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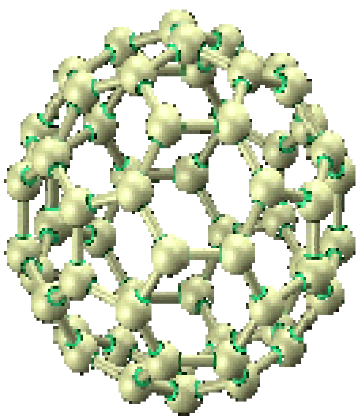
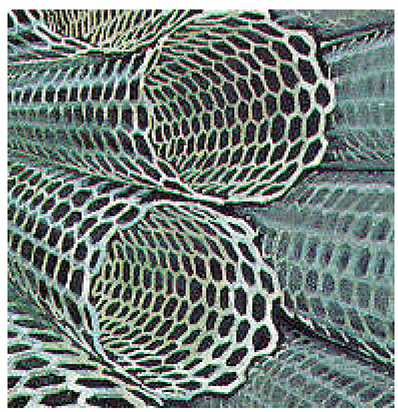
Nanotechnology: The Next Industrial Revolution – Military and Societal Implications





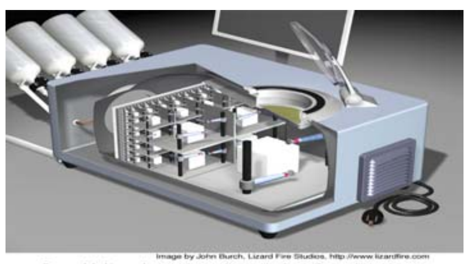


Image by John Burch, Lizard Fire Studios, http://www.lizardfire.com

Proposed desktop-scale molecular manufacturing appliance. Tiny machines join molecules, then larger and larger parts, in a convergent assembly process that makes products such as computers with a billion processors. (Parts shown as white cubes.)

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Army Environmental Policy Institute
1550 Crystal Drive, Suite 1301
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This paper will examine nanotechnology and its potential impact on the American soldier. Its goal is to create a document that is a readable, interesting and influential aid to senior policy makers. Nanotechnology will have an impact equaling or exceeding that of motorization, airpower or computers on the manner in which wars are waged. The history of nanotechnology is briefly reviewed as are the basic technological underpinnings of the science. There follows a discussion of the environmental and health implications of the array of new technologies as well as a discussion of its sustainability. The technologies, as they develop, may cause major societal changes analogous to those of the industrial revolution. The military ramifications of nanotechnology are briefly reviewed in the context of the National Defense Strategy. The paper offers recommendations and conclusions: nanotechnology will develop regardless of the wishes of ethicists or national leaders. It is virtually certain to be employed by both the United States Army as well as the enemies of the United States. If properly developed, nanotechnology can enhance the joint and expeditionary capabilities of American Forces. The goal should be to understand and influence the impact and consequences of this new technology on the soldier?s environment.

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The images on the cover depict some important aspects of nanotechnology.

Top Left
A bucky ball, named after futurist Buckminster Fuller, is a spherical structure consisting of 60 carbon atoms. The bucky ball is hollow and can be used to carry and deliver some other agent such as a medication. The bucky ball can also accept specific coatings.

Top Right
Carbon nanotubes are one of the fundamental building blocks of nanotechnology. The nanotube may be thought of as a rolled sheet of carbon, one atom thick. By altering the twist (chirality) of the sheets of carbon and through the addition of layers, the carbon nanotube may be given specific attributes.

Bottom
A desk top factory represents the ultimate fruition of nanotechnology. From a source of feed stocks the raw materials are fed into the factory where, through the use of millions of nanomachines arranged in a massive parallel structure, the raw feedstock is placed molecule by molecule into a finished product.

UNITED STATES ARMY WAR COLLEGE
CIVILIAN RESEARCH PROJECT

NANOTECHNOLOGY: THE NEXT INDUSTRIAL REVOLUTION MILITARY AND SOCIETAL IMPLICATIONS

by

COL John P. McGuinness
Army National Guard of the United States

Mr. John Fittipaldi, ODASA (ESOH)
Project Advisor

Army Environment Policy Institute
Arlington, Virginia 22202-4144

ABSTRACT

AUTHOR: McGuinness, John P.

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ACRONYMS

AEPI	……………………………………………….Army Environmental Policy Institute
ANSI	……………………………………………American National Standards Institute
ATP	……………………………………………………………..Adenosine Triphosphate
CMOS	……………………………………..Complementary Metal Oxide Semiconductor
CNT	………………………………………………………………………Carbon Nanotube
EPA	………………………………………………….Environmental Protection Agency
ESOH	……………………………………Environment, Safety and Occupational Health
FRAM	……………………………………………Ferroelectric Random Access Memory
ISN	………………………………………………Institute for Soldier Nanotechnology
NGO	……………………………………………………Non Governmental Organization
NIOSH	………………………………National Institute of Occupational Safety and Health
NNI	………………………………………………….National Nanotechnology Initiative
OSHA	……………………………………………...Occupational Safety and Health Act
STM	……………………………………………………Scanning Tunneling Microscope
TSCA	……………………………………………………….Toxic Substances Control Act
USAWC	……………………………………………………United States Army War College

INTRODUCTION

From time to time, revolutionary new technologies appear and cause dramatic changes in the course of human history. Past changes have included the development of the sailing ship, the exploitation of fossil fuels, and advances in aviation. In the last decade or so, the sciences of biology, chemistry and physics have converged to shape a new technology which will have enormous impacts on the course of history. Nanotechnology, which refers to a technology in which materials are designed and manipulated on a molecular scale, represents a technological leap on a scale analogous to the first industrial revolution. From the perspective of the soldier, nanotechnology will alter the way in which wars are fought similar to the transition from horse drawn to motorized transport or from ground warfare to airpower or from analog data management to the digital battlefield. The goal should be to understand the impact that nanotechnology will have on society in general and war fighting in particular and to seek to shape the consequences of this new technology on the soldier's environment. Accordingly, the goal of this civilian research project is to present an interesting and informative document to aid the senior decision makers in shaping the application of nanotechnology to our national defense.

This paper should be read with three caveats in mind: first, the term nanotechnology may seem to suggest that there is a single body of knowledge which encompasses all there is to know about the techniques of working with the very small. This is not true; the term nanoscience is more accurate since the methods of nanotechnology will apply to many industrial and research activities ranging from coatings on the internal surfaces of jet engines through computer memory chips to drug delivery devices. Second, the changes discussed in this paper will be incremental rather than abrupt but they will affect virtually all areas of human endeavor. As nanotechnology nears its full potential, human beings will find it difficult to contemplate life before the technology. Third, and this caveat has particular applicability to the military use of nanotechnology, the acceptance of the technology and related products will encounter resistance. Inevitably, the cry "That's not how we have always done it." will be raised and will fall on some receptive ears. This complaint notwithstanding, nanotechnology will advance with or without military participation; in any case, national interests will be served by taking a leadership role in the development and application of nanotechnology.

OVERVIEW OF NANOTECHNOLOGY

The most remarkable feature of nanotechnology is the scale on which the technology operates. Nanometers are quite small. The prefix nano- comes from the Greek for dwarf. By definition, a nanometer is one billionth of a meter. It would take ten hydrogen atoms side by side to equal the width of a nanometer and it would take nearly a thousand nanometers to equal the size of a typical bacterium. A pinhead is a million nanometers in diameter. As compared to the diameter of a redwood tree, a human hair would be one nanometer in diameter. At these very small dimensions familiar materials may display new properties; insulating materials may become conductors and insoluble substances may become soluble. Materials that are inert in their accustomed forms may become dangerously explosive.

Why is small size so important? One of the key themes in the history of mankind's pursuit of technology is the effort to make things smaller, better and faster. Nanotechnology will aid in this effort. For example, the semiconductor industry has made huge leaps in the last generation allowing the size of computer chips to shrink. Unfortunately, the traditional complementary metal oxide semiconductor (CMOS) technology will reach the limit of its ability to shrink in the next few years with a circuit size of approximately 60 nanometers.[1] Nanotechnology will allow circuit sizes of 1-2 nanometers. In order to maintain U.S. defense and economic dominance it will be critical that we master nanotechnology to allow us to maintain technological leadership.

Milestones in nanotechnology

The nano-level world is an entirely different place where materials with familiar properties take on new and unfamiliar properties. At this level of scale, often referred to as the mesoscale, physical properties are subject to a combination of rules of quantum and classical physics.[2] Therefore some basic definitions are given below.

Basic definitions and concepts

Nanotechnology is still an emerging technology and the nomenclature and classification of the materials is yet to be developed. The American National Standards Institute (ANSI) is in the process of establishing a standardized nomenclature for nanomaterials and has formed a Nanotechnology Standards Panel which first assembled in late September 2004.[3] For now, the basic concepts in nanotechnology may be known by multiple names, but some of the generally accepted terms are discussed here.

Nanoparticle

Typically, a nanoparticle is formed from a single element or a simple compound and has at least one dimension less than 100 nanometers. At this magnitude, the laws of classical physics become blurred and at sizes less than 50 nanometers, the rules of quantum physics take precedence. As opposed to classical physics, quantum physics is the special set of physical rules applicable to matter on the molecular or atomic scale. The transition from classical physics to quantum mechanics begins at approximately 50 nanometers; at this very small scale familiar materials take on new properties. For example, materials have different colors and their magnetic qualities are altered.[4] What is more interesting is that as the size of the particle shrinks, the ratio between mass and surface area changes and the surface area becomes proportionally much greater. It is possible for one gram of a nanomaterial to have a surface area of 1000 square meters.[5] Because chemical reactions take place at the surface interfaces, nanoparticles are much more reactive than their bulky macro relatives.

There are particular subtypes of nanoparticles.

Nanotubes

A nanotube is a cylindrical and hollow structure usually less than 100 nanometers in length, but may be much longer. Carbon nanotubes were discovered by the NEC Corporation in 1991. Nanotubes may consist of materials in addition to carbon, but the prototype for the nanotech building block remains the carbon nanotube (CNT), a hugely versatile object. The CNT is a tubular form of carbon with diameter of 1 nm and a variable length ranging from nanometers to microns. The cylindrical CNT is basically a layer of carbon atoms arranged as a sheet rolled into a tube. The CNT has special properties; it has extraordinary strength, nearly 100 times stronger than steel and is as stiff as a diamond with a tensile strength to 200 GPa. In addition, the CNT has a maximum strain that is 10% more than any other known material and a strength to weight ratio 500x more than aluminum.[6]

The electrical properties of nanotubes make them particularly interesting; the CNT can be metallic or semiconducting depending on chirality. (Chirality is a term reflecting variation in the number of layers and the direction in which they spiral.) The nanotube has a tunable bandgap and electrical properties which may be altered by application of a magnetic field or mechanical deformation. The conductivity of a CNT is 6 orders of magnitude higher than that of copper and with a very high current carrying capacity. Interestingly, the thermal conduction of a CNT is directional; it is much greater in the axial direction versus the radial direction and it far exceeds copper's ability to retain heat with almost no thermal leakage. The tubes can carry electrical charges at twice the speed of silicon circuits. Carbon nanotubes may allow the construction of three dimensional integrated circuits, something not possible with contemporary silicon technology.[7] All these unique properties make CNT especially valuable to the microelectronics and computer industries.

Buckyball

A buckyball, or fullerene, is named after Buckminster Fuller, a futurist and global thinker best known for the invention of the geodesic dome. The structure consists of 60 carbon atoms arranged in a sphere with a pattern of hexagons and pentagons similar to a soccer ball. The buckyball is hollow, but can be used to carry another material; the outside surface of the buckyball can also be coated. A buckyball is also a semiconductor and small enough to penetrate biomembranes ordinarily thought relatively impenetrable such as cell walls or the blood brain barrier. Given these unique properties, it is not surprising that buckyballs are source of great interest to engineers and pharmaceutical researchers. The discovery of the fullerene was important enough to earn Richard Smalley, Robert Curl and Sir Harold Kroto the 1985 Nobel Prize for chemistry.

Quantum dot

Quantum dots are nanoscale crystals made of a few hundred atoms. Their small size allows them to be inserted into cell and they can be used to trace biological changes in the cell. Quantum dots can be made from a variety of substances and can be designed to fluoresce in almost any color.

Although humans have always been exposed to nanoscale particles from forest fires or volcanic eruptions, the recent history of nanotechnology dates to 1959. In a December 1959 speech to the American Physical Society at the California Institute of Technology, Physicist Richard Feynman reports that the laws of physics, as he understood them, did not prohibit man from designing devices intended to move individual molecules.[8] The term nanotechnology was introduced by Norio Taniguchi in 1974 and taken to mean the very precise, indeed, the ultra precise, machining of materials on a molecular scale. Implied in this notion are the concepts of nanomeasurement and nanomanipulation, namely, the notion of manufacture on a molecular level. The goal of nanotechnology is described as the ability “to produce complex products on demand using simple raw materials”.[9]

The next milestone in the evolution of nanotechnology came in 1981: Binnig and Rohrer of the IBM Zurich Research Laboratory invented the scanning tunneling microscope (STM) for which they received the 1986 Nobel Prize in Physics. The STM allowed researchers to “see” materials on the atomic scale and led to the development of the atomic force microscope which allows the manipulation of nanoparticles on surfaces, i.e., nanoparticles could now be arranged to form structures.[10] The STM does not function like a conventional microscope. Visible light waves are too large to illuminate the details on a nanocoated surface; the STM employs a probe to feel the surface under examination and provide an image of the contours.

Five years later, in 1986 K. Eric Drexler published *Engines of Creation: The Coming Era of Nanotechnology*[11] in which he discusses a coming change in manufacturing methods and he visualizes molecular assemblers. The molecular assembler, as proposed, is a nanoscale device, basically a machine that would assemble other machines. In theory, given the raw materials, time and the proper instructions, the assembler could manufacture a vacuum cleaner or similar object in a few hours and with a minimum of energy and virtually no waste or pollution. Contrast this method of production with the current system of top down production in which requires an enormous source of raw materials, including a source of copper and iron ore, a coal mine, etc. and then to refine and process the raw materials to derive the components of the vacuum cleaner all the while using substantial amounts of energy[12] which produce excess heat and waste greenhouse gases. Drexler believed that the assemblers will build with molecular precision, using only the precise amounts of resources and energy required and avoiding virtually all pollution and with no adverse environmental impacts. This technique of manufacture was described as “bottom up” manufacture as opposed to the conventional methods which are described as “top down” manufacture. He suggested that nanotechnology may even enable man to colonize solar system and approach immortality. However, Drexler saw some potential danger with uncontrolled self replication of robots. There was some fear that self replicating nanorobots might escape and embark on a rampage of self replication with widespread and uncontrolled consumption of raw materials. This would lead to swarming waves of nanorobots forming a sort of “grey goo”. This fear was found unjustified based on considerations of energy requirements for the nanorobots.[13]

In 2000 the Clinton administration announced the National Nanotechnology Initiative (NNI) dramatically increasing the funding to the fledging industry in the United States. The initial budget for the NNI was $500 million.

The developmental path of nanotechnology was not entirely smooth. In 2001, Bill Joy, cofounder of Sun Microsystems, authored an article in *Wired* magazine titled “Why the Future Doesn’t Need Us”. The gist of his argument was that the rapid pace of progress in technology, particularly in genetics, robotics, and nanotechnology posed a threat to humans. In the article, Joy proposed that until demonstrably ethical standards are implemented to guide development of nanotechnology, there should be a moratorium on further studies. (Interestingly, he quotes Ted Kaczynski, the Unabomber, in his article.)

Nanotechnology reached the popular press in 2002 when Michael Crichton authored *Prey*, a novel whose plot revolves around out of control self replicating nanomachines; of course, the nanomachines are cast as villains.[14] Also in 2002, Roco and Bainbridge published a report *Converging Technologies for Improving Human Performance* in which they saw the convergence of four areas of research (science, bioscience and medicine, information technology and cognitive science); the resulting new discipline will become the body of knowledge for nanotechnology. They predicted that the new technology will lead to major improvements in social outcomes, human abilities, productivity, quality of life and overall environmental improvements over the next 20 years.

In early 2004, Drexler and Chris Phoenix withdrew their earlier concerns about self replicating robots, the so-called “grey goo”, and instead warned that nanotechnology lends itself to the development of new weapons systems that may lead to undesirable shifts in economic and political power, even beyond the shifts occurring with globalization. Nevertheless, Drexler favored aggressive development in nanotechnology.

A 1995 study by RAND (Max Nelson and Calvin Shipbaugh) suggested that nanotechnology may not have a certain future and hinted that nanotechnology may go the way of controlled nuclear fusion, i.e. a good idea on paper but either not capable of being harnessed or simply more difficult than anticipated. The authors proposed a number of hurdles that nanotechnology must overcome in the years after 1995 to demonstrate the technology’s viability: first, materials would have to be produced at the nanoscale and then processed into components. Second, the components would have to be connected and made to interface with the macroenvironment. Third, there must be the ability to control a massive number of nanodevices in a coordinated fashion. Finally, these devices would subsequently have to be powered. All but the last of these hurdles has been surpassed thus suggesting that the technology will demonstrate its viability as a discipline.

ENVIRONMENT, SAFETY AND OCCUPATIONAL HEALTH: RISKS AND BENEFITS

Harm and Risk

The nanotechnology revolution will come at a price. The adverse consequences we can foresee can be avoided; it is those adverse consequences we cannot see that will be the most troublesome. By definition, harm is the potential to cause damage while risk is the quantification of the possibility that harm will occur. Risk is further determined by the concentration of the suspect material in the environment (exposure) and the amount of the suspect substance that actually reaches a target organ (dose).[15] We will examine the risk harm and benefits of nanotechnology from the perspective of the environment, safety and then occupational health.

Environmental effects of nanotechnology

Nanotechnology should have a number of beneficial environmental effects. On a broad scale, as the technology develops, it is likely the production of green house gases will decline which may lead to an abatement of the global warming process. Because nanotechnology employs a bottom up manufacturing process, there will be a decrease in industrial waste, both in terms of wasted energy and solid waste production.

Nanotechnology will likely have specific environmental benefits. Nanodevices can be designed to cleanse specific contaminants from the environment. For example, it may be possible to design a nanomachine to seek out and encapsulate lead particles from the soil of a firing range thereby avoiding the need of a costly cleanup involving soil removal. Other nanodevices may allow the development of specific sensor devices to adjust fuel-air mixtures for maximum combustion and the detection of pollutants at minuscule levels. Similar devices may be used to clear areas of residual radioactivity.

Environmental Risks

If the knowledge of the risks of nanoparticles to humans can be described as sparse, the knowledge of the risks of the particles to the flora and fauna is virtually non existent. The application of nanoparticles to the soil or water sources, for example as fertilizers, may hold many unknown risks. Other important questions about the extent of bioaccumulation and persistence of nanoparticles remain to be answered. For example, are nanodevices any more or less biodegradable than current devices? We also know that as surface area increases, the rates of chemical reactions will also increase such that substances which are normally inert in normal forms become explosive as finely divided powders. How will the increased reactivity of nanomaterials affect the environment?

Global warming, not surprisingly, is a major consideration in new technologies. Nanotechnology may allow the manufacture of materials with less energy consumption and fewer waste gases, but the effect on global warming is yet to be determined. Current evidence suggests that nanotechnology may cause either warming or cooling of the atmosphere.[16]

Sustainability

Is nanotechnology sustainable? Sustainability is an important characteristic for any new technology. Sustainability may be thought of as the principle in which one generation does not rob a subsequent generation of vital resources or burden it with onerous waste. For example, the use of fossil fuels in the last century or so precludes subsequent generations from using the same fuel resources; fossil fuels are not sustainable. Similarly, nuclear power will burden future generations with the requirement that the waste products of nuclear power be safeguarded for thousands of years to come.[17]

Proof that nanotechnology, as a new innovation, is sustainable will be critical to its long term success, particularly given the time frame that the technology will break into popular consciousness. Predictably, just as nanotechnology becomes better known, the era of fossil fuels will be drawing to a close, probably with some inconvenience and economic turbulence. For Americans to accept nanotechnology, they will reasonably expect it to last longer than the fossil fuel era, in other words, responsible Americans will expect that a new technology be sustainable.

In general, there are four conditions required for a technology to be considered sustainable.[18] First, to the maximum extent possible, the technology must not rely on substances extracted from the ground. Nanotechnology will likely to be able to use established stockpiles of materials for production. As the technology matures, individual molecules will be used again and again as the need arises, thus the constant acquisition of new raw materials from the ground will be rendered unnecessary. The second condition requires that the technology not promote an increase in the waste products released into the environment. Nanotechnology, at least within the limits imposed by the Second Law of Thermodynamics, will minimize environmental contamination. Nanotechnology may be thought of as recycling on a molecular basis. Waste products less visible to the eye will be minimized as well; the amount of heat generated by processes on a nanoscale will be less by orders of magnitude compared to the heat byproducts now generated and released into the atmosphere. Third, sustainability also requires that a technology not degrade the environment by physical means, for example, restriction of water flow for power generation, or production of thermal pollution, etc. Here again, because nanotechnology emphasizes the assembly of products on a molecule by molecule basis, the degradation to the environment will be minimal. Fourth and finally, a sustainable technology is expected to meet human needs on a world wide basis. The current vision of nanotechnology holds that if advances in the technology are shared between nations and ethnic groups, all humans stand to benefit. Thus, by these measures it would seem that nanotechnology offers a sustainable process for new industries.[19]

Regulatory Authority

How can the risks of nanotechnology be identified and regulated? In discussing the risks associated with nanotechnology, it is important to recognize that substances which are thought to be harmless on a macroscale may take on noxious properties on a nanoscale; for example, chunks of coal are not explosive, but a mixture of coal dust and air is very explosive. It is also essential to differentiate between applications of materials on a nanoscale, for example, construction of memory chips, and the nanoscale substances themselves, such as carbon nanotubes. The fixed applications have a relatively low health risk, but the nanoscale powders may represent new sources of pathology. Although the general consensus is that for the most part nanotechnology does not represent new risk, the size of the particles does represent some dangers. For example, the threat posed by free floating nanoparticles is uncertain. Titanium dioxide is not toxic on a macroscale and is used as a white pigment in paints and cosmetics such as sunscreens, but as a nanosized particle, titanium dioxide can be harmful to cells.[20] Such particles may be absorbed through the skin or accumulate in environmental reservoirs. Since most people all ready inhale millions of nanosized particles each day in the form of diesel or exhaust fumes, individuals working with nanomaterials would be at greatest risk.

Another concern cited by observers of the technology is the aforementioned “grey goo”. This notion represents fear that nanomachines may be set loose in a frenzy of self replication soon extending across the countryside. Even Prince Charles has registered his concern about the possibility that the small devices may lead to a disaster reminiscent of the thalidomide debacle of two generations ago.[21]

Fortunately, this extreme scenario is now deemed impossible. Most researchers agree that the technology does not represent new or unique risks and can be subjected to existing regulations.[22] Nevertheless, the liberation of nanoparticles in the environment should be controlled until better understood. A reasonable approach to new nanomaterials would be to consider them as new chemicals and subject the materials to various safety checks to evaluate their potential for environmental harm.[23] Perhaps it will be necessary that research efforts be conducted in clean rooms.

At present the regulatory authority for nanomaterials is with the Environmental Protection Agency (EPA) although the Occupational Safety and Health Agency (OSHA) also have regulations which could be used to regulate the use of nanomaterials. The EPA has the authority to regulate substances with known or even suspected adverse properties under the Toxic Substances Control Act (TSCA). This legislation authorizes the EPA to regulate chemicals and materials not otherwise regulated by other agencies such as the Food and Drug Agency. The authority granted by the TSCA is extensive and includes market entry requirements as well as requirements for recordkeeping and adverse effect reporting and the EPA can apply these regulations regardless if nanomaterials are determined to be existing materials or “new materials”.[24] In any case the key issue of regulation will be to recognize potential or real risks and to communicate these risks to other agencies and to the public.

Safety Aspects of Nanotechnology

From our earliest existence, humans have always been exposed to nanoparticles. The air above the ocean contains nanocrystals of salt and combustion emits nanoparticles in smoke. These common nanoparticles have particular properties that render them safe for humans: the salt particles dissolve in body fluids and the nanoparticles present in smoke are relatively short lived since they tend to conglomerate and form larger particles which settle. The newer engineered nanoparticles will likely not have these benign properties.[25]

What are the safety risks of nanomaterials to human health? The answer to this question will require much closer cooperation between toxicologists, epidemiologists and pharmacologists than currently exists. Although the answer is not known at this time, we do have precedents, for example the adverse effects of quartz particles on various organs and the well known as is the sad history of lung damage to shipyard workers due to asbestos exposure. Notably, however, carbon nanotubes are significantly different from quartz particles of asbestos fibers since they are difficult to disperse in an aerosol form because they tend to form clumps. Indeed, the tendency of carbon nanotubes to clump represents an obstacle to their economic manufacture.

But the risks from nanoparticles are related to more than just their small size; it appears that the much greater surface area presented by nanoparticles amplifies the magnitude of their risk. For example, the toxicity of quartz crystals is known to be related to their large surface area and their propensity to form free radicals which damage cells.[26] In addition, toxicities are associated with the physical dimensions of the particle which may allow it to penetrate biomembranes and any coatings present on the particle's surface that may affect the reactivity and the solubility of the particle. Some workers in the nanotechnology field propose that nanomaterials be considered new substances and evaluated as such.

Occupational Health Aspects of Nanotechnology

The risks to the individual worker and soldier are best examined from the perspective of occupational health. Occupational health is best conceptualized as a process rather than a specific outcome and a successful occupational health program does not have a specific endpoint, rather it is defined as an absence of workplace health problems. Within the framework of the Army, the occupational health provider offers technical advice and support to the commander on issues related to the safety and health of the workplace. In doing so, the occupational health provider formulates policies, standards and procedures linked to reporting systems designed to limit and treat workplace related disabilities. In short, the occupational health team establishes and maintains the workplace with an eye to minimizing workplace health and safety hazards in order to enhance the productivity and well being of workers and soldiers.

Nanoparticles have also have a remarkable degree of mobility and nearly unrestricted access to the human body; some nanoparticles are known to cause inflammation in the respiratory tract leading to tissue damage much the same as the fine particles of silicon. In the intestinal tract, nanoparticles are known to accumulate in the liver and provoke immune and inflammatory responses. The long term effect of nanoparticle accumulation in the liver is uncertain, but it is likely to be associated with some damage.

The means of human contact with these substances will likely be via the transdermal, inhalation, or oral routes. The ability of nanoparticles to penetrate intact human skin is still uncertain. The evidence thus far is conflicting, some studies indicating that the particles can cross the dermal barrier and other studies finding the particles cannot.[27]

<u>Lungs</u>

There are at least three mechanisms postulated by which nanoparticles cause damage to human lungs. The first is related to the increased reactivity of the nanoparticle. The surface of the particle may simply react with adjacent tissue to form a new chemical entity. A second theory posits the formation of free radicals, molecular bodies with a charge making them highly reactive. This charged particle reacts or binds with normal tissues making larger charged particles which may eventually lead to abnormal cellular growth or tumor formation. The third mechanism suggests that the nanoparticles may reach the alveoli which are the microscopic sacs in which the exchange of oxygen and carbon dioxide takes place. The alveoli are protected by a class of cell called macrophages which may be thought of as cellular vacuum cleaners. It is an easy matter for large numbers nanoparticles to overwhelm the macrophages and thereby cause damage themselves or permit other pulmonary pathogens to cause damage without resistance by macrophages.[28]

Thus, there is still a great deal of research necessary to determine the magnitude of the threat of nanoparticles to the lungs. Studies in animals have shown some alarming results, however, the transferability of these findings to human beings is uncertain. For example, though nanoparticles can cause pulmonary damage to rats, the process of inhalation in humans is very different. Clearly animal studies alone cannot predict the risks of nanoparticles to human beings; in any case many of the industrial applications of nanomaterials will take place under vacuum conditions thus limiting aerosol spread.

At a minimum studies are required to measure exposure limits as well as studies to ascertain the damage done by nanoparticles to cell systems. Even the simple measurement of nanoparticles is a challenge since many of the particles are too small to be measured by existing devices. Undoubtedly, this research will require animal studies. Additionally, the ability of various filter materials to block nanoparticles must be determined.[29]

How long will it take to evaluate the potential for damage to the lungs posed by nanotechnology? It is not possible to offer a definite date, but it should be less than the one hundred or so years that passed from the time asbestos was identified by a British factory inspector as being a hazard to the ultimate ban of asbestos products by the European Union in 1998.[30]

<u>Ingestion</u>

As the use of nanomaterials increases, it is likely that nanoparticles will enter the food chain; what happens to nanoparticles that are ingested? These particles are absorbed in the intestines, often by specific lymphatic tissues. The nanoparticles are ultimately able to enter the bloodstream. Although the particles encounter macrophages which may absorb them, their small size allows the particles to be absorbed by other cells, for example, red blood cells. Because red blood cells have a finite life span, the particles, which are now coated by a protein marking them as foreign matter, are released again as the red cell is scavenged by normal body processes. Ultimately, the marked nanoparticles are sequestered in the liver or spleen where, as they accumulate, the extent of damage remains to be determined. Still other nanoparticles are excreted by the body by ordinary means.[31]

There are a number of ways that nanoparticles can enter the digestive tract, but the most likely method is via the food chain. Waterborne fullerenes have been shown to accumulate in fish. Dr. Eva Oberdorster at Southern Methodist University placed nanosized particles in a tank with fish. The fish were subsequently sacrificed and the nanoparticles were found in the brain and liver of the fish. Interestingly, Oberdorster found that some genes were turned on or off by the fullerenes. The applicability of theses findings to humans is uncertain, but certainly deserves study.[32]

Many questions about the effects of nanotechnology on humans remain to be answered; a number of employee and soldier issues are prominent; for example, how do the following factors impact on the ability to work in nanotechnology related fields? Because aging leads to a diminution in the body's immune system, will a worker's age affect the ability to resist nanoparticles? Will gender have an effect on the vulnerability to nanoparticles? Of course child bearing is limited to the female gender and the possibility of accumulation of nanoparticles in eggs or reproductive structures deserves further study.

Worker protection

The need for worker or soldier protection will be shaped by a number of factors. The nature of the work with the nanomaterials will be a major consideration. For example, will the work require exposure to free nanoparticles as from explosive materials or will the particles be affixed to a device such as a memory chip? Similarly, whether the process takes place in the open atmosphere or under a vacuum will help to determine the need for respiratory protection. The route of exposure will be considered; the consequences of dermal exposure versus respiratory exposure versus digestive system exposure will mandate different protective measures. The potential mechanisms of injury will be an issue; for example, what are the consequences of contaminating an open wound with nanomaterials? Perhaps one of the most important factors in shaping worker protective measures will be the establishment of baseline requirements for special training for workers and supervisors. The new processes involved in the applications of nanomaterials will necessitate new methods of production. Responsible agencies must also consider that chronic disabilities may develop over a prolonged period, thus worker protection may extend beyond the period of employment. Consider too that nanoparticles may be brought into the worker's home on clothing or equipment thus offering a potential exposure to family members. One of the most important components of the worker protective process will take place even before employment begins. It may be prudent to limit the exposure of individuals with certain diseases to nanomaterials. For example, persons with asthma or respiratory disease may not be good candidates to work in areas with any potential for exposure to airborne nanoparticles. Likewise, persons with pre existing liver disease probably should not risk ingestion of nanoparticles. Even age or gender may become a limiting factor in risking exposure to nanomaterials.

The primary method used to protect workers and soldiers from these hazards will be surveillance. In the context of occupational health, surveillance looks at the increased risk of a particular disease outcome in a population. Within the context of the Army's use of nanotechnology, surveillance would be used to identify new or recognized cases of occupational diseases not prevented by proper industrial hygiene. The target population for the surveillance effort would be both the civilian work force involved in the production, transport and storage of the materials and also the soldiers who will likely be the end users of the products in the field. In both populations, the surveillance efforts would have to extend for some term beyond the acute exposure in order to adequately assess the potential for late developing pathology. Of course, the key components of a surveillance program are adequate tracking of exposed individuals and record keeping. The National Institutes for Occupational Safety and Health (NIOSH) is in the process of preparing regulations for the management of nanomaterials; the initial regulations will likely be released in 2005.[33]

Regardless of the protective regulations promulgated, new means of protection will be necessary. Current personal air filtration technology is not effective against nano sized particles. Because the particles are so small, they can traverse the filter mechanism unhindered. Even water filtration technology is inadequate to trap the nanoparticles. New filtering methods for nanoparticles may rely on chemical or electrical reactivity of the particles.

<u>Prevalence</u>

Sensitivity the portion of afflicted persons in a group who are identified. A test with high sensitivity will identify more of the afflicted individuals. In addition to high sensitivity, a good screening test must have high specificity. Specificity is derived from the ability of the test to accurately identify individuals in the group who are not afflicted with the disease. Not surprisingly, a good monitoring test has both a high specificity and a high sensitivity. To insure adequate protection, it is likely that both biological monitors and toxicological screens will be necessary. Of course, the cost of the test will be of concern and should be measure against the potential costs of the harm the test is intended to prevent.

In the environment, safety and occupational health (ESOH) arena, nanotechnology holds great promise. Nanodevices will aid in temperature modulation and scavenge environmental contaminants. For example, nanodevices could be instructed to remove lead from contaminated soil. Other specially programmed devices could serve as locators, or detectors for fatigue, drug use or alcohol intoxication. The health applications for nanotechnology are enormous. Devices could be tailored to the needs of particular individuals and used to monitor personal exposure levels, warn of impending toxicity, etc. Similar devices could be implanted in at risk individuals to warn of incipient pathological conditions such as hypertension or diabetes.

Nanotechnology has great potential to expand computer memory. The current memory technology is based on ferroelectric random access memory (FRAM) which utilizes electric fields. FRAM is radiation susceptible, an obvious flaw for military and aerospace applications. Magnetic random access memory is nanotechnology based and is both radiation hardened and non volatile; it also allows increased memory capacity. Other nanotechnology based memory devices use carbon nanotubes to provide a radiation resistant, low power memory that is also high density and high speed. The nanotube based memory is also adaptable to a variety of memory applications which ordinarily require specifically designed chips.

SOCIETAL AND DEFENSE IMPLICATIONS OF NANOTECHNOLOGY

Societal implications

Just as the industrial revolution began with the mundane need to pump water out of coal mines, the initial applications of nanotechnology provide us with improved tennis balls and better cosmetics; like drier coal mines, these modest benefits are hardly the foundation stones of an historical shift. But just as the steam engine progressed to the internal combustion engine and then far beyond the needs of the coal industry to a society with unprecedented mobility, nanotechnology will have profound societal implications. At this point in time, any discussion of the societal implications of nanotechnology is purely speculative, however, if based on a set of assumptions described here, some likely outcomes may be predicted and speculative societal implications can be derived from the proposed outcomes.

Assumptions

There are a number of reasonable and realistic assumptions that can be made about the future success of nanotechnology. First, this scenario is looking up to 25 years and beyond in the future. It seems likely that this is a long enough interval to allow nanotechnology to advance to the point that nanoscale machines will be employed in a systematic fashion to construct atomically precise products at very low cost and with a minimum of waste material and with much less energy and extraneous heat. The machines, in aggregate, will be powerful and able to produce massive quantities of products at low cost, probably in the range of a dollar per pound, exclusive of development, legal, insurance, environmental, safety and marketing costs.[34] In essence, industrial society will reach a point where it will be possible to arrange atoms in an efficient and economic fashion limited only by the laws of nature. It is likely that there will be nanoscale actuators and sensors suitable for robots as well as artificial muscles.[35] It is probable that there will be some limitations to the nanodevices. Memory will be limited and energy carrying capacity will be limited as well. The devices will be able to respond to short messages.[36] It is also fair to assume that many of the major applications of nanotechnology will be to the improvement of human health and the environment.

The second assumption is that the governmental and regulatory environments will permit nanotechnology to develop with a minimum of hindrances. This may require an expedited patenting process, improved intellectual property laws and adequate insurance mechanisms. The current patent application process hinders development of rapidly advancing technologies. For example, an inventor may have an excellent idea, but before he can bring it into production he will seek venture capital funds. The venture capitalist will insist, not surprisingly, that the idea be patented before investing. Because the patent application process presently requires a long process, enough time may pass that the inventor’s concept is obsolete even before it comes into production. Adequate protection of intellectual property will be essential to the success of nanotechnology. Because nanoproducts will be quite inexpensive to produce, traditional notions of profit margins of up to 30% may be insufficient to justify investment. Further, since nanofactories are quite portable, theft of technology will likely be a deterrent to development. Strong intellectual property laws will insure that investors and inventors will benefit from their work.

The third assumption is that the public will accept nanotechnology. This is not a certainty as past experiences with technological improvements such as nuclear power or genetically modified food have shown. Nanotechnology has an advantage over these technologies however, in that nanotechnology will appear incrementally and will demonstrate obvious consumer benefits. In addition, researchers now understand that the public must have an input to the development of new technologies; perhaps the degree of public input should be guaranteed by law or public policy.

These assumptions are not farfetched. It is already possible to design proteins and enzymes; it will soon be possible to design proteins for specific purposes.[37] There are substantial costs involved in reaching this point in nanotechnology; however precedent exists for such expenses in such projects as the development of nuclear weapons or the Apollo moon landing effort.[38] Whether or not the pubic is willing to accept these costs remains to be seen. Both the Manhattan Project and the Apollo Moon Project had a significant impetus; for the Manhattan Project the impetus was propelled by a desire for decisive victory in the war; the Apollo Project was driven by the fear that the United States had fallen behind in the space race. Perhaps the impetus for the development of nanotechnology will be the diminution of sources of fossil fuels. Based on these assumptions, a number of outcomes are likely.[39] [40]

Nanotechnology will encourage the adoption of sustainable processes in industrial production; most of the world will enjoy a First World living standard. By employing highly specific catalysts and focused processing, nanotechnology will allow the production of products on an as needed basis. Because the fabrication can be widely distributed, products can be made at or near the point of use eliminating much of the transportation and storage infrastructure and associated costs. The use of molecular construction methods will blur the line between waste and resource; molecules can be used again and again obviating the need for mines and refineries.

The way in which a corporation derives profit will change. At present, a business creates or conceptualizes a product, gathers the raw material and manufactures the product via a labor intensive production process. At each step, and there are many, the value of the raw material is enhanced and the ultimate cost of the end product increases until the item is ready for retail sale.

Nanotechnology will change this process. The initial design process will be quite complicated and require extensive computing resources to derive the instructions for the nanomachines. Once the machines are designed and programmed, however, the process of making products will be quite automatic and fairly inexpensive (one estimate says that most manufactured goods will be sold by the pound). The present production methods for software provide a model of the process described. For example, the development process for Microsoft Word was long and expensive making the first copy of the program quite expensive, but the second copy of the program cost very little to produce. Because nanotechnology can produce subsequent copies of a product very cheaply, the value and importance of the intellectual property behind the original design will be dramatically increased.

This change in the intrinsic value of products will lead to increased friction between corporations and consumer in much the same way that the controversies surrounding the Napster case caused friction. In a similar fashion there will likely be frictions as traditional factory based manufacturers combine with their labor force to resist nanotechnology based industries.

Clean water will be widely available to the over 1 billion humans who do not have access to this resource. Filters based on nanotechnology will allow the cheap and on site production of potable water in vast quantities; even seawater will be treated made potable through low pressure nano based filter materials. As a result, disputes over water rights should diminish.

Information technology will be very widely available. As memory devices benefit from nanotechnology, the cost of memory will decrease and the size of devices will decrease dramatically. As a result, advanced information processing will become widely available. The access to information processing technology will help to enable third world nations to compete in the global marketplace.

Medical advances will allow the treatment of most infectious diseases and many more surgical conditions. In the short term, nanotechnology will provide improved drug delivery systems, for example, medications can be directly targeted to tumor locations. In the advanced state, nanodevices will be able to remove plaque from coronary arteries and other blood vessels thereby alleviating the leading cause of cardiovascular disease.

Global energy needs will be met, likely with some variant of solar energy provided at the point of use. With fuel cells using nanotechnology, it will be possible to provide energy via chemical processes minimizing thermal pollution and with much less air and noise pollution.

Off Earth resources will become accessible. The extraordinary strength and light weight of nanomaterials will allow dramatic decreases in vehicle and payload mass making near Earth explorations far less expensive. The notion of a space elevator rests on the development of nanofiber arrays capable of guiding satellites to a low earth orbit.

These outcomes, as described, will have important implications for society. The notion of resources will change. For example, because an atom can be recycled again and again, it will not be necessary to remove new raw materials from the soil; this property of nanotechnology will allow enormous strides toward the achievement of a sustainable economy. Areas with abundant strategic minerals, such as copper, tungsten or titanium, will no longer have an advantage over resource poor areas. In a literal and figurative sense, dirt will be as valuable as gold and regions now thought of as desolate will be on a par with resource rich areas.

We will find ourselves in a far more competitive world. National wealth will be less a function of location and conventional natural resources and more a reflection of the technological sophistication of an educated population. In essence, the economic playing field will be dramatically and suddenly leveled and many current national advantages will be zeroed out. Since the means of production can be widely distributed, the traditional advantages conveyed by geography will be minimized. The notion that areas such as the Ruhr Valley are industrial dynamos will be altered. Though access to capital markets will still be important, especially in the early stages of molecular manufacturing, the degree to which a nation displays initiative and will accept innovation will become the primary determinant of the nation's rank among nations.

The size of the population will stabilize or even shrink. As nations have moved from an agrarian to an industrial economy, population growth has stabilized, or in some areas, even reversed. The shift to a nanotechnology based economy will likely continue the trend. As a result, smaller populations may lead to smaller cities with populations susceptible to control measures through the use of nanotechnology based monitoring devices. There may even be competing notions of governance; for example, because nanotechnology will probably lead to a system of large industrial monopolies, population centers may be governed by for-profit corporate entities. Because molecular nanotechnology will decrease the number of manufacturing, transportation and warehousing jobs, life will be less labor intensive. This may, however, lead to fewer wage earners and thus fewer consumers. The structures of taxation may change and lead to novel methods of government finance.

Indeed, the very concept and role of government may be forced to change. In nations with an established history of popular government, the governing bodies may be able to respond to the changes in the industrial base with legislation designed to protect both individual rights and intellectual property. Because the technology will advance quickly, government must seek to avoid tensions and to shape anticipatory solutions. This will require attention to issues such as privacy and new forms of leisure. Significant support must be provided to the educational system to prepare the population for the new demands of a nanotechnology based economy. Because nanotechnology may provide dramatic economic benefits, the government must provide a mechanism to prevent abuse of wealth by industrial oligarchs. It is likely that displaced or unemployed workers will need an extensive social support system as well.

The protection of human rights is one of the most important functions of a government and nanotechnology has serious implications for the preservation of human rights. On the one hand, nanotechnology will help provide a safer society though the use of advanced monitoring and tracking technologies, but on the other hand, such techniques may have adverse consequences for the privacy of individuals. One of the major challenges confronting government will be the mediation between the right to privacy and the availability of sophisticated means of surveillance.

As nanotechnology narrows the differences between have and have not nations, ideology will assume a greater role as a source of cultural pride; depending on the nature of the ideology, extremist views may become more prominent to the point of becoming a nidus of conflict. For example, in Western nations, the traditional notion of personal responsibility leads to an internal locus of control, however, Islamic nations, in which a strong tradition of an external locus of control exists (e.g., the will of Allah), it is likely that the rules imposed on man by Allah's will will persist despite any benefit from nanotechnology. Nevertheless, the changes to the industrial base from nanotechnology will enable Islamic nations to compete with Western nations on a more level playing field. Such competition will highlight the competitions between ideologies as compared to the competitions between economies.

There are many issues nanotechnology will not mitigate. Regardless of the widespread use of nanotechnology and benefits it offers, notions of racial superiority will not be eliminated. Indeed, the leveling nature of the technology may accent the differences imposed by race or religion. Post World War I Germany had homogenous linguistic, cultural and economic conditions that transcended the lines drawn by religion, but the results of a notion of racial superiority are well known. It is not likely that nanotechnology will erase these fissures in society.

Similarly, nanotechnology probably will not eliminate territorial envy. Nations may harbor desires for adjacent territories based, for example, on historical events such as the Serbian desire to annex Kosovo long after the Battle of Kosovo or the Russian quest for warm water ports which can lead to hostilities even centuries later and despite the benefits brought by nanotechnology. Other sources of friction with the potential to lead to conflict include traditional transnational rivalries such as between the Koreans and Japanese or the Vietnamese and the Chinese. Even within the political borders of nations, nanotechnology will not eliminate ethnic conflicts as between the Hutus and Tutsis.

If nanotechnology results in a decreased interdependence between nations, the threshold for conflict may be lowered. Likewise, because production costs will decrease and products will be widely available, investors will want to insure adequate markets for products. This need for markets may provide an impetus for investor nations to seek to develop captive, or at least dependent, nations as markets. In the American colonial era, a similar predatory arrangement, dubbed Triangular Trade, helped contribute to the American Revolution; Great Britain and China became involved in the Opium Wars for a similar reason. Nations may find it necessary to use force to limit the spread or dissemination of dangerous or proprietary technologies; this may lead to preemptive conflicts. In any case, it is unlikely that the technological advances offered by nanotechnology will abate human self interest or ambition.

Nanotechnology may satisfy many human needs, but it is unlikely that it will satisfy all human wants. No matter how much food or how many possessions people have, they always seem to want more. Thus there will continue to be a drive to create newer, better, faster and more shiny things; thus a military force will continue to be necessary and may become more important.

Nanotechnology and National Defense

The current and future world security environments offer many challenges to the United States; some of the most formidable challenges will be found at the intersection of technology and radicalism; the magnitude of these challenges is only amplified by the increased mobility of modern society. Our recent successes and current technological domination must not be allowed to lull us into a sense of false security. The global proliferation of nanotechnology and nanotechnology based weapon systems will change the face of conflict and it is critical that our nation maintain its technological superiority. The effect of nanotechnology on weapons systems remains to be defined. On the one hand new and more destructive weapons are possible using nanodevices, but on the other hand, nanotechnology may make the production of conventional weapons so cheap, perhaps as little as a dollar per pound, that the threat will be derived from the massive production of traditional weapons.[41]

Nanotechnology represents both a challenge and an opportunity for the national defense. The National Military Strategy of the United States of America (2004) accurately notes that technology is one of the key determinants of the security environment particularly the diffusion of and ease of access to technology by potential adversaries of the United States and its allies. In response to the threats present in the national security environment, the document cites agility and integration as two of the principles guiding the development of the Joint Force as it seeks to attain its military objectives: protection of the United States against external attacks and aggression, prevention of conflict and surprise attack and to prevail against adversaries. To sustain and increase the existing military advantage held by the United States will require a transformation of traditional and parochial mindsets; this transformation will require a combination of technological, intellectual and cultural changes across the joint community.

Nanotechnology as a challenge

Nanotechnology may find fertile ground for growth at the intersection of radicalism and technology. Information about the developmental aspects of the technology is freely available in scientific journals, seminars, etc. and is available to various state and non-state adversaries. The methods for processing nanomaterials do not require the substantial infrastructure required to manufacture conventional weapons, thus nanotechnology is well suited to be an asymmetrical weapon. Indeed, nanotechnology may be more than just a breakthrough technology in the way that development of transistors allowed breakthroughs in the electronics industry; nanotechnology may be better described as leap ahead technology because the nations or organizations that dominate the technology in its developmental stages may come to dominate other entities with a lesser grasp of the technology. Because of its significance, nanotechnology must not be allowed to develop and to proliferate beyond our sight.

Applications of nanotechnology may threaten the United States with both disruptive and catastrophic challenges. The nature of the technology makes it virtually undetectable and it could be used, for example, to sabotage petroleum or food supplies. It readily lends itself to applications much like a silent but potent WMD against civilian population clusters or economic centers and it is not detectable through the usual means of detection for chemical or biological agents. As a new weapon against civilians, nanotechnology could have devastating and dramatic negative psychological effect on the American population.

Nanotechnology as a tactical threat

Consider this scenario: A column of soldiers moves through the close confines of a city. Because of the potential for hostilities, the soldiers are maintaining a MOPP level 2 posture and chemical detectors are deployed in the column. Suddenly from the surrounding rooftops, there are gunshots and a number of canisters are hurled off the roof tops. Within moments, portions of the column are enveloped in hazy cloud and within a minute or so the soldiers closest to the canisters are twitching and salivating uncontrollably and even those soldiers who were able to don their protective masks and gloves are showing the same symptoms. Soldiers from the rear of the column move forward having easily cleared the roof tops with automatic weapons fire in an effort to aid their comrades. Although the chemical agent detectors show no evidence of conventional chemical agents, they administer nerve agent antidotes in accordance with their training, but the victims worsen and quickly die. Within a few minutes, even the fully garbed soldiers find themselves salivating beyond control and trembling. Soon, they too are dead; the chemical agent detectors remain silent.

What happened here is but one possible result of nanotechnology harnessed to do the will of terrorists. Traditional chemical agents are largely prohibited by treaty or agreement and the precursors of traditional agents can be tracked. As nanotechnology advances, it will be possible to design materials that act like chemical agents, in this case a cholinesterase blocking agent, but are not classed as chemical agents under any existing protocol, do not trigger existing chemical agent detectors and in any case do not respond to known nerve agent antidotes and, because of their small size, can penetrate protective fabrics and even mask filters.

Centers for the development of nanotechnology are scattered around the world and are limited by the availability of local talent and access to information; consequently there is little to impede these centers for development. Wherever there is a confluence of expertise in biology, physics, and chemistry and information technology, there is the potential to advance nanotechnology. Thus academic centers, research facilities and commercial organizations, as well as interested individuals, can develop nanotechnology threats. Dual use technologies should be a special focus of concern, particularly in the areas of pharmaceuticals, information technology and high resolution imagery.

As an example of the development of nanotechnology in countries of interest to the United States, consider Iran. The *Teheran Times* reported recently that a center for nanotechnology was established in Isfahan province.[42] This is notable for a number of reasons. The Minister of Science, Research and Technology, Ja'far Towfiqi, claims that Iran is one of the world's leading nations in science and has budgeted, "Two hundred billion rials (approximately 25 million USD) for the development of nanotechnology, biotechnology and support of research…."[43] Even Iranian President Khatami included references to nanotechnology in his report to Ayatollah Ali Khamenei during his annual Government Week report of August 2004; the president claimed he had established a nanotechnology council under his own supervision 8-10 months before. The importance of a nanotechnology center in Isfahan is further highlighted by the fact that the city is the home of the Isfahan University of Technology and is suspected to be the focal point of much of Iran's defense and research industries. The city is also the site of the Iranian nuclear program.[44]

China represents another area in which advances in nanotechnology are of interest to the United States; not much is known about the Chinese effort. The Chinese are known to have an interest in post nuclear weapons and have established Project 863 which purportedly focuses on nano weapons. This project is thought to involve applications of nanotechnology designed to destroy or disable nuclear submarines. In addition, China has sponsored conferences on nanotechnology such as the one held in Beijing in November, 2002 with support from the People's Liberation Army General Equipment Detachment and the National Defense Science and Engineering Committee. A number of the presentations included discussions of molecular self assembly which is a key component of advanced nanotechnology.[45]

The existence of nanotechnology will require new methods of deterrence as well as new operational methods should deterrence fail. Intelligence systems must be able to identify hotbeds of nanotechnology research among our adversaries. At a minimum, it must be possible to detect advances in nanotechnology that may offer a threat, identify the origin and significance of the advances and track the spread of technological advances as they become known to researchers. Because it is an emerging technology, the goal must not be to simply catalogue current capabilities, but to create a time line projecting future developments.

Nanotechnology as an opportunity

Nanotechnology can help the United States maintain a decisive qualitative advantage in the application of will. As it develops, nanotechnology will find applications in a variety of force concept areas. Within the realm of force application, the technology will enhance the explosive force of conventional explosives. When combined with nuclear weapons, nanotechnology enables the design of much smaller devices which, combine with precision guided delivery systems, can find wider applicability on the battlefield; it may be conceivable that weapons developers may advance from back pack sized nuclear devices to cigarette carton sized devices.

Nanomaterials have particular value in protective applications. For example, current efforts are underway to design body armor which has the look and weight of ordinary uniform material but, when an electrical field is applied, becomes many times stiffer offering ballistic protection. Similar materials may have the ability to change color thus providing new methods of camouflage; even an illusion of invisibility may be possible. There are numerous possible applications of nanotechnology in the field of military medicine. Body sensors are envisioned which will permit the vital signs of individual soldiers to be tracked from a distance. The technology will offer new drug delivery systems as well. At some point the technology may be able to offer a generalized immune booster thus obviating the need for a series of immunizations prior to deployment. In a similar fashion, such an immune boosting agent may have the ability to resist biological and chemical agents designed by an adversary to circumvent conventional medical defenses. There is also great potential for nanotechnology to aid in the design of devices to detect hidden explosives, for example car bombs or improvised explosive devices.

Application of nanotechnology to the military logistics process will yield major benefits. Advances in nanotechnology will help to further miniaturize radiofrequency labels for materials; because the memory on chips constructed with nanotechnology is nonvolatile, the energy consumed by the radiofrequency labels will be minimized. Such labels will permit accurate tracking and stocking of supply items and will aid in just in time delivery to the end user. Advances in nanotechnology will also decrease the maintenance burden. New coatings will offer both better environmental protection and chemical agent resistance. Nanomaterials will offer superior lubricants and extend the useful life of machinery. There is an excellent possibility that nanotechnology will offer lighter and more energy efficient means to generate power in a wide range of settings from installations to tactical settings.

As an aid to battlefield awareness, nanotechnology will offer an unprecedented, and as yet hardly imagined, array of sensors. These will be very small, inexpensive and internally powered devices which can be spread across a battlefield by a variety of means such as artillery shells or unmanned aerial vehicles to offer early warning of an adversary's size, activity, capabilities and intentions. Such device could also be used in an unconventional or counter terrorism modality to track items or persons of interest.

When applied to command and control functions, nanotechnology may have its most immediate applicability. Within the visible technology horizon, nanotechnology will offer much smaller and more powerful communications devices and memory chips. Memory chips made with nanomaterials have the advantage of much denser and thus greater storage capacity and they also offer non volatile memory, thus the memory persists without consumption of electricity even when the device is not powered. The technology will offer the combatant commander a better view of his troop dispositions because the technology will enable much larger display screens with better resolution than now available.

Nanotechnology and the joint force

Two of the major principles of the Joint Force are agility and integration; nanotechnology will have a major impact on both of these concepts. Agility is defined in the National Defense Strategy as "the ability to rapidly deploy, employ, sustain and redeploy capabilities in geographically separated and environmentally diverse areas". As it develops, nanotechnology has the potential to greatly decrease the load carried by the soldier and the logistical tail needed to support a soldier in theatre. Within the foreseeable future, nanotechnology will help to miniaturize communications devices, make armor lighter and energy sources smaller and more powerful. A decrease in the load carried by the soldier will translate in faster movements both into and within theatres as well as fewer sorties and platforms required to move the force.

Integration is a concept which “focuses on fusing and synchronizing military operations among the Services”. Because nanotechnology is in an early stage of development, it will be possible for the Services, other governmental agencies and non governmental organizations (NGOs) to integrate nanotechnology in a seamless fashion across a wide variety of applications. For example, the development of individual communications devices may be standardized thus decreasing both per unit costs and the number of repair parts required. Because nanotechnology is in such an early stage of development, it still has the potential to be ““born joint,” i.e., conceptualized and designed with joint architecture and acquisition strategies.”

Indeed, because nanotechnology is at such an early stage of development and will have such wide applications, both in an out of the Armed Forces, the joint development of the technology for military applications may serve as a vehicle to advance the concepts of a joint force with expeditionary capabilities. Development of new command control and communications tools using a common derivation of nanotechnology will help to break down the cultural barriers between Services and offer a common ground for joint planning and operations.

Nanotechnology, as it develops and flourishes will change the way warfare is conducted in much the same way that gunpowder brought about the end of the era of edged weapons. Indeed, nanotechnology will offer national decision makers a wider range of responses. Our current military technology emphasizes destructive force. Advances in nanotechnology will provide a range of response options from total destruction to total control. For example, total destruction is well understood and may be obtained by conventional means but total control may be obtained by employing nanodevices which neutralize an opponent’s energy sources thereby freezing his communications and mobility.

A mastery of nanotechnology, both it threats and benefits, is a key to maintaining unchallenged military superiority; such mastery will require substantial investment. Unfortunately some experts believe that the United States is all ready under funding nanotechnology as compared to other nations and predict that our failure to provide adequate funding will result in a loss of U.S. defense and economic leadership over the next 20 years.[46]

Another proposed role for nanotechnology in weapons development is in fourth generation nuclear weapons. These explosives employ inertial confinement fusion methodology to create weapons with yields ranging from a fraction of a ton to tens of tons. When delivered by a precision guided device, such weapons will have devastation effects combined with comparatively small size and almost no fallout.[47]

Current Army effort

The current Army effort in nanotechnology is focused at the Institute for Soldier Nanotechnologies (ISN) housed at the Massachusetts Institute of Technology. The ISN was established in 2002 by a five year 50 million dollar contract from the United States Army and its primary goal is to create a “21st century battle suit” intended to enhance soldier survivability. A key goal of the program is to use nanoscale devices to decrease the weight of the soldier's equipment. For example, one concept under investigation is "dynamic armor"; a fabric containing nanomaterials is made many times stiffer when an electrical current is applied. Such a fabric could be used to offer body armor on demand or as an instant splint for an injured extremity. The institute uses a team approach to examine a wide range of projects. One team investigates energy absorbing materials while another team looks at mechanically active materials and another team examines sensing and counteraction devices.[48]

The notion of a 21st century battle suit is part of the Army's effort to transform itself into a campaign quality force capable of deploying with much greater agility; nanotechnology is seen as offering dramatic improvement in the mobility of the individual soldier and small units. In particular, the ability of nanomaterials to shrink the volume and weight of a soldier's equipment will aid in the rapidity of deployment.

What are the next steps? Nanotechnology will likely cause major changes in the social, economic and political dynamics of the United States. The magnitude of these changes will mandate a national strategy as well as an Army strategy to insure a smooth transition to a new technology.

One of the keys steps in a national strategy will be the development of the educational resources needed to support a nanotechnology industry to include basic educational skills and specific technical training programs. Unfortunately, the number of American graduates with advanced scientific degrees is dwindling while the numbers of PhD prepared foreign graduates from American universities is increasing. Attainment of an adequate number of graduates in the scientific disciplines may require commitment to scientific education analogous to the commitment seen in the United States after the launch of the Sputnik.

A flourishing nanotechnology industry will bring a great deal of wealth to an as yet to be determined number of people. As the industry develops in the United States, efforts must be made to insure that the benefits of the technology are shared by all citizens. Major social disruptions were seen as the industrial revolution advanced; such disruptions may occur as nanotechnology advances. To the extent that society is capable of learning from past experiences, we should strive to see a more equitable distribution of the wealth created by nanotechnology.

An Army strategy will develop as an outgrowth to the national strategy, but the Army strategy will be oriented toward the application of nanotechnology to military purposes. Predictably, since the Army draws from the civilian populace, Army strategies will spill over into the civilian concepts about nanotechnology and thereby help to shape the expectations of Americans regarding the technology. The Army's strategy must be keyed to both tangible milestones as the technology evolves and to the important goal of establishing nanotechnology as a sustainable process.

Reasonable and tangible milestones for the development of the technology could be based on the criteria of the National Institute of Nanotechnology (Canada). At first, simply the assembly of devices on a liquid surface would be achieved, and then followed by the application of a power source, perhaps derived from ATP or some other chemical source.

Subsequently, it would be reasonable to expect that the nanodevice be able to recognize changes in its surroundings. An advanced device should be able to perform specific elective functions as determined by a user.[49] These are not intended to be all inclusive milestones, but are examples to demonstrate how progress in nanotechnology could be monitored.

An implementation strategy for nanotechnology

Because nanotechnology represents a new and dramatically different approach to manufacturing and utilization, it would behoove the Army to enlist public support from the earliest possible time. To the maximum extent possible, an effort should be made to involve stakeholders to avoid issues similar to the lingering and unsubstantiated concerns surrounding genetically modified foods. Thus, the Army should encourage citizen participation in the development of nanotechnology for military applications.

Army acquisition strategy, through the Acquisition, Logistics and Technology infrastructure can be used to shape the development of nanotechnology in a manner both protective of the worker and soldier as well as protective of the environment. The Army Environmental Policy Institute (AEPI) can provide guidance and oversight of the safety and environmental aspects of the acquisition requirements and process.

The Army, and specifically AEPI, can influence the progress of nanotechnology through a carefully crafted acquisition strategy. For example, the Army can demand high standards for testing new materials. Developmental shortcuts may be tempting, but the goal must be the safe advancement of the technology without the lingering environmental disasters that were experienced with the manufacture of nuclear weapons. Similarly, the Army must insist that contractors must comply with the recognized best practices in the nanotechnology industry.

WHAT LIES AHEAD: PREDICTIONS

There is a great deal that remains to be learned about nanotechnology. Because the materials have new and rather different properties, a whole new set of manufacturing challenges will emerge. It will require time, effort and funding to resolve these challenges. Particular areas of challenge include the ability to control nanodevices from the macroworld as well as the altered nature of physics when the surface to volume ratio of material is changed to the nanoscale.[50]

Our competitors, both nations and NGOs will continue to develop nanotechnology; regardless of the ethical implications of nanotechnology, the technology will progress; for example, hundreds of tons of nanomaterials were synthesized in the United States in 2003 and within a decade, the market in these materials is predicted to exceed $1 trillion.[51]

Because the basic elements to initiate a nanotechnology research program are relatively simple and because the world's economy is becoming increasingly globalized, nanotechnology will develop simultaneously in a number of different locations and in a number of different directions. This will make it difficult to monitor developments in the technology and will make it especially difficult to detect efforts to weaponize the technology. Nevertheless, it is vital that the potential for harm from nanotechnology be identified and tracked. Additionally, it is essential that links between research and development nodes with a nanotechnology focus and manufacturing facilities be carefully monitored.

Nanotechnology will cause major changes in our way of life. In the same way that nighttime progresses through dawn to daylight, the changes wrought by nanotechnology will be gradual.

It is inevitable that nanotechnology will be weaponized and employed against the United States. The form that the employment will take remains to be defined, but nanotechnology will offer radical new changes in the way in which we wage war at both the strategic and tactical levels. The changes could include effects identical to recognized chemical weapons or small nuclear weapons or attacks on food supplies or even devices to attack particular age groups or populations. It will be necessary for the United States to develop countermeasures to nano weapons.

RECOMMENDATIONS

The Army leadership should develop a specific focus on nanotechnology. Because the technology has uniquely transdisciplinary characteristics, the observers must be prepared to incorporate principle of chemistry, physics, biology, computer science and ethics as the technology matures. In particular, the effort should take pains to distinguish the real applications of the technology from the imaginary. For now, anyone who delves into the potential of nanotechnology must assume that they don't know what they don't know.

a. The Army should develop a specific focus on the implications of nanotechnology for land warfare. The development of such a focus will likely require the input from a variety of disciplines including electrical engineering, biomedical engineering, and environmental sciences. The potential use of nanomaterials by opposing forces must be a clear interest.

b. There should be continued research on the ESOH effects on nanomaterials on the soldier and his/her environment. Particular attention should be paid to the biological effects of nanomaterials, both beneficial and harmful. The continued research in nanotechnology must be seen favorably by the public. There is a danger that the pubic may misperceive and exaggerate the risk of the technology such that nanotechnology is viewed as a fatally flawed technology such as genetically modified foods or nuclear power.[52]

c. There should be the identification of the predictable consequences and an effort to uncover the unintended consequences of nanotechnology.[53]

(1) Special attention must be given to aspects of the technology which may impact public health and the environment.

(2) Within the workplace, the Army must promote the recognized best practices of the industry in terms of risk assessment and environmental safety and security.

(3) Careful surveillance of the nanotechnology workplace to identify known and new forms of occupational diseases; in particular efforts should be made to gather data on worker and soldier exposure, toxicology and dose response.

(4) The Army should cooperate with other stakeholders in the development of standardized risk assessment tools and appropriate regulations.

(5) To the maximum extent possible, the Army should strive to minimize the production and release of nanoparticles into the environment.

d. Determine if nanomachines are chemical weapons under the provisions of the Chemical Weapons Convention.

e. Include the applications of nanotechnology in the war gaming scenarios used to train Army leaders.

CONCLUSION

The evolution of nanotechnology from concept to ordinary reality includes many uncertainties which will require study and preparation. Future researchers will explore in much greater detail the changes nanotechnology will bring to areas such as energy, space travel, health care, models of government and commerce as well as the art of war.

New technologies periodically reshape the world. Of itself, technology is neither good nor evil, rather the impact of the technology on human history is determined by the manner in which the technology is designed and applied. Just as gunpowder spelled the end of feudalism and improved navigational instruments made possible the age of exploration, nanotechnology will bring about a new revolution in industrial processes and military hardware. Our challenge is to prepare for the revolution to insure the safety, health and preeminence of our Nation and its Armed Forces.

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