National Water Research Institute

presents

The 2011 Clarke Prize Lecture*

Nanomaterials, Water, and the Directed Self-Assembly of Environmentally Responsible Industries

Mark R. Wiesner, Ph.D., P.E.

James L. Meriam Professor of Civil and Environmental Engineering

Duke University

Durham, North Carolina

Abstract

Nanomaterials and the technologies they inspire have great potential to advance water treatment and protect environmental quality.

Nanomaterial-based membranes, adsorbents, and catalysts for water treatment or groundwater remediation are among the first generation of technological innovations in the environmental sector. Although the potential for nanotechnology in water quality engineering is great, our challenge is to ensure that nanotechnology evolves as a tool for sustainability rather than as an environmental liability.

An increased production of nanomaterials will likely lead to the introduction of these materials into natural waters and ecosystems, with unknown consequences. In addition to any direct environmental impacts from nanomaterials, potential exists for environmental degradation stemming from waste byproducts and energy or materials usage associated with nanomaterial production, use, and disposal.

Nanotechnology is just one example of a continuous stream of technologies that require the proactive evaluation of possible impacts on human health and ecosystems. Such evaluations are fundamentally a public good that must be nurtured by the public sector to ensure not only the safety, but also the advancement and commercialization, of emerging technologies.

*For more information on the Clarke Prize and to download this lecture or previous Clarke Prize lectures, please visit www.nwri-usa.org/laureates.htm.

Introduction

The history of civilization is often described by the materials we use: the Stone Age, the Bronze Age, the Iron Age, the Age of Plastics, and the Silicon Age. These materials shape our architecture, our art, the way we harness sources of energy, our fashion, and the manner in which we procure water. Today, we are able to manipulate matter with unprecedented degrees of sophistication. New materials may be enablers for new medicines and technologies for providing water and energy. And, they may create unforeseen challenges to the wellbeing of our water resources, the environment at large, and our health. These concerns echo the observation by Gordon Fair in his 1949 address, *Sanitary Engineering in a Changing World*, where he stated that, "…wastes from organic sources, production of antibiotics, and the utilization of atomic energy present new and startling demands on our water resources."

My remarks today concern the opportunities and potential risks for water treatment and water resources presented by a nascent nanotechnology industry in specific, and by emerging technologies in general.

What Is Nanotechnology?

Nanotechnology is the control of matter at the atomic and molecular scale to create structures or devices. The vision of nanotechnology is to build objects atom-by-atom, molecule-by-molecule, through self-assembly or molecular assemblers. Self-assembly is a process where disordered components spontaneously assemble to form ordered patterns or objects, and directed self-assembly involves the use of external forces or fields to accelerate self-assembly. To see an example of nanotechnology, look at yourself in the mirror. A key promise of nanotechnology is to produce a wider range of materials and products, with new properties and potentially with atomic precision. Nano*materials* are the building blocks of nanotechnologies, and engineered nano*particles* are one category of nanomaterials. I will define a nanoparticle here as an object having a characteristic dimension from 1 to 100 nanometers and having "unique" or "novel" properties that are not shared by larger particles with the same chemical composition (note, however, that this definition is not without controversy). To give one example, consider gold, which is typically considered to be inert. When gold is divided into smaller and smaller pieces, it becomes reactive once the gold particles are around 2 nanometers in size. Thus, the properties of gold change with size. Quantum dots, such as cadmium sulfide nanoparticles, emit different colors when excited by light, depending on their size. It is as though the periodic table has a third dimension – that of size. At the nanoscale, matter may display new properties that can be exploited to achieve a range of benefits.

How small is a nanometer? A nanometer is one billionth of a meter, or 40,000 times smaller than the thickness of a human hair. If the coast-to-coast distance of the United States were 1 meter in length, 1 nanometer would be a bit smaller than the length of a grain of rice (0.2 inches). When objects are this small, most of the atoms that make up these objects are on the surface. Atoms on the surfaces of objects have different properties than those in the interior "bulk" – which is one source of the "novel" properties that are observed with nanoparticles.

A fascinating class of nanomaterials is the "fullerenes," a group of carbon nanomaterials named for the architect Buckminster Fuller because the first of these materials, discovered by Rick Smalley, Bob Curl, Harold Kroto, and colleagues, is a soccer ball-shaped molecule (buckyball) that has a structure that reminded them of Fuller's geodesic domes. Although first discovered in the laboratory, buckyballs were ultimately found to come from natural and incidental sources, as well as geologic deposits (Heymann et al., 1995; 1994), candle soot, and meteorites (Becker et al., 2006). Carbon nanotubes are another type of fullerene that are 100 times stronger than steel and 10 times more electrically conductive that copper, yet are very light. Hundreds of variations of fullerenes have now been fabricated, and the novel properties of fullerenes suggest a wide range of applications in many different disciplines.

In fact, when we study matter at this scale, differences between disciplines begin to blur. What we learn at the nanoscale has relevance for making new medicines, understanding how cells replicate, creating stronger materials, devising faster computers, and understanding how water behaves on surfaces or how sunlight is converted to chemical energy. Nanotechnology cuts across scientific disciplines and business sectors. As a result, we can expect to come in contact with the products of nanotechnology in many settings, with nanomaterials already incorporated into thousands of products. Water is one case, where nanomaterials may be introduced intentionally during treatment or find their way inadvertently into our water resources. Let us first consider just a few of the possible applications of nanotechnology to water treatment.

Nanotechnology Applied to Water Treatment

Water pollution control, groundwater remediation, and potable water treatment are among the activities being advanced by nanotechnology through the development of nanomaterial-based membrane technologies, adsorbents, and catalysts. Next-generation *active* nanosystems, based on more complex interacting systems of nano-scale components, are being conceived to desalinate water, recover valuable materials from wastewater, and perform water quality sensing and distribution system diagnostics.

Pressure-driven membrane technologies – largely considered in themselves to be exotic technologies of limited interest to water treatment only 30 years ago – now are playing an increasingly important role as unit operations for water and wastewater treatment and water reuse. The performance of these membranes has been enhanced through the incorporation of nanomaterials, such as zeolites, carbon nanotubes, and silver nanoparticles, into the membrane matrix. We have shown that membranes incorporating even small amounts of carbon nanotubes resist breakage to a much greater extent than membranes without carbon nanotubes (Figure 1).

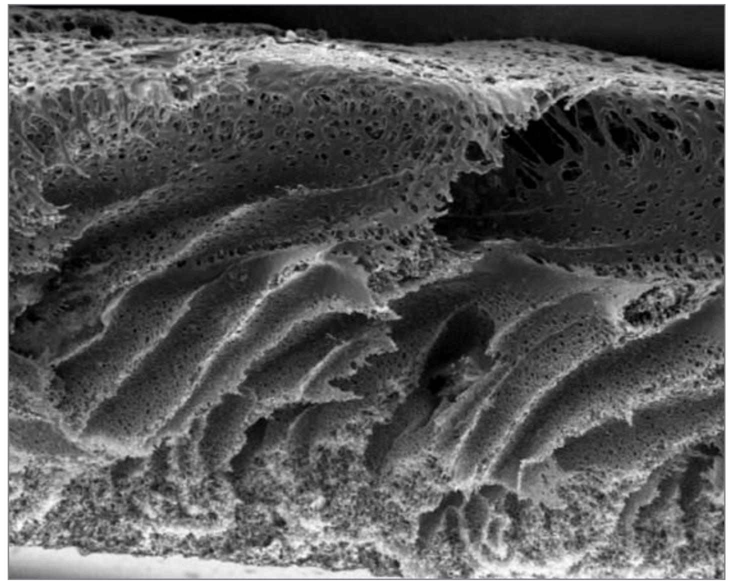

Figure 1. Membrane reinforced with carbon nanotubes. Image provided by Dr. Elif Soyer, Duke University.

Others have shown that water flows thousands of times faster than predicted by theory through membranes made from aligned carbon nanotubes. Membrane processes based on even more advanced nanoscale control of membrane architecture may ultimately allow for multi-functional membranes that not only separate water from contaminants, but also actively clean themselves and check for damage, detect contaminants, or combine detection, reaction, and separation. They may also enable new desalination processes, such as forward osmosis and membrane distillation, that depend on differences in concentration or temperature to transport water across membranes, rather than depend on pressure.

The remediation of contaminated groundwater is a second example where nanotechnology has already been employed with some success. In most cases, pumping contaminated groundwater to the surface to remove contaminants and reinjecting the treated water has proven to be both cost-prohibitive and incapable of meeting cleanup goals. As a result, *in situ* treatments such as biodegradation have been explored extensively. Physical-chemical approaches to *in situ* treatment have included the use of zero valent iron and catalysts to promote redox reactions that degrade contaminants. Nanomaterials have been developed to promote such reactions at high rates. However, an important barrier to more widespread application of this technology is the ability to better deliver nanoparticles to the contaminated aquifers by, for example, manipulating nanoparticle surface chemistry. Improvements in the approach might also include tailoring nanoparticle reactivity for specific contaminants, or engineering particles that "seek and destroy" by actively accumulating at contaminated "hot spots" where the nanoparticles then begin to degrade the contaminant of interest.

We have been exploring a similar "seek and destroy" approach for disinfection using nanoparticles. Conventional disinfection involves surrounding microbes in a "bath" of disinfectant, such as chlorine or ozone. As Clarke Laureate Philip Singer's work has shown us, these disinfectants may react with other compounds in the water, such as natural organic matter, to form harmful disinfection byproducts. As an alternative to bathing microbes in disinfectant, we consider the possibility of introducing nanoparticles that seek out microbes, attach to them, and then release or manufacture disinfect that is delivered directly to the microbe, thereby reducing the formation of disinfection byproducts. Buckyballs with appropriate modifications to their surfaces so that they do not aggregate with one another but do attach to viruses appear able to efficiently produce a reactive form of oxygen (singlet oxygen) that inactivates viruses when exposed to ultraviolet (UV) light (Figure 2). This reaction suggests one strategy for improving disinfection by UV, which, while efficient for protozoa and bacteria, is less so for viruses. In addition to these applications, there is a boom in literature on the use of nanomaterials as the basis for sensors. Highly specific adsorbents are yet another application frequently cited. Nanomaterials appear to be destined to revolutionize water treatment.

What's Stopping Us?

Although the potential for nanotechnology in water treatment is great, our challenge is to ensure that nanotechnology evolves as a tool for sustainability rather than as an environmental liability. First, we need to ensure that nanomaterial production, use, and disposal do not degrade our water resources or present a threat to human health and the environment and, second, we must address social concerns and economic consequences associated with the introduction of these new technologies.

Creating order and purity at the nanoscale requires energy that, in addition to its environmental effects, may create a barrier to widespread availability to some nanomaterials. Professor Timothy Gutowski of the Massachusetts Institute of Technology estimates that making a gram of carbon nanotubes requires over a thousand times more energy than a gram of material made using conventional production methods, like injection molding. Furthermore, creating order at the nanoscale can be costly. The proposed use of nano-iron (or so-call "nano-rust") for removing arsenic from water represents a cost that is approximately 10,000 times more expensive than the use of conventional ferric sulfate or ferric chloride. Separation and purification

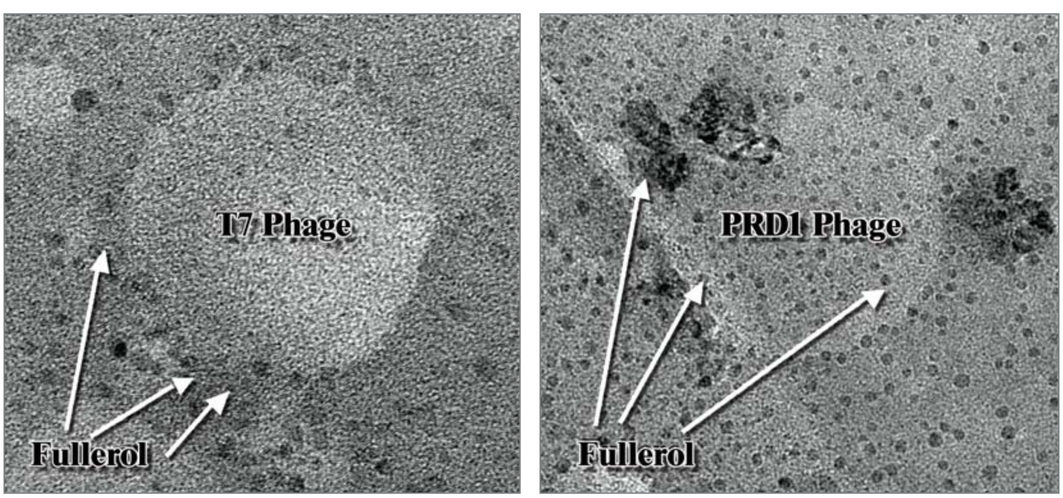

Figure 2. Attachment of fullerene nanoparticles on viruses. Image provided by Dr. Raju Badireddy, Duke University.

steps are important contributors to the lifecycle footprint and costs of making nanomaterials. In contrast with our current methods, nature makes nanomaterials with a regularity and purity that require relatively small amounts of energy. Nature's efficiency in nano-scale fabrication will be the ultimate benchmark that will define the sustainability of nanomaterial production and will inspire new production methods. The environmental footprint of nanomaterials goes beyond that associated with energy use. There are indirect risks associated with nanomaterial fabrication arising from chemical feedstocks (Robichaud et al., 2005) and waste side-streams (Plata et al., 2008) that may include substances that are known to be toxic. The "collateral damages" associated with the emerging nanomaterials industry and lifecycle issues may prove to be the dominant concerns for human health and the environment. An immediate need exists for information that will allow us to produce nanomaterials with minimal environmental impact and properly treat any waste streams that result.

The use of precious metals and rare earth elements to make nanomaterials introduces an additional wrinkle to the sustainability of nanomaterial-based technologies. The fate and impact of these materials in our environment, the monetary and energy costs associated with obtaining these materials, the security issues associated with the control of mineral resources, and the impacts on water resources associated with mining these minerals, conspire to reduce the sustainability of the resulting nanomaterials. In the short-term, the financial expense of nanomaterial production will limit the use of some nanomaterials in water treatment. In the long-term, there is much work to be done if the social and environmental dimensions of nanomaterial production are to be sustainable.

Are Nanomaterials Emerging Contaminants?

In 1948, the Swiss chemist, Paul Müller, was awarded the Nobel Prize in Physiology or Medicine for his discovery of the insecticidal qualities and use of dichlorodiphenyltrichloroethane, better known as DDT. This discovery was, and still is, important for the control of insect-borne diseases such as malaria and yellow fever. In addition to being an important tool for public health, DDT use was credited with increased crop yields and was used extensively. However, only 20 years later, serious environmental consequences of DDT became apparent. These consequences include direct and indirect toxicity, a high potential for biomagnification through the food web, and interference with calcium deposition in egg shell formation, resulting in interference with the reproduction of carnivorous birds, such as the bald eagle. Today, DDT manufacture in the United States has ceased. But, in many parts of the world, DDT manufacture continues; the pesticide is seen as a highly beneficial chemical. In 2006, the World Health Organization announced a policy change to actively support the use of DDT as a means of controlling malaria. This story illustrates the trajectory of a new material from cure to contagion and the trade-offs that occur between benefits and risks. Past technological accomplishments, such as the development of nuclear power, genetically modified organisms, information technologies, and synthetic organic chemistry, have followed similar trajectories.

Our goal is to get this technology right. One difference this time is that, along with the early euphoria and hype that typically surround the roll-out of many new technologies, the scientific community itself has taken the lead from the outset in raising questions regarding the safety of nanotechnology … well before its wide-scale commercialization, and well before there was even public awareness of the issue. This approach is a good thing for both nanotechnology and society as a whole. Raising questions when nanotechnology is still in the early stages of its developmental trajectory may result in better, safer products and less long-term liability for an emerging industry. Indeed, due diligence is the standard demanded by the law, if not the public as well.

Constructing a research strategy to evaluate the environmental and health implications of nanomaterials is a highly interdisciplinary affair that brings together a community of chemists, sociologists, ecologists, toxicologists, material scientists, computer scientists, risk assessment experts, geneticists, geochemists, economists, ethicists, atmospheric modelers, and environmental engineers. It is also an effort that spans many length-scales of investigation, ranging from field sites, to mesocosms (Figure 3), to laboratory beakers, to individuals cells.

Human- and eco-toxicologists may study nanomaterials interactions at the scale of individual genes within a cell and at the scale of populations of individuals. Ecologists study nanomaterial impacts on ecosystem functions, such as nutrient cycling at laboratory to field scale. To evaluate and interpret the toxicity or ecosystem-level effects of nanomaterials, some notion of the relevant levels of possible exposure is needed. This effort, in turn, requires an estimate of the amount of nanomaterials produced, the trends in their production, and the uses of these materials in products. Chemists and material scientists provide us with information on new kinds of nanomaterials, while social scientists provide us with critical information on market trends, human behavior in product use, and the manner in which technologies and products disseminate throughout a social network.

Figure 3. Mesocosm for studying controlled release of nanomaterials. Photo provided by Dr. Benjamin Espinasse, Duke University.

Environmental engineers provide information on where, once released, nanomaterials will go in the environment, how fast they will get there, and how long they will stay. Geochemists study the processes of nanoparticle transformation and formation in natural systems, methods for measuring these particles (Figure 4), and means of differentiating between a nanoparticle that comes from, for example, a factory (engineered), a smokestack (incidental), or a forest fire (natural). Before any of this can happen effectively, these researchers need methodologies, protocols, and a nomenclature that are adapted to the challenges presented by nanotechnologies.

It is now just more than a decade since we began to assemble such a community of researchers to look at the environmental implications of nanomaterials. What have we learned? We have observed that nanoparticles can be taken up by plants, that they may bio-magnify in food webs, and that (in some cases) they may produce toxic or developmental effects in the laboratory. We have learned (without surprise) that nanoparticles are toxic when they are made of materials such as heavy metals or fibers that we know to be toxic. Findings like these suggest that nanomaterials might find their way onto a list of emerging contaminants. However, we are also finding that nano-scale particles of natural or incidental origin have been a ubiquitous, if poorly understood, element of environmental and physiological systems for centuries. Advanced spectroscopy using high-energy light sources, electron microscopy, and other portals to the nano-scale world allow us to observe nanoscale particles and better understand how life has evolved to use and protect itself from these nano-scale materials. The bottom line is that, to date, there are no documented cases of a specific human disease or incidents of environmental damage attributed to engineered nanomaterials. While this likely reflects some good luck and a production of nanomaterials that is a still relatively limited, I believe that it also reflects the success of our community's efforts to convince an emerging nanotechnology industry to apply caution and consider risks as we move forward.

For the time being, the regulatory outlook for nanomaterials

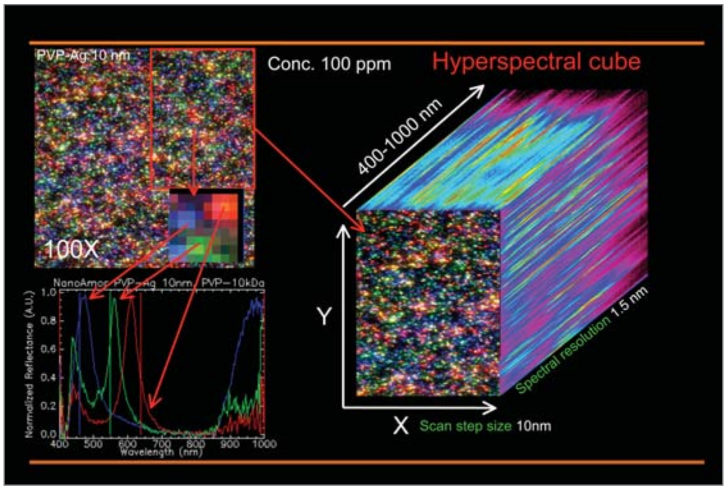

Figure 4. Hyperspectral image of silver nanoparticles. Image provided by Dr. Raju Badireddy, Duke University.

will likely be case-by-case, or grouped into categories that relate to currently regulated materials (such as all nanomaterials containing heavy metals). But, with a nearly infinite variety of nanomaterials that might be made, it will not be possible to evaluate each nanomaterial individually. We must ultimately relate nanomaterial properties to their environmental behavior and make predictions concerning the possible risk that a given nanomaterial might pose. The challenge of forecasting risk for a broad number of materials is further complicated by large degrees of uncertainty concerning production amounts, the characteristics and uses of these materials, exposure pathways, and a scarcity of data concerning the relationship between nanomaterial characteristics and their effects on organisms and ecosystems.

One vision for attacking this problem is to implement high throughput screening platforms for nanomaterials. High throughput screening allows for the rapid analysis of specific responses – typically, by bacterial or human cell cultures, plants cells, or perhaps embryos of highly characterized species of fish – to a vast number of different variables for nanomaterial properties and environmental conditions. Each condition is produced in very tiny "wells" of a microtitre plate that may contain an array of thousands of these tiny "test-tubes," each with a volume of only several micro liters. The responses of cells within these wells are read automatically, and data recognition or "nanoinformatics" procedures are then used to relate large amounts of information on nanomaterial properties and the observed responses. We will learn much from this variety of discovery science. However, the approach (analogous to a highly efficient search throughout your house for your car keys) does not replace and, indeed is strengthened by, theory-driven research that tells you to look in the pocket of the last jacket you wore. Moreover, the method is only as good as our choices of conditions and responses. It will do us no good to look in the house for our keys if we have left them at the store. When we reduce nature to a few microliters, we are liable to miss something. In fact, we have learned that organisms in complex systems, such as mesocosms, may respond in an entirely different manner than when they are placed in a laboratory – apparently due to complex interactions that we did not provide for in our laboratory experiment. This latter observation is very important as it suggests that larger-scale studies will be critical elements in providing feedback to the way that we perform high throughput screening. Feedback is also needed in the form of risk forecasts that provide updates on what we should be most concerned about and where our next experiments are likely to be most productive in clarifying risk.

Options for Managing Risk

Whether something poses a risk depends not only on its potential hazards (such as toxicity, mutagenicity, or impacts on ecosystem services), but also to what degree the material comes in contact with organisms and ecosystems (exposure). All that is hazardous is not necessarily risky. For instance, while the hazards of electricity may be large, the risks are small when exposure to electricity is properly managed. Any effort to forecast risk must, therefore, consider what one might do to manage that risk. Risk management for the nanomaterials industry should begin at the point when nanomaterials are conceived. However, the potential for managing the risk of nanomaterials by designing them to have low hazard offers a limited range of options as it is often the properties of a material that produce the hazard that make the material useful in a specific application – for example, gasoline burns. Can we mitigate risk by designing safer nanomaterials? I believe that the answer is yes if we focus on the exposure side of the equation. A risk management strategy for nanomaterials rooted in a fundamental understanding of the possible pathways of exposure leads to a broad array of options for managing risk, which include protective devices for workers in nanomaterials fabrication industries, standards for product disposal or recycling, water treatment and air treatment technologies, changes in human behavior, and (in extreme cases) an outright ban on the production of a given nanomaterial. At the design stage of nanomaterials, one can envision nanomaterials that retain the novel properties that make them of interest, but that are modified to limit bioavailability, mobility, or persistence.

This discussion underscores the vast amount of work to be done if we are to understand how first-generation nanotechnologies in the form of nanomaterials behave in the environment and how we might responsibly make and use them. However, nanomaterials are only the first step towards manipulating matter at the nanoscale. Nanomaterials are not only chemicals, but "places" at the nanoscale where complex interactions may occur. We will ultimately design these places as hubs of activity that perform specific functions. When such active nanosystems become environmental detritus, our challenge may more closely resemble that of understanding the environmental behavior of a virus rather than of a chemical.

Nanotechnology and Future Technologies

The case of evaluating the environmental and health implications of nanotechnology that I have described is only one in a continuous stream of emerging technologies. On the horizon are developments in metamaterials, synthetic biology, artificial photosynthesis, and biofuels (just to name a few emerging technologies) that will require an examination of their sustainability.

Elements shared by emerging technologies in the generic sense include high degrees of uncertainty and an evolving profile of perceived risk and benefits. At the heart of the problem is the question, "How do you forecast risk to human health and the environment for an industry that doesn't exist yet?" A process for forecasting the risk of an emerging technology should include the ability to generate forecasts and associated levels of uncertainty that provide both long-term guidance and relevance for the issues of immediate concern that typically announce the arrival of a new technology. A risk forecasting process should include lifecycle impacts that account for energy and material use, as well as wastes generated. It should have the ability to adapt and update risk forecasts as new information becomes available, and it should provide feedback to inform the scientific process and improve emerging technology.

We are presented with the opportunity to design entire industries from the ground up as environmentally beneficial enterprises. Proactive, preventative research to realize that possibility is not free. But, how much should society invest in preventive research and how do we judge the success of this investment? Recent investments in research of this nature in the nanotechnology sector have been estimated to be no more than 5 percent of the total investment under the United States National Nanotechnology Initiative. Reported public investments by European Union countries appear to be of a similar magnitude. Well-established components of the private sector that may be users of nanomaterials have also shown interest in investing in such research. However, the credibility of private-sector financed research in this area has been questioned by environmental non-governmental organizations (NGOs) (Powell, 2004) and the public may be reluctant to validate data produced by such efforts. Public trust in science and technology information appears to differ based on whether the information originates from government, NGOs, the press, or private sector institutions. Moreover, there are important cultural differences in the trust that the public places in each of these institutions. For example, Europeans tend to place greater confidence in information provided by NGOs while viewing information from government, industry, and the press with more skepticism than their American counterparts (Jensen, 2000). These differences are likely to translate into public policy and become important factors in the dissemination and acceptance of emerging technologies. The precautionary principle, often used to describe the Western European approach to regulation and frequently championed by environmental NGOs, might be summarized as "no data, no market." In contrast, the risk-based approach that has come to typify regulatory development in the United States might be reduced to the philosophy of "no data, no regulation." Indeed, the European Union is positioned to regulate nanomaterials under its Registration, Evaluation, Authorisation, and Restriction of Chemical substances legislation (REACH), which places greater responsibility on industry to identify at an early stage the intrinsic properties of chemical substances that may present risk and to provide safety information on new substances entering European markets. The European Chemicals Agency is formulating technical instructions to help companies include nanomaterials in their registration dossiers under REACH and other compliance obligations for substances they make or import. Japan is moving in a similar direction under its Chemical Substances Control Law that, as amended, requires companies to report hazard and use information for chemicals manufactured in or imported into Japan. While the position in the United States may differ from that of other developed nations, constituencies in all cases appear to be calling for more reliable data.

These data are a public good that is not readily provided by the private sector. Government support for research to produce impartial data on the environmental and health implications of emerging technologies is needed to assure the public of the credibility of the data and to provide information to the private sector, particularly start-ups, which in turn helps ensure the flow of investment capital and trouble-shoot potential problems with proposed products. International academic collaborations can only enhance the perceived quality of this research and improve commerce. This is not to imply that good information, made available to all parties, will be sufficient to avoid public health or environmental calamity. Risk-taking in the face of well-informed, unfavorable odds is well-documented, and we need only look to last year's experience in the Gulf of Mexico with the application of the highly advanced technology of off-shore drilling to observe the environmental consequences when risk, lax regulation, and underfunded enforcement meet bad luck. In addition to promoting better information, governments have a vital role to play in facilitating economic prosperity and social wellbeing through well-conceived and rigorously applied rules by which we all play. Or, to put it in nano-terms, government is an external force that accelerates the "self-assembly" of environmentally responsible industries in competitive markets. The costs and consequences of under-investment in public goods, such as enforcement, education, and research in the area of public safety and environmental quality, will be borne by future generations every bit as heavily as any debts those generations may inherit.

I would like to summarize these remarks with three messages: First, the development of new technologies and a precautionary, proactive examination of the possible impacts of these technologies are not activities in opposition. An evaluation of the possible impacts of emerging technologies on human health and the environment is essential to the adoption and advancement of the technologies themselves. It is an investment in future generations and an insurance policy that encourages commercialization of new technologies by protecting companies and investors against damages, liability, and the loss of investment.

Second, this effort will not happen by itself. Recognition has grown in the scientific, business, and civil sectors of the legitimacy of examining the broader implications of new technologies. But when push comes to shove, there is always the temptation to do the equivalent of spending the car insurance money on gas.

Governments must create a level playing field for industries to operate responsibly while aiding the commercialization of new technologies and protecting public safety with a set of priorities that ensure “implications” research happens as an integral part of “applications” work.

Finally, in the face of important global challenges, I am optimistic that technological innovations, such as those inspired by nanotechnology, will ultimately provide us with cleaner sources of energy, greater access to potable water, and improved sanitation services. Unfortunately, these technological advances can only serve to treat the symptoms of the more fundamental problems of overconsumption, waste, and market incentives that favor short-term gain over the interests of our planet’s current and future generations.

Thank You

In closing, I would like to thank the Joan Irvine Smith & Athalie R. Clarke Foundation, the Irvine Family, and the National Water Research Institute for making the Clarke Prize possible. I thank Clarke Laureate Phil Singer for nominating me, and the Clarke Prize Executive Committee for selecting me for this honor. I am truly humbled to be in the company of the Clarke Laureates, a group that includes many of the inspirational individuals who have taught me through their publications and their example. Among them, I am deeply indebted to Charlie O’Melia and Jerry Schnoor, who have been such important mentors to me. I thank my co-doctoral advisor, Jerry Cohon, my student-colleagues with whom I have had the privilege of working and learning from, and my family who has given me opportunity, purpose, and much support.

References

Becker, L., R. Poreda, J. Nuth, F. Ferguson, F. Liang and W.E. Billups (2006). “Fullerenes in Meteorites and the Nature of Planetary Atmospheres,” in *Natural Fullerenes and Related Structures of Elemental Carbon*, F.J.M. Rietmeijer, Editor, Springer, Netherlands, p. 95-121.

Heymann, D., L.P.F. Chibante, R.R. Brooks, W.S. Wolbach, and R.E. Smalley (1994). “Fullerenes in the Cretaceous-Tertiary Boundary-Layer.” *Science*, 265(5172): 645-647.

Heymann, D., L.P.F. Chibante, and R.E. Smalley (1995). “Determination of C-60 and C-70 Fullerenes in Geologic Materials by High-Performance Liquid-Chromatography.” *Journal of Chromatography A*, 689(1): 157-163.

Jensen, P. (2000). “Public trust in scientific information,” in *Institute for Prospective Technological Studies, Joint Research Center, European Commission, Seville, Spain.*

Powell, K. (2004). *Green groups baulk at joining nanotechnology talks: International Council on Nanotechnology accused of industry bias.* news@nature.com (last accessed June 15, 2011).

Plata, D.L., P.M. Gschwend, and C.M. Reddy (2008). “Industrially synthesized single-walled carbon nanotubes: Compositional data for users, environmental risk assessments, and source apportionment.” *Nanotechnology*, 19(18): 14.

Robichaud, C.O., D. Tanzil, U. Weilenmann, and M.R. Wiesner (2005). “Relative risk analysis of several manufactured nanomaterials: An insurance industry context.” *Environmental Science and Technology*, 39(22): 8,985-8,994.

The 2011 Clarke Prize Honoree

MARK R. WIESNER, PH.D., P.E.

Environmental engineer Mark R. Wiesner, Ph.D., P.E., was selected as the eighteenth recipient of the NWRI Athalie Richardson Irvine Clarke Prize because of his groundbreaking efforts and leadership in improving water quality through advancements in membrane and nanotechnology research. He is the James L. Meriam Professor of Civil and Environmental Engineering at Duke University in Durham, North Carolina.

Dr. Wiesner was among the first American scientists to research the application of low-pressure membranes to water treatment. He initiated research on the factors controlling membrane performance, and proposed using coagulants as a pretreatment to remove organic matter and prevent membrane fouling. Later, he and his students developed cost models that predicted the circumstances in which membrane filtration would be cost-competitive with conventional water treatment technologies. The following year, he edited and co-authored the first membrane process book for environmental engineers.

His efforts to improve the performance of water treatment membranes led him to a new area of research: investigating the uses of technology at the molecular level ("nanotechnology"). Initially working in the area of applications of nanochemistry to membrane science, he has also explored the use of nanomaterials for environmental remediation, as advanced sorbents in water treatment, and as "smart" disinfectants that inactivate viruses without creating harmful byproducts. His work in developing nanomaterial-based technologies for water treatment led him to consider the possible detrimental effects that these materials might have on human health and the environment – in effect, pioneering the field of environmental implications of nanotechnology.

Since the late 1990s, Dr. Wiesner has taken the lead in studying the fabrication, transport, fate, toxicity, and risk of nanoparticles in the environment. One of his major accomplishments was the creation of the Center for the Environmental Implications of NanoTechnology (CEINT) at Duke University, where he serves as Director. A multidisciplinary research effort supported by the National Science Foundation and U.S. Environmental Protection Agency, CEINT is focused on understanding nanomaterial behavior from the nano-scale to the ecosystem-scale and identifying possible risks to human health and the environment. These efforts, among others, have earned Dr. Wiesner recognition as the leading researcher in water treatment and environmental nanotechnology.

The

ATHALIE RICHARDSON IRVINE

Clarke Prize

for Outstanding Achievement

in Water Science and Technology

The 2011 Clarke Prize Lecture, Nanomaterials, Water, and the Directed Self-Assembly of Environmentally Responsible Industries, *by Mark R. Wiesner, Ph.D., P.E., was presented on Thursday, July 14, 2011, at the Eighteenth Annual Clarke Prize Award Ceremony and Lecture, held at Hyatt Regency Newport Beach in Newport Beach, California.*

The National Water Research Institute (NWRI) of Fountain Valley, California, established the Clarke Prize in 1993 to recognize research accomplishments that solve real-world water problems and to highlight the importance of and need to continue funding this type of research. Dr. Wiesner was the eighteenth recipient of the prize, which includes a medallion and $50,000 award.

The Clarke Prize was named after NWRI's co-founder, the late Athalie Richardson Irvine Clarke, who was a dedicated advocate of the careful stewardship and development of our water resources. Mrs. Clarke's daughter, Mrs. Joan Irvine Smith (also an NWRI co-founder), is patron of the award.

NATIONAL WATER RESEARCH INSTITUTE

18700 Ward Street ✦ P.O. Box 8096

Fountain Valley, California 92728-8096

(714) 378-3278 ✦ Fax: (714) 378-3375

www.NWRI-USA.org