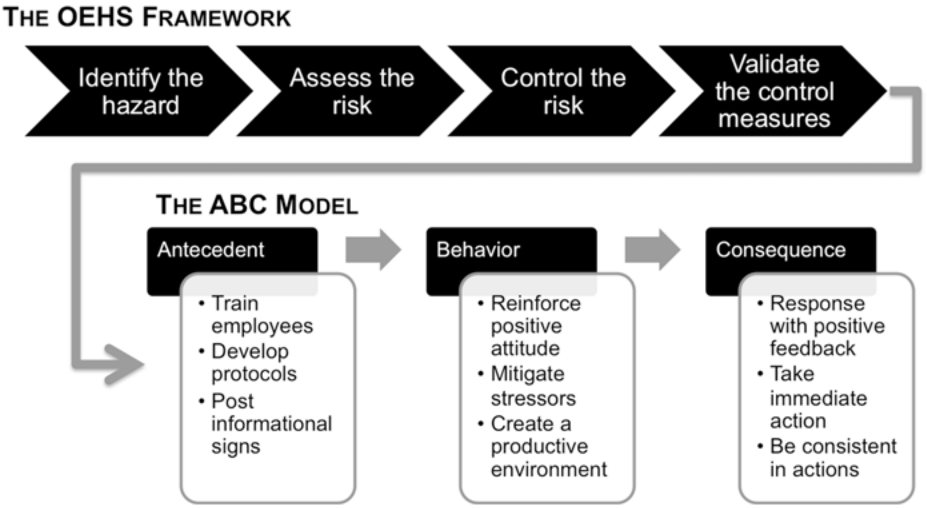


Fig. 9.1: The flow of information from the occupational and environmental health and safety (OEHS) framework to the antecedent, behavior, consequence (ABC) model.

neglect range from regulatory intervention to a high frequency of employee turnover because of increased incidence of injury and/or disease. The negative consequences may result from insufficient or inadequate understanding of the unique technology and its proper operation/manipulation. As with any industry, the principles that govern an ABC model in a new industry, such as nanotechnology, can and should be designed to fit the particular requirements of individual companies. BBS should add to an organization's performance and market demands.

9.4 Exposure Scenarios Along the Nanomaterial Value Chain

In the context of this chapter, exposure is the state in which someone is susceptible to a harmful agent. The nanomaterial value chain is the set of activities that a company performs to bring a nanoenabled product to market. Along the nanomaterial value chain, different types of exposure can occur. Some examples are exposure of occupational workers to pristine nanomaterial starting material, exposure of the environment to nanointermediates used as waste products in landfills, and exposure of consumers to nanoenabled products. Depending on the hazardous nature of that nanomaterial, the exposure could heighten undesired risks. In an effort to understand the risks associated with nanomaterials along the value chain, an environmental risk assessment is often conducted. Environmental risk analysis is the field of study that attempts to understand events and activities that bring risk to human health or the environment [21–23].

Exposure to nanoparticles can occur at any point along the product value chain. There are unique stages in the development and implementation of nanoenabled products throughout its life. The four stages of a product value chain are production and manufacturing, distribution and transit, formulation and use, and disposal and recycle/reuse. In each stage of the chain, different people are exposed to different forms of nanoparticles for different amounts of time. Understanding the exposure in each stage, as well as the possible health outcomes after each unique exposure, can lead to a safer work environment.

The main routes of exposure relevant to nanomaterials along the product value chain are dermal, ocular, inhalation, and ingestion. The following list details these routes of exposure and the related health effects:

1. Dermal exposure (e.g., skin contact) may lead to irritation, sensitization, or allergic reaction. Nanopowders have been shown to penetrate the epidermal layers and intercalate within cells or to cross the blood–brain barrier [24].
2. Ocular exposure (e.g., eye contact) can result in irritation and permanent damage. Nanopowders have been shown to absorb through the mucous layers of the eyeball and into the tear ducts [25, 26].
3. Inhalation exposure (e.g., breathing) can result in both structural and functional changes to the lung. In the case of inhalation, the size of the particles determines

the level of penetration into the lungs. The smaller particles can penetrate deeper into the lung and cause more damage. Continuous damage and inflammation can lead to fibrosis, cancer, and other chronic diseases. For example, titania (TiO_2) nanopowders have been shown to decrease lung function and cause fibrosis of lung tissues [27].

4. Ingestion exposure (e.g., swallowing) can alter the commensal microbial environment of the gastrointestinal tract. Nanopowders have demonstrated antimicrobial effects in bacteria associated with normal intestinal digestion [28]. The gastrointestinal system has the ability to transport nanoparticles into the circulatory system, which can expose other organs.

The value chain in the nanotechnology industry is a highly discussed topic [29–31]. A value chain generally refers to the process or activities by which a company adds value to a nanoenabled product, starting with the discovery phase through the production and marketing phase to the end-of-life phase. Parallel to the nanoenabled product value chain is the life cycle of the product of interest. Life cycle analysis is the systematic approach of looking at a product's complete life, from cradle (i.e. raw materials) to grave (i.e. final disposal of the product) [32]. This "cradle-to-grave" analysis of a nanoenabled product considers occupational, consumer, and environmental exposures and potential adverse impacts [33]. For the purposes of this chapter, the nanomaterial product value chain consists of four main stages: production and manufacturing, distribution and transit, formulation and end-users, and disposal and recycle/reuse (Figure 9.2). These stages are discussed in Sections 4.1–4.4.

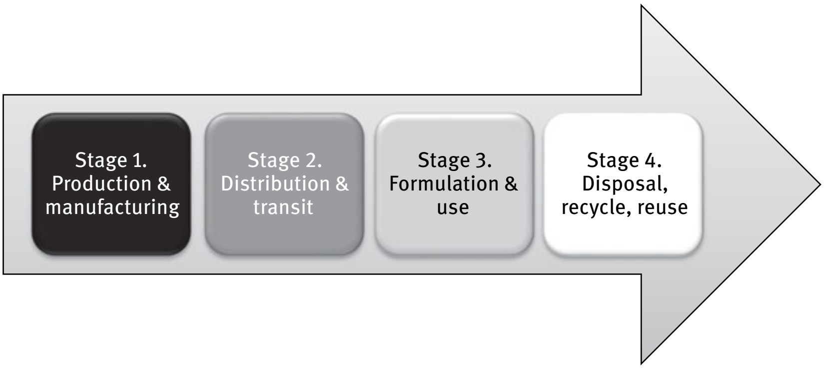
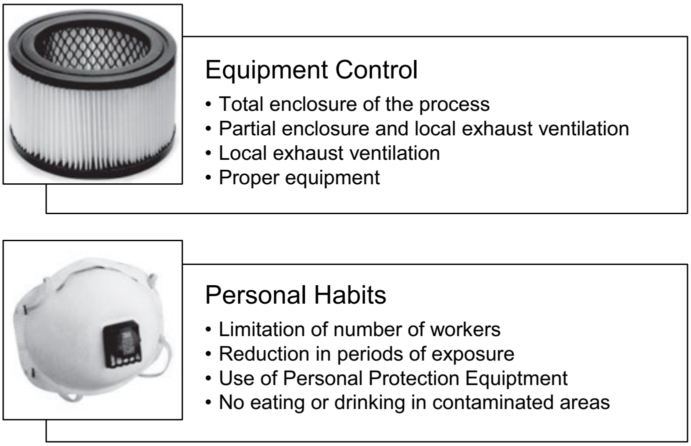


Fig. 9.2: The product value chain as it relates to nanoenabled products, intermediates, materials, and/or particles. Stage 1 is the production and/or manufacturing of the nanomaterial to be incorporated into a final product. Stage 2 covers the issues related to nanomaterial or nanointermediate transport from one location to another. Stage 3 revolves around the formulation and use of nanoenabled products entering the marketplace. Stage 4 focuses on the disposal, incineration, recycling, or reusing processes associated with product (or waste) end-of-life.

9.4.1 Stage 1: Production and Manufacturing

Production of nanoparticles can result in the highest incidence for exposure [34, 35]. However, in a laboratory or industrial setting, there is equipment available that can accommodate this exposure. Engineering controls and safety protocols are an easy way to ensure that there is minimal risk of exposure to nanomaterials. Protocols can range from safety training to use of PPE to the installation of control gear, such as fume hoods and ventilation (Figure 9.3).

Understanding the parameters within the production and manufacture of nanomaterials can help focus safety strategies. For example, during "top-down" synthesis, ultrafine particles are generated through mechanical breakdown. If the particles are collected and stored in a single location, there is a possibility of spontaneous combustion because small particles burn readily. This specific particle size range (i.e., <250 nm in diameter) increases the likelihood of spontaneous combustion [36, 37]. Small particles burn readily when their ignition point is reached, and tend to ignite coarser particles. Potential sources of ignition are open flames, welding torches, matches and cigarettes, faulty electrical equipment, and static electric discharges. These conditions and behaviors must be minimized in work areas close to nanopowder production. Inserting preventative measures, such as enclosing the system or installing proper ventilation, can mitigate this workplace risk. In "bottom-up" synthesis of engineered nanomaterials, production involves the growth of nanoparticles in solvents or gas under high temperatures and pressures. This could lead to exposure of workers to toxic fumes, burns, or explosions. Anticipating these potential risks can aid in creating a safe and healthy workplace environment.



Equipment Control
- Total enclosure of the process
- Partial enclosure and local exhaust ventilation
- Local exhaust ventilation
- Proper equipment

Personal Habits
- Limitation of number of workers
- Reduction in periods of exposure
- Use of Personal Protection Equiptment
- No eating or drinking in contaminated areas

Fig. 9.3: Examples of how employers can implement engineering control and personal protection within a nanotechnology workplace.

9.4.1.1 Nanopowder Dust Generation, Collection, and Disposal

Nanopowder dust generation is a potential risk during the “production & manufacturing” stage and the “formulators and end-users” stage of the product value chain [38, 39]. The National Institute for Occupational Safety and Health (NIOSH) recommends worksites to install dust collectors at the site of material manipulation. Fume hoods, safety cabinets, enclosures, and ductwork should be installed and constructed of rustproof, nonsparking metal. Dust collection systems handling nanopowders should act as dedicated-use systems. Periodically, the systems should be cleaned using wet or damp cloths, which should be disposed of in sealed containers. Specific to fume hoods and safety cabinets, high efficiency particulate air (HEPA) filters are strongly recommended as an effective barrier to prevent particles appearing in recirculated air. Ductwork should be minimal to prevent circulation of particles throughout the entire workspace.

9.4.1.2 Good Housekeeping Practices for Nanomaterials

One route of exposure is a workplace that uses engineered nanomaterials as starting material in a production or manufacturing workroom [7, 39]. A dirty or unorganized workroom is more hazardous than a tidy one [40]. Therefore, the practice of good housekeeping is important to prevent accidents and exposures in the workplace, especially within the nanopowder worksite. For instance, dust accumulation should not be allowed on floors, piping, ductwork, conduits, or walls. Recommended cleaning tools include HEPA vacuum pickup and wet wiping methods. Other relevant good housekeeping practices are not necessarily unique to nanomaterials, bur should be practiced nonetheless: avoid food or beverage consumption in workplaces where nanopowders are handled, require hand-washing before and after each powder handling scenario, and provide facilities for showering and changing clothes. Dry sweeping or air hoses should never be used to clean nanopowder work areas because these methods may aerosolize particles and, consequently, increase exposure to workers. Additionally, cleanup should be conducted in a manner that prevents worker contact with waste. Synthetic fiber brushes or plastic tools should be avoided because these instruments tend to accumulate static charges, which, upon ignition, may cause a fire.

9.4.2 Stage 2: Distribution and Transportation

In Stage 1, the risk of exposure is contained to a laboratory or industrial setting. Thus, the risk of exposure primarily falls upon employees and other personnel who are aware of the possible exposure. In stage 2, the risk of exposure to nanomaterials may be unknown. The opportunity for nano-safety training for an occupational worker outside of the nanomaterial laboratory or industrial setting may not be available or as comprehensive as needed. Occupational workers in the transportation sector also handle engineered nanomaterials [41, 42]. These materials are presumably packaged, but have the potential to spill or leak if handled improperly. Therefore, inhalation, ingestion, ocular, and dermal exposure are possible outside of the contained worksite.

Safe behavior practices are crucial when nanomaterials are transported or delivered. Both the deliverer and receiver of the material should be well informed and have primary responsibilities throughout the process. Safety measures often include administrative, technical, or engineering facets, as well as involvement of health and safety personnel. Oral and written communication also helps to ensure understanding of the physical and chemical properties, the amount, and distance traveled relevant to the specific nanopowder being transported.

Because the occurrence of an accident during the transport of dangerous goods can lead to catastrophic consequences, guidelines and regulations have been established to protect workers, society, and the environment (https://www.osha.gov/Publications/OSHA_FS-3634.pdf). Spillages are also possible when materials are not properly packaged, handled, or labeled; therefore, it is important that material be adequately prepared for both shipment and storage. In addition, the risk of an accident increases when the material is left unattended.

9.4.2.1 Specific Conditions Can Increase the Risks

There are a few special conditions that, if left unchecked, can greatly increase the risks associated with distributing and transporting nanomaterials along the chain of custody [43]. For example, some engineered nanomaterials may become hazardous when the particles come into contact with air, reactive gases, water/humidity, or reactive solvents. When some forms of iron nanoparticles react with water, reactive oxygen species are readily generated and can cause skin sensitization or other systemic toxicities. The pressure within sealed packages can rise with heat and cause uncontrolled reactions (e.g., fire). By extension, any change in temperature can affect the quality of the engineered nanomaterial, potentially rendering it useless.

In 2011, the United Nations published "*Recommendations on the transport of dangerous goods*," a book written by a committee of experts on material safety. The book states: "In the light of technical progress, the advent of new substances and materials, the exigencies of modern transport systems and, above all, the requirement to ensure the safety of people, property and the environment…the [international community needs revised] regulation of the transport of dangerous goods" [44].

9.4.3 Stage 3: Formulators and Users

In stage 3, the risk of exposure falls on the formulator or user. The user may not be aware of the exposure to a nanomaterial and thus may not understand the possible outcomes. Exposure to nanoenabled products in stage 3 depends on the product and its intended use. There can be intended and unintended consequences associated with use of the product; both could lead to inhalation, ingestion, ocular, or dermal exposure to engineered nanomaterials and their products.

Each industry has unique occupational exposure scenarios during product formulation and consumer exposure during final product use. Some products are ingested (as in medicines or foods), others are touched (as in electronics or toys), and others are inhaled (as in fragrances or cleaning products) [45–47]. In understanding nanosafety and the risks in these exposure scenarios, specific consumer exposure information must be collected and used in screening the types and amounts of exposure to high production volume nanomaterials. This information is often collected by the United States Consumer Product Safety Commission (CPSC), an agency whose mission is to “protect the public from unreasonable risks of injury or death associated with the use of the thousands of types of consumer products under the agency’s jurisdiction” (http://www.cpsc.gov). The specific consumer exposure information for one product can be applied to other consumer products when there are gaps in data. Simultaneously, hazard information is gathered and put into context with exposure concentration (or dose) to characterize risk.

Within the occupational exposure of formulators, enclosed structures designed to prevent or reduce exposure to hazardous chemicals or vapors are just as important in this stage as in production and manufacture [48]. It is important to keep in mind that stage 1 exposure is often to a single particle-type (e.g., TiO_2 nanoparticles), whereas stage 3 typically involves exposure to a mixture (e.g. TiO_2-enabled paint: nanoparticles plus latex, water, and pigment). In either stage, mechanical exhaust systems should be used to prevent the accumulation of toxic particles, vapors, or fumes. Currently, some hazardous composite materials (e.g., polyvinyl chloride, arsenic, benzene) are prohibited from being used in the aerosolized state because they are very toxic to humans when inhaled. When working with nanoenabled products that are intentionally toxic to bacterial and viral organisms, as in cleaning products, integrated data sets of exposure information plus material hazard data are needed to characterize the risks posed by these formulator or end-user exposures.

9.4.4 Stage 4: Disposal, Recycle, and Reuse

The disposal, recycle, and reuse of a nanomaterial all occur in the end-of-life stage. Given the variety and variability of these processes, the risks associated with each nanomaterial must be considered on an individual product basis [49]. However, there are instances where products with many similar components or ingredients may be processed and analyzed together (i.e., plastics, electronics, metal scraps, etc.). When providing guidance for workers on working safely with engineer nanomaterials at the end-of-life stage, the first priority is determining whether the material is included on any hazardous chemical watch lists. As with any chemical disposal protocol, nanomaterials must be segregated by hazard class. Dry nanopowders should be packaged in cardboard boxes that do not weight more than 10 kg. The box should be labeled with the contents, amount, date, and description for easy reference.

9.5 The Role of the Employer

In a facility for nanomaterial manufacture or formulation, the employer's role in the promotion of worker safety and awareness is vital to the success of the company and health of its employees. Safe practice and adherence to Occupational Safety and Health Administration (OSHA) regulations starts at the top of the corporate pyramid with executive leadership, and then moves on to include the efforts and examples of personnel managers [50]. The job of senior leadership personnel requires the development and implementation of an environmental safety committee devoted to the safety and education of the workforce. A safety committee or a risk management team could then be responsible for maintaining a safe working environment through three main strategies: safety information dissemination, safe practices training, and safety regulation enforcement.

Safety information dissemination is the first and most important defense against occupational accidents and injuries [51]. In order for workers to do their job safely and effectively, they must be well informed about the engineered nanomaterials they are working with, and trained on how to handle the materials properly. Other safety precautions, such as the use of PPE and standard operation procedures, must be followed to prevent exposure to nanomaterials, nanowaste, nanointermediates, nanoenabled products, or other potentially harmful materials in the workplace. Safe practice training is a second safety measure utilized to prevent harm to the worker. The objective of this training is to provide the technical skills and hands-on experience for safe and appropriate practices in nanoenabled product development. The third safety measure is enforcement of safety regulations, which is necessary to ensure that the workforce upholds the established protocols and standards every time a worker enters or exits the workplace. Together, the three strategies promote worker awareness and establish confidence.

Like any other risk management process, the role of the employer in maintaining a safe work environment is an iterative process that involves setting goals, observation, feedback, and continuous reinforcement to achieve improvement.

Risks associated with different nanoparticle states

Excerpt summarized from NIOSH document "General safe practices for working with engineering nanomaterials in research laboratories"

- When nanomaterials are in a dry powder, handle with care so that it does not become airborne dust particles
- When in a liquid matrix, the risk for dermal exposure is high; there is also risk of aerosolization during certain procedures
- Nanomaterials in a solid matrix pose the least risk; if the matrix is disrupted (cutting, sawing, sanded, etc.) then nanoparticles can be released

Administrative controls relevant to nanomaterial production

Excerpt summarized from NIOSH document "Current strategies for engineering controls in nanomaterial production and downstream handling processes"

- Educate the workers on safe handling of nanomaterials
- Obtain a material safety data sheets (MSDS)
- Clean up spills in accordance with procedures
- Provide additional control measures (e.g., decontamination facilities, sticky mats, buffer area, restricted access to the laboratory)
- Conduct industrial hygiene and medical monitoring to ensure that work practices are properly executed

9.6 Questions for Contemplation

- What is behavior-based safety?
- What are the six tasks completed by an occupational health officer?
- Describe the four parts of a life cycle.
- Why would you want to complete a risk assessment before you develop a nano-enabled product?
- Explain an A-B-C analysis. What are the major characteristics?
- What are the benefits and limitations of conducting a behavioral assessment?
- Explain how developing nanoenabled products differs from developing a traditional product.

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10 The Future of Nanotechnology Safety

Before moving forward with this chapter, the editors would like to tell a fictional story of things to come in the future. If anyone, from top management down to the worker, neglects the Occupational Safety and Health Administration (OSHA) standards, the normal protocol is that OSHA conducts an investigation of a potential violation reported by a worker(s). If a violation is found, then the company receives a monetary fine and an abatement plan. The situation is no different for the manufacturing and handling of nanomaterials.

On 20 April 2025, OSHA receives a complaint from an undisclosed company that there has been an incident of spillage of a highly advanced nanomaterial used for hypersonic air. The complaint also indicates that management does not have the proper personal protective equipment (PPE), ventilation systems, or adequate training to safely handle and work with these highly advanced nanomaterials. As a result, the company is fined. With new standards and abatement programs in place for nanomaterials, OSHA can effectively do their job based on years of research of hazards, engineering and administration controls, toxicity findings, and advances in PPE equipment. The research findings were crucial in establishing standards and protocols for worker safety. However, even in the year 2025, we as observers and industrialists cannot escape human fallibility.

The purpose of this book is to assist manufacturers and managers understand the dangers and hazards of handling nanomaterials. This is currently one of a few books discussing nanotechnology safety, which is an indication that researchers are becoming concerned. As you may know, technology acts as a double-edged sword, meaning there are good and bad aspects. Humans are fallible and make mistakes. According to an article written by Behavioral Safety Management Systems (BSMS, 2017), who are experts in behavioral-based safety, “People often behave unsafely because they have never been hurt before while doing their job in an unsafe way: ‘I’ve always done the job this way’ being a familiar comment.”

Nanotechnology, compared with microlevel technology, is a field where the safety required is ten times the current requirement for human attention and requires a lower threshold of human error to prevent hazards. This is not say that people cannot work under a comprehensive safety environment with nanomaterials, but the level of knowledge to identify hazards and to act to control/prevent hazards requires a high level of understanding and action in the face of uncertainty.

Engineers and scientists have gathered information on over 650,000 known chemicals used in industry. For decades, data on toxicity, associated hazards, physical and chemical properties, hazard identification, exposure controls, and PPE have been collected to help workers understand the careful handling of dangerous materials. Now

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science has entered the 1–100 nm realm, where the majority of safety measures used for chemicals are virtually useless because (i) the properties of these new materials are unknown; (ii) properties change according to nanosize; (iii) there are no data on the effects of exposure for either humans or the environment; (iv) current available equipment cannot operate effectively at the nanoscale; and (v) guidance and regulations are contradictory. The list is actually much larger, but these are the main points.

On a positive note, there is a promising side to the longevity of nanotechnology. Let us take a look into the future of nanotechnology safety. In the year 2025, nanomaterials and other advanced materials will be commonplace for enhancing technology for consumer and commercial goods. The quality of life for humans will have increased due to advanced medicines using nanomaterials. Federal safety regulations and standards will be fully adopted by industries. Advanced safety controls operated by artificial intelligence will be able to decrease human error to almost zero. This is all very possible, but will take national and international efforts to make it a reality. In the world of higher education, nanotechnology safety will be its own discipline because use of nanomaterials will be commonplace and a necessity for industry. To work in an area of nanomaterials, certification will be required for professionals.

The future outlook is hopeful if we implement appropriate controls for the application of innovative technology for production and use of nanomaterials in areas such as consumer goods, medicine, and the military. The world we live in is based on remaining profitable in order to remain in business, even though the scientists developing nanomaterials see them as a new industrial revolution or the next big step resulting from human ingenuity.

Industrialized nations can embrace the unlimited possibilities of nanotechnology; however, our paradigm of thinking and how we approach technologies must change. National and international governing bodies need more stringent guidelines for worker safety regarding nanomaterials and not guidelines based on political correctness. As we progress into the future with highly advanced nanomaterials, safety protocols must evolve to stay current.

Even though nanotechnology is relatively new in society, the unknowns keep safety managers up all night trying to find ways to maintain a high level of safety. The authors believe that more government funding is needed for research into the hazards of current and new nanomaterials and for designing new PPE and engineering controls. As more nanomaterials are created, industry must be cognizant of constant improvement in the training needs of workers. A workforce well-trained in safely handling nanomaterials will lessen the likelihood of catastrophes and decrease public skepticism.

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