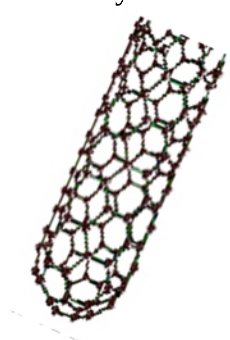
CHAPTER 6. SCIENCE AND TECHNOLOGY

6.2 Nanotechnology: Future Military Environmental Health Considerations

Study conducted in 2004–05

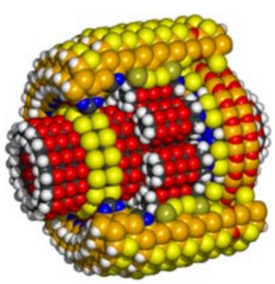
A Brief Overview of Potential Environmental Pollution and Health Hazards Resulting from Possible Military Uses of Nanotechnology with Implications for Research Priorities Helpful to Prevent and/or Reduce Such Pollution and Hazards

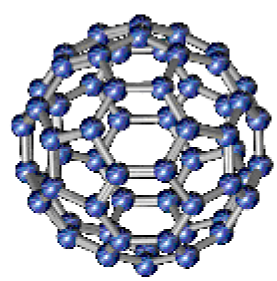
Buckytube



Buckyball

Nanomachine concept





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FOREWORD

Lux Research estimates that more than $8.6 billion will be spent this year on nanotechnology R&D worldwide and that the majority of funds are shifting from basic research to the development of applications. Little is known about the environmental and health risks of manufactured nanomaterials. In 2003 the European Union funded the NANOSAFE project to assess the technology's environmental and health risks. In July 2003 the US Environmental Protection Agency invited proposals to study environmental and health impacts of nanotechnology.

The military is a major force in nanotechnology R&D; hence, it can play a key role in understanding and managing nanotechnology risks. As a result, the Millennium Project conducted a two-round Delphi to identify and rate important forms of nanotechnology-related environmental pollution and health hazards that could result from any military activities and to suggest military research that might reduce these problems. An expert panel on these issues was asked their judgments on the full range of nanotechnologies of the present and future— from nanobulk-process nano (simple structures) and top-down nano (low-volume production) to nano-built nano (high-volume, low-cost, complex high-performance components and even whole products).

For the purposes of this study, the definition of Vicki L. Colvin of Rice University was used to define engineered nanomaterials as "inorganic materials of high uniformity, with at least one critical dimension below 100 nm, specifically engineered for applications." Also included in this study are structural materials made of nanotubes of all kinds—carbon, carbon-silicon, and other materials—plus "metamaterials" (nanopatterned bulk materials with unique electromagnetic properties due to nanostructuring and other manufactured nanoparticles), as well as productive nanosystems and their products.

The US government has budgeted $39 million in 2006 for studies of environmental, health, and safety impacts of nanotechnology, which is 3.7% of the total National Nanotechnology Initiative budget.

EXECUTIVE SUMMARY

An expert panel of 29 participants identified potential military uses of nanotechnology that might occur between 2005–2010 and 2010–2025 with their potential for causing health hazards or environmental pollution.

Some examples between 2005 and 2010 are:

- Nanosensors to detect trace concentrations of biochemicals could lead to absorption of nanoparticles through the skin into the body and environment, concentrating in water and soil, and eventually linking with natural organisms, causing unknown environmental changes
- Nanomaterials (e.g., nanotubes) in uniforms and equipment to make them stronger and lighter could lead to nanofiber-like materials that break off from uniforms and equipment and enter the body and environment
- Nanoparticles as surface coverings to make it harder, smoother, and/or more stealthy could erode and be inhaled by military staff and the general population
- Nanomaterials used as filters to remove selected impurities from fluids could become very low in cost and hence ubiquitous, and result in many small but discrete concentrations of possibly toxic impurities.

Some examples between 2010 and 2025 are:

- Artificial blood cells (respirocytes) that dramatically enhance human performance could cause overheating of the body, bio-breakdowns, and their excretion could add to the environmental load.
- Large quantities of smart weapons — especially miniaturized, robotic weapons and intelligent, target-seeking ammunition without reliable remote off-switches could lead to unexpected injury to combatants and civilians, destruction to infrastructure, and environmental pollution.
- Small receptor-enhancers designed to increase alertness and reduce the reaction times of humans could cause addiction and/or subsequent Chronic Fatigue Syndrome, leading to weakness, neural damage, and death.

Research Priorities: The expert panel also identified and rated research questions whose answers might produce knowledge to help prevent or reduce the health hazards and environmental pollution from potential military uses of nanotechnology. Those research questions or directions that would produce the most new knowledge to prevent or reduce **health hazards** (rated 4 or higher on a 5-point scale) are:

- How are nanoparticles absorbed into the body through the skin, lungs, eyes, ears, and alimentary canal?

- Once in the body, can nanoparticles evade natural defenses of humans and other animals? What is the likelihood of immune system recognition of nanomaterials?
- What are the sizes, aspect ratios, and surface activity determinants of nanoparticle impacts on living organisms (research must be conducted for specific nanoparticles)?
- What are potential exposure routes of nanomaterials - both airborne and waterborne?
- Are the current toxicity tests used for chemicals appropriate and/or useful for nanomaterials?

The research directions that would produce the most new knowledge to prevent or reduce **environmental pollution** from future military use of nanotechnology (rated 4 or higher on a 5-point scale) are:

- How biodegradable are nanotube-based structures?
- Could nanoparticles enter the food chain by getting into bacteria and protozoa and accumulate there?
- How will nanomaterials enter the environment and will they change when moving from one medium (e.g. air) to another (e.g. water)?
- How to identify and dispose of nanomaterial litter?
- How might nanoparticles get into plants and other organisms?
- Regardless of the question, the research should be interdisciplinary and international.
- Do nanoparticles act like bioaccumulants in Nature?
- How can nanotechnology be used for post-battlefield cleanup (including biological, chemical, and nuclear wastes) so that they do not pollute soil and water?
- What technologies can be used to minimize exposure to nanomaterials?

INTRODUCTION

A nanometer is one billionth of a meter (10-9 meter). Nanotechnology manipulates matter at this nanoscale. It is more of an approach to engineering than a science, although it draws on the scientific knowledge of biology, physics, chemistry, and materials science and is expected to change these sciences dramatically. (See CD Appendix E2 for a list of other definitions.) Eric Drexler introduced the term “nanotechnology” in *Engines of Creation* (1986) to describe the “manipulation of individual atoms and molecules to build structures to complex, atomic specifications” and said that “perhaps the ‘arrival’ of the concept of nanotechnology came about in physicist Richard Feynman’s landmark 1959 lecture called ‘There’s Plenty of Room at the Bottom’: *The principles of physics... do not speak against the possibility of maneuvering things atom by atom... it has not been done because we are too big*.”

Today, many other kinds of nanotechnology have attracted much attention. Global nanotech investments in 2004 were estimated at $8.6 billion, and revenues from nanotech products should equal that of information technology in 10 years.[1] President Bush signed into law the 21st Century Nanotechnology Research and Development Act,[2] providing $3.7 billion beginning in 2005 and spread over four years—the largest governmental funding of scientific projects since the space program.

The applications of nanotechnology range from next generation flat-panel TVs, advanced solar panels, and chemical and biosensors to nanomedicine and energy transmission efficiencies. Richard Smalley, who discovered the first fullerenes (called “buckyballs” (C_{60})) and who is developing the use of “buckytubes,” expects nanotech to help improve energy transmission efficiencies.[3] (Buckyballs are the hollow C_{60} spheres; a fullerene is any pure carbon molecule with 60 or more atoms—e.g., carbon nanotubes.)

Nanotechnology approaches range from “top down” (large machines that make very small things today, like nanomaterials in tennis rackets, clothing, and sunscreens) to “bottom up” (molecular assemblers that one day may make molecular machines that make larger things). This study invited input on the full range of approaches to nanotechnology from an expert panel via a two-round Delphi. The invitation letters and Delphi questionnaires are available at www.acunu.org/millennium/nanotech-rd1.html and www.acunu.org/millennium/nanotech-rd2.html.

The 29 expert Delphi panel respondents had backgrounds in nanotechnology R&D with potential military applications, medicine, and/or environmental research related to nanotechnology. The study was conducted between September 2004 and January 2005. The Delphi panel was asked to suggest potential environmental pollution and health hazards that might result from military uses of nanotechnology in the time periods 2005–10 and 2010–25.

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[1] www.nanalyze.com/articles/foresight_oct_04/page3.aspx
[2] [2] www.smalltimes.com/smallstage/images/nanobills189.pdf
[3] [3] www.alternet.org/envirohealth/19812/

POTENTIAL USE AND POTENTIAL IMPACTS BETWEEN 2005 AND 2010

The Delphi panel was asked to suggest potential environmental pollution and health hazards that might result from military uses of nanotechnology in the time periods 2005–2010 and 2010–2025.

The following is an **unranked list** of the panel's suggestions (edited and condensed for clarity) that might occur **between now and 2010**:

- Nanomaterials in sunscreens, camouflage creams, and/or bioweapons skin shields might be absorbed through the skin and/or flushed into the environment and enter the food chain.
- Nanomaterials in uniforms and equipment to make them stronger, harder, smoother and/or lighter could be damaged and/or through normal usage and aging break off and enter the body and environment, including plants, other animals, water, and fish.
- Nanoparticles in fuel as additives might be inhaled by military staff and the public.
- Nanoparticles as surface coverings to make it harder, smoother, and/or more stealthy could erode and be inhaled by military staff and the general population
- Nanosensors to detect trace concentrations of biochemicals could lead to absorption of nanoparticles through the skin into the body and environment, concentrating in water and soil, and eventually linking with natural organisms, causing unknown environmental changes.
- Very low cost filters/membranes using nanomaterials to remove selected impurities from fluids (liquids and gases) could become ubiquitous and result in many small but discrete concentrations of possibly toxic impurities that could become more toxic than the initial materials.
- Nanoparticles in weapons such as depleted uranium could be inhaled by military in the battlefield and civilians if dispersed via wind or other means.
- Similarly, nanoparticles created by the blast of high technology weapons and/or high temperature combustion processes could lead to diseases like cancer, lymphoma, or leukemia in humans and other animals induced by inhalation of nanopollution or ingestion of contaminated food (e.g., inhaled nano-sized pollution in the Twin Towers Collapse Phenomenon).
- Nanoparticle accelerants and explosives could be accidentally dispersed into the environment.
- If implanted into the body, radio frequency identification device tags to track soldiers and equipment could result in materials "leaching" into the body; those in equipment could enter the environment.
- More effective prophylactics and therapeutics—such as time-released polymers that would replace multiple vaccinations—would give better control over contracting and spread of illness and disease; however, those polymers would end up in the environment.

- The biocompatibility of improved prosthetic devices (non-friction microscopic coatings) and implanted medical devices has yet to be established.
- Disposal of highly efficient batteries using nanomaterials could affect ecosystem and human health.

POTENTIAL USE AND POTENTIAL IMPACTS BETWEEN 2010 AND 2025

The following is an **unranked list** of the panel's suggestions (edited and condensed for clarity) that might occur **between 2010 and 2025**:

- Artificial blood cells (respirocytes) that dramatically enhance human performance could cause overheating of the body and bio-breakdowns, and their excretion could add to the environmental load.
- Large quantities of smart weapons—especially miniaturized, robotic weapons and intelligent, target-seeking ammunition without reliable remote off-switches—could lead to unexpected injury to combatants and civilians, destruction to infrastructure, and environmental pollution.
- Small receptor-enhancers that increase alertness and reduce the reaction times of humans could cause addiction and/or subsequent Chronic Fatigue Syndrome, leading to weakness, neural damage, and death.
- Inorganic, non-biodegradable nanoparticles (and perhaps also non-biocompatible) nanoparticles for drug release or cancer treatment, or "permanent" nanosensors, might induce a foreign body reaction.
- Proteomic targeting, genetically selective "designer quasi-viral components," engineered to select specific human targets based on definable genetic markers, might mutate, creating a biological pandemic.
- Nanoparticles to "clean up" contaminated areas might create new compounds that could have unknown impacts on the environment, including long-term leaching into groundwater reserves.
- Ubiquitous surveillance systems deployed without strong controls on the use of information could lead to psychological stress from the sense of being watched by strangers.
- Numerous centimeter-scale buoyant platforms deployed in the atmosphere might interfere with birds and aircraft, and damaged devices might fall as precipitation at uncontrolled locations over Earth's surface.
- Nanoscale time-released bioweapons for inhalation might have long-term effects on those handling the bodies of victims and on the environment in general.
- The deliberate high-volume production and use of nano-built weapons and ammunition might occur without sufficient disposal methods after the need for use has passed.
- Nanoscale biomolecule-driven motors that enhance the efficiency of ATP (adenosine triphosphate) usage, the frequency of generation of ATP, and the life of ATP molecules in endurance athletes and/or long-haul soldiers could cause overheating of the body and

biobreakdowns and could possibly lead to Rapid-Onset Muscle Soreness after a stipulated duration; if allowed to function beyond this duration, they may kill the organism thus modified.

- Ubiquitous sensing in the oceans via large numbers of small drifting devices linked by acoustically based data-packet networks, and countermeasures to disable them, could affect sea life from these materials, as well as from acoustic pollution.

Other interesting suggestions for the period 2010–25 that are not conventionally thought of as health or environmental impacts included:

- Nanocomputers could remove humans from the battlefield, making warfighting less costly for the side with the nanotechnology and therefore making warfighting more likely. Better sensors, effectors, and computational systems, with lower-cost production, allow deployment of teleoperated “soldiers” able to occupy territory without risk to human soldiers; this could destabilize military balances, prompting preemptive wars or wars of aggression, enabling inexpensive conquest and subsequent suppression of insurgencies, and even reducing moral sanctions against wars of aggression. Rapidly deployed high-volume production of superior weapons and ammunition might have similar impacts.
- Automated or remote-controlled weapons, rather than removing humans from the field of battle, may make it easier to take the battlefield to the humans. Although these new weapons may shift the focus of conflict away from conventional battlefields, new battlefields will have to be developed, and many of them will overlay civilian populations.
- Inexpensive, high-performance military systems make nonlethal weapons economical as a means of projecting force, despite their lower effectiveness per unit cost.
- Antisatellite systems based on inexpensive, high-performance launch and orbital systems could lead to dense clouds of hazardous objects in near-Earth space, posing collision threats and strategic destabilization and precipitating war.
- Special operations nanorobots designed to shoot from the inside, after being ingested, might miss their targets and lead to random killings.

RESEARCH PRIORITIES

3.1 Research priorities for addressing health hazards

The Delphi Panel was also asked to identify and rate research questions, that if pursued might help prevent or reduce environmental and health impacts. The following scale was used to rate the questions:

Potential for gaining new knowledge from the research

5 = Will lead to critical knowledge for preventing and/or reducing problems

4 = Very likely to lead to critical knowledge for preventing and/or reducing problems

3 = May lead to critical knowledge for preventing and/or reducing problems

2 = Not likely to lead to critical knowledge for preventing and/or reducing problems

1 = A complete waste of time

The following tables present the averages of the ratings by the Delphi panel listed in order of their potential for gaining new knowledge important to reducing or preventing potential health impacts noted previously.

Health Hazard Research Questions and Priorities––
Sorted by Knowledge Gain Potential

How are nanoparticles absorbed into the body through the skin, lungs, eyes, ears, and alimentary canal?	4.46
Once in the body, can nanoparticles evade natural defenses of humans and other animals? What is the likelihood of immune system recognition of nanomaterials?	4.38
What are the sizes, aspect ratios, and surface activity determinants of nanoparticle impacts on living organisms (research must be conducted for specific nanoparticles)?	4.14
What are potential exposure routes of nanomaterials - both airborne and waterborne?	4.00
Are the current toxicity tests used for chemicals appropriate and/or useful for nanomaterials?	4.00
What are the surface properties of nanoparticles that alter toxicity? What are the distinct properties of nanoparticles that may alter toxicity?	3.87
Do nanoparticles concentrate at critical sites like synapses and tumors?	3.80
Effect of exposure to nanoparticles on all lifestages, from fetus to old age, and on all major systems, including neural and immune systems.	3.79
How are nanomaterials metabolized and eliminated by the body?	3.73

What are the important unknowns about nanomaterials crossing the brain/blood barriers and traversing neural pathways?	3.64
What is unique about the health hazards of manufactured nanomaterials vs. health hazards of particles of a similar size?	3.60
Can nanomaterials concentrate inside humans? If so, in which organs are they most likely to accumulate?	3.53
Can nanoparticles enter egg and sperm cells, altering DNA?	3.53
How are namomaterials distributed throughout the body?	3.50
What is the nature and quantitative effectiveness of the mechanism for removing nanoparticles from the lungs?	3.50
Compared to existing weaponry, how much more deadly will nano-built smart weapons be--especially miniaturized, robotic weapons and intelligent, target-seeking ammunition?	3.42
Develop uniform nomenclature for research and presentation of results.	3.36
How are nanomaterials biotransformed within different species?	3.36
Organize data on impacts based on group or class of nanoparticles with respect to chemical composition, size, aspect ratio, and surface activity.	3.23
What are the regulatory options to investigate?	3.20
Is there built-in auto destruction within the nanoparticles? If so, what happens to the waste materials?	2.92
What psychological aspects should be considered?	2.85

3.2 Research priorities for addressing environmental pollution

**Research Questions and Priorities for Addressing Environmental Pollution––
Sorted by Knowledge Gain Potential**

How biodegradable are nanotube-based structures?	4.36
Could nanoparticles enter the food chain by getting into bacteria and protozoa and accumulating there?	4.21
How will nanomaterials enter the environment and will they change when moving from one medium (e.g., air) to another (e.g., water)?	4.20
How can we identify and dispose of nanomaterial litter?	4.14
How might nanoparticles get into plants and other organisms?	4.14
How can research in these fields be made more interdisciplinary and international?	4.08
Do nanoparticles act like bioaccumulants in nature?	4.07
How can nanotechnologies be used for post-battlefield cleanup (including biological, chemical, and nuclear wastes) so that they do not pollute soil and water?	4.00
What technologies can be used to minimize exposure to nanomaterials?	4.00
What are the potential environmental impacts of nanotech water purification systems?	3.93
Conduct real inhalation studies (vs. simulation).	3.83
Are nanoparticles changed in composition (as they go through the body or environment), or do they accumulate as pollutants in the environment?	3.79
How do engineered or manufactured nanomaterials behave as compared with natural nanomaterials or those resulting from combustion processes?	3.71
Study nanotech impacts on ecological systems, and not just on single organisms.	3.54
What climate change impacts are possible from extremely large-scale operations to provide energy (especially solar) or from mass-produced nano-built weaponry and/or military infrastructure?	3.54
Compared with existing weaponry, how much more damage could nano-built weapons do to buildings, roads, and infrastructure, and how much of a pollution hazard will these create?	3.50
How might nanomaterials leach into water tables?	3.42
How can we study current nanoparticle contaminations in post-war fields by high-technology weapons, including smoked cigarette tobacco polluted with depleted uranium?	3.09
What strategies could prevent uncontrollable growth (or the “gray goo” problem)?	2.79

3.3 Priorities of general questions to gain further insight into nanotech impacts––sorted by Knowledge Gain Potential

Priorities of General Questions and Objectives to Gain Further Insight into Nanotech Impacts––Sorted by Knowledge Gain Potential

Toxicologists and pharmaceutical scientists cannot solve or understand all these nanotech problems acting just within their disciplines. Biomaterialists, immunologists, and embryologists have a better cultural background to understand the physical-chemical and biological interactions of nanoparticles with human life and environment. A multidisciplinary team is needed.	4.43
What training will be necessary to provide the capacity for oversight for safe development and application of nanotechnology?	4.17
What are the most useful methodologies and protocols for environmental pollution and health hazard studies for the range of nanotechnologies?	4.07
What is a useful classification system to provide a framework to make research judgments and keep track of the state of knowledge about nanotech's potential pollutions?	4.00
How can toxicologists and pharmaceutical scientists investigating nanoparticles' ability to evade cell defenses to target disease best be brought together?	4.00
How can energy consumption be minimized and waste/pollution be prevented in the manufacturing of nano/military materials and products? (This research would address green manufacturing of nanomaterials, applying green chemistry and green engineering principles.)	4.00
How can standard metrics for nanotech pollution/hazards be developed?	3.86
Are there ways to use novel testing methods, protocols, and technologies (e.g., toxicogenomics) to increase the efficiency with which we can generate important risk data for new nanomaterials?	3.86
How can specific research into nano-related environmental pollution and health hazards effectively take into account the fundamental ways that all systems (ecological, economic, political, and social) may be disrupted and transformed by molecular manufacturing on local, national, and global scales?	3.71
What will be the development timeline for nano-built nanomachines (exponential manufacturing) with military potential? How soon do we have to prepare?	3.69
What are the commonalities between anthropogenic and manufactured particles?	3.69
At what stage in the life cycle of nano/military materials and products do the major environmental impacts occur (e.g., resource extraction, manufacture, use, end of life)? (This research would address life cycle assessment of nanomaterials used in military activities.)	3.67
What are the "representative" nanomaterials that should be used for testing in terms of which nanomaterials may cause high exposures?	3.46
How can remotely controlled switches be created to deactivate nanotech weapons?	3.18
Can nanoparticles be made preferentially symbiotic with human hosts, creating a new breed of terrorists?	3.14
How can nano-built nanoproducts intensify earlier problems of nanomaterials and create important new ones?	3.00
How can arms control measures prevent the deployment of powerful nanomanufacturing systems able to produce unprecedented quantities of advanced weapons?	3.00
Establish nanotech-environmental summits.	3.00

4. ADDITIONAL COMMENTS FROM PANELISTS ABOUT POTENTIAL MILITARY AND/OR TERRORIST USE OF NANOTECHNOLOGY

Applied nanobiology being utilized for the engineering of "next generation" bio-weapons, including the development of hybrid genetic marker targeting quasi-viral components and potentially hypervirulent "designer prions": I am greatly concerned that this work is already well under way. Certainly the "tools of the trade" for this type of endeavor already exist. Unlike nuclear devices, even those that have been purchased ready-made (such as the infamous Russian "suitcase nukes"), which require substantial complex maintenance and can be detected, designer bio-entities, especially viruses and viral hybrids, can remain dormant for very long periods of time, with very little or no maintenance, and are essentially undetectable until eventually released.

Even once released, if the proteomic/genetic signature of the newly created hybrid organism is of an unknown origin (and therefore not in the current genetic library of known bio-pathogens), it can slip through even comprehensive biological scans until it is eventually isolated and analyzed. By that time, it has already been well established in the targeted population, and its desired effects have become manifest.

Indeed, the artform of inventing this new generation of bio-weapons is not just in creating extremely virulent and deadly quasi-viral entities that are proteomically selective for keyable genetic markers but also are designed to have "stealth" proteomic signatures that mimic relatively harmless or benign organisms.

Furthermore, prions, which are responsible for pathologies such as the so-called mad cow disease (and similar pathologies that have occurred in other species, including humans), are still relatively new and somewhat unexplored as a potential military asset. No doubt, however, this is also being considered, and this is truly in the arena of nanobiology, in that prions are much smaller than even viruses (roughly speaking, prions are somewhat like a proteomic fragment of a virus).

The interesting and relevant point here about prions is that they are extremely hard to detect, can be hypervirulent, can remain dormant and "hidden," even within the targeted host victim, until they become activated via a biological trigger, and, most important, are virtually indestructible. Extreme temperatures, most chemicals that would usually kill viruses, and even extremely high dosages of radiation have no effect on these entities. They can "lie in wait" anywhere, in soil and water, in living tissue, waiting for their cue to become active.

Once activated, they can create horrendous neurological pathologies—and death.

Worst case scenario: Hypervirulent "designer prions" get released into a general human population, as part of a scheme hatched not by a military organization but as the outcome of an ideological agenda where simply death and mayhem on a mass scale is the intended goal. The end result is just that, death and mayhem on a scale almost unimaginable, leaving in its wake a new class of "sub-organism" entity that is essentially indestructible and ubiquitous. Even after the initial pandemic may be resolved by some form of treatment or antidote, it will lie in wait for centuries, like the ultimate bio-timebomb quietly waiting to be recatalyzed into action on an unsuspecting future population.

This scenario could in fact come to pass well within our lifetime. As a last note on this topic, once again making the comparison to “traditional” nuclear weapons: creating designer bio-entities does not require nearly the scale of enormous overhead, exotic resources, and facilities as nuclear device development. Essentially, the right collection of molecular biologists and other specialists in certain areas of expertise could be quietly ensconced in an ordinary office building setting anywhere and could obtain the required equipment off the shelf as standard biological research purchases directly from the suppliers of such technology without ever even the raising the suspicions of the vendors.

Hence, the prevention of this scenario should be a priority for military research.

* * *

Another area where nanotechnology could become truly terrible as a weapon platform—beyond the more obvious applications such as smart or autonomous artificial intelligence–enhanced vehicles, robots, swarms of “intelligent nanobugs,” distributed intelligence “smart dust,” and so on, and even the much more terrifying advent of proteomically selective nanobiological agents (mentioned above)—would be in the theoretical realm of “selective disassembly.”

The deployment of selective disassembly would be somewhat like a “controlled” version of the infamous “gray goo” concept, in that specific domains of material/chemistry regimes would be targeted for “molecular chaos” to ensue when the invading nanomaterial was triggered or catalyzed into action.

That this type of research would even be considered should be enough to cause very legitimate concern and regulatory action. There is no global authority that can actually regulate and prevent such a concept from being secretly explored and potentially deployed.

Who might do this is an area for debate, but if a country or group did so, then an entirely different potential future for nanotech could unfold, instead of its being a promising solution to so many of the world’s current problems.

* * *

Although there is much thought given to carbon nanofibers, there are many different forms of nanostructured materials already in development (and deployment) that have nothing at all to do with carbon fullerene chemistry. For example, various forms of “smart” sensory garments without carbon fullerene chemistry of any type are being patented now. Carbon nanofibers are probably not particularly threatening, as per the same logic that applies to asbestos fibers, although there is as yet no specific data to support or deny this position.

Also, in the arena of nanoparticulates utilized for filtration purposes (such as in water treatment, for instance), perhaps in the long term there could be cause for concern, but, again, there are no data to my knowledge that support this. Furthermore, if nanofiltration techniques provide a ready solution for many water problems, then a balance between the perceived potential threat of these materials and the real (and immediate) benefits of freshwater access has to be assessed.

* * *

Another nanomaterial is “qauntum dots.” Cadmium sulfide is the common material of choice for creating quantum dots—spectrally selective/resonant nanoparticles whose resonant frequencies are determined by the physical size of the particle. The applications are many and highly interesting, but cadmium is also highly toxic (carbon, for instance, is not). However, it should also be pointed out that there are already various alternative (and less toxic) material variants being investigated for potential quantum dot manufacture, particularly in potential medical applications.

* * *

I think that language that makes the following points would help to clarify the reported results: Current nanofabrication uses large things to make nanoscale things, often crudely, messily, and expensively. Future productive nanosystems will use small things to make both large and nanoscale things and can be precise, clean, and inexpensive. Expertise in nanoscale products is often associated with confused assessments of productive nanosystems, which are long-term goals of a different field. Accordingly, mixing discussions of productive nanosystems with discussions of current nanoscale products can lead to mixed results.

* * *

There seem to be three general categories of questions about the effects of nanomaterials on the body: Are they physically large enough (individually or with massive accumulation) to obstruct a bodily function at the tissue (capillary, bronchiole, neural synapse), cellular, or subcellular levels? Does the body interact with or metabolize them? And what is the function of the particular “nanobot” in question?

Our skin, GI tract, and lungs are constantly exposed to particles of all sizes without much effect unless the particle is large enough or the exposure is large enough…as in smoke inhalation, asbestosis, etc.

But we do interact with and metabolize many things regardless of size or amount that our body uses. These are either chemical reactions (e.g., carbohydrate, protein, fat metabolism, Na pump, K pump, etc.) or allergens. Much work has been done to study chemistry and allergy in the human body, and it is likely that the chemical makeup of most nanomaterials is not new to the study of the human body. Therefore I think the real question of harm to the body is about the function for which the “nanobot” is created. What job is it supposed to do? Because the creator of the “nanobot” knows its function, (s)he would probably already know how to stop that function or should create along with it an “off- switch” mechanism, antidote, or decay mechanism (or vaccine?) that would arrest any harmful or pollutant effect. I believe this principle should apply to any scientific creation of any scale that could be harmful to humanity.

* * *

An additional research question should be: What will be the potential environmental and human health impact of the convergence of nanotechnology with biotechnology, cognitive technology and information technology?

* * *

I do not follow how the development of nanosensors leads to environmental damage. Is the concern the eventual environmental ubiquity of nanosensors, which themselves would be absorbed through the skin and then excreted from the human body, to later build up concentrations of nanosensors in the environment, which would somehow alter natural organisms? This seems like a tortured series of assumptions to me. Military development of nanosensors to detect trace biologics? Yes. Military use of nanoparticulate “stuff” (drugs, nutrients, etc.) as skin creams for transdermal delivery? Yes. Concentrations of nanowaste in the environment? Plausibly. Unforseen nanowaste manipulations of natural organisms? Possibly. But all of these strung together? Doubtful.

* * *

Nanoparticulates and nanofibers have two different dimensional challenges to entry into the body. Nanofibers have a reasonable length to them, which boosts them dimensionally into the micro range, which the human body deals with differently – so trapping and excreting them is more likely and thus less of a health threat (this addresses the physical threat, but obviously not any chemical threat that they might pose, in any size). There has already been a study which showed cytotoxicity, but NORA (National Occupational Research Agenda created by the National Institute for Occupational Safety and Health) is still looking into the nanofiber toxicity issue.

* * *

Since filtration systems are designed to capture, not release the filtrants, nanotech should not be an issue. If anything, the concentration of toxics in a filtration system is a good thing, not a negative environmental impact. You would be removing them from the environment.

* * *

Nutritional and vaccination applications of using nanotech are not mentioned. Both of these are possible within five years. Drug delivery is mentioned once, but the health-related applications go beyond that. From a nutritional (human systems performance) perspective, the greater solubility, greater ability to cross the blood-brain barrier, greater dosing efficiency, better time-release functions, etc. of nanotech-enhanced nutraceuticals provides high value on the battlefield. Research on several vaccination applications for nanotech are in process, the objective of which is to leverage nanotech’s delivery advantage over conventional vaccination technologies.

* * *

Consider the possible consequences of hostile agents breaking into communications and control of nanosystems, either in their intended activity or (worse) replication activities—particularly if the intended activity is as a weapon. (Nanoterminator III?)

* * *

Nanorobots for the elimination of the nanoparticles inside the blood can have a positive impact on human health. Nanomotors for moving nanoparticles outside of the human body can also have a positive impact on human health. Low-cost, disposable nanostructured platforms for diagnostics of diseases and biocontamination can be very effective and provide rapid response in biowarfare and control of disease outbreaks in adverse environments. Nanostructured energy scavenging devices could provide low-cost power generation for micro-devices that would allow better, real-time, and pervasive monitoring of environmental conditions.

5. References for Related Research

The following are references for research related to potential environmental and health impacts of military use of nanotechnology. An initial list was provided by the research staff. The panel added to the list during both rounds of the Delphi. (Note that long Web addresses may have to be copy/pasted into the browser address window.)

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K. Donaldson, V. Stone, L. Tran, W.G. Kreyling, and P. Borm, *Nanotoxicology: a new frontier in toxicology*, Occup Environ Med 61:727–728 (2004)

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Robert A. Freitas Jr., *Nanomedicine, Volume I: Basic Capabilities*, Georgetown TX: Landes Bioscience, 1999. http://www.nanomedicine.com/NMI.htm (First textbook ever published on nanomedicine and medical nanorobotics; includes over 3700 literature references)

Robert A. Freitas Jr., *Some Limits to Global Ecophagy by Biovorous Nanoreplicators, with Public Policy Recommendations*, Richardson TX: Zyvex LLC (preprint), April 2000. http://www.foresight.org/NanoRev/Ecophagy.html (First technical discussion of ecophagy risk or "gray goo.")

Robert A. Freitas Jr., *Nanomedicine, Volume IIA: Biocompatibility,* Georgetown TX: Landes Bioscience, 2003. http://www.nanomedicine.com/NMIIA.htm (First comprehensive textbook ever published on the biocompatibility of nanomaterials, nanoparticles, and nanorobots in the human body, especially diamondoid and carbon-based materials; includes over 6200 literature references)

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Sonia E. Miller, Esq., *The Convergence of N: on Nanotechnology, Nanobiotechnology, and Nanomedicine*, New York Law Journal (December 2, 2003) http://www.ctba.us/articles.asp

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Chris Phoenix and Eric Drexler, *Safe exponential manufacturing*, Nanotechnology 15:869-872 http://www.iop.org/EJ/abstract/0957-4484/15/8/001/ — This paper explains that the so-called 'gray goo problem' is now less of a concern than are the implications of other forms of molecular manufacturing. The authors say "Nanotechnology-based fabrication can be thoroughly

non-biological and inherently safe: such systems need have no ability to move about, use natural resources, or undergo incremental mutation. Moreover, self-replication is unnecessary: the development and use of highly productive systems of nanomachinery (nanofactories) need not involve the construction of autonomous self-replicating nanomachines. [However,] other concerns present greater problems. Since weapon systems will be both easier to build and more likely to draw investment, the potential for dangerous systems is best considered in the context of military competition and arms control."

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Overview of Completed and Ongoing Activities in the Field: Safety and Risks of Nanotechnology, Version 2.2, Technologie Management, Switzerland, November 18, 2004. http://www.temas.ch/WWWTEMAS/TEMAS_Homepage.nsf/vwRes/Safety/$FILE/NANOSafety_Version2_2.pdf

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The Wise-Nano project, a collaborative website to study the facts and implications of advanced nanotechnology. It is a site for researchers worldwide to work together, helping to build an understanding of the technologies, their effects, and what to do about them. http://wise-nano.org

The following Websites should also prove useful:

http://www.aist.go.jp/NIRE/eco_tec_e/hyouka_e.htm—National Institute for Resources and Environment (Japan) – Evaluation Technologies for Environmental Effects and Ecotechnology. Excellent technical discussion, with many graphics.

http://www.AZoNano.com—"The World's Premier Online Nanotechnology Information Site"—A commercially sponsored portal and news site with an extensive collection of information.

http://www.eurekalert.org/nanotalk/20041207/talk.php — A useful portal and news site sponsored by the American Association for the Advancement of Science.

http://www.euronanoforum2005.org/—Web site of the conference, "EuroNanoForum 2005"—"Nanotechnology and the Health of the EU Citizen in 2020"—6-9 September 2005

http://www.luxresearchinc.com—Site of Lux Research Inc., a "leading nanotechnology research and advisory firm". Links to corporate-related events, and white papers.

http://www.nano.gov/—The home page for the U.S. government's National Nanotechnology Initiative. Offers current news and a variety of links.

http://www.nanoforum.org—"European Nanotechnology Gateway". Sponsored by the EU. News and a small number of links.

http://www.nano.org.uk—Site of the (UK) Institute of Nanotechnology. Links to events and various other types of resources.

APPENDICES

Appendix A. The Delphi Panel

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Appendix B. Definitions of Nanotechnology

In recent general usage, any technology related to features of nanometer scale: thin films, fine particles, chemical synthesis, advanced microlithography, and so forth. As introduced by the author, a technology based on the ability to build structures to complex, atomic specifications by means of mechanosynthesis; this can be termed molecular nanotechnology. www.foresight.org/Nanosystems/glossary/glossary_n.html

The science and art of making devices that are smaller in scale than MEMS, often at a molecular size, generally fabricated by chemical processes that result in the growth or formation of certain useful structures. www.isye.gatech.edu/~tg/publications/ecology/eolss/node2.html

Nanotechnology is a new technology for creating MEMS structures in the "Nano" range which is three orders of magnitude, or 1000 times smaller than the current generation of MEMS devices. Refers to devices ranging in size from a nanometer to a micron. www.allaboutmems.com/glossary.html

The manufacture of systems of molecular size that emulate the behavior of larger systems. Any life system is potentially creatable in these dimensions, using standard biological or even inorganic components. www.calresco.org/glossary.htm

A manufacturing technology able to inexpensively fabricate most structures consistent with natural law, and to do so with molecular precision. www.nanotech-now.com/nanotechnology-glossary-M-O.htm

The application of science to developing new materials and processes by manipulating molecular and atomic particles. www.nanoelectronicsplanet.com/glossary/article

The science of creating highly miniaturized machines that work on the molecular level. www.morphonix.com/software/education/science/brain/game/brainarium/brainarium_glossary.html

Atomic engineering--the ability to devise self-replicating machines, robots, and computers that are molecular sized. www.levity.com/mavericks/glossary.htm

A precise molecule by molecule control of products and byproducts in the development of functional structures. www.biotech.ca/EN/what_glossary.html

…is the science of building devices at the molecular and atomic level. For example, a single data bit might be represented by only one atom some time in the future. Beyond being used in computers and communications devices, nanotechnology could be used to build devices, change the properties of materials, and extensively in biotechnology. www.beta-rubicon.com/Definitions.htm

Constructing things one atom or molecule at a time or using programmed molecular sized robots called 'nanobots', for example treatment of disease from within the human body using nanobots. www.iib.qld.gov.au/itcareers/talk.asp

The development and use of devices that have a size of only less than 200 nanometres. www.eppic-faraday.com/glossary.html

…the creation of nanoscale devices (up to 100 nanometers) www.eetimes.com/story/OEG20020912S0030

Research and technology development at the atomic, molecular or macromolecular levels in the length scale of approximately one to several hundred nanometers. www.solexa.co.uk/Glossary/g.htm

— technology that changes atoms to create something new www.nasaexplores.com/lessons/02-057/5-8_glossary.html

"an experimental technology which uses individual atoms or molecules as the components of minute machines, measured by the nanometer, or a millionth of a millimeter."* www.hale.nrsd.net/HaleLibraryHome/LibraryWeb_folder/SciWebPages/Topic_Define.html

(n.) is synonymous with molecular systems engineering. An interdisciplinary field where devices are constructed at the molecular scale and function at this scale. This technology is expected to allow the construction of very compact and high performance computing devices. www.new-npac.org/projects/html/projects/cdroms/cewes-1999-06-vol1/nhse/roadmap/applgloss/applgloss.html

This refers to the construction and use of structures and devices that range in size from one to 100 nanometers. www.midlandstech.com/jlh/ast/glossary/n.htm

…the branch of engineering that deals with things smaller than 100 nanometers (especially with the manipulation of individual molecules) www.cogsci.princeton.edu/cgi-bin/webwn

Nanotechnology is the projected ability to make things from the bottom up, using techniques and tools that are being developed today to place every atom and molecule in a desired place. If this form of molecular engineering is achieved, which seems probable, it will result in a manufacturing revolution.http://www.crnano.org/whatis.htm