nanotechnology DeMYSTiFieD

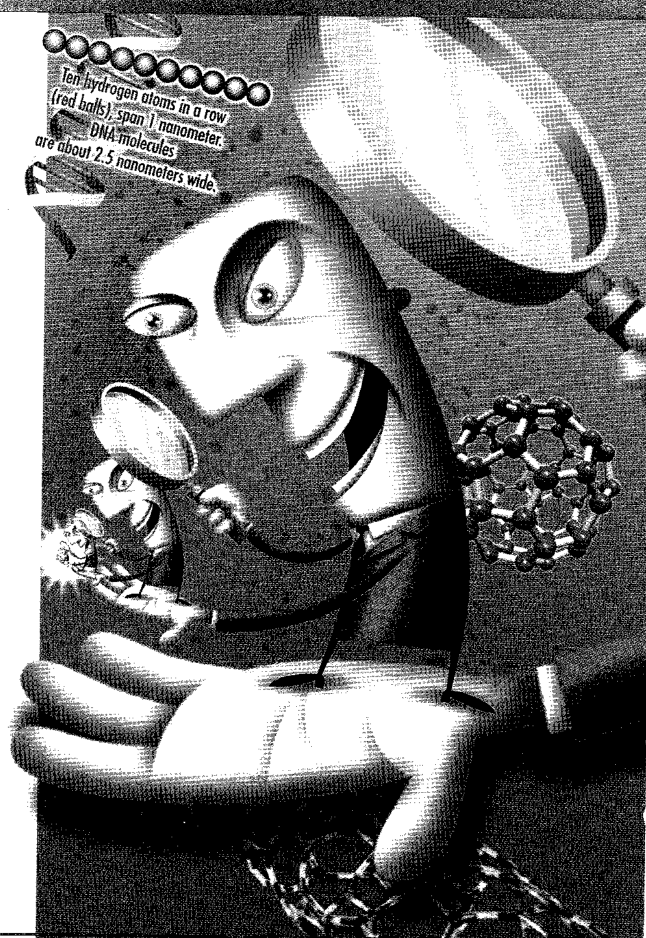
A SELF-TEACHING GUIDE

Learn about this HOT NEW TOPIC and its FUTURE global IMPLICATIONS

Explore IMPACTS on energy, pharmaceuticals, engineering, medicine, communications, and more

Loaded with "Nanotech Notes" throughout to HIGHLIGHT tips, NEWS, and trends

Complete with chapter-ending QUIZZES and a final EXAM



Linda Williams
Dr. Wade Adams
Director of Center for Nanoscale Science & Technology, Rice University

CHAPTER 13

Nanotoxicity and Public Policy

Killer organisms, doomsday weapons, evil geniuses, and science run amok are often the stuff of science fiction thrillers. Bigger and fiercer monsters and machinery grabs audiences' attention and pocketbooks. Today's media types unveil the latest sci-fi hero or evil empire with everything from action figures to video games. Nearly everything seems capable of destroying the world!

Over time, the public has been trained to look for the "dark side" of technology. With lawsuits focusing on everything from too hot coffee to dangerous pharmaceuticals, the public questions everything and distrusts everyone (until it has proof to the contrary).

The media often champions this approach, and with enough spin, anything becomes the big story. It's not surprising, then, that every new technology to come along is viewed with a mixture of unease and excitement.

However, communications research has shown that the media may not have as much of an impact on people's opinions about technology as previously thought.

lot of nano public opinion research shows that people are generally accepting of nd positive about technology. Although they may be fairly unfamiliar with nano-echnology, most people are taking a wait and see attitude. As in the past, some new aterials have seemed promising, only to cause unanticipated harm in the long run. Discoveries can be a two-edged sword—they allow progress, but they may open a andora's Box if not studied carefully.

Just because something is useful doesn't mean it is risk-free. It wasn't too many ears ago that everyone was praising asbestos, thalidomide, chlorofluorocarbons, nd DDT as important advances/products in many areas. Only after big problems howed up did we think that increased caution might be important.

Some critics think that the same technologies that many scientists believe may omeday cure cancer and solve our global energy transmission problems could also estroy the planet. They want all advanced bio and nano-research stopped to keep from wiping out the human race. Well, who wouldn't want a global marauder topped? Time will tell if nanotechnology is a boon or bane to society.

In an April 2000 article in *Wired*, "Why the Future Doesn't Need Us," Bill Joy, o-founder and chief scientist at Sun Microsystems, stated the current pace of tech-ological progress was a very real threat to the future of humanity. He saw three big reats to humanity: genetic engineering, nanotechnology, and robotics.

Although no one has a crystal ball to see the future, world collapse predictions eem a bit over-reactive. While it's true that science/engineering methods used for ill tent are dangerous, to give up on good things out of fear seems counterproductive. he watch word must be thoughtful development, education, standardization, and ternational cooperation. Fifty years ago, many people thought the world would soon d in nuclear holocaust, but we still survive, even though the risk remains real.

It's important to heed concerns (part of the scientific method is to question every-ing) and go forward with caution and care. At the same time, we need to realize at the best could be just beyond our reach.

Nanotechnology and You

he industrial age has provided us with new products galore. New discoveries and aterials have made it possible for old products that were originally made of wood d paper to be updated with oil and petroleum-based materials. A simple example restaurant take-out boxes; first made of paper, many are now plastic, which don't t soggy and leak. Plastic, based on petroleum, is a technological product.

Science, engineering, and computer design were the glory fields of the twenty-st century. There was only one problem, however: sometimes they leapt before ey looked. New was cool. Cutting-edge was the place everyone wanted to be.

We weren't as careful with or didn't care about new products' impacts. As long as something was "new and improved," it was seen as good!

Eventually our carelessness came back to bite us. The air, land, and water became polluted, often with a mixture of compounds. The United States and other governments were forced to spend billions of dollars cleaning up chemical runoff and toxic landfills, and educating industries and the public on pollution. It took a while, but we are slowly starting to realize that the Earth can't put up with poor stewardship forever.

With nanotechnology, more and more scientists, government officials, and industrialists are trying to look before they leap and do things right from the start. Everything nano is promising news today, but by learning from past oversights, we can identify and eliminate potential toxic effects from the beginning.

Solubility and Toxicity

In early assessments of emerging nanotechnology, the solubility of nanoparticles has been of particular interest since soluble molecules can enter biological systems and the environment more easily.

You learned in Chapter 1 that the first fullerene was Buckminster fullerene (C_{60}). Since its original discovery in 1985, research has found that C_{60} molecules cluster into nanoscale crystals that are active in watery environments. Additionally, soluble C_{60} clusters have been shown to be *cytotoxic* (cell killers) *in vitro* and have been linked to brain tissue damage in fish.

However, Rice University scientists Vicki Colvin, Jennifer West, and Joe Hughes discovered that by attaching small molecular fragments to the surface of C_{60} molecules, in a process called *functionalization*, the cytotoxic effect was eliminated. Non-functionalized fullerenes (used in the fish study) were toxic to 50 percent of the cultured cells at a concentration of 20 ppb. Figure 13-1 illustrates this neutralization of toxicity.

The functionalization method seems to work additively. By attaching more and more molecular fragments to the C_{60} molecules' surfaces, the cytotoxicity drops until the fullerene's surface is covered and not enough nano-C_{60} exists to kill 50 percent of the cells. This important study showed how nanoparticle risks are dependent on the material's particular form and that simple techniques can be used to reduce and/or eliminate risks.

So the take home message was that once the nanomolecules' surface properties were better understood, it took a relatively simple chemical modification to negate risks. This may or may not work for other nanoparticles, materials, devices, and processes. Nanomaterials' unique properties (e.g., surface chemistry, strength, reac-

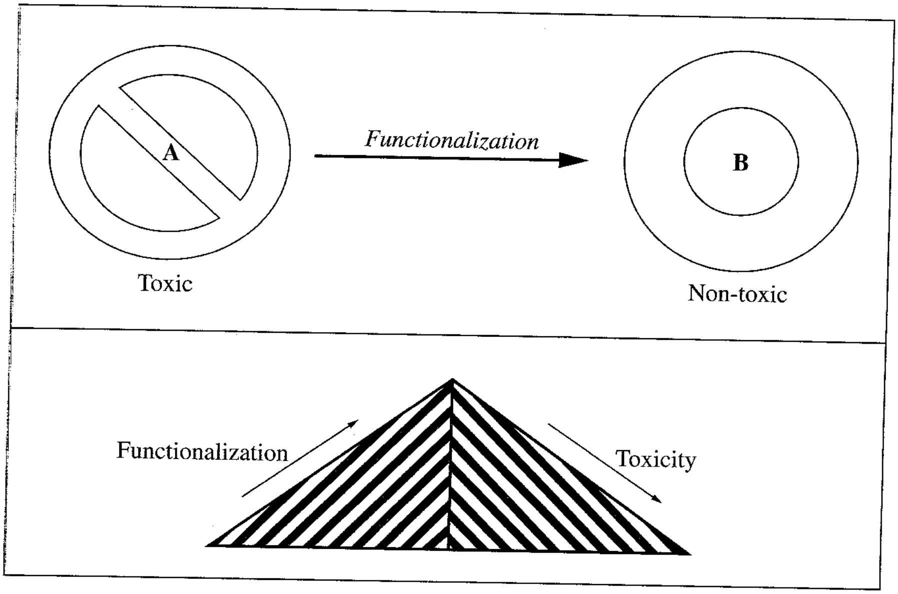


Figure 13-1 Nanotoxicity goes down as functionalization increases.

ivity, and thermal/electrical conductivity) may require other application-specific changes before their fullest potential can be utilized.

Moreover, modifications often affect a material's properties. In some applications, modifying the surfaces may engineer out the very property that is desired. However, innovations in communications, medicine, materials, energy production/efficiency, water treatment, and environmental clean-up may become reality.

NANO-CELL INTERACTIONS

Understanding the toxicological effects of engineered nanoparticles in liquid phase reactions is an important goal of some nanotechnology research areas. While a lot of information is available about aerosol effects upon living systems through inhalation exposures, very little is known about the toxicology of engineered nanoparticles in the liquid phase.

Toxicology studies on engineered nanoparticles' interactions with cells are underway to determine whether surface coatings can be used to affect the toxicity of the nanoparticles. Testing has shown that in water, C_{60} in concentrations up to 100 ppm forms nanoscale clumps (10–50 ppm) with hydrophilic (dissolves in water) surfaces. This is very important because C_{60} itself is considered insoluble (hydrophobic), so the clustering makes it soluble and environmentally significant, for example, if the particles were to be released into a natural stream or river system.

Other nanoparticles have served as bactericidal agents against both gram positive and negative bacteria. Contact between nanoparticles and bacterial membranes points toward possible disinfectant effects in a hospital setting, since nanoparticles' have a tendency to become airborne (super small size) and/or cross biological membranes.

Derivatization

Size, though, isn't the only factor for predicting the nanoparticle toxicity: chemical composition, aggregation, surface charge, particle shape, structure, and surface properties/coatings are among the other factors that must be considered.

In C_{60} cytotoxicology tests using human dermal (skin) cells, the toxicology of nano-C_{60} in culture was 20 ppb. Although this is fairly toxic compared to other cytotoxic chemicals, the toxicity of nano-C_{60} and other water soluble fullerenes was connected to their level of *derivatization*.

> ***Derivatization*** takes place when a chemical compound is transformed into a product of similar chemical structure called a **derivative**.

Often, a chemical compound's functional group (a side element or molecule that helps a compound function) is derivatized in a reaction. This changes the original compound (A) into a product (B) with a slightly different reactivity, boiling point, melting point, solubility, and/or chemical composition. Derivatization is also important in altering unwanted properties (such as toxicity) in a biological or manufacturing process.

Fullerene toxicity affects cell membranes through the production of oxygen radicals. Tests show that this toxicity can be shut down through the derivatization of the C_{60} molecule.

Work with nanoscale quartz, titanium and labeled iron oxides is being done in cell culture and lung studies to figure out how specific particle size and surface chemistry change nanoparticles' biological effects/biodistribution.

MOBILITY

Another globally important angle of nanotechnology risk concerns the extreme mobility of nanoparticles. Because they are super small, they can get into almost everything. Think of dust that is so fine, it can't be seen. This is a benefit when attacking disease and local viruses, but it could cause a lot of environmental problems if not handled correctly.

In Chapter 7 you saw how iron may be used to clean up environmental contaminants. Before this method and others can be put to widespread use, researchers must be sure that they can recover the nano-iron after the toxic clean-up.

However, this might not be necessary. Wei-xian Zhang at Lehigh University claims that because iron is already found in the environment, these particles may not need to be recovered. However, the same may not be true for particles of different composition. Since different nanoparticles can be highly reactive with certain compounds in certain conditions, any broad environmental use, no matter how safe it seems at the time, must be handled carefully.

In order for researchers, industry, and the public to buy into the awesome potential that nanotechnology offers, we have to learn from our mistakes with DDT and other "helpful" chemicals. This is being done through a variety of efforts currently underway in the United States and abroad.

Icon

The International Council on Nanotechnology (ICON) was established at Rice University to assess, communicate, and reduce environmental and health risks connected with nanotechnology. To carry out this goal, ICON is working with academics, industry, government officials, and representatives of environmental organizations. As described in Chapter 7, its activities include research into nanoparticle/cell interactions, policy, standards, terminology, and social analysis on risk perception and education.

NANOMATERIALS DATABASE

By combining the nanotechnology industry's resources, along with governments, and academia, ICON can network related projects and serve as a central repository of information. Along with the Department of Energy and scientists from Rice University and Oak Ridge National Laboratory, a new database was created that is centered on the environmental, health, and safety implications of nanomaterials. This catalog of scientific literature (http://icon.rice.edu/research.cfm) was launched in August 2005 to help researchers and government agencies make up-to-date decisions about nanomaterials' safety.

The CBEN database, free of charge on the Internet, is an evolving document that is as useful for the general public as for researchers. Visitors are able to tailor searches to "nanoparticle type" and "production method." Information on the latest information about health and environmental implications of nanomaterials can be found on this website.

Future ICON plans include summaries, written for the general public, of the database's most significant papers. These would include review articles such as the health, safety, and environmental impact of cadmium selenide quantum dots or the pulmonary toxicology of engineered nanoparticles.

ICON's goal is to create an information bank that will keep everyone current on the latest nanoscience/nanotechnology discoveries and public policies. In this way, innovations, standards and regulations can be organized.

Responsible Development

The National Nanotechnology Initiative's (NNI) plan for responsible nanotechnology development is divided into several areas. These include environment, health, and safety implications as well as ethical, legal, and other public issues. Realizing that new science/technology advances offer public benefits as well as risks, the NNI has begun researching these priority areas.

Federal regulatory and research organizations are working with the NNI to identify existing regulatory procedures that cover the production and use of nanomaterials. Where regulation gaps exist, steps will be taken to change or increase regulatory standards.

BEST PRACTICES

The National Institute of Occupational Safety and Health plans to develop and issue a best practices document for working with nanomaterials. It will also work with industry and academia to develop nanomaterials nomenclature.

As discussed in chapter 2 nanotechnology academic and industry members are working toward the standardization of measurements. Early standardization will allow scientists to compare apples to apples. Best work practices will lay out a plan to ensure the safety of technicians and those working in all parts of the nanotechnology research environment. Once these practices are well established and a sizeable history of well-investigated nanotechnology uses in several key areas (e.g. medical, environmental, health and safety, etc.) is completed, public and private concerns should drop off quite a bit.

SOCIETAL OUTLOOK

Levelheaded nanotechnology development requires that governments consider and address societal outlooks as well as science/engineering challenges. Some of the different angles to think about include the following:

- Access to nanotechnology benefits
- Effects on jobs
- Medical innovations and methods
- Manufacturing impacts
- Potential health/environmental effects
- Privacy issues (e.g., information from nanosensors)

Responsible development of nanotechnology also means that the government has to establish public communication channels through the NNI. Since technology has gotten so much attention in science fiction and the movies, it is understandable that people are a bit skittish about science that seems too good to be true. Open information lines allow the public and the government to make well-informed decisions and build a solid knowledge/trust foundation.

There's an old saying: "Perception is truth." In our fast paced world, everyone is bombarded with information, opinions, research data, and ideas. It is often tough to tell the difference between truth and what is thought to be true (but based on rumor or appearances). Understanding and acceptance of new technology are key parts to weaving new methods and materials into the fabric of everyday life.

GRADIENT INTRODUCTION

Before the government can "get it right" with nanotechnology, it needs to promote a graded/gradual introduction of nanotechnology into common use. This is not intended to slow nanotechnology's introduction, but to make sure all issues are considered. Such a plan could use existing abilities and structure to make sure that nanomaterial risks are identified before they are included in manufactured products; manage identified risks from start to finish, keeping safety of workers, users, and the environment in mind; develop research and use standards that make sense; and include everyone in the process (e.g., industries, health organizations, consumer groups, environment organizations, investors, and the public).

Environment, Health, and Safety Implications

The NNI sponsors a wide range of research to evaluate the environmental, health, and safety impacts of nanotechnology. The NNI's research support has grown with the discovery of new nanoparticles, nanostructures, nanomaterials, and nanotechnology products.

As both nanotechnology's cheerleader and watchdog, the NNI has a tough, but interesting job.

The NNI's various policy projects include the following:

- Study potential health risks of nanomaterials.
- Integrate the efforts of the National Institute of Environmental Health Sciences, National Institute of Occupational Safety and Health (NIOSH); Environmental Protection Agency; Department of Defense; Department of Energy; and National Science Foundation.
- Develop new standards with the National Institute of Standards.
- Facilitate communication among the member agencies.
- Identify and rank research necessary for regulatory decision-making.
- Encourage better interaction within governmental, industrial, and scientists/engineers at colleges and universities.

These NNI tasks are coordinated by the Nanotechnology Environmental and Health Implications Working Group (NEHIWG), with supporting membership from nanotechnology research and regulatory agencies.

One of the working group's aims is to understand the fate and transport of manufactured nanomaterials along with the development of nanomaterial life cycle evaluation methods. Research focusing on nanotechnology's environmental and health implications will grow as needed. Working with the international scientific community on important nanotechnology research is important for building a global picture of nanotechnology use and focus.

CURRENT NNI RESEARCH

In 2004, the National Nanotechnology Initiative funding for initial health and environmental research was estimated at $105.8 million, or around 11 percent of total NNI funding. This amount included basic research, applications, and implications of nanoscale materials. The NNI's federal research and development program that's coordinating nanotech research from 23 separate U.S. government agencies has earmarked another $39 million to study the health and environmental effects of nanotechnology in 2006.

To understand the health and environmental impacts of molecular manufacturing, research into naturally occurring nanoscale material exposures is being considered. Currently this type of molecular exposure comes from desert dust, volcanic ash, forest fire smoke, bacteria, and viruses. Older technologies and processes produce substances such as combustion soot, diesel exhaust, paint pigments, and welding fumes.

The important thing to remember about nanoparticle risk is that it is related to the level of toxicity and length of exposure time.

RISK = TOXICITY × EXPOSURE TIME

For example, a person's risk is affected by a material's toxicity just as much as the time he/she is exposed. If someone is exposed to a mildly toxic compound for a short time, then the risk is fairly low (depending on the compound and tissues affected), but if exposure extends too many years, risk goes up.

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Research geared toward a better understanding of nanoparticles' impact on human health and the environment will help to prevent and clean up potential problems. Although exposure to engineered nanomaterials such as carbon nanotubes or buckyballs is currently limited to people who work with them in laboratories and production facilities, that may change a lot in the next decade.

Risk Assessment

Manufacturing exposures and risk must be kept in perspective. Engineering Professor Mark Wiesner at Duke University and colleagues are studying various nanomaterials for toxicity problems.

They performed a comparative risk assessment for industrial fabrication of different nanomaterials. Based on the likelihood for large-scale production and commercialization, five nanomaterials were tested: single walled carbon nanotubes, buckyballs (C_{60}), quantum dots, alumoxane nanoparticles, and nano-titanium dioxide. The study looked at risks associated with nanomaterial fabrication, not specific impacts or risks of the nanomaterials themselves.

The researchers kept track of input/output materials, as well as waste streams for each fabrication step. This information was then entered into a database that included factors such as temperature and pressure. The physical/chemical properties and quantities of the test materials were used to compare relative risk based on volatility, toxicity, flammability, mobility, and persistence.

Test results show that fabrication risks are fairly comparable to standard manufacturing risks. Figure 13-2 shows how normal operational risk of manufactured nanomaterials compares to operational risks in other industries.

Products like cosmetics and sunscreens among others, are also on the market that may need a closer look as long term exposure data becomes available.

NNI-funded research is intended to boost basic understanding of nanomaterial interactions at the molecular and cellular level through *in vitro* and in *vivo* experiments and models; enlarge knowledge of nanomaterials' interactions with the environment; enhance understanding of the fate, transport, and transformation of nanoscale materials in the environment; identify and characterize possible exposure; determine possible human health impact; develop standardized control

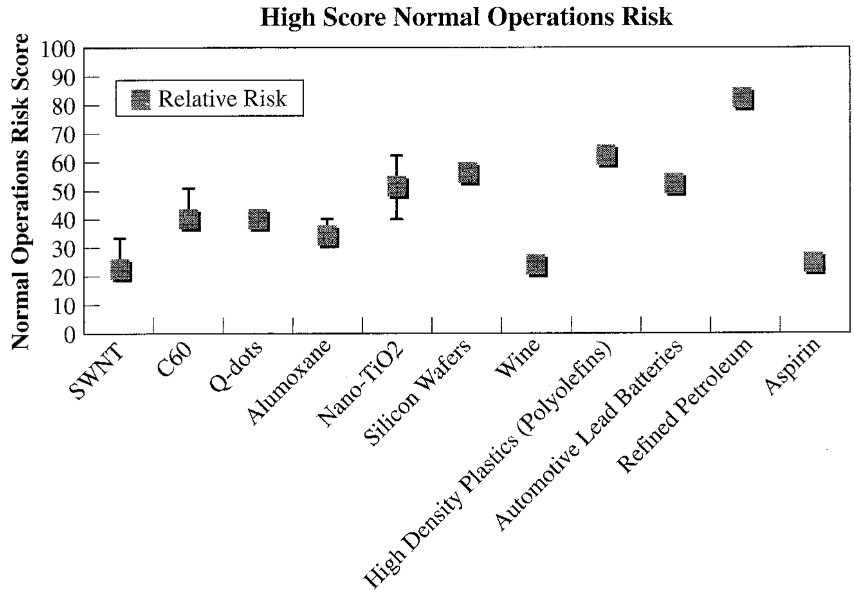

Figure 13-2 Relative risks of nanomaterial manufacturing can be compared to current material manufacturing risks.

methods for occupational exposure to nanomaterials; and establish safe working procedures for nanomaterials.

In collaboration with the NEHIWG, NIOSH's new guidelines for best practices will be a huge step toward safe working conditions when producing and handling nanoscale materials. NIOSH and other NNI departments and agencies plan to deliver these guidelines to the research, business, emergency response, and related communities and outline them on the NNI and NIOSH websites.

Getting the Word Out

In order for nanoscience/nanotechnology to be explained simply, information must be shared with the public and the media in a way that makes sense. Discoveries, technologies, and applications must be separated from media hype. It doesn't fly if nanotechnology is seen as science fiction—fantastic or frightening technology. There is enough amazing real science/technology out there without adding to the confusion with way out claims for nanotechnology.

Nanotechnology must be generally understood to the extent that the workings of the telephone, computer, or a vaccine are understood. People don't want to become experts. In fact, most people don't really care how things work until they break down.

A lot of people have the *Jerry Maguire* film attitude, "Show me the money!" They want to know what nanotechnology has done for them lately. What will it accomplish in the future? People want a general understanding of the world and how new technology affects them personally.

NANOTECHNOLOGY EDUCATION

Nanotechnology touches society in many areas—economic, cultural, ethical, and legal. Fingers of nanoscience/nanotechnology reach into science, engineering, computer science education, quality of life, and national security.

With nanotechnology innovations creating compounds and devices from the bottom up, there will be an impact on educational and workforce requirements. Education is also important in removing potential economic barriers for nanotechnology's use in commerce, industry, healthcare, or environmental clean-up. Just as other industries (e.g., automobile or energy) have been regulated for the national and public good, nanotechnology policy makers must approach this tsunami of scientific and technological advances with an eye for great benefits at low cost within safe margins. They must also answer ethical concerns when choosing research priorities and federally-funded applications.

Currently NNI-supported research involves the following nanotechnology societal implications:

- Help create interdisciplinary nanotechnology opportunities and exchanges
- *Consider and explore the public's understanding of/outlook on* nanotechnology
- Explore nanotechnology impacts on economic growth, standard of living, and competitiveness
- Involve college and university researchers in nanotechnology influences from many different areas.

With everyone having a role in how and in what direction nanoscience/nanotechnology takes, expectations and issues will be tackled as they arise. These precautions will make it possible for nanotechnology to develop in a well thought out and safe way.

International Coordination

It goes nearly without saying that something as big as nanotechnology must include the international community. By making sure that open exchange and discussion on energy, environment, health, and security are ongoing, the chance for mistakes or miscommunication decreases. Adjustments in the way international nanotechnology businesses work together will change with advances in computing, materials availability, and international trade.

Countries are forming alliances based on areas of mutual interest in nanotechnology. In 2005, Canada announced it would spend $5.5 million in research collaboration with India on the development of biotechnology and nanotechnology.

To support international communication, the National Science Foundation sponsored an international workshop in 2000 that ended in a joint declaration by participants from 25 countries and the European Union to support responsible nanotechnology development.

In January 2006, the first international symposium on nanotoxicology was held in Miami, Florida. The program included presentations and discussion on purified and non-purified nanomaterial toxicity, antioxidants, as well as tissue specific response, recognition, and clearance of nanoparticles.

Like any new venture, international nanotechnology research and development must have a plan of action that covers all bases. From economic impacts to manufacturing pitfalls and worker safety, everyone interested in nanotechnology must work together.

Bottom Line Risks and Benefits

Some people believe molecular manufacturing is possible and that the risks must be considered. They believe that it has the potential to disrupt a society for the better and or worse. (Note that most scientists dismiss the claims of these groups as science fiction.)

While it's possible that weapons and surveillance devices that are smaller and cheaper might be created, it could also be argued that future, low cost manufacturing could bring on economic upset or potential environmental damage.

Moreover, poorly planned and/or severe restrictions could lead to higher demand for risky and difficult-to-detect black-market products. In fact, all kinds of different risks can be imagined. But the truth is that any technology or practice used poorly can cause problems, and every leap in technology brings risk.

When the looming cloud of bad publicity threatens, it's important to keep in mind the great benefits nanotechnology offers:

- targeted drug delivery
- lab-on-a-chip diagnostics
- curing genetic diseases
- nanoelectronics
- nanocomposite materials
- nanosensors

- optical arrays
- fuel cells
- space exploration for industry and tourism
- efficient energy generation and transmission

Growing pains are never without discomfort. Nanotechnology has huge potential for good and evil. In fairness, the list of nanotechnology positives must be placed alongside any list of negative what-ifs. The solution is not simple. Only understanding, communication, and careful planning will prevent and avert possible dangers.

Nanotechnology is well on its way to the inexpensive production of lots of society changing products in many areas. Since the final steps of developing technologies can be much easier than the first steps, they may seem like overnight successes. The advent of widespread nanotechnology techniques may not allow enough time for everyone to adjust to its many implications.