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Section of Environment, Energy, and Resources

Ethical Considerations Regarding the International Development and Application of Nanotechnology and Nanoscale Materials

Rex R. Raimond[1]
Meridian Institute
Dillon, CO

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Opportunities and Risks of Nanotechnology

Perceived by many as the next "transformative technology," like electricity or the Internet, nanotechnology encompasses a broad range of tools, techniques, and applications that manipulate or incorporate materials at the nanoscale (a nanometer is one billionth of a meter) in order to yield novel properties that do not exist at larger scales. These novel properties may enable new or improved solutions to problems that have been challenging to solve with conventional technology. These solutions may include more efficient, effective, and inexpensive water purification devices, energy sources, medical diagnostic tests and drug delivery systems, durable building materials, and other products. Additionally, nanotechnology may significantly increase production capacities by enabling manufacturing processes that create less pollution and have modest capital, land, labor, energy, and material requirements.

Both the public and private sectors in developed and developing countries are investing heavily in nanotechnology research and development. More than 20 countries, including emerging economies such as China, South Africa, Brazil, and India, have national nanotechnology programs, and many more are developing or expanding nanotechnology research and development capacity. The collective public and private sector investment in 2005 was approximately US$10 billion, up 20% compared to 2004.[2] In addition, the number of patents on nanotechnology-related inventions (including those from developing country researchers),[3]

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[1] Rex Raimond is a Mediator with Meridian Institute. Meridian Institute is a not-for-profit organization with a mission to help people solve problems and make informed decisions regarding complex and controversial societal issues. Rex designs, convenes and facilitates collaborative processes on issues regarding: nanotechnology; science and technology; intellectual property; international development; agriculture and biotechnology; forestry; water and watershed management; climate and energy; and security.

[2] M. W. Holman, et al., "The Nanotech Report, 4th Edition", 2006, Lux Research.
[3] K.A. Singh, "Intellectual Property in the Nanotechnology Economy", 2007, Institute of Nanotechnology.

scientific literature citations (up to 12,000 publications per year),[4] and nanotechnology-based products reaching the market are skyrocketing globally.

The rise in nanotechnology investments and proliferation of applications has contributed to growing international dialogue about implications of the rapid evolution of nanotechnology, including potential near- and long-term social and economic disruptions, human health and environmental risks, and ethical, legal, and other impacts. Governments, companies, NGOs, universities, international institutions, standardization bodies, and other stakeholders have initiated a number of efforts to discuss, develop, and implement risk assessment, governance, standardization, and public involvement strategies to address these potential implications.

The following pages provide illustrative examples of possible opportunities and risks presented by nanotechnology. The broad range of issues associated with responsible research and development of nanotechnology, specific technologies, opportunities, risks and other issues are described in the context of nanotechnology applications for water purification.

Nanotechnology Opportunities

Water

Nanotechnology for water purification has been identified as a high priority because water treatment devices that incorporate nanoscale materials are already available and global needs for clean water are pressing. Poverty and water are closely linked and access to water resources has become widely equated with ensuring that basic human needs are met.

In 2002, 1.1 billion people lacked access to safe drinking water, and 2.6 billion people lacked access to adequate sanitation. The consequences of lack of access to clean water and adequate sanitation are overwhelming - waterborne diseases and water-related illnesses kill more than five million people a year worldwide, 85% of these being children, according to the World Health Organization.[5]

Given the importance of clean water to people in developed and developing countries, numerous organizations are considering the potential application of nanoscience to solve technical challenges associated with the removal of water contaminants. Technology developers and others claim that these technologies offer more effective, efficient, durable, and affordable approaches to removing specific types of pollutants from water. A range of water treatment devices that incorporate nanotechnology are already on the market and others are in advanced stages of development. These nanotechnology-based products include nanofiltration membranes; nano-ceramic, clay, and polymer filters; zeolites; nanocatalysts; magnetic nanoparticles; and nanosensors.

Nanofiltration membrane technology is already widely applied for removal of dissolved salts from salty or brackish water, removal of micro pollutants, water softening, and wastewater treatment. Nanofiltration membranes selectively reject substances, which enables the removal of harmful pollutants and retention of nutrients present in water that are required for the normal functioning of the body. It is expected that nanotechnology will contribute to improvements in

[4] V. Colvin, "Responsible Nanotechnology: Looking Beyond the Good News", 2002, EurekAlert, http://www.eurekalert.org/context.php?context=nano&show=essays&essaydate=1102.
[5] Task Force 7 on Water and Sanitation, UN Millennium Project. 2004. *Interim Full Report.* Available at: http://www.unmillenniumproject.org/documents/tf7interim.pdf.

membrane technology that will drive down the costs of desalination, which is currently a significant impediment to wider adoption of desalination technology.

Rensselaer Polytechnic Institute in the U.S. and Banaras Hindu University[6] in India devised a simple method to produce carbon nanotube filters that efficiently remove micro- to nanoscale contaminants from water. Made entirely of carbon nanotubes, the filters are easily manufactured using a novel method for controlling the cylindrical geometry of the structure. Carbon nanotube filters offer a level of precision suitable for different applications as they can remove 25-nanometer-sized polio viruses from water as well as larger pathogens such as E. coli and Staphylococcus aureus bacteria. The nanotube based water filters were found to filter bacteria and viruses and were more resilient and reusable than conventional membrane filters. The filters were reusable and could be cleaned by heating the nanotube filter or purging. Nano-engineered membranes allowed water to flow through the membrane faster than through conventional filters.[7]

Argonide[8] in the United States, using grant money from the U.S. National Aeronautics and Space Administration, has developed a filter comprising oxidized aluminum nanofibers on a glass fiber substrate. These alumina fibers are positively charged, which enables them to filter bio-organisms such as bacteria and viruses from the water flow. Even though the pores in this filter are relatively large, the end result is extremely effective because the process provides a much higher flow rate than traditional membranes. The filter retains up to 99.999% of viruses, is currently in production, and can be used to clean water by applying muscle force with no extra energy needed, ideal for rural contexts.

A project by North West University in South Africa, incorporated nanofiltration elements from Filmtec, a U.S. subsidiary of Dow Chemical Company, to purify drinking water supplies in rural communities. The Filmtec elements are used to treat municipal water supplies where salts such as nitrate, phosphate, sulphate, chloride, calcium, magnesium, and sodium ions must be removed[9]

The Long Beach Water Department, a public utility in the U.S., has developed a nanofiltration process referred to as the Long Beach Method, which uses existing nanofiltration membrane technology for desalination, but adds an innovative two-staged nano-filtration process that requires much lower pressure than other desalination methods. This unique process is now being tested on a larger scale.[10]

Zeolites, clays, and nanoporous polymers are also materials used for nanofilters. While these materials have been used for many years to purify water, recent improvements in scientists' ability to manipulate on the nanoscale allow for greater precision in designing these materials, for instance, allowing much greater control over pore size of membranes.[11]

Zeolites are microporous crystalline solids with well-defined structures. Generally they contain silicon, aluminium, and oxygen in their framework and cations, water, and/or other molecules

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[6] Efficient Filters Produced from Carbon Nanotubes through Rensselaer Polytechnic Institute – Banaras Hindu University Collaborative Research, 2004, <http://news.rpi.edu/update.do?artcenterkey=435>.
[7] A. Srivastava et al., "Carbon Nanotube Filters," *Nature Materials* 3, 2004, pp. 610–614.
[8] Argonide, <http://www.argonide.com/>.
[9] T. Hillie et al. "Nanotechnology, Water, and Development," 2006, pp. 35 – 39, Meridian Institute http://www.merid.org/nano/waterpaper/.
[10] Water Industry News, "Long Beach Water Department Wins $3 Million California Grant for Innovative Seawater Desalination Project," April 12, 2005, <http://www.waterindustry.org/New%20Projects/desal-20.htm>.
[11] Cientifica, "Nanoporous Materials," 2003, <http://www.cientifica.com/>.

within their pores. Many occur naturally as minerals and are extensively mined in many parts of the world. Others are synthetic and are made commercially for specific uses or produced by research scientists trying to understand more about their chemistry. Zeolites can be used to separate harmful organics from water and to remove heavy metal ions from water.[12]

CSIRO in Australia has developed a process that enables low-cost, local production of synthetic anionic clay called hydrotalcite that can be used to remove arsenic and possibly fluorides from water and groundwater. Hydrotalcite, which is currently used in a variety of applications including antacids and time-release fertilizers, is synthesized by combining an ammonia solution with a mixed solution of magnesium or aluminum. The magnesium and aluminum solutions are both prepared with commonly occurring materials called magnetite and bauxite. CSIRO's process salvages magnetite and bauxite from aluminum cans, reducing production costs and enabling local production. The production process can be scaled up or down and can be carried out in small plants or incorporated into nitrogenous fertilizer plants due to a similarity in production process. Methods are now being developed for deploying this technology in a product aimed at low-income communities. The clay could be sprinkled on top of the water, or sold in teabags that are steeped in water prior to drinking. At the community level, hydrotalcite can be installed in the form of an in-line filter in hand pumps.

Researchers at Los Alamos National Laboratory have developed a new class of nanoporous polymeric materials that can be used to reduce the concentration of common organic contaminants in water to parts-per-trillion levels.[13] These organic nanoporous polymers with narrow pore-size distribution (0.7 – 1.2 nm) have been synthesized using cyclodextrins as basic building blocks. The researchers say that the binding between organic contaminants and the nanoporous polymer is 100,000 times greater than the binding between organic contaminants and activated carbon, which is commonly used in wastewater treatment. These materials can be used for the purification of municipal water supplies or for recycling and reuse of industrial wastewater.

Nanocatalysts include enzymes, metals, and other materials with enhanced catalytic capabilities that derive from either their nanoscale dimensions or from nanoscale structural modifications. These substances promote the chemical reaction of other materials without becoming permanently involved in the reaction. Controlling a material's size and/or structure at the nanoscale can produce catalysts that are more reactive, more selective, and longer lasting. Consequently, smaller quantities of catalysts are needed, reducing raw materials consumption, byproducts and waste, and, potentially, the overall cost of catalysis.

Nanocatalysts such as titanium dioxide (TiO_2) and iron nanoparticles can be used to degrade organic pollutants and remove salts and heavy metals from liquids. People expect that nanoelectrocatalysts will enable the use of heavily polluted and heavily salinated water for drinking, sanitation, and irrigation.[14] Using catalytic particles either dispersed homogeneously in solution or deposited onto membrane structures could chemically degrade pollutants instead of

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[12] British Zeolite Association, <http://www.bza.org/>.
[13] M. C. Roco, et al. (eds.), "Visions for Nanotechnology Research and Development in the Next Decade," Interagency Working Group on Nanoscience, Engineering, and Technology, Loyola College, Maryland, September 1999, Section 10, "Nanoscale Processes in the Environment," pp. 143 – 153, <http://www.wtec.org/loyola/nano/IWGN.Research.Directions/Section10.pdf>; and Los Alamos National Laboratory, "Nanoporous Polymers for Water Purification," http://www-emtd.lanl.gov/TD/Remediation/NanoPorousPolymer.html.
[14] "Forging Ahead: Technological Innovation and the Millennium Development Goals," Task Force on Science, Technology, and Innovation, UN Millennium Project, November 8, 2004, <http://www.cid.harvard.edu/cidtech/TF10Edit11-8.pdf>.

simply moving them somewhere else. Catalytic treatment of polluted water could be specifically targeted to degradation of chemicals for which existing technologies are inefficient or cost prohibitive.

PARS Environmental, an environmental engineering firm in the US, manufactures nanoscale zero-valent iron (NZVI) used for in-situ remediation of microbial and organic (VOC) contamination in groundwater.[15] This technology has been approved and field-tested by the US Environmental Protection Agency (EPA) for the remediation of a so-called Superfund site that is highly contaminated with Trichloroethylene (TCE). NZVI functions simultaneously as an adsorbent and a reducing agent, causing organic contaminants to breakdown into less toxic simple carbon compounds and heavy metals to agglomerate and stick to the soil surface. NZVI can be injected directly into the source of contaminated groundwater for *in situ* treatment or embedded in membranes for *ex situ* applications. Once released in the environment, the NZVI cannot be removed, though their consumption during reactions with contaminants and relatively low mobility may reduce the risk of environmental impacts.

U.S.-based Inframat Corporation is developing a material composed of a highly porous nanofibrous structure that can be used to remove arsenic from drinking water by combining a nanofibrous MnO_2 oxidative process with a granular ferric hydroxide adsorptive process.[16] The technology supposedly circumvents the limitations of today's active-site nanoparticulate materials that have a strong tendency to form agglomerates, which limit the permeability of the reactive constituents into and through the agglomerated mass. Another company, EnvironmentalCare from Hong Kong, has developed a nano-photocatalytic oxidation technology for the removal of bacteria and pollutants from water.[17] It uses nano-coated TiO_2 filters that trigger a chemical process, which converts harmful pollutants into the harmless end products of carbon dioxide and water. In photocatalysis, water passing through a nanomaterial is also subjected to ultraviolet light, leading to the destruction of contaminants.

Another example of potentially promising research is provided by researchers in the United States at the Universities of Illinois and Pittsburgh and Yeshiva University who are exploring the use of nanocatalysts to reduce pollution of oxidized contaminants (e.g., nitrates). Nitrate is a stable and highly soluble ion with a low potential for co-precipitation or adsorption so that removal of nitrates using conventional water treatment is difficult. This research focuses on identifying the most promising catalysts (e.g., bimetallic metal catalysts such as Pd-Cu) to use for the reduction of nitrate and other oxidized compounds and to gain fundamental understanding of the reactivity and selectivity of these new catalytic materials.[18]

Researchers at Rice University in the United States are exploring nanocatalysts to remove tri-cholorethylene and organic aromatic contaminants, mainly pesticides, from groundwater.[19] The researchers suggest that although each system requires a different catalyst and overall remediation strategy, nanoscale engineering of materials permits the design of more efficient systems. For instance, the researchers have developed a new way to produce high surface area (> 250 m2/gm)

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[15] See http://www.epa.gov/Region5/sites/nease/background.htm and http://www.parsenviro.com/nanofeaw-1.html.
[16] Inframat, "Description of Nanofibrous MnO_2 Bird's-Nest Superstructure Catalyst," <http://www.inframat.com/cat2.htm>.
[17] Nano-Fotocide, <http://www.fotocide.com/index.html>.
[18] H. Xu et al., "Structural Changes of Bimetallic PdX/Cu (1-X) Nanocatalysts Developed for Nitrate Reduction of Drinking Water," *Materials. Research Society Symposium Proceedings*, Vol. 876E, 2005, <http://pubweb.bnl.gov/users/frenkel/www/MRS/MRS-2005-1.pdf>.
[19] Center for Biological and Environmental Nanotechnology, "Nanocatalysts for Remediation of Environmental Pollutants," <http://cohesion.rice.edu/centersandinst/cben/research.cfm?doc_id=5099>.

nanocrystalline titania, which under UV illumination is capable of photo-oxidizing a variety of molecules. Additionally, ongoing work on the environmental implications of fullerenes, particularly C_{60}, led these researchers to hypothesize that the oxygen radical production capabilities of nanoscale C_{60} aggregates in water could be leveraged for degradation of contaminants.

Magnetic nanoparticles are being investigated for a variety of chemical separation applications including water treatment because they have high surface areas and can bind with chemicals without the use of auxiliary adsorbent materials. Additionally, the application of surface coatings can functionalize the chemical reactivity of magnetic nanoparticles, making them suitable as nanocatalysts for the chemical decomposition of chemicals. Once adsorption or catalysis has occurred, the magnetic nanoparticles can be removed from the water using a magnet or a magnetic field and reused.

Rice University in the U.S. is developing a method for circulating loose magnetic nanoparticles in contaminated water to bind with contaminants such as arsenic, and then removing the magnetic nanoparticles and the attached arsenic from the water using a magnetized filter. This technology is currently in the laboratory stage of development, and manufacturing methods are still being studied.

Tata Chemicals in India has developed candle filters embedded with magnetic nanoparticles. The manufacturing costs of these filters are expected to be as low as five percent of currently available and comparable technologies. Additionally, the filter material could be made locally using available materials such as sand and rice husks.

The University of Brasilia in Brazil has developed a technology consisting of magnetic nanoparticles designed to absorb and remove oil from water. The technology can be used to magnetize clay to separate oil, for example in case of oil spills. The clay can then be collected using a magnet. Reversing the magnetic charge allows both the clay and the oil to be reused, although the clay will eventually become less effective as it gets clogged and loses its porosity. The technology has been tested in the lab and seems promising for magnetic separation of contaminants and nanoparticles, and could be promising in combination with other clays for specific applications because of its “tune ability,” affinity, and reactivity. The technology can also be used as “tags” to magnetize yeast cells to metabolize dyes in wastewater from textile plants. It is expected that the magnetic nanoparticles can also be used to magnetize other bacteria for treating additional contaminants.

Nanosensors for the detection of contaminants and pathogens can improve health, maintain a safe food and water supply, and allow for the use of otherwise unusable water sources. Nanosensors can detect single cells or even atoms, making them far more sensitive than counterparts with larger components. Conventional water quality studies rely on a combination of on-site and laboratory analysis, which requires trained staff to take water samples and access to a nearby laboratory to conduct chemical and biological analysis. New sensor technology combined with micro- and nanofabrication technology is expected to lead to small, portable, and highly accurate sensors to detect chemical and biochemical parameters.

The European Committee funded project BioFinger in developing a portable, versatile, and low-cost molecular detection tool. BioFinger is developing a handheld device that incorporates nano- and microcantilevers on a microchip. The microchip is disposable after each use, allowing it to be reconfigured with new on-chip cantilevers configured to detect different molecules. Each disposable chip is expected to cost around 8 Euros.[20] The system could be used to analyze chemicals and bacteria in water. The BioFinger project was due to begin testing its system in 2005 amid expectations for a commercial product to be available on the market within two to three years.

Researchers from the University of Buffalo in the United States, with funding from the National Science Foundation, are developing a handheld sensor that can detect the presence of toxins potentially used as agents in biological warfare.[21] The sensor will be composed of three components—an LED (i.e., light-emitting diode), a xerogel-based sensor array, and a complementary metal-oxide semiconductor detector, commonly used in miniature digital cameras. In experiments using this sensing system, the researchers successfully designed a prototype that detected the presence of oxygen. According to the researchers, the sensors can be constructed to detect many different toxins or to detect the same toxin in different ways as a fail-safe. When light from the sensors is imaged onto the face of the CMOS detector, an electrical signal is produced, which can be read by a personal digital assistant, mobile phone, or similar handheld device.

A Binghamton University chemist has been awarded a three-year grant from the U.S. Environmental Protection Agency to develop advanced nanosensors for continuous monitoring of heavy metals in drinking water and industrial effluent.[22] The researchers have already developed a prototype nanosensor that can concentrate and trap lead particles ten times smaller than a human hair. The researchers intend to develop a one-square centimeter prototype nanoreactor that is capable of detection and remediation of lead, cadmium, arsenic, chromium 6, and copper.

Energy

Energy is a large factor in international environmental debates (e.g., climate change), poverty alleviation (e.g., 2.4 billion people still use traditional biomass energy), and geopolitics (e.g., impact of oil dependence and global markets). Alternative energy sources, increased energy storage and transportation are all considered critical elements of a more sustainable energy future.

Cheap solar-powered electricity has long been an aspiration for many countries, but glass and silicon photovoltaic panels remain too expensive and delicate. Nanotechnology may allow for the production of cheap photovoltaic films that can be unrolled across the roofs of buildings. It may even be possible to paint solar power films onto surfaces.

U.S.-based company Nanosolar has developed nanotechnology-based solar panels that are produced by printing photovoltaic cells directly onto flexible plastic and foil.[23] Nanosolar says that its panels are as efficient as silicon panels, but can cost one-fifth as much to produce. Nanosolar plans to sell the panels for use on the rooftops of large buildings and as stand-alone

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[20] BioFinger, <http://www.biofinger.org/>; and Information Society Technologies, "Portable Molecular Detection Tool to Revolutionise Medical Diagnosis," <http://istresults.cordis.lu/index.cfm/Section/news/Tpl/article/BrowsingType/Features/ID/77729/highlights/biofinger>.
[21] J. Della Contrada, "UB Researchers Developing Sensors to Detect Agents Used in Biological Warfare," *UB Reporter*, December 4, 2003, <http://www.buffalo.edu/reporter/vol35/ vol35n14/ articles/TitusBiosensors.html>.
[22] S. E. Barker, "A Featherweight Solution for a Weighty Problem: BU Chemist Wins $351K EPA Grant to Develop Nanoreactor to Detect, Trap Heavy Metals in Water," *discover-e*, 2003, <http://research.binghamton.edu/Discovere/june2003/TopStories/OSadik.htm>.
[23] Paul Rogers, "World's largest solar plant planned in Bay Area," Mercury News, June 21, 2006, <http://www.nanosolar.com/cache/sjmnwl.htm>.

power plants, but is also developing solar panels designed to fit archways, columns, and other architectural elements.

Global energy company BP and the California Institute of Technology in the U.S. are developing solar cells made from an array of nanorods that will be able to absorb light and collect solar electricity more efficiently than conventional solar cells.[24] The use of nanorods is also expected to make new design approaches for low-cost solar cells possible.

Much research is also focusing on the development of hydrogen fuels. Researchers from the Ecole Polytechnique Fédérale de Lausanne in Switzerland are developing nanostructured thin films containing cobalt and silicon to more efficiently produce hydrogen for fuel cells from water with solar light through a process known as photocatalytic water splitting.[25] Iron oxide has long been considered for use in solar panels because of its water resistance, but its use has been limited by the inability of electrons to easily escape the material. The researchers overcame this limitation by adding the silicon to the material and forming it into structures with very high surface area that allows most of the material's atoms to touch the water, improving the electron conductivity of the material. The researchers report that the enhanced films convert an "unprecedented" 42 percent of ultraviolet photons in sunlight into electrons, achieving an overall efficiency of 4 percent. UK company Hydrogen Solar is now developing a method to mass-produce solar cells containing the new material for use as a clean, CO_2-free fuel for transport and home energy installations.

Energy storage systems can store energy produced at off-peak times to be used at peak times; they can help provide photovoltaic energy throughout the day and night. Nanotechnology approaches include using nanoparticles and nanotubes for batteries and fuel cells. U.S. nanomaterials manufacturer Altair Nanotechnologies is developing lithium ion batteries containing their proprietary nano-titanate material instead of graphite that can recharge and discharge significantly faster and more often than existing lithium ion batteries.[26] Because the nano-titanate material does not have to expand or shrink when ions enter and leave its particles during charging and discharging, the nano-titanate batteries can be charged over 9,000 times while retaining 85 percent of their charge capacity, while conventional lithium ion batteries typically have a useful life of 750 charges. The nano-titanate batteries can also be charged to 80 percent of their capacity in about one minute.

Researchers from Seoul National University in South Korea have identified a polymer material with large hydrogen storage capacity.[27] The material is a conducting polymer called polyacetylene with titanium atoms attached, and it can hold 63 kilograms of hydrogen per cubic meter, which is more than any other material identified by the researchers. The researchers say that this new material can store large quantities of hydrogen under practical conditions.

Health

[24] "BP Sees Potential Breakthroughs In Solar Energy Using Nanotech," Inside Green Business, July 11, 2006.

[25] Kevin Bullis, "Solar-Powered Hydrogen Generation," MIT Technology Review, December 12, 2006, <http://www.technologyreview.com/Energy/17887/>.

[26] "'Nano-Titanate' Car Batteries," EcoWorld, September 11, 2006, <http://www.ecoworld.com/blog/2006/09/11/nano-titanate-car-batteries/>.

[27] Belle Dumé, "Top hydrogen-storing polymer revealed," Nanotechweb, August 29, 2006, <http://nanotechweb.org/articles/news/5/8/11/1>.

Nanotechnology offers a range of possibilities for healthcare and medicinal breakthroughs, including targeted drug delivery systems, extended-release vaccines, enhanced diagnostic and imaging technologies, and antimicrobial coatings.

Starpharma, an Australian biotechnology company, has developed VivaGel microbicide, a topical gel that could reduce the risk of HIV infection in women.[28] It is said to be the world's first drug based on nanoscale polymers known as dendrimers, which according to a company spokesman "stick to the AIDS virus surface like molecular Velcro and prevent it from attaching to the cells it is trying to infect."

Nanotechnology could also enable simple, accurate, small, and stable diagnostic tests and devices. U.K. nanotechnology firm Akubio is developing a portable, low cost rapid-response device for diagnoses of diseases such as malaria, avian flu, E. coli, meningitis, and some cancers.[29] The device employs the quartz crystal element used in wristwatches to determine the presence of specific disease marker proteins within blood samples.

Nanoporous membranes may help with disease treatment. Making the nanopores only slightly larger then the molecules of drugs can control the rate of diffusion of the molecules, keeping it constant regardless of the amount of drug remaining inside a capsule. U.S. nano-biopharmaceutical company NanoViricides, Inc. has developed a viral therapy that uses an engineered flexible nanomaterial containing encapsulated active pharmaceutical ingredients to target specific viruses such as avian flu and common influenza, and block and dismantle the viruses before they can infect cells.[30] The Multi-Imaging Center at the University of Cambridge in the U.K. is developing a slow release vaccine that may reduce vaccination costs by eliminating the need for boosters.[31] The vaccines are embedded in microspheres of calcium phosphate glass, a chemical that dissolves in the body. Nanoparticles within the microsphere regulate the slow release of the vaccine over time. The vaccines will be stable enough to be stored without a cold chain and will not require reconstitution or bactericides, both of which can compromise the safety of vaccines and lead to waste.

Nanomaterials such as silver nanoparticles are being used in a variety of products such as textiles, paints, and coatings to provide antibacterial and antimicrobial protection. Australia's Nanovations Pty Ltd. has developed Bioni Hygienic, a nanotechnology-based wall coating for hospitals that can kill microorganisms, fungal spores, and bacteria, including methicillin-resistant Staphylococcus aureus (MRSA), an antibiotic resistant strain of Staphylococcus aureus.[32] The coating is reported to be emission free and effective over time regardless of exposure to disinfectants and chemical cleaners.

Food and Agriculture

Several studies suggest that nanotechnology will have major, long-term effects on agriculture and the production of food, but it remains unclear how these changes will affect developing countries.

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[28] L. Moldofsky. 28 October 2004. *Biotechnology: Smarter Products with Nanotechnology*. Financial Times Australia.
[29] "New disease detector wins £826,000 grant," Cambridge Evening News, October 13, 2006, <http://www.cambridge-news.co.uk/news/city/2006/10/13/5ab61e1a-086f-404e-8601-675a217dde9e.lpf>.
[30] "NanoViricides Invited to Vietnam's Hi Tech Park," Business Wire, November 21, 2006.
[31] Gregory Roumeliotis, "Researchers give 'one-off vaccines' a shot," in-Pharma Technologist, March 20, 2006, <http://www.in-pharmatechnologist.com/news/ng.asp?id=66534>.
[32] "Nanotechnology coating is battling hospital superbugs," Infolink, September 7, 2006, <http://www.infolink.com.au/articles/FD/0C044BFD.aspx>.

Many of the promised advances for agriculture are similar to some promised advances in drug delivery in human medicine: time-controlled release; remotely regulated, pre-programmed, or self-regulated delivery of nutrients or disease treatments; transplanted cells protected by membranes; bio-separation; and rapid sampling and diagnosis of plant or animal health.[33] Nanotechnology may also help make food products cheaper and production more efficient and more sustainable through using less water and chemicals.

For example, Indian chemical company Tata Chemicals is developing nanotechnology-based crop-specific, high-value fertilizers to improve agricultural yields.[34] Because of their nanoparticle form, less fertilizer can be used for greater results. Australia's NanoChem Pty Ltd. has developed a water treatment technology called MesoLite that removes ammonia from waste water and concentrates it into commercial fertilizer.[35]

The ability to manipulate the molecules and the atoms of food could allow the food industry to design food with more precision and help lower costs, claims a study by the Helmut Kaiser Consultancy.[36] The study argues that foods in the future will be designed by shaping molecules and atoms and predicts that nanoscale biotech and nano-bio-info will have a major impact on the food and food-processing industries.[37] This could enable developed countries to produce more food, more economically, making them less dependent on cheap agricultural products from developing countries.[38]

Risks and Cross-Cutting Issues

Nanotechnology products are entering the global marketplace at an increasing pace and strong competitive and economic drivers will likely accelerate this trend, leading some observers to argue that the sheer momentum of efforts to develop nanotechnology could be overwhelming the need to examine and manage associated risks such as near- and long-term socioeconomic disruptions, human health and environmental impacts, and ethical, legal, and trade implications.

Participants in the Global Dialogue on Nanotechnology and the Poor: Opportunities and Risks (GDNP)[39] have contributed to the development of a matrix of priority cross-cutting issues, including risk issues. These issues and their definitions should be considered when evaluating the potential implications of nanotechnology and specific nanotechnology applications. While these issues may be generally applicable to technologies, the unique characteristics of nanotechnology may result in different considerations for each cross-cutting issue, which, in turn, could require new and different strategies for addressing these issues. In addition to being applicable to multiple technologies, these cross-cutting issues may also be relevant to multiple economic

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[33] M.C. Roco. 2003. *Nanotechnology: Convergence with Modern Biology and Medicine*. Current Opinion in Biotechnology, Volume 14, pp. 337–346. *See also*, N. Scott and H. Chen. 2003. *Nanoscale Science and Engineering for Agriculture and Food Systems*. Cooperative State Research, Education and Extension Service, US Department of Agriculture.

[34] Rabin Ghosh, "Tata Set to Go Nano, Focus on High-Value Fertilisers," Daily News and Analysis, July 17, 2006, <http://www.dnaindia.com/report.asp?NewsID=1042258>.

[35] "Australian Nanotechnology Water & Environment," Government of Australia, March 2006, < http://www.investaustralia.gov.au/media/IS_NA_Nano_Water.pdf>.

[36] Helmut Kaiser Consultancy. 2004. Study: Nanotechnology in Food and Food Processing Industry Worldwide. 2003-2006-2010-2015.

[37] FoodProductionDaily.com. 16 September 2004. Available at: http://www.foodproductiondaily.com/news/news-NG.asp?n=54760-nanotechnology-a-food.

[38] ETC Group. 2004. Down on the Farm: The Impact of Nano-Scale Technologies on Food and Agriculture. Ottawa, Canada.

[39] Global Dialogue on Nanotechnology and the Poor: Opportunities and risks. Information available at: http://www.merid.org/nano/gdnp/.

sectors. These issues include, but are not limited to:

- Product Research and Development – Systematic activities to increase knowledge and apply it to the (further) development of new applications. In the context of the workshop, participants focused on assessing the maturity of specific nanotechnology applications and the steps that would be necessary for further development.

- Environmental, Human Health, and Safety Risks – Potential harm that may arise from a material, combined with probability of an event (e.g., exposure). In the context of this document, the focus is on potential risks to the environment, human health or worker safety.

- Socio-Economic Issues – Impacts on individuals, institutions, or society resulting from a policy or project (e.g., the introduction of a product, of a market intervention) such as price changes, welfare changes, and employment changes.

- Ethics – A branch of philosophy concerned with evaluating human action, in particular what is considered right or wrong based on reason. In the context of nanotechnology, ethical questions have focused, for instance, on applications related to human enhancement and performance, privacy questions resulting from research into nanotechnology monitoring systems, and questions about possible malevolent or military uses of nanotechnologies.

- Intellectual Property Rights and Access – Intellectual property rights (IPRs) are legal protections for intellectual property claimed by individuals or institutions. Copyrights, patents and trademarks are common mechanisms for protecting intellectual property. IPRs are intended to spur innovation and commercialization, but may limit the ability of individuals and institutions to access technology.

- Public Participation and Engagement – Processes that affect whether and how individuals participate in societal discourse, including public information, public education, and public discussion and dialogue regarding nanotechnology.

- Governance – Processes, conventions, and institutions that determine how power is exercised to manage resources and societal interests, how important decisions are made and conflicts resolved, how interactions among and between the key actors in society are organized and structured, and how resources, skills and capabilities are developed and mobilized for reaching desired outcomes. This includes risk governance (i.e., comprehensive assessment and management strategies to cope with risk) and governance for innovation (i.e., programs targeting nanotechnology R&D for public objectives). Using this definition, governments, governmental and intergovernmental institutions, as well as public and private corporations, non-governmental organizations, and informal associations are examples of institutions involved in governance.

- Capacity Building – Assistance provided to develop a certain skill or competence, including policy and legal assistance, institutional development, human resources development, and strengthening of managerial systems.

- International Collaboration and Cooperation – Collaborative partnerships between individuals, and institutions from developed and developing countries at a local, national, regional level on any aspect of nanotechnology, including North-South (i.e., developed and developing) and South-South (i.e., developing – developing)

- Scalability, Delivery, and Sustainability – The ability to scale-up production and distribution of products so they reach large numbers of people (i.e., success not limited to pilot projects) and the sustainability of products, which relate to numerous factors including, for example, costs, ease of use, and durability.

Environmental, Human Health, and Safety Risks

There is slow but growing availability of studies on the environmental, human health, and safety (EHS) impacts of engineered nanomaterials, including data on the toxicity, fate, and transport of nanoparticles. Only a limited number of studies have been published on the potential toxicity of specific nanoscale materials, and the incongruity of results of initial research results demonstrates the complexity of assessing EHS risks.

Several fundamental aspects of nanotechnology cause concern that the risks associated with nanomaterials may not be the same as the risks associated with the bulk versions of the same materials. For instance, as a particle decreases in size, a larger proportion of atoms is found at the surface as compared to the inside. Thus, nanoparticles have a much larger surface area per unit mass compared with larger particles. Also, as the size of matter is reduced to tens of nanometers or less, quantum effects can begin to play a role, and these can change optical, magnetic, and electrical properties of materials. Since growth and catalytic chemical reactions occur at surfaces, a given mass of nanomaterials will be more reactive than the same mass of materials made up of larger particles. These properties might have negative health and environmental impacts and may result in greater toxicity of nanomaterials.[40]

The study of nanoparticles' toxicity is complicated by the fact that they are highly heterogeneous. Not only are they exclusively engineered to specification but in many cases nanoscale materials will alter in physical size upon interaction with aqueous systems. Furthermore, the surface coating of nanoparticles can be altered to completely change the material's toxicity. For example, changing the surface features of the material can change a hydrophobic particle into a hydrophilic one.[41]

Nanotechnology handlers, consumers, and other people could be exposed to nanoparticles through inhalation, ingestion, skin uptake, and injection of nanoscale materials. Nanoparticles could also interact with ecosystems, animals, plants, and microorganisms. . Furthermore, use of nanomaterials in the environment may result in novel by-products or degradates that also may pose risks. To date, very few ecotoxicity studies with nanomaterials have been conducted. Studies have been conducted on a limited number of nanoscale materials and in a limited number of aquatic species. There have been no chronic or full lifecycle studies reported.

Socioeconomic Issues

Given the potential rapid and radical technology innovations that may be enabled by nanotechnology, some people and publications have expressed concerns that nanotechnology

[40] I. Bruske-Hohlfeld, et al., "Do Nanoparticles Interfere with Human Health?" *GAIA*, Vol. 14, No. 1, 2005, pp. 21–23, <www.oekom.de/gaia>.
[41] L. Goldman and C. Coussens (eds.), "Implications of Nanotechnology for Environmental Health Research," National Academy of Sciences Roundtable on Environmental Health Sciences, Research and Medicine, Environmental Health Research, 2005 <http://www.nap. edu/catalog/11248.html>.

applications could have adverse socioeconomic effects on developing countries. [42] Other people, however, have said nanotechnology applications – as described extensively above – may yield significant economic and social benefits for developing countries.

In particular, some people have raised questions about the socioeconomic effects of nanotechnology applications that could impact global demand for agricultural, mineral, and other non-fuel commodities.[43] The term "commodities" usually refers to "undifferentiated, widely traded raw materials and agricultural products that are traded principally on the basis of price." Impacts on commodity markets are important, because ninety-five of the 141 developing countries derive at least 50 per cent of their export earnings from commodities. In 2003 fifty-four of those countries depended on non-fuel commodities for more than half of their export earnings (e.g., copper and zinc account for 61 per cent of Zambia's export earnings; cotton makes up 72.7 per cent of Mali's earnings). UNCTAD estimates that a total of two billion people—a third of the global population—are employed in commodity production, half of those in agriculture.[44]

Although the exploitation of natural resources may contribute to economic development and enhanced public welfare, many developing countries that are highly dependent on commodity export as a primary source of revenue appear low on the United Nations Development Programme's Human Development Index. Dependence on revenue from a narrow range of commodities is risky for countries and producers, because they depend on international markets that have shown long-term price declines and sharp short-term price fluctuations. These countries and producers often find themselves with limited access to credit for production inputs, capital for investments, and know how.

Nanotechnology applications are being developed that could impact global demand for agricultural, mineral, and other non-fuel commodities. Some applications of nanotechnology could increase global demand, while others could lead to a decrease in demand for specific commodities. Applications that result in reductions or increases in the demand for commodities could have potentially far reaching socio-economic and other effects in developed and developing countries. The dependence of many developing countries on one or two commodities is likely to accentuate the socio-economic effects resulting from changes in commodity markets in comparison to countries with more diversified economic bases.

Ethics

In an international context, some people have identified an ethical tension in balancing the urgency of alleviating the critical needs of developing countries with nanotechnology and ensuring that those populations are not exposed to the unknown, but potentially significant, risks posed by those technologies. This ethical dilemma includes questions about whom (e.g., developed or developing country governments, international organizations, civil society, poor people) should make such risk-benefit decisions and what should be their motivation (e.g., economic competitiveness, humanitarianism, modernization).

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[42] ETC Group. 2004. *Down on the Farm: The Impact of Nano-Scale Technologies on Food and Agriculture*. Ottawa, Canada.

[43] South Centre, (2005) "The Potential Impacts of Nano-Scale Technologies on Commodity Markets: The Implications for Commodity Dependent Developing Countries," Geneva, Switzerland.

[44] United Nations Conference on Trade and Development, (2005) "Trends in World Commodity Trade, Enhancing Africa's Competitiveness and Generating Development Gains." Report by the UNCTAD secretariat for the 2nd Extraordinary Session of the Conference of African Union Ministers of Trade, 21–24 November, 2005, Arusha, Tanzania.

A number of reports have discussed the ethical issues related to nanotechnology and equity. Some have said that past science and technology advances such as vaccines have enabled mass application of solutions to human development needs. But, empirical studies have also shown that introduction of new technologies have resulted in further marginalization of the poor, for instance because the underlying commercial and distribution infrastructure remains in the control of developed countries. Some groups have also argued that the current approach to nanotechnology research and development is overly top-down and does not take into account existing solutions including traditional, alternative, or complementary practices, such as herbal medicine and traditional pest management, despite the cultural significance and an increase in use of these practices in many developing countries.[45]

The US and European governments and researchers in other developed and developing countries are working, to different extents, on nanotechnology research related to human enhancement and performance. Some groups are now asking about the ethical implications of nanotechnology applications, such as materials that enable bone, tissue, and nerve regeneration, that would benefit disabled people in developed countries, but possibly be unaffordable for those in developing countries.

There are also a number of ethical considerations regard nanotechnology's implications on privacy. Some say that nanoscale information gathering systems such as transmitters could be both ubiquitous and invisible because of their small size. Some say that nanoscale health monitoring devices that could be temporarily or permanently implanted in the body could also have negative privacy implications.

Intellectual Property Rights (IPRs) and Access

Several publications have expressed concerns related to IPRs and the impact of patents and technology management strategies on the ability of developing countries to access new technologies. For example, the potential for broad nanotechnology patents on conventional and natural materials at the nanoscale raises the possibility that such patents could give patent owners excessive control over the use of nanoscale materials.

Some groups are urging that the effects of patents, conditions in technology licenses, and impacts of government and corporate policies on people's ability to use nanotechnology for societal benefits be considered now, even though some of the potential benefits of nanotechnology may be years away. Without this discussion, they argue, the technology will be controlled by multinational corporations, primarily benefit consumers in the North, and lead to a deepened divide between developed and developing countries.

Public Participation and Engagement

With nanotechnology investments continuing to rise and applications proliferating, awareness and understanding regarding the implications of nanotechnology for developing countries is increasing. However, this awareness is still generally limited – few people involved with nanotechnology are considering development issues; few people involved in the development community are considering the potential role of nanotechnology in addressing humanitarian needs. These gaps continue to be a significant concern, as current and future decisions in both developed and developing countries may result in policies, practices and systems that can have long-term impacts on whether nanotechnology can help address specific societal needs and, if so,

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how quickly. More robust mechanisms are needed to engage the public in dialogue about the responsible innovation and governance of nanotechnology.

Governance

The growing realization that nanotechnology applications are already being developed and used in both developed and developing countries is contributing to heightened interest in discussions about the governance of nanotechnology. A small, but growing number of national and international initiatives are addressing components of the issue, yet, there is still significant confusion about what is meant by "governance of nanotechnology." There are currently a range of opinions on the adequacy of existing systems for governance of nanotechnology versus the need for new nano-specific governance frameworks.

International Standardization and Coordination
Driven by the global nature of nanotechnology research and development efforts, a desire to avoid public backlash against the technology, and opportunities to enhance benefits and reduce risks, several international nanotechnology governance initiatives are underway. They include the following:

International Organization for Standardization (ISO)[46] – ISO is developing standards in the field of nanotechnologies that includes either or both of the following:

1. Understanding and control of matter and processes at the nanoscale, typically, but not exclusively, below 100 nonametres in one or more dimensions where the onset of size-dependent phenomena usually enables novel applications,
2. Utilizing the properties of nanoscale materials that differ from the properties of individual atoms, molecules, and bulk matter, to create improved materials, devices, and systems that exploit these new properties.

Specific tasks include developing standards for: terminology and nomenclature; metrology and instrumentation, including specifications for reference materials; test methodologies; modelling and simulations; and science-based health, safety, and environmental practices.

Organisation for Economic Co-operation and Development (OECD)[47] – OECD is developing a large body of work. Under the Committee on Scientific and Technological Policy (CSTP) a Working Party on Nanotechnology was established in March 2007. The objective of this Working Party is to promote international co-operation that facilitates research, development, and responsible commercialisation of nanotechnology in member countries and in non-member economies. A work program is currently being launched to start addressing some of the main policy challenges. This program will include work on statistics and indicators of nanotechnology; examination of the business environment for nanotechnology; work to foster international collaboration in nanotechnology research; work on public perceptions towards nanotechnology and the engagement of stakeholder communities in the debate on nanotechnology; as well as a dialogue on policy strategies to spread good policy practices towards the responsible development of nanotechnology.

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[46] http://www.iso.org/iso/standards_development/technical_committees/list_of_iso_technical_committees/iso_technical_committee.htm?commid=381983

[47] http://www.oecd.org/findDocument/0,3354,en_2649_37015404_1_119817_1_1_1,00.html

The OECD Working Party on Manufactured Nanomaterials (WPMN) is a subsidiary body of the Chemicals Committee. This program aims to promote international co-operation on the human health and environmental safety of manufactured nanomaterials, and involves approaches to the safety testing and risk assessment of manufactured nanomaterials. The Programme of Work addresses three main areas listed as follows: 1) Identification, Characterisation, Definitions, Terminology and Standards; 2) Testing Methods and Risk Assessment; and 3) Information sharing, Co-operation and Dissemination.

International Dialogue on Responsible Research and Development of Nanotechnology – The International Dialogues have provided a forum for representatives from 25 countries to combine ideas and issues that may otherwise not be adequately addressed in their own respective forums. The first meeting took place in 2004 in the USA and the second meeting in 2006 in Japan. A third meeting is scheduled for to take place in the European Union in 2008. These meetings, each involving representatives from more than 25 countries and the European Union, focused on how to best ensure nanotechnology research and development programs are carried out in a responsible manner. Both meetings covered a broad range of topics, including issues related to regulation and governance, health and safety, the environment, and ethics, as well as issues unique to developing countries.

International Risks Governance Council (IRGC)[48] – The first of IRGC's projects focusing on nanotechnology addressed the need for adequate risk governance approaches at the national and international levels in the development and commercial release of nanotechnology applications and nanoscale products. Using the IRGC's risk governance framework as a conceptual starting point and with the contributions of experts at two technical workshops, the project team developed a generic global framework for the risk governance of nanotechnology, analyzed the associated risks, identified deficits in risk governance structures and processes and developed recommendations for nanotechnology risk governance, including the management of these deficits.

Conclusion

While application of nanotechnology is still regarded to be a relatively young scientific discipline, there are already hundreds of products available (with hundreds more in development) to consumers that utilize the novel characteristics of nanotechnology. With strong competitive and economic drivers likely to accelerate this trend, the perception that nanotechnology products were "years away," which seemed to be the prevailing view only a few years ago, is now being displaced by a growing interest in catalyzing specific actions that support the emergence of creative and appropriate approaches to nanotechnology innovation and governance.

[48] http://www.irgc.org/nanotechnology