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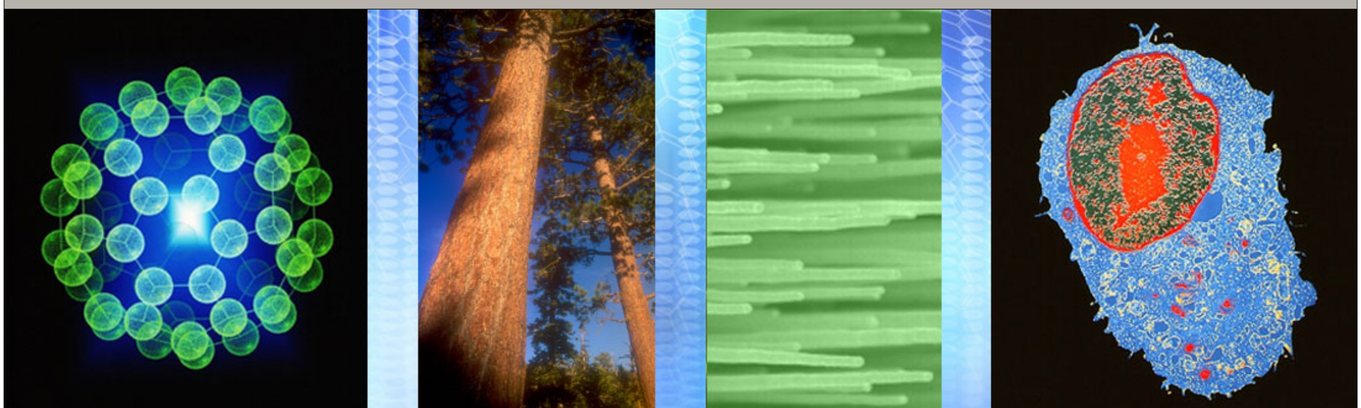
Nanotechnology Stewardship

March 2005



Canadian Stewardship Practices for Environmental Nanotechnology

Prepared for

Environment Canada

Science-Metrix

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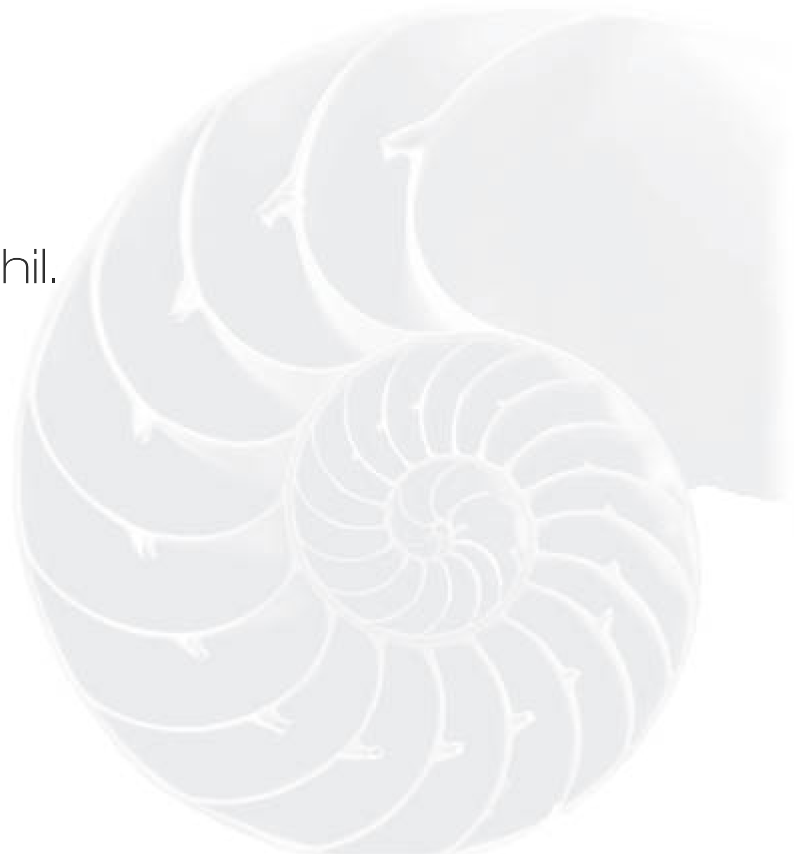

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Prepared for
Environment Canada

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Executive summary

Although nanotechnology has the potential to create a wide range of new exciting and innovative technological applications for the environment and other sectors such as medicine, electronics and communication, it also has some adverse effects on health and the environment. Until recently, nanotechnology had eluded social, political and regulatory scrutiny, and relatively little is known about the risks from nanoparticles in the workplace and in commercial products. Environment Canada recognizes the need to improve understanding about nanotechnology as a prelude to shaping its development in an environmentally sustainable and responsible manner. Science-Metrix was selected to conduct a study to identify best practice in terms of environmental nanotechnology-related issues. The study involved Science-Metrix examining more than 500 documents. As a result it is clear that, to date, stewardship practices linked to the environmental dimensions of nanotechnology are fairly sparse, thus providing an opportunity for Canada to play an international pioneering role in this area.

This study examines current research in nanotechnology related to environmental applications and covers both research focusing on nanotechnology applications designed to benefit the environment, and developments that may present environmental risks and potential threats (Section 2). The study also includes a comprehensive review of strategies and policies developed by the US, European and Asian countries to identify and reconcile stewardship issues associated with the development of nanotechnologies (Section 3). Finally, recommendations are formulated to assist Environment Canada in targeting environmental applications, maximizing the benefits and minimizing the potentially adverse effects associated with developments in nanotechnology, setting the basis for the establishment of best stewardship practices in Canada (Section 4).

Environmental applications

One of the most important environmental applications of nanotechnology is the use of nanoparticles to create a new generation of sensors with enhanced monitoring capabilities for pathogens and pollutants, for treating (remediation) contaminated water, soil or air, and for enabling green technologies to eliminate or decrease harmful emissions and waste from industrial processes, including the development of clean energy sources such as solar energy and fuel cells. Engineered nanoparticles such as Au, Pt, CdS, TiO2, quantum dots and nanocrystals (e.g. CdSe-ZnS), nanostructures such as nanowires, carbon nanotubes and porous silicon, as well as lab-on-a-chip and microarray technologies are intensively studied in relation to sensor applications, while engineered nanoparticles such as TiO2 and ZnO, carbon nanotubes, metallic nanoparticles (e.g. iron, nickel etc.), magnetic nanoparticles and amphiphilic polyurethane nanoparticles could be useful for remediation. Interestingly, ZnO seems to have the ability to simultaneously sense and destroy toxic chemicals. Carbon nanotubes have been extensively studied for green technologies, allowing the creation of stronger and lighter products using fewer raw materials and requiring less energy, thereby conserving natural resources. In addition, carbon nanotubes could be filled with hydrogen and used as energy cells for automotive applications, offering the potential to reduce atmospheric emissions. CdSe nanoparticles are used in the production of higher efficiency and lower cost solar cells while other nanoparticles, such as ceria, nickel and silica, could be used to reduce fuel consumption over time, to recycle or replace toxic compounds or to enable the creation of more environmentally friendly nanocatalysts with improved catalytic properties.

Environmental risks

Because of their high surface reactivity and very small size, which allows them to circumvent the immune defences of living organisms, nanoparticles represent a threat to health and the environment. Carbon black, nanotubes, fullerenes, gold and TiO nanoparticles have been described as potentially harmful. Some produce free radicals and oxidative stress, cause DNA damage and gene alteration that increase the probability of cancer, accumulate in animal organs, are highly toxic in rat lungs, affect macrophage and defensive cells, can be transferred from mother to foetus, induce damage in fish brains and can travel along nerves and circumvent the blood-brain barrier. Additionally, fullerenes can travel through the soil and could be absorbed by earthworms, while carbon nanotubes induce air pollution by aggregating in the air and forming toxic nanocrystals. Moreover, unprocessed carbon nanotubes form aerosols during handling or with agitation, threatening workers in factories that use this type of nanoparticle.

Research Avenues

Over the next decade, research in environmental nanotechnology should increase understanding of the impact of nanomaterials on organisms, the food chain and ecosystems by collecting data on exposure levels, characterizing dose-response and performing toxicological and ecotoxicological tests. The persistence level of nanoparticles in the environment, the evaluation of nanoparticle production and utilization, and the fate of nanomaterials through life-cycle analysis, the identification of nanomaterials release and the mechanisms by which they are transported in the environment to living organisms are all avenues of research that are crucial and should especially focus on such issues as biodegradability and bioaccumulation of nanoparticles in organisms. It is important to evaluate whether current standards and treatment methods are effective in detecting and removing nanoparticles from the environment, and how they work. Research should be undertaken to develop the most efficient tools to detect, measure and eliminate these nanoparticles. Efforts should be devoted to establishing new standards for nanoparticle levels and methods of risk assessment. Statistical and epidemiological studies are required to study the effects of nanoparticles in specific ecosystems, and on disease development in humans and animals, and to evaluate the health risks for factory workers. More research is needed to understand the precise molecular mechanisms associated with nanoparticle toxicity, and multidisciplinary teams should investigate whether the environmental benefits to be gained from nanotechnologies compensate for their potential risks and adverse effects.

Current stewardship practices

In the US, nanotechnology policies consist of federally- and state-directed programs with very diverse objectives, targeting mainly academic research and research institutions. The private sector is fairly independent of federal initiatives and operates in an autonomous manner. Asian countries support both the public and the private sector, and Asian policies and strategies are generally aimed at developing industry and generating economic benefits leading to concrete and rapid national advancement, and improved international competitiveness. This philosophy has little room for the environmental and social aspects of nanotechnology and explains why Asian countries lag behind Europe and the US with regard to policies in this area. Nanotechnology policies developed by the European Union are unique and differ greatly from the positions adopted by the US and Asian countries. European policies appear to balance out the opportunistic approach of developing the industrial and commercial applications of nanotechnologies, and academic and social visions focusing on nanotechnologies' social rather than economic benefits. In addition, EU policies present a good balance between national control and independent initiatives developed by Union members at the national level.

The environmental and social dimensions of nanotechnology policies are in their infancy and very few programs or strategies offer concrete solutions to known problems, or offer practical foundations for establishing effective regulation. Countries involved in nanotechnology should proceed swiftly with the formulation of policies aiming at minimizing the adverse effects associated with nanotechnologies since policy implementation and integration in society involve long lead times and this presents the risk that policies will be formulated to react to problems rather than to prevent potential problems associated with this potentially revolutionary enabling technology. In this context and guided by the precautionary principle, Science-Metrix has formulated several recommendations.

Recommendations

Recommendation 1: Science-Metrix recommends that Canadian strategies and policies on nanotechnology follow a similar orientation to Europe's, with a proper balance between central and independent initiatives, also between economic and industrial development, and social, ethical and environmental considerations.

Recommendation 2: Environment Canada should create a multifunctional research center devoted to studying the environmental and social dimensions of nanotechnology by a multidisciplinary research team.

Recommendation 3: Establish an institution to monitor nanotechnology developments and evaluate the relevance of nanotechnology policies, and assess the potential issues or risks associated with the utilization of nanotechnology.

Recommendation 4: Environment Canada should work in collaboration with granting councils to establish a grant program to support the work of scientists who would perform research on environmental issues of nanotechnology and to support the training of nanoscientists.

Recommendation 5: Establish a group to study the evolution of public attitudes towards nanotechnology and to suggest measures to mitigate the risks perceived by the public.

Recommendation 6: Create a Canadian index of potentially harmful nanoparticles for the environment and health with associated standard operating procedures. This must be an international effort it it is to be fully effective.

Recommendation 7: Environment Canada should act as a catalyst in the creation of interdepartmental advisory committees to conjointly establish standards, guidelines, legislation and regulations to protect the environment and human and animal health against known threats such as nanoparticle toxicity.

Acknowledgements

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Disclaimer

The views expressed in this report are those of the authors and do not necessarily reflect the views of Environment Canada.

Contents

1 Introduction

The emerging science of nanotechnology arose out of a convergence of conventional scientific fields, such physics, chemistry and biology. The word “nano” derives from the Greek *nanos*, which means dwarf and was defined by the Los Alamos National Laboratory as the creation of functional materials devices and systems, through control of matter on the nanometer (1 to 100nm) length scale and the exploitation of real properties and phenomena developed at that scale (LANL 2002). A nanometer is one billionth of a meter in length, and, depending on the size of the atom, between three and six atoms will fit inside a nanometer (nm), (Choi 2003). The essence of nanotechnology is its ability to work at the molecular level and to create structures with fundamentally new molecular organizations. When matter is modified at the nanoscale, it acquires new and useful properties not previously created or observed (Choi 2003).

The physicist Richard Feynman is widely considered to be the father of nanotechnology (Phoenix 2005). In 1959, Feynman suggested that it should be possible to build machines small enough to manufacture objects with atomic-level precision. Feynman's vision was realized with the invention by Gerd Binnig and Heinrich Rohrer in 1982 of the scanning tunnelling microscope (STM), for which they were awarded the Nobel prize in physics (Binning *et al.* 1982). These were the first tools to allow observation and manipulation of atomic structures and they were the basis of the huge advances and great progress that would be made in nanotechnology (Nature editorial 2003).

Another breakthrough discovery that revolutionized nanotechnology consisted of new carbon shapes. In 1985, researchers reported the discovery of buckyballs (named after Buckminster Fuller), which were perfect spheres consisting of sixty carbon atoms. This in turn led to the 1991 discovery of a related molecular shape known as the carbon nanotube. These nanotubes are about 100 times stronger than steel, but just a sixth of its weight, and they have unusual heat and conductivity characteristics that guarantee they will be important to high technology in the coming years (Keiper 2003). Several of the tools and approaches used in the field of nanotechnology are based on carbon nanotubes or buckyballs, and these discoveries were important drivers in the development of nanotechnology.

Many experts, researchers, engineers, social scientists and policy makers believe that nanotechnology will lead to important changes in society and that these changes may be of the same magnitude as was the introduction of computers. This new enabling technology has made it possible to manufacture materials that have not previously existed in our environment, and is helping create a wide range of potentially exciting and innovative applications for the environment and other sectors such as medicine, electronics and communication.

Nanotechnology has made it possible to manufacture new materials which present the potential for both positive and negative effects on health and environment. For instance, nanosensors are high-sensitivity detectors of pathogens or pollutants in soil, water or air. Nanotechnology is expected to play an important role in the remediation of polluted soil and in the development of green manufacturing processes that reduce emissions and wasteful production, reduce the amounts of raw materials needed and thus conserve natural resources.

However, nanotechnologies could also have undesirable and harmful effects on health and the environment, such as those created by nanoparticle toxicity. Nanoparticles have for many years been used in commercial products including sunscreens, cosmetics, photographic film, petrochemicals, tires, tennis balls and lightweight tennis racquets. In addition, the manufacture of several everyday products, such as car bumpers and automobile catalytic converters, paints and coatings to protect against corrosion, glare-reducing coatings for eyeglasses and cars, dental-bonding agents, burns and wound dressings, inks, metal-cutting tools, magnetic recordings, biolabels, electroconductive coatings, optical fibres and stain-free clothing involves nanoparticles. Currently, there is very little regulation relating to the disposal of nanoparticle-based products, yet there uncertainty about their environmental safety.

Until recently, nanotechnology and nanoparticles have evaded social, political and regulatory scrutiny, particularly in relation to their safety in the workplace and in commercial products. This situation is creating concern, and opens the floor to public debate because of their rapidly increasing use. One of the most radical opinions about nanotechnology came from Eric Drexler, who has predicts that nanotechnology will enable molecular manufacturing using nanomachines which can place atoms in almost any feasible arrangement, thus allowing humans to build almost anything that the laws of nature allow (Keiper 2003). Based on this assumption then, nanomachines could self-replicate thus leading to an exponential growth of assemblers. Drexler's supporters predict catastrophic events and a very dark future if nanotechnology is not developed in a responsible manner. On the other hand, Richard Smalley, who discovered fullerene (buckyballs), has a dramatically different conception of nanotechnology, which does not include the concept of molecular assemblers. Smalley does not think molecular assemblers as envisioned by Drexler are physically possible (Baum 2003). Nevertheless, he agrees that nanotechnology needs to be developed in a responsible manner to avoid exposure to risks, and negative impacts. Edward Tenner from Princeton University, who has written several essays, reviews and articles in leading scientific journals offered his own prediction about the future of nanotechnology based on the history of technology and on previous human experience with scientific discoveries and their application:

> The history of technology [...] can help prepare us for the surprises that have always been the result of human ingenuity. We can expect five things: (1) The experts will be seriously wrong about at least some important things. (2) Long-term, cumulative problems will be a greater problem than the perils of catastrophe. (3) Organizing and supervising nanotechnology will create dilemmas. 4) Successes may be as costly as failures. (5) We probably have not imagined the greatest benefits of nanotechnology, either because they seem too technologically modest or because they may result from improbable chains of events (Tenner 2001: 241).

Tenner's second proposition has potentially important consequences. According to Teller, long-term, cumulative problems, such as the nanoparticle pollution of the environment and risks to health, present greater threats than such catastrophes as the world being taken over by self-replicating nanorobots. A good illustration of this is nuclear technology. During the Cold War, destruction of the world by nuclear bombs was tangible and produced fear among the public, while cumulative problems, such as the Chernobyl and Three Mile Island accidents, and radiation leaks, have generated more damage and negative impacts. Science-Metrix based the present study on

Environment Canada's definition of stewardship as being the act of entrusting the careful and responsible management of the environment and natural resources for the benefit of the general community (EC 2005). In this context, stewardship practices have to take into account the likelihood that nanoparticle toxicity, and the social, ethical and environmental issues raised by nanotechnology represent important cumulative problems and that they must be considered as a whole in order to minimize their cumulative negative impacts.

Organization of the report

This analysis includes both research focusing on nanotechnology applications that are expected to present environmental benefits (Section 2.1) and research that may expose the environmental risks and potential threats associated with nanotechnology (Section 2.2). The study subsequently undertakes a comprehensive review of strategies and polices developed in the US and in European and Asian countries to identify and reconcile stewardship issues associated with nanotechnologies (Section 3). Several recommendations are made to help Environment Canada target environmental applications, maximize benefits and minimize the potentially adverse effects associated with the development of nanotechnology, and to lay the groundwork for best stewardship practice (Section 4).

Science-Metrix has examined and studied more than 500 documents and used information from about 200 of them to guarantee depth and robustness for the analysis presented in this study. This in-depth review of the literature shows that stewardship practices linked to the environmental dimensions of nanotechnology are fairly rare, thus providing Canada with an opportunity to adopt a pioneering role in this area. Finding such a low level of activity in the area of stewardship after reviewing so many documents raises challenges: it is always difficult to deal with negative results. They raise the possibility that some evidence has been overlooked and it is for this reason that the review in Section 3 is so detailed. Science-Metrix widened the perspective of what was considered to be the potential impacts of nanotechnologies on the environment and what activities related to stewardship in environmental nanotechnology. Thus our report considers a wide range of initiatives, strategies and policies that refer to the social, ethical and technical aspects of nanotechnology. These may seem to deviate from a purely environmental perspective and to fall outside the scope of the study as initially envisaged. The initiatives chosen were selected because they either represent a model or contained elements that should be considered and adapted to establish efficient stewardship practices targeting the environmental dimensions of nanotechnology.

2 Current research in the environmental aspects of nanotechnology

Nanoscience and nanotechnology have the potential to produce major impacts on the environment. Advances in the field could also produce tangible benefits for the environment, but the risks associated with nanotechnology should not be ignored. This section examines current research efforts and recent advancements in environmental nanotechnologies (Section 2.1) and subsequently examines current research on the adverse effects of nanoparticles and nanotechnology (Section 2.2).

2.1 Research on the beneficial effects of nanotechnology on the environment

This section examines advances in nanotechnology that will help to monitor and also mitigate the environmental impacts of human and industrial activities. Promising technologies include sensors and other devices used for pollution detection, and treatment and remediation techniques, together with various forms of green manufacturing and so-called green energies.

2.1.1 Sensors

A wide variety of biosensors and related techniques have been introduced on the market in the last few decades. The forms and functions of these devices have remained fairly constant over time: these analytical devices are composed of biological recognition elements (e.g.: enzymes, antibodies, microorganisms, nucleic acids) which are interfaced with signal transducers. These devices react to the presence and the concentration of analytes and produce a measurable response (Bousse 1996). There are three principal types of signal transducers: electrochemical, piezoelectric, and optical (Homola 2003) and three major electrochemical methods have been employed in biosensor development: potentiometric, amperometric, and impedimetric.

Miniaturization, including the use of nanotechnology, is increasingly important in the development of biosensors (Haruyama 2003; Jain 2003). Nanotechnology could allow the creation of fast and precise sensors to detect contaminants, pathogens and toxic compounds at the molecular level. The sensitivity and performance of biosensors is enhanced with the use of nanomaterials. The submicron dimensions of nanosensors, nanoprobes, and other nanodevices have allowed simple and rapid *in vivo* analyses. Portable instruments capable of continuous monitoring are becoming progressively more widely available. Nanotechnology promises t new generations of sensors that will enable real-time, accurate sensing of several compounds simultaneously, at extremely low concentration levels. These sensors are expected to play a key role in various applications including manufacturing process control, compliance, ecosystem monitoring and environmental decision making. These applications will obviously be significantly improved as more sensitive and cheaper techniques for contaminant detection become available.

Research is currently being conducted on the development of nanosensors for efficient and rapid *in situ* biochemical detection of pollutants and specific pathogens in the environment, and includes work on sensors capable of continuous measurement over large areas, and real-time continuous monitoring such as nanochip and lab-on-a-chip technologies. Novel nanomaterials and nanostructures such as nanoparticles, nanocrystals, carbon nanotubes, nanorods, nanofibres and thin film have been characterized to determine the parameters of their application as sensing devices.

Nanoparticles have numerous applications in sensors. Functional nanoparticles bound to biological molecules (e.g. peptides, proteins, nucleic acids) have been developed for use in sensors to detect and amplify various signals, allowing detection of pathogens, proteins and chemical compounds detection (Jianrong *et al.* 2004). As discussed below, several technologies were employed in the last decade for the production of nanosized sensors.

Nanoparticles

Quantum dots and luminescent semiconductor nanocrystals (CdSe-ZnS) represent a class of nanosensors with the potential to detect toxins present in the environment. It has been demonstrated that quantum dots and nanocrystals conjugated to specific antibodies could simultaneously detect four toxins including ricin, cholera toxin, toxin-1 and staphylococcal enterotoxin B (Goldman *et al.* 2004). These types of nanosensors could eventually be used to simultaneously detect several contaminants or pollutants in soil or water samples with high sensitivity detection capacity.

Another approach is based on resonance enhancement of metal nanoclusters bound to a surface by biorecognitive interactions. These have been shown to be effective for use in bio-optical sensory devices. Analytes induce the binding or dissociation of metal nanoclusters and could be transduced into a detectable optical signal through resonance enhancement of clusters interacting with their mirror dipole (Bauer, Pittner and Schalkhammer 1999). Using nanoparticles such as Au, Pt, CdS, or TiO_2 and a quartz crystal, antibody-modified nanoparticles indirectly bind to an electrode surface by complexing to an analyte that has itself been captured by an antibody immobilized on the electrode surface. The mass of the bound nanoparticles affects the vibration frequency of the quartz crystal, and this is used as the basis for detection (Liu, Tang and Jiang 2004). This approach should allow the creation of ultra-sensitive sensors that can be used for environmental applications.

Many electrochemical sensors have been fabricated with or improved through the use of metallic nanoparticles which increase the amount of immobilized biomolecules captured by sensors. For instance, enzyme-gold colloids have been used on the surface of electrodes to fabricate biosensors for DNA, peroxide, glucose, xanthine, and hypoxanthine (Cai *et al.* 2001; Crumbliss *et al.* 1992; Jianrong *et al.* 2004; Zhao *et al.* 2002). Therefore, by interacting with DNA, sensors based on metallic nanoparticles could be used to detect the presence of pathogens in the environment, and represent a powerful tool to monitor water, soil and air quality.

Researches in sensors also include using nanoparticles and nanotechnologies to improve the properties of existing sensor devices. For example, the detection capacity of optical biosensor platform as surface plasmon resonance (SPR) is greatly improved with the use of gold nanoparticles (Hu *et al.* 2004).

Nanoparticles for sensor and other environmental applications are generating great interest in the scientific community and efforts are being expended on nanoparticle research to study their potential to sense or remove pollutants from the environment.

Other nanostructures

A great deal of research has focused on tubular and porous nanostructures such as carbon nanotubes. These nanostructures are used in biosensors to increase the quantity and activity of immobilized biomolecules. The nano-dimensions, graphitic surface chemistry and electronic properties of carbon nanotubes make them ideal materials for use in chemical and biochemical sensing. Enzymes such as glucose oxidase, horseradish peroxidase, or oxidoreductase are immobilized by coating onto the surface of nanotubes and used as probes (Azamian *et al.* 2002; Guiseppi-Elie, Lei and Baughman 2002; Zhao *et al.* 2002).

Another structural material that has been studied extensively for nanosensing applications is porous silicon. Porous silicon has a high surface-to-volume ratio, and its tiny nanopores emit light at room temperature (Jianrong *et al.* 2004). Because of these characteristics, porous silicon is commonly used in the fabrication of biosensors and allows for the detection of small molecules such as biotin and digoxigenin at pico- and femtomolar concentrations (Di Francia *et al.* 1999; Lin *et al.* 1997).

Nanoprobes based on semiconducting nanowires such as boron-doped silicon nanowires, had been reported to create highly sensitive, label-free, and real-time detection of a wide range of chemical and biological species (Cui *et al.* 2001; Cullum *et al.* 2000; Tuan 2002). The small size of these nanowires allows for measurements in individual cells, enabling in vivo monitoring of processes within live cells. In addition, some scientists have used optical fibres coated with antibodies to detect chemicals and pathogens (Jianrong *et al.* 2004).

In the biosensors field, research is mainly devoted to the creation of nanoprobes that have the potential to detect a wide variety of analytes or proteins. Unlike many biosensors which are designed for the detection of specific proteins (e.g. glucose monitoring), these nanoprobes could be useful as diagnostic tools to monitor, for example, different types of toxins and contaminants in animal organs or animal cells and in the environment.

Lab-on-a-chip and microarray technologies

A novel array-based electrical detection of DNA with nanoparticle probes was presented by Park and colleagues (Park, Taton and Mirkin 2002). Captured strands of alkylthiol-modified oligonucleotides were immobilized onto the activated surface of SiO_2 substrate between the two ends of gold microelectrodes with 20 Am gaps. The binding events localized gold nanoparticles in the electrode gap. Silver deposition facilitated by the gold nanoparticles bridged the gap and led to readily measurable conductivity changes.

The combination of electronics and nanotechnology to develop sensors is the focus of a great deal of research, especially for nano-electromechanical system (NEMS) technologies. Using integrated-circuit manufacturing technology and methods developed for micromachining, it is now possible to create complex electrical, mechanical, fluidic, optical, thermal and magnetic nanostructures or nanodevices. The small size of these systems means they possess properties that would not be present in larger devices. For instance, microcantilevers can be produce by NEMS technologies and are used as sensor for DNA or antigen detection. Scientists have also developed a microarray of cantilevers to detect multiple unlabeled molecules simultaneously at nanomolar concentrations

(Arntz *et al.* 2003; McKendry *et al.* 2002). In addition, the DNA detection function of microcantilevers has been improved by the presence of gold nanoparticles (Su, Li and Dravid 2003). Nanofabricated electrodes (width ranging from 200 to 500 nm) have also reportedly been used for the detection of affinity binding of biomolecular structure including DNA or antigens by measuring impedance variation (Van Gerwen *et al.* 1998).

The convergence of nanotechnology, electronics and biology creates a powerful framework for the development of lab-on-a-chip technologies. Lab-on-a-chip is the term used to describe complex devices integrating several functions such as sample and reagent mixing, separation, cell lysis and detection. These powerful microdevices perform numerous stages of analysis: sample preparation and detection, cell lysing, PCR, etc. These microdevices include several components such as micro-pump, micro-fluidics system, microscale flow for manipulation and transport of biological species and integrate optical (e.g. laser tweezers) or electrical signals (e.g. electrophoresis, electroosmosis etc.). Numerous reports have demonstrated the usefulness of lab-on-a-chip for protein, DNA and cell detection (Bashir 2004). Lab-on-a-chip and nanodevices enabled by NEMS are powerful devices with huge capacities that could be used as sensors to detect pollutants or pathogens in the environment, and represent an important part of the research efforts in nanotechnology for sensor application.

Most of the nanosensors and nanotechnology-based tools could eventually be used for sensing application and one of their great advantages is that the sensing elements are reduced to the scale of the target species, thus providing a higher and more specific sensitivity. Moreover, the small size of these sensors decreases the reagent volume and associated cost, and reduces time to result.

Nanotechnology will enable the miniaturization of current biosensor platforms to produce a portable device for field applications. For example, despite its volume, weight and the current need for a laboratory environment to be fully functional, the SPR platform is a remarkable tool for sensing application. Texas Instruments and Nomadics have succeeded in reducing SPR to a portable version (e.g.: model SPREETA). Incorporation of nanosensors or portable sensors for field monitoring decreases sample transportation thus reducing the risks of errors and of contamination due to mishandling as well as associated costs, and facilitating faster decision making.

It is anticipated that nanotechnologies will lead to an increase in highly sensitive, fully automated and inexpensive sensors being routinely used both in the field and in the laboratory for rapid pathogen and toxic agent detection. Moreover, with the creation of high precision monitoring and dosing nanodevices, the amount of chemicals used in agriculture could be reduced, representing another important benefit for the environment. The use of nanotechnologies in pollution reduction and remediation is covered in the next section.

2.1.2 Pollution treatment and remediation

Manufacturing and industry generate waste and often result in soil, air and water contamination by a plethora of harmful chemicals. Due to the rapidly increasing population and to increasing demands for the devices that many associate with a high standard of living, such as cars, televisions, washing machines, etc., we are increasingly being faced with the challenge of pollution control, decontamination and maintenance of soil, water and air quality. There are two main approaches to these problems: the first is to control pollution at source to minimize or eliminate waste production or harmful emissions; the second is to remedy the pollutants that accumulate in the environment. Considering the enormous scale of soil and groundwater contamination, the complexity of the task seems intractable. Nanotechnology offers a number of promising solutions to these environmental issues and represents a new approach to the clean-up of contaminated sites and waste streams, particularly for those substances that are highly toxic, persistent, or difficult to treat using conventional means. Nanotechnology also includes green manufacturing and green energy production to reduce pollution at source (see Section 2.1.3). Nanotechnology promises the creation of improved, more specific, faster and more cost-effective solutions for pollution treatment.

The early impact of nanotechnology research has been seen mostly in remediation and treatment technologies (Masciangioli and Zhang 2003). Numerous reports have examined how nanoparticles can be used for pollution treatment and contaminant remediation. Generally, methods used in the synthesis of nanoparticles can be divided into two classes (Meyer *et al.* 2004): nanoparticle formation within solution, which is probably the more common procedure, and nanoparticle formation based on polymeric matrices.

TiO_2 and ZnO nanoparticles

TiO_2 nanoparticles have been extensively studied for oxidative transformation of organic and inorganic contaminants. These are now used in a variety of products such as self-cleaning glass, disinfectant tiles, and filters for air purification (Fujishima, Hashimoto and Watanabe 1999). TiO_2 electrodes have the capacity to determine the chemical oxygen demand of water and are used as sensors for monitoring contaminated water (Kim *et al.* 2001). TiO_2, nanoparticles can be immobilized on different supports which are used for the solar detoxification of water and air. These engineered nanoparticles are known for their interaction with organic, inorganic and biological contaminants such as heavy metals, organochlorine pesticide, arsenic and phosphates in water (Dionysiou 2004; Yang *et al.* 2004). Induced by ultraviolet light, TiO_2 leads to pollutant degradation through two everyday chemical reactions: reduction and oxidation. Once excited by UV, TiO_2 electron-hole pairs develop. These electrons have sufficient oxidizing potential to oxidize pollutants in wastewater (Bahnemann 2004). Interestingly, the combination of UV and TiO_2 generates bactericidal activity, which attacks several types of bacteria (Srinivasan and Somasundaram 2003). This approach thus provides a comprehensive treatment procedure since chemical species and pathogens can be removed from wastewater simultaneously.

Other nanoparticles with semiconducting properties, such as ZnO, ZnS, F_2O_3 and CdS, can be used for photocatalysis and pollutant oxidation. TiO_2 is biologically and chemically inert and has demonstrated great resistance to corrosion along with the capacity to be used repetitively without substantial loss of catalytic activity and it is therefore inexpensive to use. In light of these properties, TiO_2 is potentially more attractive for environmental applications than other oxidative nanoparticles (Pirkanniemi and Sillanpaa 2002). However, TiO_2 requires ultraviolet light and consequently, is effective only for treatment of transparent wastewater. Several research groups have attempted to overcome this limitation by extending the nanoparticle excitation into the visible light with the doping of TiO_2 with transition metal ions or sensitizing dye such as Ru(II) polypyridyl complex, or investigated an approach involving a tube reactor production based on hollow glass tubes (Kamat and Meisel 2003; Pirkanniemi and Sillanpaa 2002). The tubes are externally coated with TiO_2 and UV-light passes through the hollow tubes.

Preliminary results suggest that combining ultrasound processes such as sonolysis and photocatalysis improves pollutant oxidation and could be an effective approach (Kamat and Meisel 2003). Several pilot projects are under way to evaluate the potential of solar reactors to generate the energy required for TiO_2 excitation and detoxification of polluted water. If these attempts are successful, sunlight could play an economic and ecologically part in the treatment of wastewater.

Unlike TiO_2, semiconductor nanoparticles such ZnO are able to emit strongly in the visible region, and the visible emissions of ZnO are usually very sensitive to hole scavengers such as phenols or iodide ions (Kamat and Patrick 1991). ZnO nanoparticles thus seem good candidates for use as sensors for chemical compounds. It has been claimed that sensor systems based on ZnO could reach a detection sensitivity of 1 ppm (Kamat and Meisel 2003). Furthermore, ZnO has the ability to induce contaminant degradation under ultraviolet light (Kamat and Meisel 2003). Consequently, use of ZnO can be considered as a promising way to simultaneously sense and destroy toxic chemicals. It has been reported that nanostructured ZnO films could simultaneously detect and degrade organic compounds in water (Kamat, Huehn and Nicolaescu 2002). Such a catalyst system is useful to induce contaminant degradation where the system senses a targeted molecule, thus avoiding destruction of inoffensive molecules present in the environment.

Carbon nanotubes

Carbon nanotubes (CNTs) have unique mechanical, electrical, optical and thermal properties and are used in a wide variety of applications such as hydrogen storage materials, superconductors, sensors, reinforced materials, etc. Furthermore, carbon nanotubes have demonstrated excellent adsorption capacity and many scientists have investigated exploitation of this specific characteristic to develop new tools for environment remediation. Arsenic water contamination is due to mining, processing of mineral deposits, discharge of industrial pollutants and natural leaching of rocks containing arsenic. Arsenic is known for carcinogenic and toxic effects on plants, animals and humans. It is therefore crucial to remove arsenic from water. Recently, a new kind of engineered carbon nanotube was developed for the removal of arsenate from water. Ceria (CeO_2) molecules were combined with carbon nanotubes and the resulting nanomaterials showed good adsorption of arsenic (Peng *et al.* 2005). Minerals such as calcium and magnesium enhanced their adsorption property, which suggests that ceria supported on carbon nanotubes might be used for drinking water purification (Peng *et al.* 2005). In addition, carbon nanotubes demonstrated high adsorption capacity for lead and could be used for the removal from water of toxic metals such as Pb^{2+},Cu^{2+},Cd^{2+} (Li 2003; Li *et al.* 2002). Carbon nanotubes have also demonstrated good capacity for the removal of many chemicals compounds from water including bisphenol A, 4-n-nonylphenol and 4-*tert*-octylphenol (Cai *et al.* 2003).

Metallic nanoparticles

The preparation of ultrafine "nanoscale" powder made from iron, one of the most abundant metals on earth, seems to be a remarkably effective tool for the transformation and detoxification of a wide variety of contaminants, such as chlorinated organic solvents, organochlorine pesticides and PCBs (Zhang 2003). Due to their large specific surface areas, iron nanoparticles have a high surface reactivity, thus providing a cost-effective solution and great flexibility for *in situ* application. For instance, it is possible to directly inject iron nanoparticles in aquifers to decontaminate groundwater. According to Zhang, iron nanoparticles remain reactive to contaminants in soil and water for extended periods of time (> 4-8 weeks) and could flow with groundwater over distances of 20 m (Zhang 2003). Furthermore, due to the low cost and absence of known toxicity, many US regulatory agencies and users have accepted environmental applications for iron (EPA 2003).

Researchers have reported the creation of bimetallic (iron and nickel) nanoparticles immobilized on cellulose acetate membrane to remove toxic chlorinated organics from water (Meyer *et al.* 2004). These hybrid nanoparticles with a diameter of 24 nm can induce efficient trichloroethylene (TCE) destruction. A reduction of 75% in TCE level was observed in contaminated water (Meyer *et al.* 2004). Use of other hybrid nanoparticles (e.g. iron-cobalt, iron-palladium, etc.) has also been reported for remediation or treatment application (Lien and Zhang 2001; Manova *et al.* 2004).

It is well recognized that zero-valent metal nanoparticles are excellent for reducing chlorinated hydrocarbons, chromium and lead (Schrick *et al.* 2004). In 1995, Glavee and collaborators developed a method to produce zero-valent iron nanoparticles (Glavee *et al.* 1995). Since 1995, zero-valent iron has been studied widely, and several other zero-valent nanoparticles such as silicon, platinum or gold have been developed and studied for their potential to remove toxic compounds (Crossley and Hill 2004; Doong *et al.* 2004; Fierro-Gonzalez and Gates 2004). Despite their potential, the colloidal chemistry of these particles is such that they tend to aggregate, which prevents their flow through soil. Obviously, several factors such as particle size, pH, ionic strength, flow velocity and soil composition affect nanoparticle dispersion, and many scientists have attempted to improve the adsorptive properties of nanoparticles in soils since this would represent a great advance in effective utilization of nanoparticles in soil remediation. Recently, Schrick, Mallouk and coworkers developed a new approach to prevent nanoparticle aggregation and enhance their dispersion in soil. These researchers described the creation of a delivery vehicle for zero-valent iron nanoparticles. This vehicle-carrier binds strongly to nanoparticles and transports them to the location where activity is needed such as contaminated sites (Schrick *et al.* 2004). The carrier helps to decrease the aggregation and sticking coefficient of zero-valent metal nanoparticles in contaminated soil.

Magnetic nanoparticles

Utilization of “magnetic” bacteria seems useful for metallic ion and heavy metal removal from aqueous solutions (e.g. Ag, Hg, Pb, Cu, Zn, Sb, Mn, Fe, As, Ni, Al, Pt, Pd and Ru) (Watson *et al.* 2000). In the presence of magnetic ions such as iron sulphide, heavy metal precipitates onto bacterial cell walls, making the bacteria sufficiently magnetized for removal from suspension by magnetic separation procedure. Some research has shown that certain bacteria could produce iron sulfonide, which would act as an adsorbent for several metallic ions (Watson *et al.* 2000).

A novel concept was proposed to synthesize mesoporous magnetic nanocomposite particles. These particles could be used for the removal of harmful agents present in the environment. This new method using employs molecular templates to coat nanoparticles of magnetite (Fe_3O_4) with mesoporous silica (Wu, Zhu and Xu 2004). These engineered nanoparticles had a significantly increased surface area and the silica coating did not interfere with the magnetic effect of Fe_3O_4. Moreover, the nanoparticles were protected by the coating which should increase their resistance for outside applications (Wu, Zhu and Xu 2004). According to Wu et al., these nanoparticles have a wide range of applications, including toxin removal, waste remediation, catalysis and biological cell separations.

Amphiphilic polyurethane nanoparticles

A new generation of nanoparticles was custom-designed for the removal of polycyclic aromatic hydrocarbons (PAHs) which are well known as being difficult to eliminate from contaminated soil or water. Amphiphilic polyurethane (APU) nanoparticles seem to be efficient at removing PAHs from contaminated soil (Kim, Shim and Shim 2003; Tungittiplakorn *et al.* 2004). Depending on experimental conditions, APU nanoparticles have a soil washing effectiveness similar to or higher than detergents such as Triton X-100 and, in contrast to detergents, APU nanoparticles extracted absorbed phenanthrene from aquifer material (Kim, Shim and Shim 2003). Furthermore, APU nanoparticles can be designed with application-specific properties. For example, APU nanoparticles can be engineered with hydrophobic interior regions that confer a high affinity for phenanthrene or with a hydrophilic surface that facilitates particle mobility in soil (Tungittiplakorn *et al.* 2004). The affinity of APU nanoparticles for the contaminants can be controlled by changing the size of the hydrophobic segment, and the mobility of the particles can be adjusted with the charge density or the size of the pendent water-soluble chain on the particle surface (Tungittiplakorn *et al.* 2004). In other words, the characteristics and the properties of APU nanoparticles can be controlled to generate different types of nanoparticles, and optimized for specific contaminants.

Nanofiltration

A nanofiltration membrane is a type of pressure-driven membrane with properties set between reverse osmosis and ultra filtration processes, which are used to remove multivalent salts such as calcium, iron, manganese, uranium, and some pesticides (Hilal *et al.* 2004). In contrast to the methods and technologies described above, nanofiltration is not a nanotechnology *stricto sensu*. However, since nanofiltration allows the capture of particles of between 0.5 and 8 nm diameter (Dijkstra, Van Klink and Van Koten 2002), some people classify this process as a nanotechnology (Royal Society 2004). In this context then, since reverse osmosis is used to capture smaller particles, it should also be considered as a nanotechnology.

Nanofiltration is useful for the treatment of wastewater and ground and surface water. Due to its capacity to remove microorganisms, turbidity and hardness, nanofiltration is also used in water treatment for drinking water production. Furthermore, nanofiltration has been shown to be an efficient method of desalination (Hilal *et al.* 2004). Several experts have raised the question of shortage for drinking water as a major issue for the twenty first century and an efficient method such as nanofiltration for desalination of ocean water could help alleviate this problem. In recent years, nano and ultrafiltration techniques were used in catalyst recycling (Dijkstra, Van Klink and Van Koten 2002). Macromolecular catalysts could be created by coupling a catalyst to a soluble organic support and, using this approach, catalysts can be recovered from product streams by nanofiltration and re-used (Dijkstra, Van Klink and Van Koten 2002). Catalyst recycling by nanofiltration represents an environmentally friendly solution which produces smaller quantities of byproducts and waste materials. In addition, nanofiltration will be instrumental in catalytic processes that have a high selectivity and activity, and will decrease the amount of catalyst used, thus reducing costs (Dijkstra, Van Klink and Van Koten 2002).

Pollution control through maintenance of environment quality and remediation of contaminated soil, air and water, represents a huge and costly challenge. Engineered nanoparticles, and tools based on nanotechnology, promise an affordable and effective approach to removing or preventing the diffusion of harmful substances in the environment.

2.1.3 Green technologies

Utilization of nanotechnology for this specific environmental application tends to develop technologies that eliminate or decrease harmful emissions and waste from industrial processes and includes the development of clean energy sources such as solar energy and fuel cells.

In comparison to conventional manufacturing processes, nanotechnologies will allow the creation of materials and devices with more innocuous byproducts, and could decrease harmful emissions. In terms of quantity, nanodevices and other nanotools require very few raw materials (e.g. carbon, silicon etc.) to produce the desired end-product. Therefore, such approaches should generate fewer byproducts and hazardous substances and decrease the risks.

Several tools used in the field of nanotechnologies are based on carbon, usually in the form of carbon nanotubes or buckyballs. Carbon is plentiful, can easily be found and could eventually be extracted from carbon dioxide present in the air as a raw material for nanotube or buckyball production, thus offering at least a partial solution to greenhouse gas problems (Reynolds 2001). Furthermore, carbon nanotubes are 100 times stronger than steel and six times lighter (Keiper 2003) allowing the creation of stronger products using less material and therefore saving natural resources. In addition, energy requirements for these products will decrease for a number of reasons. For instance, stronger cars, planes or any vehicle with a fraction of the weight of current models could be produced and would require less fuel, thus reducing energy consumption.

Soon after the discovery of carbon nanotubes in 1991, various research groups succeeded in filling carbon nanotubes with different elements, and some seemingly very promising experiments suggested high hydrogen storage capacities for carbon nanotubes. However, :data obtained from different experimental methods for various carbon nanostructures produced contradictory results, and are more and less controversial (Cheng 2001; Hirscher and Becher 2003). Although at this point it is difficult to be definitive, several scientists still believe that carbon nanotubes can store the amount of hydrogen required for automotive applications and could be used as energy cells, an application that could reduce atmospheric emission (Cheng 2001). In addition, nanoparticles such as ceria are being investigated for their capacity to improve fuel economy by reducing the degradation of fuel over time (Oxonica 2003).

Nanoproducts such as solar and fuel cells could lead to commercially viable alternative clean energy sources. Hydrogen used as fuel in fuel cells is usually generated by catalysis of hydrocarbons and the potential utilization of nanoparticles to engineered cell surface and nanomembranes to enhance catalytic processes could enable higher-efficiency, small-scale fuel cells (Royal Society 2004). These improved cells could eventually be used as sources of energy, offering a more efficient, more ecological and safer way to produce energy than current sources such as hydroelectricity or nuclear energy.

Solar cells based on CdSe nanoparticles assembled on a rod forming tuned to absorb different colours within the solar spectrum produce a high efficiency and inexpensive solar cells to produce energy (Teague 2004). In addition, using these types of nanoparticles, different methods have been developed to produce a light emitting diode (LED) (Chen *et al.* 2004; Chen, Grouquist and Roark 2002; Kowshik *et al.* 2002). One of the simplest methods includes the utilization of CdSe or CdTe nanoparticles dispersed homogeneously in liquid, which can be coated easily on a substrate using a simple coating method such as spray or dip coating (Su and Lin 2004). Therefore, a low cost, large area, high efficiency and reproducible light emitting source can be produced easily. Use of nanoparticles in LED technology could reduce light energy consumption and decrease carbon emissions. For example, a conventional traffic light signal uses a powerful incandescent lamp (140 W) with a red filter. A corresponding signal LED would require 18 red LEDs which would consume only 14 W (Karn 2004).

Research is also being undertaken to recycle or replace toxic and harmful products. For instance, it has been proposed that nickel nanoparticles could efficiently recycle CO_2 in methane to produce energy (Hashimoto *et al.* 2001). Since CO_2 emissions grow with increased economic activities, and induce global warming, CO_2 recycling by nanotechnology could prevent global warming and supply clean and renewable energy. A low temperature method has been developed to recycle sulphuric acid from waste water in nanocrystalline zinc ferrite powder (Lopez *et al.* 1998). Due to their surface properties, zinc ferrite nanocrystals are used for several applications including starting materials for magnetic applications and sorbents in combustion gas purification processes. These nanoparticles are also used to obtain ceramic products with high densification (Lopez *et al.* 1998). This approach generates a great ecological interest since it allows waste water treatment by the conversion of harmful acids in nanoparticles, which can be reused in many applications. Dr Majid Abdul who is associated with the Nanostrucutured Materials Institute for Chemical Process and Environmental Technology (ICPET) has carried out several research projects in nanotechnology. Abdul's interest includes the development of silica nanoparticles to replace toxic species such as cadmium or chromium (NRC 2005). Recently, Kakisawa and collaborators developed a low temperature method based on atomization to recycle copper-rich scrap iron to produce iron and copper nanoparticles with enhanced properties such as improvement in material strength and plasticity (Arcuri, Ricceri and Matteazzi 2001; Kakisawa *et al.* 2003).

Miniaturization and nanotechnology are key drivers in the evolution of electronics and data processing and communication. Although these fields may appear to be remote from environmental applications, they could have a relatively important, albeit indirect, environmental impact. Nanotechnologies and other miniaturization techniques enable more efficient and smaller computers and electronic devices, which require less electrical energy. Considering the ubiquity of electronic devices and the growing number of computers in our society, this could represent a considerable economy in terms of energy production.

Catalysts are of major importance in cleaning up the environment: they speed up the rate of chemical reactions. The speed and efficiency of nanotech catalysts will make such processes more economical. Petroleum and chemical processing companies are using nanostructured catalysts to remove pollutants. The catalyst market was worth about $30 billion in 1999 and is forecast to reach $100 billion by 2015. (Buff 2003). Generally, nanoparticles have a high surface area providing higher catalytic activity. It may also be possible to engineer nanoparticles for selective catalytic activities with more active and durable properties. Considering the limited availability of conventional catalysts such as platinum and derived metals, nanoparticles offer an opportunity to decrease the demand for these materials, thus saving the natural stock of platinum, and could one day replace platinum in catalytic reactions (Royal Society 2004).

The use of nanotechnologies for green industry and energy would reduce the quantities of waste-products and harmful emissions. It may be possible to reduce or eliminate solvent use, develop more environmentally friendly materials and create improved catalysts leading to leaner, safer and cheaper production methods. By creating products and applications with optimal (i.e. minimal) feature size that require less raw materials and less energy for their production and operation, nanotechnologies decrease the use of resources. Lighter weight materials decrease transportation fuel energy use and efficient electronic or product manufacturing requires less energy to be functional.

2.1.4 Future applications

According to reports and scientific publications written by experts in fields as varied as nanotechnology, engineering, toxicology, biology, chemistry, health and others, the future of nanotechnology appears to be unbounded. For instance, some authors have proposed that nanoparticles could be used to produce energy. Many bacteria can produce hydrogen which can be used as a renewable source of energy. Using gold nanoparticles which are selectively deposited on bacteria, it is possible to produce electrically conducting bridges. Gold nanoparticles allow electron transfer from bacteria to an electrode (Berry, Rangaswamy and Sara 2004). Carbon nanotubes could also be used as channels to pump hydrogen from bacteria. Nanoparticles and nanotechnologies could become an alternative means of producing energy, but might raise issues related to the safety and the risks associated with these new approaches. For example, nanoparticles may increase the mutation rate of bacteria and could represent a potential threat to the environment and to human health.

Nanotechnology may enable existing products to be more efficient. The incorporation of nanoparticles in paint, it is suggested, means that nanotechnology may enable the production of paints with improved properties requiring little or no solvents. For example, nanometer-size carbon (nanodiamonds) has been used to create paint with enhanced resistance to impacts, scratches and lower friction (Vogt 2004). In the near future, it will be possible to produce more ecological paint. Currently, most paints contain isothiazolin-3-ones to increase their shelf life, but this reagent is known to be harmful to ecosystems since it inhibits the growth of mould and fungi (Kandavelu, Kastien and Ravindranathan Thampi 2004). The presence of nanocrystals of TiO_2 and ZnO, which are activated by light, enable isothiazolin-3-ones degradation (Kandavelu, Kastien and Ravindranathan Thampi 2004). In other words, it will soon be possible to produce paint which can self-decontaminate. In addition, paint could contain nanoparticles that react to their environment by changing colour when stimulated by temperature or light. Energy-saving applications would include infrared reflection to decrease heat-loss. However account must be taken of the fact that paint erodes with the time, representing a potential source of nanoparticle emission for the environment and a potential threat if the nanoparticles are toxic.

Although sensors to detect pollution and contaminants currently exist, nanotechnology would allow the creation of new generations of sensors with enhanced capabilities which could detect pollutants at very low levels of concentration, providing continuous data and real-time information. These nanosensors would be useful for a network for a specific area (e.g. around a city or a specific ecosystem) allowing rapid detection of toxic compounds and would represent an important weapon against terrorist attacks or massive chemical releases.

For a large part of the population, the word nanotechnology is synonymous with microscopic robots with a capacity to enter the body and repair cells. Obviously, this is a largely imaginary construct which is more the stuff of science-fiction than reality. Despite this, several scientists believe that in the near future, nanorobots, that is, simple microscopic devices, could be injected, for instance, into the circulatory system as sensors. Following an infection, these nanorobots could detect small concentrations of pathogens and destroy them. Such sensor do not yet exist but devices that exploit the change in conductivity of carbon nanotubes or nanowires when exposed to specific substances are perhaps the closest that exists to nanorobots with sensory functions (Requicha 2003).

It is important to keep in mind that all these examples are extrapolations of the current research, concepts and available data. Although these projections suggest several new interesting environmental applications, many of these proposals might never materialize.

2.2 Research on the adverse effects of nanotechnology on the environment

Despite the promises of nanotechnology for delivering new and improved environmental technologies, this emerging field could also have adverse effects, such as the creation of new classes of toxins, and the unintended diffusion of nanomaterials and nanoparticles in ecosystems, all of which may have unforeseen consequences. As nanotechnology is a rapidly expanding field, the potentially harmful effects of nanoparticles and other nanotechnology applications need to be anticipated and prevented.

Though nanoparticles and nanomaterials are often engineered, they can also produced by natural processes such as combustion. Nanoparticles could be released in the environment and reach human, animals and plants by several routes. For instance, factories and laboratories which use nanoparticles for industrial processes could release nanomaterials by the waste and discharge produced, by the manufactured product which contains nanoparticles (e.g. titanium dioxide particles in sunscreen), leakage during transport and, of course, direct contamination of exposed workers. Nanoparticles could also directly reach the environment if they are used as tools for remediation or other environmental applications. If nanomaterials are released in the air, it may directly be inhaled by organisms. This is the dominant pathway for exposed workers in factories and for organisms exposed to nanoparticles from natural sources such as combustion and atmospheric photochemistry. Exposure to nanoparticles could also occur by direct contact with the skin or from ingestion (e.g. cosmetic and sunscreen, organism living in contaminated soil or water, nanoparticles bioaccumulation in the food chain etc.).

2.2.1 Engineered nanoparticles

Researchers have recently started to study the negative effects of engineered nanoparticles and several issues have been completed on the safety of these new materials. The high surface reactivity of nanoparticles represents one of their most attractive properties and was exploited in a wide range of applications but it could also represent a potential threat for health and environment. This enhanced reactivity creates concerns among scientists because nanoparticles have the potential to interact in an uncontrolled and unforeseeable manner with the many molecules present in the environment or in the cells of organisms. A second property which could represents a potential threat for environment and health is the feature size. The very small size of nanoparticles, smaller than common irritants and pollen, has led to the formulation of the hypothesis that nanoparticles could evade immune system defence. Some of breathed particles can reach air sacs in the lung which are patrolled by macrophages and other scavenger cells to eliminate them and prevent passage of these particles in blood. However, macrophages appear to have difficulty recognizing particles less than 70nm in diameter, and they can be easily overwhelmed by too many particles.

Some evidence supports this argument. For instance, it has been reported that nanoparticles such as carbon black and titanium dioxide, which are increasingly used in industrial processes and that increasingly contribute to air pollution, induce inflammation, epithelial injuries and are retained in the lung, allowing dose accumulation (Moghimi and Hunter 2001; Renwick *et al.* 2004). Furthermore, Knowland, Dunford and collaborators from the UK, which are among the first scientists to reveal the potentially harmful effects of nanoparticles on human health, have demonstrated in 1997 that titanium dioxide/zinc oxide nanoparticles from sunscreen cause free radicals in skin cell, damaging DNA (Dunford *et al.* 1997; McHugh and Knowland 1997). DNA damage is well-known to induce mutations, leading to alterations in protein structure and function that can result in tumorigenesis and cancer development (Poirier 2004). As mentioned previously, considering that titanium dioxide nanoparticles have been extensively studied and used in many applications including bioremediation to remove contaminants from soil, air or water, in a variety of day-to-day operations and as biosensors, these particles could easily be released in the environment. Although very little data are available on the persistence and bioaccumulation of these nanoparticles, it is possible that following their release in the environment, herbivore or fish ingested these potential carcinogenic particles resulting in an entry point into the food chain. Consistent with this hypothesis, researchers from the Center for Biological and Environmental Nanotechnology (CBEN, Rice University, Houston) reported to US EPA in 2002 that engineered nanoparticles accumulate in the organs of lab animals and are taken up by cells (Brown 2002). In addition, if bacteria or protozoa may take in nanoparticles through their cell membranes, they will provide a new entry point into the food chain and it will contribute to a wider diffusion of these nanoparticles among organisms present in ecosystems.

It is well known that miners and workers exposed to microparticles of quartz minerals, which are considered as carcinogen, are subject to important diseases. In fact, exposure for few years to micrometer-size quartz particles, in concentrations of the order of a milligram per cubic meter of air, leads to potentially fatal form of lung fibrosis while low exposure to these particles induces severe lung inflammation, cell death, fibrosis and tumours in rats (Seaton *et al.* 1995; Vallyathan 1994). In 2003, scientists from NASA/Johnson Space Center reported that studies on the effects of carbon nanotubes on the lungs of rats produced more toxic responses than quartz dust (Hogan 2003). Supporting these data, a comparative study to evaluate pulmonary toxicity of quartz, carbon black and carbon nanotubes particles on rodents demonstrated that all of these particles induce severe lesions, inflammation and cell necrosis in dose-dependent responses. These results also suggested that carbon nanotubes are much more toxic than carbon black and quartz particles (Lam *et al.* 2004). It has been demonstrated that the surface of quartz or carbon nanoparticles, which is highly reactive, generates free radicals leading to oxidative damages in macrophages and defensive cells (Renwick *et al.* 2004; Renwick, Donaldson and Clouter 2001). Based on these studies, it appears that surface reactivity and particle size are key factors in the toxicity of nanoparticles.

Human epidermal keratinocytes exposed to carbon nanotubes result in accelerated oxidative stress, accumulation of peroxidative products, a decrease of glutathione and depletion of antioxidant molecules and vitamin E. Additionally, several structural alteration and morphological changes were observed following exposure to carbon nanotubes (Shvedova *et al.* 2003). Taken together, these data tend to corroborate the hypothesis of the cellular toxicity of carbon nanotubes for human cells.

Carbon nanotubes aggregate in the air and have a greater propensity to form nanocrystals than diesel particles do. The nanocrystal form of carbon particles has the potential to be more harmful to living organisms than non aggregated forms. Combustion sources such as gas cooking stoves, industrial gas combustion and a variety of domestic heating source produce aggregates containing hundred or thousand of carbon nanotubes and related nanocrystal structures, including buckyballs (Murr *et al.* 2004a; Murr *et al.* 2004b). Experimental evidence provides an indication that unprocessed carbon nanotubes can form aerosol during handling or with sufficient agitation (Maynard *et al.* 2004). Although further research into mechanisms by which aerosol particles are released from bulk carbon nanotubes materials is needed, this study highlights a potential health risk associated with handling carbon nanotubes. In this regard, we can assume that factories which produce or use carbon nanotubes-based materials expose their workers to health hazards. Moreover, manufactured carbon nanoparticles such as fullerene (buckyballs), which is being produced in large quantities in the US, induces glutathione depletion and oxidative damage in brain of exposed fish (largemouth bass), causing changes in gene functions. Furthermore, evidence suggests that fullerene can travel through the soil and that earthworms could easily absorb buckyballs, possibly allowing them to move up the food-chain (Brumfiel 2003; Halford 2004; Oberdorster 2004).

These research reports suggest that carbon based nanoparticles could be highly toxic and could generate serious environmental hazards. It is important to note that a majority of studies and scientific data concerning pulmonary injuries induced by nanoparticles are mainly based on the study of titanium dioxide, diesel and carbon nanoparticles with rat models and, at this point, very few other animal models have been studied. Rat is known to be an extremely sensitive species for developing adverse lung responses to particles. In this regard, chronic inhalation studies in rats could exaggerate nanoparticles effect due to particle-overload in the rat lung (Warheit 2004). This question is particularly relevant, considering that other rodent species such as mice and hamster exposed to the same particles have demonstrated different lung responses. In addition, a study conducted by Warheit et al. has provided contradictory data. Rat exposed to carbon nanotubes produced a non-dose-dependent physiological response (Warheit *et al.* 2004). Therefore, it appears primordial to study nanoparticles effects on as many animal models as possible with various methods (nanoparticles injection, inhalation etc.) to adequately evaluate their effects on physiology and health.

At Nanotox 2004, a conference at Daresbury Laboratories in England, Dr. Vyvyan Howard, one of Europe's leading researchers of nanoparticle toxicity, suggested that nanomaterial may be transferred from a mother into her foetus (Wootliff 2004). Scientists injected gold nanoparticles into pregnant rats to determine whether they can be transferred across to the foetus. Howard's findings were presented as part of an overview of 27 papers that looked at how nanoparticles can be absorbed into the body and distributed to the organs. She cited several studies that showed that once nanoparticles have been internalized, they appear to be able to travel across the body.

There is also evidence that nanoparticles have the ability to circumvent the blood-brain barrier in rats. It has been demonstrated that inhaled nanoparticles can be translocated in the central nervous system, suggesting that nanoparticles could travel along the nerves (Oberdorster *et al.* 2004). Supporting this finding, urban dogs living in Mexico which were exposed to air pollution have accumulated metallic particles (e.g. nickel or vanadium) in their brain. Scientists have also noted an acceleration of Alzheimer's-type pathology for these dogs in comparison with dogs present in the control group (Calderon-Garciduenas *et al.* 2003). Scientists have also discovered that quantum dots can break down in the human body potentially causing cadmium poisoning (Mullins 2004).

Research on nanoparticles suggests that when normally harmless bulk materials become toxic when they are made into ultrafine particles. Several toxicologists agree that smaller particles are often more reactive and toxic. A direct correlation seems to exist between size and particle toxicity. Nanoparticles have a comparatively huge amount of surface, which tends to become electrically charged, and thus chemically reactive. The upper size limit for the toxicity of ultra fine particles, including nanoparticles is not fully known but some experts suggest a size limit between 65 and 200 nm (Donaldson *et al.* 2000). For instance, catalysts, notably metal oxides, can change dramatically and react differently at nanoscale levels. These emerging properties generate a great deal of interest for the creation of new tools but it also represents a potential risk since their effects are unknown.

2.2.2 Natural nanoparticles

Combustion is probably the most important source of natural nanoparticles in the environment. Despite the potentially hazardous effects of these particles on health and the environment, it is important to set these concerns in context: humans have always been exposed to some types of nanoparticles with forest fire and atmospheric photochemistry. The release of engineered nanoparticles in the environment is potentially more dangerous than natural nanoparticles because they are new materials and, therefore, organisms including humans may not have or have inadequate defence mechanisms. In addition, we know very little on the effect of these new types of particles. On the other hand, with appropriate measures and precaution, it is possible to control the emission of engineered nanoparticles and to minimize their release in the environment in contrast to natural nanoparticles which are spontaneously released.

Industrial combustion and diesel combustion from vehicles represent an important source of natural nanoparticles emission. The mass concentration of exhaust particles has been significantly reduced over the past years but effective removal of particles from vehicle exhaust via catalytic materials and filters such as particulate traps represents a real challenge. The formation of nanoparticles with a diameter below 50 nm in diesel exhaust during dilution processes has been reported in several studies (Vaaraslahti *et al.* 2004). These nanosized particles do not have a solid core, but they are semivolatile and have been found to evaporate completely when heated to 175 °C (Vaaraslahti *et al.* 2004). Because of the current demand for automotive fuel economy and emission control, automobile manufacturers are introducing higher performance engines but it appears that nanoparticles cannot be effectively removed by current methods such as three-way catalysts (Al-Abadleh and Grassian 2003).

Considering the number of automobiles and other types of vehicles as well as industrial combustion from factories and processing facilities, it will be crucial to rapidly develop efficient methods to detect nanoparticles produced from various sources and create new tools to eliminate or minimize these emissions.

2.2.3 Potential mechanisms of nanoparticle toxicity

Very little information is available about the mechanism of nanoparticles toxicity. Research conducted by Oberdöster, Ferin and collaborators suggested that carbon black and titanium dioxide nanoparticles are significantly more toxic than larger particles of the same material (Ferin *et al.* 1990; Oberdörster 1996). In some cases, nanoparticles toxicity could be explained by the presence of transition metals at the particle surface, inducing free radical formation (Donaldson *et al.* 2001). It is important to keep it mind that this argument provides only partial answers to the question of nanoparticle toxicity since several nanoparticles with no transition metal have been shown to have toxic effects. For these particles in particular, *in vivo* (animal model) and *in vitro* (cell culture-based experiments) studies supported the hypothesis that the large specific surface of these particles represents a major element in the induction of oxidative stress and inflammatory response (Brown *et al.* 2000; Faux *et al.* 2003). Obviously, to understand precisely the harmful effects of nanoparticles to living organisms, further investigation and research are needed to explain.

Taken together, recent reports (Section 2.2.1) highlight nanoparticles toxicity for some animals such as rodents, fish and, potentially, humans based on *in vitro* studies. We can assume that other animals living in the ecosystem could be also affected by nanoparticles. Iron nanoparticles and buckyballs can travel in soil and groundwater thus representing a potential threat for neighbouring organisms. We know that cells can uptake nanoparticles which suggest that microorganisms such as bacteria could also absorb nanoparticles before moving to higher organisms in the food chain. Nanoparticles are generally insoluble and carbon nanotubes could form aerosol, suggesting that these particles could be easily disseminated in the air, soil and water. Considering that carbon-based nanoparticles (carbon nanotubes, carbon black and buckyballs), titanium dioxide nanoparticles and industrial/vehicles combustion are produced in still increasing quantity, it is important to develop new research avenues to answer crucial questions on the impacts of nanotechnology on the environment.

2.2.4 Perspective and new research avenues

This section describes new research avenues and critical questions raised by nanotechnologies for environmental applications. Obviously, these research efforts should be undertaken to increase our level of understanding of engineered nanoparticles but this is also true for natural nanoparticles produced by combustion phenomena which are very different by their nature and the toxicity mechanism employed.

Very little scientific evidence exists concerning the effects of nanoparticles on various types of organisms. Advancing scientific knowledge by collecting data on exposure level, characterizing dose-response and performing a wide range of toxicological and ecotoxicological studies for each known nanoparticles on a wide variety of animals including human, plants and microorganisms is essential to produce a more precise picture of the impact of these new nanomaterials on the food chain and on ecosystems.

Other important research avenues include studying the persistence of nanoparticles in the soil, water and air and evaluate the production, use and fate of nanomaterials through life-cycle analysis. Identification of nanomaterials release mechanisms in the environment and analyzing transport mechanisms from soil, air and water to living organisms with the consideration of important parameters such as nanoparticles biodegradability and bioaccumulation in organisms should be considered in an environmental study.

It is also important to evaluate whether and how effective current standards and treatment methods are in detecting and removing nanoparticles from soil, air and water. Some research should be undertaken to develop tools to efficiently detect and measure nanoparticles in the environment and to find new ways of eliminating or decreasing the adverse effects of some nanoparticles. In addition, some efforts should be spent to create standards and risk assessment methods for nanoparticles and to develop appropriate procedures for cleaning up accidental emission of nanoparticles.

Some studies should be carried out to evaluate whether the environmental benefits from nanotechnologies are superior to their potential risks and adverse effects. Although several scientists, experts and groups claim that nanotechnologies are the green solution of the future, several other aspects need to be weighted to determine the aggregate impact of nanotechnology on environment.

Some nanoparticles seem less harmful than others for living organisms. Research is needed to shed light on particle properties (physic and chemical) and answer questions such as “what makes a toxic nanoparticles biocompatible?” To foster a better understanding of nanoparticles toxicity mechanisms, research on nanoparticles effects on animal health is necessary. Preliminary evidence should be augmented with more advanced studies that need to be designed to identify the effects of nanoparticles on lungs, immune system, brain and nervous disorders. Collecting scientific data to establish a correlation between physicochemical and biological toxicological properties and to discover toxicity molecular mechanisms including transport mechanisms of particles from lungs-blood-organs pathway and nerve-brain pathway, mechanism of DNA damage and oxidative stress on protein and gene alteration and disease development such as cancer will be instrumental to a better understanding of nanoparticles toxicity in living organisms. Understanding the toxicological properties of nanoparticles and their biological effects with regards to the different types of ingestion (e.g. inhalation, skin contact) appears to be an urgent avenue for further research. Long term *in vivo* research is crucial to determine the effects of nanoparticles through time and to improve our understanding of acute and chronic effect of nanoparticles on living organisms. Statistical and epidemiologic studies are also required to establish correlation between the presence of nanoparticles in specific ecosystems and disease development in animals and humans and it is also essential to evaluate the health risks posed to factory workers.

2.3 Conclusion

Nanotechnology-based products and processes promise to be ecologically beneficial in terms of energy consumption, materials saving, replacements of toxic materials and resource preservation. However, several questions such as the toxicity of nanoparticles, the capacity to recycle products generated by nanotechnologies and the degree of environmental compatibility of nanotechnology production processes need to be answered.

A largely reported claim is that nanotechnology will present major environmental benefits by decreasing the resource required to manufacture goods or that it will increase energy-efficiency. For example, nanotechnology will decrease the weight of airplanes, thus reducing fuel consumption. In addition, these smaller planes could be also cheapest to produce, decreasing ticket costs and increasing the number of passengers. Consequently, this could lead to a multiplication of the number of airplanes flying and, if this were the case, the environmental benefits would be greatly mitigated. Thus, it is important to substantiate such claims with in-depth analyses and with an objective stance. While at first glance nanoparticles and other nanotechnology-based materials pose as green technology, considering potential risks for health and environment, it is also possible that nanotechnology will replace one set of environmental risks with new risks and problems.

3 Nanotechnology Policy and Stewardship Issues

Major industrial countries are progressively incorporating nanotechnology in their innovation systems, seeing it as an engine of wealth creation and as an effective solution to industrial problems. Governments and businesses have great ambitions and consequently they have invested considerable effort into developing nanotechnology. Reflecting this interest, over 30 national governments have launched initiatives in nanotechnology and begun to invest heavily in research and development (Choi 2003; Roco 2002). At the same time, it is recognized that nanotechnology applications raise new social, ethical and legal issues. At the most basic social level, nanoscale engineering has the potential to create massive changes in the way we live, how we interact with one another and with our environment, and what we are capable of doing.

Scientific discoveries do not usually change society directly; rather, they set the stage for the changes that come from new technological developments in a context of evolving economic and social needs. Similarly, nanotechnology is being introduced through the complex interplay of technical and social factors, and its impacts on society are complex and only partially understood. Therefore, it is important that efforts be devoted to studying the processes by which nanotechnology is developed, and to evaluate how this emerging technology might affect the future for science, economy, society, and ethics. This knowledge will help policymakers to make appropriate decisions to favour a beneficial and sustainable development of nanotechnology.

Several programs and initiatives have been launched to facilitate nanotechnology developments in countries across the world. In parallel with these efforts, some countries have established strategies to study the impact of nanotechnology and to assess the social and ethical issues of this emerging science. However, these initiatives have rarely targeted the environmental impacts of nanotechnology and, in most cases, they are concerned only with social and ethical questions. This section provides an analysis of strategies and initiatives deployed by different countries to identify stewardship issues associated with nanotechnology, and is focuses on geographic regions (The US in Section 3.1; Europe in Section 3.2; and Asia in Section 3.3). Some of these strategies can be instrumental in mitigating the negative impacts on society and although not always directly associated with environmental or social issues of nanotechnology, they represent a good example of strategies that could be reoriented or adapted to identify and handle stewardship issues associated with nanotechnology.

3.1 The US

As nanoscience and nanotechnology have advanced, and discoveries and applications have migrated from the laboratory to the marketplace, the potential contributions of nanotechnology to economic growth has attracted increasing attention from the US government. Attempts to coordinate federal work began in 1996 under the National Science and Technology Council (NSTC) and with the cooperation of several federal agencies an orchestrated National Nanotechnology Initiative (NNI) was approved under the Clinton administration in 2001 (NNI 2005).

3.1.1 The National Nanotechnology Initiative

Once the NNI had been set up, the Nanoscale Science, Engineering and Technology (NSET) subcommittee was established as a component of the NSTC. The NSTC, which is composed of senior-level representatives from the federal government's research and development departments and agencies, provides policy leadership and budget guidance for multi-agency technology programs. By contrast, the role of NSET, which includes representatives of departments and agencies currently involved in the NNI, is to coordinate the federal government's nanoscale research and development programs including those covered by the NNI umbrella (NNI 2005).

The National Nanotechnology Coordination Office (NNCO) was established to serve as a secretariat for NSET and supports NSET in multi-agency planning and the preparation of budgets and program assessment documents. It also assists NSET with the collection and dissemination of information on industry, state, and international nanoscale science and technology research, development and commercialization activities. As the main point of contact on federal nanotechnology activities, NNCO's activities also include the support of workshops as well as the preparation and diffusion of reports (NNI 2005).

The federal agencies and committees that coordinate the NNI are at the heart of initiatives and policies on nanotechnology in US. In fact, most American initiatives are directly or indirectly supported by the NNI and, overall, the US has adopted a centralized approach to coordinating the development of nanotechnology. The NNI is built around five funding themes distributed among the major agencies (e.g. NSF, NIH, DOD, DOE, NASA, NIST, EPA, etc.) currently funding nanoscale science and technology research (NRC 2002). Current themes include performing basic research, meeting major challenges (which include support for interdisciplinary research and education teams that work on key long-term objectives), creating centers and networks of excellence, supporting research infrastructures (e.g. facilities, instrumentation, etc.) and studying the social implications.

The available information strongly suggests that stewardship practices in environmental applications of nanotechnology are only of marginal concern to the NNI: very few of its programs are devoted to the environmental dimensions of nanotechnology. Existing stewardship measures supported by the NNI concern mainly the social and ethical issues raised by nanotechnology development. Reflecting this situation, the majority of the US initiatives and stewardship practices described in the following sections deal mainly with the social and ethical aspects of nanotechnology. However, Science-Metrix considers that these initiatives or stewardship practices could be adapted or re-oriented to environmental issues associated with nanotechnology and therefore could provide inspiration to develop efficient stewardship practices.

In 2002, only 4% of the NNI budget was allocated to social implications themes and only two agencies, NSF and NIH, had responsibility for this field. With 88% of its budget allocated to the study of the social implications of nanotechnology, NSF was the main agency awarding grants and supporting research along this theme (NRC 2002). NRC argues that NSET did not give sufficient consideration to the social impact of nanotechnology and to stewardship practices that aim to minimize the social issues raised by nanotechnology. In fact, the NRC considers that "social implications" was only a fancy title for a relatively straightforward educational initiative targeted at graduate and undergraduate students (NRC 2002).

Since 2002, some progress has been made but, despite an increased budget allocated to social dimensions and a greater number of research projects having been funded to explore the social aspects of nanotechnology, some experts claim there is still much room for improvement. Subsequently, NSF has made more effort to support investigators in the social and behavioural sciences, and in ethics and values and, by changing eligibility requirements, NSF initiatives have lead to additional applications from researchers who are interested in the social and ethical dimensions of nanotechnology.

3.1.2 NSF and the NSEC program

To support the program deployed by the NNI to investigate the social and ethical aspects of nanotechnology, the NSF launched the NSEC program. NSF selected six facilities (Rensselaer Polytechnic Institute, Harvard, Columbia, Cornell, Northwestern and Rice universities) to establish a new Nanoscale Science and Engineering Centers (NSEC) which support programs based on multidisciplinary approaches to develop mainly basic research in nanotechnology. Each facility focuses on a particular area of basic research.

The majority of these facilities involved in the NSEC program are already engaged in research concerning the social and ethical implications of nanotechnology, the exception being the Center for Biological and Environmental Nanotechnology (CBEN) facility at Rice University, which is mainly devoted to the environmental issues raised by nanotechnology and investigates efficient solutions to minimize these issues (CBEN 2005; Northwestern 2005; NSF 2005a; Renss.Poly.Inst. 2005). In the US, CBEN's activities represent one of the most important initiatives related to, and openly dealing with, stewardship issues linked to the environmental dimensions of nanotechnology.

CBEN is highly specialized in environmental nanotechnology and is devoted to studying how to make the nanomaterials industry environmentally sustainable and investigate the potential environmental impacts of nanomaterials such as nanoparticles (CBEN 2005). Specifically, the program is aimed at predicting the fate and paths of nanomaterials in natural systems, and whether nanomaterials will behave in the same way as other more common environmental pollutants. In addition, the program aims to determine whether nanomaterials can be treated before they are released into the environment to minimize their impact. Previous research has provided information on how structures such as fullerenes clump together in water to form larger particles. This study is the first to show what factors affect the size of these aggregate particles (CBEN 2005).

CBEN has also integrated a set of programs that aim to address the scientific, technological, environmental, human resource, commercialization, and social barriers associated with nanotechnology. For instance, a specific project was designed to ensure that productive and highly engaged discussion about the social and ethical nature of science would occur across disciplines (e.g. anthropology, nanotechnology etc.) (CBEN 2005). Another project was devoted to establishing a scientific model of trust and risk perception for emerging nanotechnologies. CBEN's vision is based on the necessity to evaluate the potential risks associated with the applications of nanotechnologies.

Such information enhances public communication about nanotechnology, and allows policymakers to take well grounded decisions about risk management in this new industry. CBEN is certainly one of the most important models to study in the balanced development of nanotechnology and care for environmental stewardship.

Rensselaer Polytechnic Institute, which has expended considerable efforts on studying dimensional and compositional nanostructures, has brought together a team of researchers who will consider strategies for managing issues expected to emerge out of nanotechnology research as an initiative within the part of the NSEC program that covers the social dimensions of nanotechnology (Northwestern 2005; NSF 2005a; Renss.Poly.Inst. 2005). This team will attempt to answer key questions such as: what are the challenges associated with the commercialization of nanotechnology? What are the challenges of nanotechnology research? What are the challenges of science and technology policy? And what are the challenges to society and the precautions required by the growth of nanoscience and nanotechnology (Renss.Poly.Inst. 2005)?

Northwestern University, which concentrates on the development of nanodevices that could be used as nanosensors, is also concerned that, to be fully accepted and integrated into society, new technologies must be aligned with social systems (Northwestern 2005; NSF 2005a; Renss.Poly.Inst. 2005). With respect to the social dimension of NSEC's program, a Northwestern University research team has launched a social science research project to explore public opinion and to study the social acceptance, resistance to, or rejection of nanotechnology. To be adequately prepared for the potentially drastic changes from the application of nanotechnology, the Northwestern University's research team believes that social reflection and organizational and institutional creativity must be brought to bear, so that social innovations evolve in tandem with technological innovations (Northwestern 2005).

Cornell University develops innovative electronic, photonic, and magnetic nanoscale systems that collectively have the potential to revolutionize information technology including electronics, communications, information storage and sensors (CNS 2005). A specific project has been designed to study social issues relating to nanotechnology. This project examines the processes that are shaping public understanding of nanotechnology from the point of view of the social implications. This analysis should improve understanding about the role of mechanisms in shaping the social implications of nanotechnology and should provide guidance to scientists and science communicators about how to interact more effectively with diverse audiences, including members of the public, policymakers, industry leaders, and investors.

Harvard and Columbia universities, also selected by NSF for the NSEC initiative, have conducted research into electronic and magnetic applications of nanotechnology (Columbia 2005; Harvard 2005). Compared with the other universities participating in the NSEC programs, Harvard and Columbia universities seem to have the weakest program for exploring the social and ethical issues associated with nanotechnology. In fact, their focus is on the training of students in nanotechnology and on promoting a close integration of research, education and public outreach (Columbia 2005; Harvard 2005).

3.1.3 NSF and the NIRT program

The social aspects of the NNI also include the Nanotechnology Interdisciplinary Research Teams (NIRT) awards program supported through the NSF. NIRT focuses on collaborative research involving experts and researchers from a wide range of fields. Although NIRT develops research programs to explore nanotechnology applications and R&D activities, efforts are being made to pursue multidisciplinary research projects concerning the social and educational implications of nanotechnology.

Dr. Lynne Zucker at the University of California in Los Angeles (UCLA) received a NIRT grant to establish a Science and Commercialization NanoBank. The project aims at building an integrated database about nanotechnology called NanoBank.org, which will be made available to the public through the Internet. The database will provide useful information to scientists and researchers to identify relevant research, as well to investors and firms seeking to invest in promising technologies, and to social scientists and policymakers attempting to assess the effects of alternative policy proposals (UCLA 2005).

In 2001, the NanoCenter at the University of South Carolina was founded to pursue nanoscale research and subsequently, a number of humanities scholars at the University of South Carolina formed a working group for the Study of the Philosophy and Ethics of Complexity and Scale (SPECS) (USC 2005). Funded by the University of South Carolina and the NSF through a NIRT grant (NSF 2005b; USC 2005), SPECS' objectives include the development of a scientific, philosophic and ethically informed understanding of the critical developments of technologies such as nanotechnology, robotics and genetic engineering and the science underlying them. SPECS supports interdisciplinary dialogue on nanoscale science and technology, providing fruitful communication between the scientists and engineers working in nanotechnology, and the public (NSF 2005b; USC 2005).

NSF is supporting two Nanotechnology Undergraduate Education projects to develop undergraduate programs incorporating courses on social dimensions. John Jaszczal at Michigan Technological University heads a team working on the preparation of modules and problem sets related to nanoscience and its applications, which is also developing a course on its social implications (NSF 2005b). Paul Petersen directs the Rochester Institute of Technology project on nanotechnology including aspects such as principles, applications, ethics and social change (NSF 2005b).

3.1.4 NSF and the NNIN initiative

NSF has also launched a major national network. The National Nanotechnology Infrastructure Network (NNIN) is an integrated partnership of thirteen user facilities and universities, providing extensive support to nanoscale fabrication, synthesis, characterization, modeling, design, computation and hands-on training in an open, hands-on environment, available to all qualified users (NNIN 2005).

Although NNIN was mainly created to facilitate scientific and technological advances in nanotechnology, this initiative also comprises a social dimension and several nodes of the network include research into the social and behavioural sciences (NNIN 2005). NNIN brings together researchers who have an interest in ethical issues associated with the context of nanoscience and technology; public and researcher understanding, awareness, and responsiveness to social and ethical issues associated with nanoscience and technology; work processes and structures within the nanoscience and technology community; technology transfer/diffusion between the research community and industry and social and historical analysis of the growth of nanoscience and technology (NNIN 2005).

3.1.5 Initiatives developed by other federal agencies and bioethical organizations

Several federal agencies are indirectly or directly involved in research activities focusing on nanotechnology. However, very few agencies support stewardship practices for the environmental dimension of nanotechnology. Not surprisingly, the Environmental Protection Agency (EPA) is certainly the most active in relation to this aspect.

The EPA plans research directions for the environmental application and impact of nanotechnology. Through its own research as well as through its collaboration with other agencies, EPA awarded 32 research grants accounting for more than $11 million, in the environmental application of nanotechnology. The Agency is awarding 12 additional grants for the study of health and environmental risks from manufactured nanomaterials, and has announced a new grant in partnership with NSF and NIOSH for work in the same area. In addition, EPA's program offices are analyzing how current statutes, such as the Toxic Substances and Control Act, apply to manufactured nanomaterials (EPA 2004). In other words, this federal agency promotes concrete actions to assess the impact and potential risks of nanotechnology on health and environment, providing valuable scientific data on issues raised by nanotechnology. CBEN's and the EPA activities represent the most important US initiatives supporting stewardship practices in environmental nanotechnology.

In parallel, several groups, associations and programs have concentrated on the study of social and ethical issues and impact of science and technology. At the beginning of the 1990s, the *ethical, legal, and social implication* (ELSI) program which benefits from more than US$14 million in federal funding annually, undertook to support and manage studies related mainly to genetic and genomic research, and also supports workshops, research and policy conferences related to these topics (NHGRI 2004). Although this initiative focuses on genetic research, it is a good example of a strategy that could be useful for the identification of stewardship issues raised by nanotechnology development.

The American Society for Bioethics and Humanities (ASBH) is another initiative which is not directly related to nanotechnology, but represents another example of a strategy that could be employed to deal with stewardship issues associated with nanotechnology. ASBH promotes the exchange of ideas, and supports multidisciplinary interactions, between people from different sectors such as clinical and academic research, bioethics and the health-related humanities, teaching, policy development, etc. (ASBH 2005). While bioethics organizations are numerous in the US, one recent initiative stands out. In 2001, President Bush created the President's Council on Bioethics (PCB) which studies fundamental issues of human and moral significance related to developments in biomedical and emerging technologies. The council also explores specific ethical and policy questions concerning these developments and provides a forum for national discussion on bioethical issues (PCB 2005). The particularity of the PCB is that the President is directly advised by the council. Thus, government is rapidly informed about these issues and can react quickly to prevent negative impacts on society and the economy.

Although the ELSI program, ASBH, PCB and other similar groups address issues in fields other than nanotechnology, they are all models that could be adapted to address stewardship issues in nanotechnology, allowing the assessment of environmental, social and ethical impacts of nanotechnology and enabling a discussion platform for multidisciplinary exchange that could be useful to create efficient yet socially acceptable solutions.

3.1.6 Role played by private foundations

Independent or private initiatives such as the Foresight Institute or The Center for Responsible Nanotechnology exist in parallel with government initiatives. Eric Drexler founded the Foresight Institute, a non-profit educational organization that works to help society prepare for emerging technological revolutions, in particular nanotechnology (Foresight 2005). This institute promotes understanding of nanotechnology and its effects, and informs the public and decision makers (Foresight 2005).

The Center for Responsible Nanotechnology (CRN), which is a similar initiative to the Foresight Institute, was created in 2002 through the concerted efforts of Mike Treder and Chris Phoenix. According to its founders, CRN is an informational/ethical organization dealing with nanotechnology. CRN produces information and diffuses it widely with the objective of increasing awareness of the benefits, dangers and issues raised by nanotechnology (CRN 2005). In addition to identification of issues and obstacles, CRN is committed to finding solutions and promoting their implementation. In line with this effort, CRN has identified several areas of interest concerning different aspects of nanotechnology such as the social, ethical, environmental and scientific impacts.

Independent initiatives of scientists, including the foundation of Foresight Institute and Center for Responsible Nanotechnology and the creation of the SPECS working group at the University of South Carolina, play an important role in assessing the social dimensions of nanotechnology. Issues raised by nanotechnology are complex and affect many facets of society. Reflecting this complexity, it is important to develop policies and initiatives that include a good balance between independent and governmental initiatives, allowing exchange between scientists, citizens and academics to foster a good understanding of related issues and to set up efficient measures to address these issues.

3.2 Europe

In Europe, scientific investigation and assessment of possible health or environmental risks associated with science and technology advancement, and the establishment of appropriate policies and stewardship practices are investigated or supported by different organizations, committees and specific programs such as the European Commission's Sixth Framework Program (FP6). FP6 represents a key initiative which has a central influence on European policies targeting nanotechnology at national and supranational levels. Although FP6 provides a common vision and a centralized approach, several programs and initiatives have been developed in parallel to it. European policies and initiatives in science and technology as a whole find a balance between central planning and local initiatives.

3.2.1 The Sixth Framework Program (FP6)

In 2000, in Lisbon, the European Commission adopted a long term strategy known as the European Research Area (ERA) which is intended to strengthen the scientific and technological bases of industry and to help European industry become more competitive at the international level. The FP6 was based on this strategy and was adopted by the EU in 2000 with a budget estimated at €17.5 billion (Euros) (FP6 2005). Activities carried out under the FP6 are within seven themes: life sciences, genomics and biotechnology for health; aeronautics and space; food quality and safety; information society technologies; nanoscience and nanotechnologies; sustainable development, global change and ecosystems; and finally, citizens and governance in a knowledge-based society. The FP6 initiative encourages major efforts to stimulate technological innovation together with the transfer of knowledge and technologies to encourage industrial advances within the seven themes, including nanotechnology. This program is also aimed at coordinating and supporting the coherent development of research and development policies in Europe, integrating it's the environmental, economic, social and ethical impacts associated with emerging fields such as nanotechnology (FP6 2005). The forthcoming seventh framework program (FP7) will span the period 2006-2010 with a budget of more than €30 billion (Cordis 2005c).

The proposed budget for the thematic of nanotechnologies and nanosciences for the duration of FP6 is €1,429 million (Cordis 2005d). The primary objective of work in this thematic area is to promote real breakthroughs, based on scientific and technical excellence, opening up opportunities for industrial applications (Cordis 2005b). Particular attention will be given to the strong presence of innovative enterprises, universities and research organizations in research action. In addition, FP6 supports research activities in nanotechnology which conform to the social goal of sustainability (Cordis 2005b). For instance, FP6 objectives include measures to reduce the potentially negative impacts of nanotechnology on health and the environment, as well as more efficient use of resources leading to a reduction in consumption of primary resources. They also include the support of life-cycle safety, and the minimization of waste, chemicals and pollution through integrated approaches based on nanotechnology, and the support of actions to inform and increase the awareness of the population to the impacts of nanotechnology. Finally, with regard to the challenge raised by the industries associated with the utilization of nanotechnology, FP6 supports projects devoted to education and skills development to ensure the production of an appropriately skilled workforce (Cordis 2005b).

Therefore, in theory, FP6 supports stewardship practices and special projects which target environmental or social issues raised by nanotechnologies. However, analysis of 50 research projects and calls for proposals supported by FP6 in nanotechnology reveals that more than 95% of them are devoted to R&D activities, or aimed at industrial applications, and very few include elements that could be associated with stewardship practices related to the environmental or social aspects of nanotechnology. In other words, FP6 could be a good model for how stewardship issues linked with the environmental aspects of nanotechnology are identified by S&T governance structures, but is not adequate to address stewardship issues.

3.2.2 Network and environmental organization

Environmental organizations such as EPHA (European Public Health Alliance) and Environment Network (EEN) are also concerned with issues raised by nanotechnology. EEN, which was launched in 2004, is an association of NGOs and experts specializing in public health, science and environment (EEN 2004). EEN's key objectives are to bring health expertise to the environmental policymaking process by exploring this complex area and giving support to the European Commission's commitment to making progress in improving health and the environment. Although EEN initiatives focus on environmental problems, a part of their activities is devoted to nanotechnology, in particular the harmful effects and negative impacts of nanoparticles on the environment and health (EEN 2004).

The European Union (EU) has established a strong and well developed network on nanotechnology (see www.nanoforum.org). The Nanoforum Gateway initiative was set up in 2002 with €2.7 million funding from the European Commission (Nanoforum 2005). This initiative serves as an umbrella organization for all nanotechnology activities within the EU. It was designed to be a central location from which to access information about research programs, technological developments, funding opportunities and future activities in nanotechnology within the EU. The initiative acts as a comprehensive source of information on nanotechnology including business and economic sectors, scientific and technological fields as well as on the ecological, ethical and social aspects. The Nanoforum initiative comprises partners from different disciplines, brings together existing national and regional networks, shares best practice on dissemination, and brings together sources of national, EU-wide and venture capital funding to boost SME creation. In addition, it provides a means for the EU to interface with networks, stimulate nanotechnology initiatives in Europe's less developed countries, stimulate young scientists, publicize good research and form a network of knowledge and expertise (Nanoforum 2005). This huge initiative provides a platform to enable interaction between actors within the nanotechnology field, facilitating the exchange of ideas about solutions and strategies to resolve nanotechnology-related issues. It also acts to increase awareness and to inform the population about nanotechnology applications and related risks.

3.2.3 Organization, committee and program involved in science policies

The European Science Foundation (ESF), which is an association of 78 member organizations devoted to scientific research across 30 European countries, plays a key role in science and technology developments in Europe (ESF 2005). The ESF has coordinated a wide range of pan-European scientific initiatives to promote high quality science and ensure that there is some European value added in all of its initiatives and projects. Through its distinctive and a significant role in science policy development, the ESF provides expert and objective advice on a wide range of issues raised by science and technology (ESF 2005). For example, ESF was involved in projects focusing on research and ethics, biology and society, science and media interaction, and was also involved in assessing European programs such as the framework programs (ESF 2005).

Another European initiative was established to investigate the ethical issues raised by science and technologies. The European Commission set up the European Group on Ethics (EGE) which is an independent, pluralistic and multidisciplinary body whose purpose is to advise the Commission on the ethical aspects of science and new technologies in connection with the preparation and implementation of legislation or policies. EGE wrote a report on the Charter on Fundamental Rights related to technological innovation (EGE 2005). Interestingly, in contrast to many similar observer organizations whose impact has been limited, EGE is considered by the European Commission as an integral part of its policy advice process and it has played an active role in policymaking. EGE's vision was based on several ethical principles and on the idea that these principles must be respected and, where appropriate, enforced through regulation. According to the European Commission, the relevance of the principles established by EGE towards human and non-human applications of nanotechnology should be understood and applied (CEC 2004).

A similar initiative, the EU Research Advisory Board (EURAB), which was created in 2001 by the European Commission, is not devoted only to nanotechnology, but studies science in general. EURAB is a high-level, independent, advisory committee that provides advice on the design and implementation of EU research policy. EURAB comprises 45 experts from EU countries and beyond. Its members are act in a personal capacity, and come from a wide range of academic and industrial backgrounds, and also represent wider social interests (EURAB 2005).

The preparation and implementation of national and EU policies rely increasingly on scientific advice and knowledge. Thus, it is crucial to ensure efficient communication between the scientific community and decision-makers to create the conditions under which policy decisions in multi-level governance will be most effective in meeting social needs. Synergies between the areas of scientific advice, public participation and risk governance must be identified and exploited, paving the way for new management strategies and tools designed to improve the quality of policy-making. In this regard, the SINAPSE (Scientific Information for Policy Support for Europe) network program was launched in March 2005 to help policy makers reconcile the constraints and conditions of a global economic and technological environment with risk management and social aspirations (SINAPSE 2005). SINAPSE represents a toolkit for the practical implementation of new forms of governance, facilitating the involvement of actors who currently are heavily committed and whose expertise is difficult to access and enabling them to share their knowledge and viewpoints. The main objective of this web-based communication platform is to offer a set of tools to promote and encourage the effective exchange of information between the actors most concerned with in science and in European governance. The network will help to improve the breadth and scope of information available to the public through the direct involvement of decision-shapers and stakeholders (SINAPSE 2005).

Overall, the EU benefits from the presence of vigorous and diversified committees, advisory groups and tools such as SINAPSE, which help it to design policies related to nanotechnology that cover environmental, social, ethical, industrial, technological and scientific aspects, and other related issues. In contrast to the US, these European advisory committees have a direct impact on policies implementation and integrate a more environmental and social vision of science and technology development. These initiatives provide a useful infrastructure for establishment of efficient stewardship practices in science and technology including nanotechnology.

3.2.4 Organization and committee involved in ethical and social issues

Several associations such as the European Association for the Study of Science and Technology (EASST) and the European Working Group for Economic and Social Aspects of Nanotechnology (ESANT) are devoted to the promotion of communication, exchange and collaboration in science and technology, including nanotechnology. These groups provide a bridge and means of interaction between professionals, researchers and practitioners from different fields, and offer a forum for discussion, and encouragement for cooperative efforts in research and teaching. They look at the social implications of nanotechnology including beneficial and adverse aspects (NSF 2001);(EASST 2005).

In January 2001, the European Parliament set up a Temporary Committee to examine recent developments in the field of human genetics and other new technologies in modern medicine, and to consider the issues and opportunities raised by these emerging fields (CHG 2005). This committee organized a series of expert meetings that attracted leading figures from the scientific community, other European institutions, the parliaments of the EU Member States, and civil society. Based on the results of its examination of the scientific, medical, ethical, legal, economic and social risks and opportunities of recent developments, the Committee prepared a report aimed at providing political orientations. Although this initiative does not focus on nanotechnology, it represents a model to identify potential stewardship issues and could be useful for integrating appropriate solutions to mitigate these issues.

The Ethical, Legal and Social Aspects of the Life Sciences and Technologies (ELSA) initiative was developed by the European Commission under the Fourth Framework Program (FP4) between 1994-1998 and was adapted for the FP5 program (1998-2002) (Cordis 2005a). The ELSA program consists of a trans-disciplinary approach to promote research on issues including:

- Legal protection of inventions, biodiversity and regulatory frameworks for biological research;
- Fundamental and applied values in biomedicine, personal data protection, resource allocation in health care, data bases and ethics committee;
- Animal welfare, food safety, pesticides and crop protection, consumer attitudes and sustainable agriculture and fisheries (Cordis 2005a).

Questions and issues investigated by ELSA could be transposed to emerging fields of science and to technologies such as nanotechnology.

In parallel with the European initiatives described above, several European countries have developed their own programs or initiatives to examine the social and ethical aspects of science and technologies. The next sections briefly present some of the strategies of the major European countries with an emphasis on programs that may address stewardship issues in the environmental aspects of nanotechnology.

3.2.5 United Kingdom

Participants at the British Association for the Advancement of Science (BA) 'Festival of Science' were told on September 6, 2004 that, given that the public has little control over the uses of science, and must often suffer the adverse effects of its applications, scientists, industry and policy makers must engage in a more open dialogue with the public on the issue of emerging science and nanotechnologies. This statement was echoed by the UK Minister for Science and Innovation, Lord Sainsbury, who argued that science is crucial for creating prosperity and new technologies that benefit society as a whole. However, he warned that such technologies also raise new ethical, safety, wealth and environmental concerns, which must be fully debated before they come to market (BA 2005). As part of the UK government's efforts to encourage greater public engagement with science, Lord Sainsbury announced a new €1.75 million scheme to fund projects aimed at facilitating a dialogue between scientists and the public. The grants will support projects in what the UK government has identified as critical areas of science and technology: nanotechnology, increasingly intelligent computer systems, understanding brain processes, animal and medical research, and security in the use of IT and the Internet (BA 2005).

Other relevant initiatives in the UK involve the creation of a network program (LINK Nanotechnology Program) and the establishment of the Institute of Nanotechnology (IoN) by the National Physical Laboratory to promote nanotechnology in universities, industry, and government laboratories (Roco 1999). The goal of the IoN was to give an early awareness of nanotechnology. A Nanotechnology Strategy Committee (NSC) was established to advise the government on nanotechnology (Luther 2004). The Better Regulation Task Force (BRTF), which is an independent body that advises the UK government, attempts to ensure that regulations and their enforcements adhere to good regulatory principles (BRTF 2005). BRTF philosophy is based on learning from previous emerging technologies such that past mistakes are not repeated in the development of new technologies such as nanotechnology. More recently, the Micro and Nanotechnology (MNT) Network was established by the DTI (Department of Trade and Industry) to provide information, support and coordination to ease the path to nanotechnology development.

3.2.6 Germany

Germany has been recognized as a European leader in nanotechnology. Currently, more than half of Europe's nanotechnology companies are based in Germany and, in terms of world number of patent applications, German researchers are only beaten by the US. Since 1998, the Federal Ministry of Education, Science, Research, and Technology (BMBF) has increased its financial support for nanotechnology fourfold, spending some €125 million on the field in 2004. The BMBF provides national support for nanotechnology through various centers of excellence such as the Fraunhofer Institutes, the Max Planck Institutes, and several universities (BMBF 2005). With its Agenda 2010, the BMBF is taking an active role in a federal reform known as Innovation Initiative, to develop education, research and development of new strategies for research policy in emerging sciences including nanotechnology.

To this end, the government supports the ITA (Innovation and Technology Analysis) initiative. ITA examines technological developments during their early phases, with the aim of identifying potential opportunities, and issues and the areas for relevant research policy (BMBF 2005). The issues considered by ITA include scientific, technical, legal and social questions such as: who profits from use of a new technology; what are the needs of society for new technologies and will it accept the new technologies; how are scientific discoveries translated into innovative products and services, etc. ITA should provide orientation for our highly technological society, and should help to promote technology that is in keeping with human and social needs while remaining environmentally compatible. Relevant systematic analyses should facilitate the early identification of the potential development and application of new technologies, and propose innovative solutions to potential risks and with the aim of reducing or preventing them. Germany sees ITA as an important instrument for advising policy-makers, as well as a tool that can support industry's strategic decision-making (BMBF 2005).

3.2.7 France

The national French program R3N (National Network in Nanosciences and Nanotechnologies) will receive €210 million (€70 million per year over three years) from the government starting in 2005 (Aubert 2004). The R3N program includes three main types of support measures: the development of scientific and technological platforms; the funding of best projects in academic laboratories; and the funding of the best projects in the private sector. Scientific research supported by this program is in three areas: nanobiosciences, nanomaterials and nanoelectronics. In addition, the R3N program will coordinate thinking on ethical and social issues, including pollution and pathology, associated with the use of nanotechnologies (Aubert 2004).

Prior to this initiative, the observatory for micro and nanotechnologies (OMNT) was created in 2001 by CEA and CNRS to provide a continuous watch on key subjects in micro and nanotechnologies and on every key actor in this field. With 170 experts from different areas of micro and nanotechnologies, OMNT benefits from a strong network to provide analysis on different aspects of nanotechnology (OMNT 2005).

The French National Center for Scientific Research (CNRS) is a public, basic-research organization whose mission is to produce knowledge and make it available to society. CNRS has 26,000 employees and covers all fields of research including nanotechnology. CNRS has an internal ethics committee (COMETS), which promotes discussion and advises on the potential risks and acceptability of research projects carried out by CNRS (CNRS 2005). This French initiative is innovative since very few research centres have developed internal committee to educate their staff and to ensure that their work is compatible with social and ethical values.

3.2.8 Switzerland

Despite its relatively small size and its population of only 7 million, Switzerland is surprisingly active in micro and nanotechnologies. The Swiss Federal Institute of Technology (ETH) has established the TopNano21 program whose main objective is to strengthen the Swiss economy by stimulating the exploitation of nanotechnology (Durrenberger, Hock and Hohener 2004; Malsch 2002). Several centers of excellence, research institutes, federal programs and federal initiatives are devoted to fundamental research and nanotechnology developments for commercial application, but very few activities are related to the other aspects of nanotechnology.

Nano-World, an innovative initiative, was developed in Switzerland. Nano-World consists of a virtual nanoscience laboratory which is based on problem-orientated and cooperative learning through interactive experimentation in the field of nanoscience. The agenda was drawn up in close cooperation with the newly established National Center of Competence and Research (NCCR) in nanoscale sciences in Basle (Nanoworld 2005). People interested in nanotechnology can follow this online simulation/course, which is a powerful means of informing the general population about developments in nanotechnology.

3.3 Asia

In contrast to Europe which has developed several national-level programs and initiatives to study and develop all aspects of nanotechnology, international initiatives are less frequent in Asia. Consequently, countries operate in a more independent manner and show less cohesion in terms of their nanotechnology policies. Nevertheless, some supranational initiatives have been put in place such as the Asia Pacific Nanotechnology Forum (APNF).

3.3.1 Asian supranational initiatives

APNF is a unique platform for networking between governments, scientists and research organizations across the Asia Pacific region, and developing industry, and the venture capital market (APNF 2005). The APNF, which is an independent non-governmental, not-for-profit organization, facilitates the coordination of nanotechnology developments and programs, and cross-regional collaborations among government policy makers, industry, R&D institutions, and leading researchers. It publishes the *APNF News Journal*, and hosts conferences and numerous national symposia, workshops, seminars, and exhibitions. Since its inauguration in 2002, the APNF has maintained its key role in supporting a number of initiatives and major nanotechnology events in Asia (APNF 2005).

With support from governments and major industry from across Asia Pacific, the APNF represents a powerful platform and acts as a catalyst in the region. The APNF initiative is an effective facilitator of discussions and exchange of ideas concerning social and ethical issues raised by nanotechnology. In reaching out to all kinds of actors in the field, including scientists, business leaders and policymakers, APNF is able to obtain a wide variety of opinions and visions to facilitate the identification of issues in nanotechnology. This type of initiative promotes fruitful discussions between the major actors and could lead to the establishment of efficient solutions to minimize the adverse impacts of nanotechnology. Government and policy makers could use this type of initiative as a laboratory to explore how future regulations or government initiatives will be received by industry and by the scientific community, thus offering an opportunity to create more refined and efficient programs and regulations in nanotechnology.

It is only recently that the Asian nations have recognized the significance and the necessity of global cooperation and supranational initiatives for developing nanotechnologies. As a result, some Asian countries have attempted to establish partnerships and collaboration networks to develop common strategies for the nanotechnology sector. In 2004, the Korea Science and Engineering Foundation (KOSEF) in collaboration with the National Natural Science Foundation of China (NSFC) co-sponsored the 6th Northeast Asia Joint Symposium on Nanoscience and Nanotechnology (KOSEF 2005). Representatives from Korea, China, and Japan participated with a view to exchanging information on state-of-the-art nanoscience and technology, creating personal contacts, and identifying subjects for collaboration among the three countries in Northeast Asia (KOSEF 2005). In addition, KOSEF and NSFC organized the 8th meeting of the Korea-China Committee for Cooperation in Basic Scientific Research. The meeting reviewed 74 proposals for joint research and joint seminars, and delegates discussed other cooperation programs such as fact-finding missions in the field of basic sciences (KOSEF 2005). This initiative promotes basic scientific collaboration between China and Korea (KOSEF 2005).

Since 2004, these types of initiatives have been seen as precursors to an eventual Asian National Initiative in nanotechnology to support a common approach to nanotechnology in Asia, including the standardization of concepts and measurements, assessment of social, environmental, and health issues, and education and human resource development (APNW 2004).

3.3.2 Japan

Japan is the uncontested leader in nanotechnology among Asian countries (Nicolau 2004). Government agencies and large corporations are the main sources of funding for nanotechnology in Japan; small- and medium-size companies play only a minor role. Research activities are generally grouped in relatively large industrial, government, and academic laboratories. The three main government organizations sponsoring nanotechnology in Japan are the Ministry of Economy Trade and Industry (METI), the Science and Technology Agency (STA), and the Ministry of Education, Culture, Sports, Science and Technology (MEXT). Funding for nanotechnology research is based on Japan's Science and Technology Basic Law No. 130. The objective of this law is to promote policies for the progress of science and technologies to contribute to the development of the Japanese economy and society (Nanonet 2005b).

Japan's nanotechnology strategy is largely based on science, technology, industry and economic development. Japanese representatives who participated in the 26TH workshop organized by the APNF reported that Japan's vision on nanotechnology consists of supporting infrastructure, human resources and nanoprocesses development, in contrast to Korea's concerns over the social and environmental impacts of nanotechnology (ANF 2004). In comparison with the US and Europe, Japan appears to be less concerned by social, environmental and ethical issues raised by nanotechnology and the initiatives that address these areas are less numerous.

However, some Japanese institutions are working on these aspects. The National Institute of Advanced Industrial Science and Technology (AIST) in Japan began operations in 2001. AIST, which is Japan's largest public research organization with around 2,400 researchers, is involved in a wide variety of scientific activities and pursues research by exploring broad spectra of research fields and integrating multidisciplinary subjects to promote innovation in a wide range of fields, including projects carried out at the Nanotechnology Research Institute (NRI). AIST believes that is essential to integrate scientific and engineering knowledge that is fragmented across disciplines to address highly complex socio-economic needs that are changing rapidly. Thus, AIST puts effort into developing interdisciplinary and cross-disciplinary research to inform governmental policy designed to benefit the current and future needs of society (AIST 2005).

NRI is the core of nanotechnology activities within AIST and mainly focuses on fundamental research and strategic advancement in nanomaterials and nanodevice technology (NRI 2005). The Research Center for Life Cycle Assessment (LCA) is another research institute within AIST that promotes the development of environmentally sound societies and human activities with low environmental impacts (LCA 2005). Based on life cycle assessment tools, this research center performs evaluations of the environmental aspects and potential impacts associated with products and services throughout their life span, including new tools, products or devices that have been produced by nanotechnology. The Japanese government has established a framework for an internationally standardized LCA application method. Many manufacturing companies are adopting this method to evaluate the environmental performance of their industrial products (LCA 2005). Most recently, the Research Center for Life Cycle Assessment used LCA methods to evaluate social systems, energy systems and waste treatment systems (LCA 2005). This research center has also deployed research efforts in areas such as environmental impact assessment of new technologies, green industry and green energy processes, evaluation of social acceptance of new technologies, development of efficient environmental indicators and collaboration with local government to support the decision-making process (LCA 2005). The Japanese Environmental Management Association for Industry (JEMAI) is a public corporation, not related to the AIST research centers, which was established under METI. JEMAI pursues similar goals to the Research Center for LCA by developing methods for environmental impact assessment and by researching issues relating to environmental protection (JEMAI 2003).JEMAI has contributed significantly to environmental protection programs in Japan and has been engaged in a full spectrum of activities relating to environmental management (JEMAI 2003).

Several agencies or independent organizations specialize in the assessment of government policies designed for industry, science and technology sectors and oriented to the creation of future policies. One of these agencies, The Research Institute of Economy, Trade and Industry (RIETI), was established in 2001 as a platform to bring renewal to policy making and to improve information dissemination (RIETI 2005). RIETI undertakes different types of operations such as research, studies, and data collection including statistics processing and management. Based on the results of their studies, RIETI propose new or improved policies. RIETI conducts innovative studies which are not within the government's scope of ideas, or have yet to be considered by government (RIETI 2005).

In collaboration with MEXT, the National Institute for Materials Science established the Nanotechnology Researchers Network Center in 2002 to support nanotechnology projects. This initiative makes available a wide variety of information on nanotechnology through its website, and organizes symposia and workshops to enable researchers to share the latest developments in nanotechnology. In addition, the Nanotechnology Researchers Network Center supports educational programs and international exchanges for young researchers and publishes a newsletter and the *JNNB* journal (Nanonet 2005a).

The Japan Society for the Promotion of Science (JSPS) is an independent administrative institution, established by national law for the purpose of contributing to the advancement of science in all fields of the natural and social sciences, the humanities and the environmental sciences (JSPS 2005). As one of the most important agencies in Japan, JSPS plays a pivotal role in the administration of a wide spectrum of Japan's scientific and academic programs to promote scientific advancement. JSPS's operations include the promotion of international scientific cooperation, the support of research activities and the implementation of future programs.

Japanese efforts in nanotechnology are somewhat conflicting. Although Japan has made considerable investments, including a recent national reform to promote technological and industrial advances in nanotechnology, efforts devoted to the social, ethical and environmental issues raised by nanotechnology are less well supported. However, LCA, JEMAI, RETEI and the JSPS institution are focusing on the environmental, social and ethical implications of science and technology including nanotechnology, and are involved in formulating sciences policy and involved in information and education activities. Among Asian countries, these Japanese initiatives represent the most advanced and important approaches in terms of stewardship practices related to nanotechnology and science.

3.3.3 China

Nanoscience and nanotechnology have received increased attention in China since the mid-1980s. Although spending in nanotechnology was less important than in Japan for instance, China now appears to be leading the world in the number of new nanotechnology companies and has more than 300 firms currently working in nanotechnology (Choi 2003). Two major Chinese institutions support research: the Chinese Academy of Sciences (CAS) sponsors relatively large groups, while the National Natural Science Foundation of China (NSFC) provides support mainly for individual research projects (CAS 2005; NSFC 2005).

CAS includes 108 research institutes, over 200 science and technology enterprises, and more than 20 supporting units including universities, graduate schools and documentation and information centers. CAS conducts research in basic science and technologies, including nanotechnology, but is also involved in research into protection and improvement of the environment for human survival and conducts coordinated studies in environmental science (CAS 2005). Furthermore, CAS provides scientific data and advice to government to inform decision-making, and undertakes government assigned projects with regard to science and technology issues in social and economic development (CAS 2005). In the past 15 years, NSFC has funded over 52,000 research projects and more than 68,000 scientists are supported annually by NSFC (NSFC 2005). NSFC has several priority research themes and the study of nanoscience and nanotechnology being one. It appears that the development of new concepts, structures, methods and technologies, as well the creation of new materials, devices and tools involved in nanotechnology, represent a major focus, at the expense of the social, ethical and environmental dimensions of nanotechnology. In contrast to NSFC, initiatives led by CAS cover more diverse aspects of nanotechnology, including social and environmental issues.

The Ministry of Science and Technology of the People's Republic of China is responsible for setting the strategies for science and technology development, as well as establishing guidelines, policies and regulations for science and technology to promote economic and social development. It also conducts research on key issues relating to the promotion of economic and social development in science and technology, and to determine the priority areas for science and technology development; the promotion and building of the national science and technology innovation system; and improving the national science and technology innovation capacity. To support these objectives, the Ministry of Science and Technology of the People's Republic of China established the National Program on Key Basic Research Projects (also known as the 973 Program) (MOST 2005). Based on the existing basic research programs conducted by the NSFC, the 973 Program organizes and implements key projects to meet national strategic needs (NSFC 2005). The strategic objective of the program is to mobilize scientific expertise to conduct innovative research on major scientific issues in different scientific fields, including nanotechnology. The 973 Program adopts a people-oriented approach to enhancing innovation capacity, and to strengthening and supporting research on a number of major scientific issues affecting national socio-economic development (MOST 2005).

China plans to establish an industry standard for nanotechnology using a plan coordinated by the National Center for Nanoscience and Technology (NCNST) (ANF 2004; NCNST 2005). NCNST has adopted directorship of the director responsibility system under the leadership of a governing board, which is responsible for determining disciplinary orientations and key research areas for the Center. The research direction will focus on four main disciplines of nanotechnology: nanodevices and nanofabrication; nanostructures and nanomaterials; nanobiotechnology and nanomedicine; and characterization and measurement of nanostructures (NCNST 2005). Social, environmental and ethical issues associated with nanotechnology are not included in the agenda of these disciplines within the program developed by the NCNST. NCNST claims that social and environmental impacts of nanotechnology represent an important aspect of their vision, but it has no concrete plans to study these questions (NCNST 2005).

China's vision of nanotechnology involves the deployment of massive efforts and initiatives to make advances in the industrial, scientific and technological aspects while the social, ethical and environmental dimensions of nanotechnology are being ignored. Although these dimensions are sometimes acknowledged as important objectives, the main Chinese agencies and programs seem to be providing support to others aspects of nanotechnology. Consequently, stewardship practices and related concepts concerning nanotechnology and environmental nanotechnology are not very well developed in China.

3.3.4 Korea

Since the announcement by the US of the National Nanotechnology Initiative, major developed countries have been intensifying national nanotechnology research activities in order to bid for leadership in the nanotech development area. In the Republic of Korea, the National Science and Technology Council established the "Nanotech Development Plan" in 2001 and prepared a 10-year implementation program for nanotechnology R&D and industrialization to ensure that the Republic of Korea will be among the top five countries for nanotechnology by 2010. The Korean vision of nanotechnology development rests on technological performance and economic success. Eight Korean agencies collaborated to prepare a comprehensive report on the Korean nanotechnology program entitled "Nanotechnology Development Plan to Be a World Leader in Nanotechnology", which was published in 2002 by the Korean government. According to this report, the Korean government has developed an aggressive strategy through the Law of Accelerating Research for Nanotechnology Development which was enacted in 2002 and was accompanied by massive funding to support R&D in nanotechnology, with to aim of fostering industrial development (APNW 2005; ATIP 2002). As is the case in many other Asian countries, national policies and strategies give little space to the social, ethical and environmental aspects of nanotechnology.

The Korea Science and Engineering Foundation (KOSEF) was established by a law enacted in 1977 to promote creative individual research projects in several different scientific fields including nanotechnology, to increase funding initiatives and strengthen strategic national programs (KOSEF 2005). In collaboration with two other agencies, the Korea Institute of Science and Technology of Evaluation Policy (KISTEP) and the Institute of Technology Evaluation Program (ITEP), KOSEF creates, establishes and supports R&D programs in nanotechnology under the umbrella of federal initiatives and federal laws in nanotechnology (APNW 2005). Like China and Japan, Korean research institutions include several smaller centers with unique specializations devoted to the development of strategic projects. For instance, the National Nanofabrication Center (NNFC) comprises 12 centers that operate in different fields of nanotechnology such as space, electronic, life science, nanoprocessing, etc. to support industrial and economic improvement. The NNFC, KANC (Korea Advanced Nano-Fabrication Center), NIC (Nanotechnology Integrated Centers), KAIST (Korea Advanced Institute of Science and Technology) are all major Korean organizations that develop nanotechnology and whose efforts currently focus on practical applications and pay little attention to the social, ethical or environmental aspects.

The NanoNet initiative is a specialized, integrated nanotech information site on the Internet operated by the Center for Nanotech Information (CNI) of the Korea Institute of Science and Technology Information (KISTI) (NanoNet 2005a). NanoNet provides reports, articles and other type of information on nanotechnology and provides a network accessible to scientists, policymakers, students and the general population (NanoNet 2005b). NanoNet serves as a platform to promote online education in nanotechnology and to facilitate interaction betweens industry, company representatives, policymakers, scientists and the general public. Of the major initiatives developed in Korea, NanoNet may be one with the most potential to address the social and environmental questions raised by nanotechnology. NanoNet could act as a bridge between academic, the private and government sectors, and social or environmental scientists to facilitate collaboration. This platform could also be useful in keeping the Korean population informed about some of the pressing issues raised by nanotechnology. However, up to now, and despite this potential, NanoNet has had a different focus and, similar to other Korean institutions, it eschews these questions.

Clearly, stewardship practices in nanotechnology and environmental nanotechnology do not represent a major interest in Korea which is positioned behind Japan and China among the Asian countries in this respect.

Other Asian countries such as Taiwan, Singapore, India, Thailand and Malaysia all have nanotechnology programs. Taiwan, Singapore and India have all launched national nanotechnology programs, and Thailand, and Malaysia have announced significant efforts in this promising new field (Choi 2003). However, generally, the strategies and initiatives developed by these countries focus on the scientific and technological aspects only.

3.4 Nanotechnology and the environment: still looking for stewards

This section has demonstrated that few stewardship practices and measures to develop the environmental dimensions of nanotechnology are in place in the US, the EU, and the Asian countries. Generally countries are showing a greater interest in the development of nanotechnology with commercial or industrial application, probably this offers more direct and immediate benefits for society than supporting other aspects of nanotechnology such as environmental, social or ethical questions. Where stewardship is being investigated, efforts are in large part oriented towards the social and ethical issues raised by nanotechnology, which very few strategies focusing on the environmental dimensions of nanotechnology.

Asian initiatives devoted to nanotechnology are generally controlled by the state and support the academic as well as the private sector, both of which seem to have the same goal: research activities related to economic or technological benefits. At first glance, US policies support a multilevel and a slightly more decentralized approach, but the majority of initiatives, including those developed by the federal agencies, universities or independent organisations, are directly or indirectly supported and/or funded through National Nanotechnology Initiative, a federal program. Thus, US nanotechnology policies are also governed by a centralized approach. The US government supports the study of environmental and social dimensions of nanotechnology and a number of independent organizations and initiatives coexist with federal agencies, offering a more heterogeneous environment than in the Asian countries.

Both the Asian countries' and the US approaches are based on an "opportunistic vision" that reflects a market-oriented economy. However, their perception and definition of scientific innovation is very different: while the US prefer to explore numerous and diversified fields of nanotechnology, Asian countries such as Japan build upon existing strengths and industrial capabilities such as semiconductors and electronic industries and adapt the capabilities of nanotechnology to these fields. Nanotechnology policies developed by the EU are more balanced and take into account the industrial and economic aspects of nanotechnology as well as social, ethical, legal and environmental aspects. In Europe as a whole and more particularly in countries such as France and Germany, there is a more decentralized multilevel approach (Luther 2004). In fact, European efforts in nanotechnology are based on central policies which coexist and cooperate with independent initiatives, organizations or committees. Europe presents a model for nanotechnology policies due to the balance it has struck between the economic, environmental and social aspects, and because of its multifaceted and multi-stakeholder approach to governance.

4 Discussion and recommendations

Many experts, researchers, engineers, social scientists and policy makers consider that nanotechnology will make drastic changes to many aspects of society. This report shows that nanotechnology enables the creation of a wide range of potentially exciting and innovative applications for the environment and for other sectors, but it also brings its share of threats and risks.

Section 4.1 provides a synthesis of how nanotechnology could be incorporated in environmental technologies, and outlines the environmental risks associated with nanotechnologies and nanoscale particles. Section 4.2 provides a discussion on current stewardship practices employed to identify and mitigate environmental, social and ethical issues related to nanotechnology. Finally, Section 4.3 formulates recommendations to develop a framework for best practice in environmental stewardship for nanotechnology.

4.1 Greening the environment with nanotechnology

This study has examined two types of research on nanotechnology that have environmental implications: 1) research culminating in a potential benefit for the environment; and 2) research on the potential risks of nanotechnology for the environment.

Current research on nanotechnology presenting potential benefits for the environment

There are three principal ways that nanotechnology can contribute to improving the quality of the environment. Biosensors are the most obvious application of nanotechnologies. The great advantages of nanosensors over traditional measuring devices are their potentially greater reliability, sensitivity and accuracy, and a their potential for miniaturization and thus for greater portability which facilitates in-situ analysis, which in turn further reduces both cost and time-to-results. Nanosensors will greatly help improve the quality of the environment by measuring toxic chemicals and pathogens.

There are several nanotechnologies that would appear to have environmental application. The principal technique using nanotechnology for remediation involves creating some forms of “sticky” nanoparticles that attract, agglomerate and thus render more inoffensive pollutants that have been released in the environment.

Another promising application of nanotechnology is in so-called green technologies. This is a highly heterogeneous set of solutions comprising for example applications that help to generate energy more cleanly, applications that involve increased efficiency of energy-use, and applications are designed to reduce the quantity of materials used in the manufacture of products. Some technologies involve lower emissions of toxic products, or involve replacing toxic materials with safer ones.

Environmental nanotechnology applications, such as remediation and green technology applications, are already generating huge interest among scientists and policy makers. Based on their unique properties, carbon nanotubes are currently extremely trendy, and researchers are making bold claims for a wide range of applications including sensors, remediation and green technology. Nanoparticles such as TiO_2 have been shown to have great capabilities in pollutant destruction, and are being studied by many research teams. In contrast, though, to those technologies that would seem to offer long-term potential, nanosensors offer the most promise for environmental nanotechnologybased on current research and technological developments.

Current research on the potential risks of nanoscale particles on the environment

Nanotechnologies create new challenges for the environment and present an important threat to health as a result of their high reactivity and small size, which allow them to evade the immune defence of living beings and to diffuse in the environment in an uncontrolled manner. These features and potential problems are not entirely new since there are naturally occurring nanoscale particles. Research needs to be conducted on both engineered and naturally occurring nanoparticles and a body of knowledge created about how these particles affect health and the environment.

In the short- and medium-term, the most important line of research consists of explaining toxicity mechanisms associated with nanoparticles and determining how potentially harmful effects on health and the environment can be mitigated.

4.2 Preventing risks to the environment due to nanotechnology

Section 3 described the policies, initiatives and strategies being employed by the governments of the major countries to address issues raised by developments in nanotechnology, with an emphasis on strategies designed to identify and reconcile environmental, social, ethical and legal issues.

The US, and countries such as Japan, Korea, China or Switzerland have adopted a centralized approach with coordinating bodies at national level and federal agencies to support R&D in nanotechnology, while other countries, including France and Germany, have taken a more decentralized multilevel approach (Luther 2004). Indeed, despite the fact that the US is a market-oriented economy, there have been significant interventions at the federal level to support the development of nanotechnology and also to study the associated environmental and social dimensions. In general, US nanotechnology policies are in the form of support for basic research projects rather than for commercial or practical applications. The private sector in the US is undertaking nanotechnology developments focused on commercial and more immediate applications. US nanotechnology policies encourage cooperation between scientific fields (such as the social sciences, nanotechnology, biology, chemistry, environmental sciences, etc.) and support interdisciplinary research teams to stimulate innovation in nanotechnology.

The US NNI represents an important step toward nanotechnology development and has been emulated by several industrialized countries which are establishing or are planning to establish their own national programs. Through the NNI, federal agencies such as NSF, and concrete initiatives such as the National Nanotechnology Infrastructure Network (NNIN), the Nanotechnology Interdisciplinary Research Teams (NIRT) awards, and the creation of Nanoscale Science and Engineering Center (NSEC), the US government is making concerted efforts to identify issues related to the environmental, social and ethical impacts of nanotechnology. In addition, initiatives by independent foundations, social and bioethical groups or university-led initiatives coexist with the central programs, offering a system with a democratic vision of the issues and possibilities raised by nanotechnologies. Thus, US policies in nanotechnology consist of a federal and state controlled approach with very diversified objectives, targeting mainly academic research and research institutions in parallel with independent initiatives and a private sector that operates in a relatively autonomous manner.

Asian countries such as Japan, China and Korea present a model that contrasts substantially with that of the US. For several Asian countries including China and Japan, the state has firm control over nanotechnology developments, and determines the orientation of academic and private research, its objectives and related activities, giving little room for independent initiatives. For instance, national policies in Japan provide strong direct support to both public and private sector organizations. Reflecting this, several federal Asian agencies include research institutes and privates companies, housed in the same premises that work together on particular programs (CAS 2005).

By contrast, the NNI in the US supports mainly academic and public research and, the private sector mainly receives support from other sources. Thus, the private sector and public sector are seen as separate entities with very different objectives in the US, while in Asia as the two are seen as having shared objectives. Another important distinction between US and Asian policies can be seen in their vision of scientific innovation. While the US attempts to develop numerous and diversified fields within nanotechnology, the Asian countries such as Japan focus on already existing skills and industrial capabilities, and staying ahead in traditional expertise such as semiconductors.

Policies developed by the Asian countries differ significantly from those in Europe. For instance, at present Asia does not have a strong network through which to share common visions and strategies about nanotechnology development like the EU's FP6. The Asian countries have shown strong willingness to create an Asian network in nanotechnology and representatives of several Asian countries have participated in panel discussions on the future of nanotechnology in Asia, which have recognized the importance and the benefits associated with the creation of a robust network to enable strong collaboration and the establishment of strategic alliances between Asian countries (Nanotech 2003). Despite this, concrete initiatives to establish such a network have not been established. Consequently, Asian countries for the most part work independently and compete with one another, leading to a huge focus on commercial and industrial applications and little consideration for aspects that are less advantageous commercially in the short term.

The policies and strategies developed for nanotechnology by the Japanese and the other Asian countries could categorized as an "opportunistic approach". Generally, Asian policies and strategies aimed and economic benefits from concrete developments, and rapid advancement and improved international competitiveness. This philosophy leaves little room for consideration of the environmental and social aspects of nanotechnology, which explains why Asian countries are behind Europe and the US in terms of environmental stewardship.

The EU's nanotechnology policies are different from those adopted by the US and the Asian countries. European policies represent a balance between an opportunistic approach aimed at developing industrial and commercial applications of nanotechnologies, and more ethical and social concerns that focus on providing benefits for society. The EU approach considers nanotechnology as a process with social and economic aspects that are of equal importance, and is therefore less oriented towards economic and industrial applications than Asia or, to a lesser extent, the US. In addition, unlike the US or Asian countries which operate a central control on nanotechnology development through national agencies, laws and initiatives, EU policies represent good balance between central control through FP6 initiatives and supranational committees, and independent initiatives developed by Union members at national level. Several networks, initiatives and programs have been developed in parallel with central policies to facilitate the development of nanotechnology at different levels.

Canada does not currently have a federal initiative such as the NNI or the FP6 nor does it have a coherent and comprehensive nanotechnology strategy. Despite this, nanotechnology is a Canadian research priority as shown by the establishment of the National Institute of Nanotechnology in Edmonton where Canada committed $112 million annually toward research over the next five years (NINT 2005), demonstrating a keenness to develop nanotechnology for the next decade. Also noteworthy, in 2001 NSERC launched the Nanotechnology Innovation Platform (NanoIP), a program that provides substantial support for research and the recruitment of experts, and which aims to give advantage to Canada in nanoscience and nanotechnology (NSERC 2001). At the provincial level, NanoQuébec, a not-for-profit corporation jointly funded by the governments of Québec and Canada has been established. NanoQuébec, plays a central role in structuring and planning efforts in nanotechnology (NanoQuebec 2005). In addition, Canadian nanotech companies are forming a growing industry. The time is right for Canada to establish policies and strategies to develop a comprehensive nanotechnology policy that includes care for the environmental and social dimensions.

It is clear that policies and stewardship practices linked to the environmental dimensions of nanotechnology are at an embryonic stage in the countries considered in this study, thus offering an opportunity for Canada to adopt a pioneering role in this area. Several initiatives and policies are targeting aspects of nanotechnology, such as the social and ethical dimensions and these approaches could be adapted to Canadian preoccupations. They provide the basis for the recommendations in Section 4.3. Depending on their type or their specific objectives, these approaches fall into three categories: environmental aspects, policy and regulation, and ethical and social aspects.

Environmental Aspects

This category contains initiatives and stewardship practices that are involved in the identification and assessment of environmental issues, and the environmental impacts associated with nanotechnology, and in some cases the means to identify and to mitigate adverse effects. Despite the fact that this category contains the least number of initiatives, it is central to the objectives pursued in this study. Networks and platforms that support activities such as workshops, seminars, conferences and meetings are useful to promote interactions between heterogeneous actors. The creation of specialized research centers devoted to environmental nanotechnology are crucial in this respect. These types of center would study how nanotechnology and derived products could affect health and environment and investigate efficient methods to decrease toxicity and other harmful effects of such materials.

Policies and Regulations

This set of initiatives involves stakeholders such as federal agencies, advisory committees and other organizations involved in the design of science and technology policies or in the design of regulations aiming to protect health and the environment and promote good stewardship practice. This type of intervention, which is widely used in Europe, can be divided in two types of organizations: organizations directly involved in the creation and in the integration of policies (mainly governmental organizations), and organizations that act indirectly on the policy making process, as advisors (government or private organizations). The latter group comprises organizations that provide in-depth analyses and recommendations for the definition of regulations and policies related to nanotechnology and organizations that evaluate current policies and regulations to determine whether they are sufficient to deal with nanotechnology-related issues, and how current procedures could be adapted to deal with the adverse effects of nanotechnology.

Ethical and social aspects

The contemporary history of science and technology reveals that public attitudes play a crucial role in the realization of the technological potential and in the commercial acceptability of technologies. Public attitudes toward nanotechnology, and the social and ethical issues raised by nanotechnology, have the potential to slow down or considerably complicate nanotechnology developments, and especially its environmental applications.

The majority of initiatives analyzed in the present study fall into this category. These types of approaches mainly involve social scientists and academics from the humanities, along with government committees and various organizations with an interest in the ethical, legal and social aspects of nanotechnology. These groups study the social impacts and identify the social issues raised by nanotechnology development and are often key players in the definition of solutions or recommendations to address these issues. The creation of networks or platforms to facilitate discussion, and to favour an open exchange of ideas in multidisciplinary settings, is an approach that has been adopted by several countries to provide innovative solutions to the social issues raised by nanotechnology. Other initiatives involve the creation of computer networks and holding of public meetings to inform the general public about the benefits and the risks associated with nanotechnology. Such measures can obviously increase the level of awareness concerning the potentially adverse effects of this technology, but may also decrease irrational fears generated by the unknown.

The need for a skilled workforce could also slow the advance of nanotechnology. Several potential breakthroughs in materials and manufacturing, medicine and healthcare, environment and energy will be made possible by the application of nanotechnology. A trained workforce, including skilled technicians and scientists, is crucial to the development and diffusion of this technology. Some countries (e.g. Switzerland) have developed initiatives designed to establish the infrastructures needed to support the education and the training of a skilled workforce to ensure that industries, factories, medicine, environment, energy sectors etc. will benefit for a sufficient pool of qualified personnel. Canada can play a pioneering role by providing training in nanotechnology mitigation and legislation.

In policy circles and in the mass media, nanotechnology is often portrayed as one of the most important drivers of technical, economic, and social change. Despite the benefits it may bring, there must be awareness that nanotechnology will also bring its share of risks and threats, which need to be addressed and ideally overcome. The precautionary principle has been used in the formulation of the following recommendations.

4.3 Recommendations

Recommendation on the governance structure

The extensive environmental scan conducted in this study reveals that policies and stewardship practices linked to the environmental dimensions of nanotechnology are sparse or even nonexistent in the US, EU and Asia thus providing Canada with an opportunity to adopt a pioneering role in this area.

Recommendation 1: Science-Metrix recommends that Canadian strategies and policies on nanotechnology take a similar orientation to those in Europe. A proper balance between central and independent initiatives will foster an environment that will support nanotechnology development while taking account of short and long term perspectives. Balancing economic and industrial development with social, ethical and environmental considerations seems to be the appropriate way to favour the sustainable development of this emerging technology. This view provides a basis for the following recommendations formulated to help Environment Canada in the definition of policies or strategies to adequately identify and minimize issues associated with environmental the nanotechnology.

Although a centralized approach to the development of strategies, initiatives, and R&D activities offers the lure of perfect control, it allows little diversification in terms of ideas, and may stifle innovation and block original solutions to overcoming problems generated by nanotechnology development. To avoid this negative situation, Environment Canada should interact with and consult independent firms, groups, research centers, etc., and collaborate with foreign institutions, to study and address issues related to environmental nanotechnology. Moreover, Environment Canada could encourage independent research projects and studies through special awards or grants to non university-based individuals and interest groups. Through these collaborations, the visions of nanotechnology developed by Environment Canada's scientists and policy makers can be questioned and reviewed; considered from original perspectives; and refreshed with innovative ideas.

Recommendations on the Research Infrastructure

Recommendation 2: Environment Canada should create a multifunctional research center devoted to the environmental and social dimensions of nanotechnology. The research center's activities should include research programs to develop environmental applications of nanotechnology, and programs focusing on the environmental risks associated with nanotechnology, and should explore new approaches to overcome or minimize these risks. In addition, specific research projects on issues such as nanoparticle toxicity, mechanisms of toxicity, toxicology assay on animal models and characterization of dose-responses, ecotoxicology assays, nanoparticle bioaccumulation mechanisms of nanoparticles, and the persistence and transport mechanisms of nanoparticles could be studied in this center. Special projects like the development of efficient measuring instruments to detect nanoparticles, and the development of standardized risk assessment methods should also be carried out. In parallel, social scientists could form a task force to study the social and ethical issues raised by nanotechnology and work on efficient solutions.

The Center for Biological and Environmental Nanotechnology (CBEN) research center in the US is an example of such a center. CBEN has integrated a set of programs that aim to address the scientific, technological, environmental, human resource, commercialization, and social barriers associated with nanotechnology. CBEN has made great efforts to study the biological and environmental effects of nanotechnology, and the social aspects of nanotechnology acceptance and remediation strategies for potentially hazardous materials (CBEN 2005).

The creation of a highly specialized research center in Canada, with a multidisciplinary research team including biologists, toxicologists, ecologists, engineers and social scientists to study a wide spectrum of environmental and social issues and applications, would provide a firm basis for the development of Canadian expertise in the field. A multidisciplinary team is a crucial element of this recommendation since it would provide heterogeneous visions and perspectives on specific problems, which would likely produce more innovative solutions and problem solving.

Asian initiatives have focused on this approach. Japan and China have created huge research centers made up of small, highly specialized centers. For example the Chinese Academy of Science (CAS) in China or the National Institute of Advanced Industrial Science and Technology (AIST) in Japan operates on this basis, and interactions between multidisciplinary teams and institution within the research centers lead to innovative and effective solutions. Although Asian countries use this approach for industrial ends and to rapidly find nanotechnology application that are expected to be commercially viable, it could easily be adapted to produce a Canadian model that would meet environmental or social objectives and help in identification and solving of these issues.

Recommendation 3: Establish an institution to act as a watchdog, to monitor nanotechnology developments, evaluate the relevance of nanotechnology policies and assess the potential issues or risks associated with the utilization of nanotechnology. The French observatory for micro and nanotechnologies (OMNT) conducts a continuous watch on key subjects in micro and nanotechnologies and represents a very good model.

Setting up institutions is a costly proposition. There are at least two ways to keep costs down: using existing infrastructures and establishing virtual institutes following the model of the Canadian Institutes for Health Research. Existing infrastructures could be adapted or reoriented to meet the objectives associated with responsible stewardships for nanotechnology. For instance, the National Institute for Nanotechnology (NINT) in Alberta is currently devoted to basic research in the field of nanotechnology with the long term objective of developing platforms for nanosystems and materials that can be constructed and programmed for particular applications. This research center has highly specialized instrumentation and equipment and is staffed by scientists and qualified personnel working in the field of nanotechnology. It might be advantageous for Environment Canada to negotiate with the NINT to obtain space or to share the costs of extending the center to accommodate a complete task force with a multidisciplinary team devoted to environmental and social applications and issues associated with nanotechnology. In this way, emulating the Asian model, Canada would benefit from the presence of a multifunctional research center that would be involved in all dimensions of nanotechnology, offering a dynamic environment combining basic, applied and policy-oriented research conducted by multidisciplinary research teams.

Recommendation 4: In addition to establishing a research infrastructure, Environment Canada should work in collaboration with the granting councils to establish a program to support the work of scientists to do research on the environmental issues of nanotechnology. An example of such a program is the US NSEC program which involves NSF funded multidisciplinary research projects in nanotechnology, which cover the social and ethical implication of nanotechnology (NSF 2005a).

Thus, in collaboration with the federal funding councils, Environment Canada should provide advice and financial support for grant programs to encourage academic nanoscientists to pursue research on the social and environmental aspects of nanotechnologies. Environment Canada should address the training and education of scientists and the workforce in general, to support the acquisition of the appropriate skills, knowledge and expertise in the area of environmental nanotechnology. Science-Metrix recommends that Environment Canada, in collaboration with the granting councils, supports the education of postgraduates in environmental nanotechnology and encourages provincial stakeholders to develop postgraduate programs.

To increase the expertise of its nanoscientists, Environment Canada should encourage collaboration with foreign universities that have a strong involvement in nanotechnology. Workplace training and student exchanges with relevant universities would contribute to the formation of a core of expertise in nanoscience.

The development of strong partnerships between Environment Canada and the nanotechnology companies could facilitate workplace training for nanoscientists, allowing the nanoscientists employed by Environment Canada to have access to high tech instrumentation and to become familiar with industry procedures and approaches in nanotechnology.

Recommendation on Participation of the Public and Private Sectors

Recommendation 5: A group should be established within the institution that would serve as a watchdog for nanotechnology developments (see Recommendation 3), and to study the evolution of public attitudes towards nanotechnology. This team would monitor changes in public opinion vis-à-vis nanotechnology, suggest measures allay the fears of the public, and inform Canadians about the steps being taken to secure their safety and well-being by reducing the risks. To minimize negative attitudes towards the development of nanotechnology for environmental applications, the public should be informed about the risks and benefits of nanotechnology and Environment Canada should establish an open dialogue with the population and participate in an education campaign. Moreover, open dialogue and cooperation with the population, the environment industry and nanotech firms, would produce a participative process and foster the development of voluntary measures and stewardship practices.

Reports from the United Kingdom and the European Commission have identified public awareness as a potentially important obstacle to nanotechnology developments, and recommend that the government should communicate with, and as much as possible, involve the public in decision-making in the area of nanotechnologies (EC 2004a; Royal Society 2004). The public should be informed about the risks and benefits of nanotechnology. Since nanotechnology has the potential to bring radical changes in society, it is also important that the public participates in shaping the nanotechnology. A well informed population reduces the irrational fears and panic concerning the unknown, and which could lead to a wholesale rejection of aspects of nanotechnology.

Environment Canada should facilitate open dialogue and encourage a strong relationship with the public and industry and should support activities such as workshops, seminars, meetings, and forums to increase awareness of the benefits and potential risks of nanotechnology. This group should use a web based network to diffuse information about these benefits and risks related to environmental, ethical, social and technical perspectives. This network could serve as a platform to diffuse key reports, articles, initiatives, regulations and policies from Canada and the entire world. It could serve as a forum for discussion groups, and link key people from different sectors including industry, scientific fields, the economic sector, governmental departments, etc. This network could also act as a central point and national reference database to help policy makers, scientists and industry experts by providing access to a very comprehensive set of information, and by facilitating interaction, discussion and partnership between these different players.

Several US and European initiatives have been designed with this end in mind, and could serve as models for Environment Canada. For instance, American agencies such as the NSF support particular projects including the NIRT program, which focuses on social aspects of nanotechnology. These projects involved the development by the University of California of a comprehensive database called NanoBank, which will be made publicly available, thus contributing to the education of the general public and keeping them informed about nanotechnology (UCLA 2005). The EU has created a network named Nanoforum Gateway which is a comprehensive source of information and acts as a central location for professionals and the public to access data on different aspects of nanotechnology, including research programs, technological developments, funding opportunities, future activities in nanotechnology, news from business and economic sectors, data from scientific and technological fields and communication from ecological, ethical and social communities (Nanoforum 2005). Nanoforum represents an effective tool to reach the general population and keep them informed about nanotechnology.

Recommendations on Regulations and Law

Recommendation 6: Create a Canadian index of nanoparticles potentially harmful for the environment and health. During a workshop organized by the European Commission in 2004, several international experts proposed a simple and efficient method to minimize environmental and stewardship issues associated with engineered nanoparticles. It has been proposed that all new engineered nanoparticles receive a specific classification number to create an index similar to the

Chemical Abstract Service registry numbers that is used for new chemical substances (EC 2004b). Attributing a new, unique classification number to engineered nanoparticles would bring a requirement for toxicology testing and provide information for the Material Safety Data Sheet for nanoparticles, and for nanoparticles risk assessment and risk management (EC 2004b).

The creation of a Canadian index for nanoparticles potentially harmful to the environment and health, would ease the task of regulating the utilization and the release of risky nanoparticles and reduce the adverse effects of nanotechnology on the environment and society. If potentially harmful and dangerous nanoparticles were chosen for given applications, users would need to follow specific precautionary procedures and standard protocols to minimize associated risks. These protocols and regulations should be established with the cooperation of several federal departments with different competences, such as Environment Canada, Health Canada, Natural Resources Canada etc. This initiative could help Canada reduce long term stewardship issues associated with the uncontrolled use and release of nanoparticles. Environment Canada should also initiate negotiations with other environmental agencies from foreign countries to create an international initiative, allowing the development of a common procedure that will be internationally recognized. This effort must be international to be fully effective.

However, a study conducted by the Woodrow Wilson International Center for Scholar (WWIC 2003) has reported that this type of initiative needs to be adapted to the reality of nanotechnology since strategies employed by standard indexes for chemical such as the Toxic Substance Control Act (TSCA) are not suitable for nanotechnology products (WWIC 2003). Based on a case study of carbon nanotubes in regard with the TSCA procedure, the authors noted several important issues.

For instance, if produced in small quantities, chemical substances are exempt. The small production volume associated with nanoparticles predisposes them to being granted such exemption, and avoiding the requirements of any regulation. The authors also noted that the TSCA has made mistakes in the classification of carbon nanotubes due to their unique properties and the lack of an appropriate category. It is not clear that the procedure used by the TSCA in its existing form can address the challenges posed by nanotechnology. TSCA does not consider the differences associated with nanoscale properties: the chemical compositions may stay the same, but the fundamental properties change at the nanoscale level. In addition, issues may arise from a specific utilization. Considering that carbon nanotubes may be used in dozens of different applications, it is important to develop an appropriate procedure, including rules, for each of the potential uses.

The authors conclude that the characteristics of nanotechnology such as the ability to alter the properties of a substance, the lack of conclusive research on health and environment risks, and the very few researchers or organization that have addressed the adequacy of the current regulatory system, brings confusion and introduces important challenges to the creation of an adequate regulatory structure for the control of nanotechnology (WWIC 2003). The creation of a Canadian index for potentially harmful nanoparticles should integrate these aspects to ensure the validity of the index since a wrong or ill-conceived regulatory system concerning nanotechnology products could have important economic, environmental and social consequences.

Recommendation 7: Environment Canada should act as a catalyst in the creation of interdepartmental advisory committees to jointly establish standards, guidelines, legislation and regulations to protect the environment as well as human and animal health against known issues such as nanoparticle toxicity. For instance, regulations and guidelines established by Environment Canada could address issues such as handling, production and emission of manufactured nanoparticles and nanotechnology products, and establish standards and operating procedures for exposed workers. European countries have already set up several committees or groups to work on these issues. For example, the European Centre for Standardization (CEN) working group on nanotechnology focuses on the establishment of guidelines and standards in nanotechnology. Environment Canada should establish a similar committee (CEN 2005).

Environment Canada could use these European models as a source of inspiration. In fact, this initiative must be an international effort, and developed in collaboration in particular with neighbouring countries since other countries' developments in the field of nanotechnology could also affect Canada. For example, nanoparticle emissions from US industry near the Canadian border or near a shared river network could contaminate the Canadian environment and Canadians.

Establishment of regulations and standards by Environment Canada will have a twofold advantage: it will promote the preservation of a safe environment for people, animals and plants and seeing that their government is acting in a responsible manner will increase the feeling of security of the Canadian people. The absence of regulations and responsible actions from federal departments like Environment Canada could create unease in the Canadian population, which could eventually development into a significant obstacle to the development of nanotechnology similar to that experienced in the diffusion of genetically modified organisms.

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Acronyms

Ag	Silver
AIST	National Institute of Advanced Industrial Science and Technology
Al	Aluminium
APNF	Asia Pacific Nanotechnology Forum
APU	Amphiphilic polyurethane
As	Arsenic
ASBH	American Society for Bioethics and Humanities
BA	British Association for the Advancement of Science
BMBF	Federal Ministry of Education, Science, Research, and Technology
BRTF	Better Regulation Task Force
CAS	Chinese Academy of Sciences
CBEN	Center for Biological and Environmental Nanotechnology
Cd	Cadmium
CdSe	Cadmium selenide
CEA	Atomic Energy Commission
CeO_2	Ceria
CNI	Center for Nanotech Information
CNRS	National Center of Scientific Research
CNT	Carbon nanotubes
CO_2	Carbon dioxyde
COMETS	CNRS intern committee on ethics
CRN	Center for Responsible Nanotechnology
Cu	Copper
DNA	Deoxyribonucleic acid
DOD	Department of Defense
DTI	Department of Trade and Industry
EASST	European Association for the Study of Science and Technology
EGE	European Group on Ethics
ELSA	Ethical, Legal and Social Aspects of the Life Sciences and Technologies
ELSI	Ethical, legal, and social implication
EPA	Environmental Protection Agency
EPHA-EEN	European Public Health Alliance for Environment Network
ERA	European Research Area
ESANT	European Working Group for Economic and Social Aspects of Nanotechnology
ESF	European Science Foundation
ETH	Swiss Federal Institute of Technology
EU	European Union
EURAB	European Research Advisory Board
Fe	Iron
FP6	Sixth Framework Program
Hg	Mercury
Mn	Manganese
ICPET	Institute for Chemical Process and Environmental Technology
IoN	Institute of Nanotechnology
IT	Information technology
ITA	Innovation and technology analysis
ITEP	Institute of Technology Evaluation Program
JEMAI	Japan Environmental Management Association for Industry
JNNB	Japan Nano Net Bulletin
JSPS	Japan Society for the Promotion of Science
KAIST	Korea Advanced Institute of Science and Technology
KANC	Korea Advanced Nano-Fabrication Center
KISTEP	Korea Institute of Science and Technology of Evaluation Policy
KISTI	Korea Institute of Science and Technology Information
KOSEF	Korea Science and Engineering Foundation

LCA	Research Center for Life Cycle Assessment
LED	Light emitting diode
LNP	Link Nanotechnology Program
METI	Ministry of Economy Trade and Industry
MEXT	Ministry of Education, Culture, Sports, Science and Technology
MNT	Micro and Nanotechnology
MOST	Ministry of Science and Technology of the People's Republic of China
NASA	National Aeronautics and Space Administration
NCNST	National Center for Nanoscience and Technology
NGO	Non-governmental organization
Ni	Nickel
NIC	Nanotechnology Integrated Centers
NIH	National Institute of Health
NIOSH	National Institute for Occupational Safety and Health
NIRT	Nanotechnology Interdisciplinary Research Teams
NIST	National Institute of Standards and Technology
NNCO	National Nanotechnology Coordination Office
NNFC	National Nanofabrication Center
NNI	National Nanotechnology Initiative
NNIN	National Nanotechnology Infrastructure Network
NRC	National Research Council
NRI	Nanotechnology Research Institute
NSC	Nanotechnology Strategy Committee
NSEC	Nanoscale Science and Engineering Center
NSET	Nanoscale Science, Engineering and Technology
NSF	National Science Foundation
NSFC	National Natural Science Foundation of China
NSTC	National Science and Technology Council
OMNT	Observatory for micro and nanotechnologies
PAH	Polycyclic aromatic hydrocarbon
Pb	Lead
PCB	PolyChlorinated Biphenyl
PCR	Polymerase chain reaction
Pd	Palladium
Pt	Platinum
R3N	National Network in Nanosciences
RIETI	Research Institute of Economy, Trade and Industry
Ru	Ruthenium
Sb	Antimony
SINAPSE	Scientific Information for Policy Support for Europe
SiO_2	Silica (silicon dioxide)
SME	Small and medium enterprise
SPECS	Study of the Philosophy and Ethics of Complexity and Scale
SPR	Surface plasmon resonance
STA	Science and Technology Agency
TCE	Trichloroethylene
TiO_2	Titanium dioxyde
UCLA	University of California, Los Angeles
UK	United Kingdom
US	United-States
UV	Ultra-violet
Zn	Zinc
ZnO	Zinc oxyde