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Military, Arms Control, and Security Aspects of Nanotechnology

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Abstract. We consider the social impact of nanotechnology (NT) from the point of view of its military applications and their implications for security and arms control. Several applications are likely to bring dangers – to arms-control treaties, humanitarian law, military stability, or civil society. To avoid such dangers, we propose some approaches to nanotechnology arms control.

Introduction

The announcement of the US National Nanotechnology Initiative and its counterparts in other countries has been accompanied by expressions of concern about ethical, legal and social implications, and some allotment of funding to address them, but concerns arising from military uses of nanotechnology, presumably in the service of national security, have been largely left out of the working definition of "societal and ethical implications". From the perspective of international security and arms control analysis it appears that systematic study by scholars in the hard and social sciences has hardly begun, with only a few scholarly articles published.[1] This is curious, since the parallel popular discourse on nanotechnology (NT) has not failed to notice that promises made for the possibilities of NT would in practice have profound implications for military affairs as well as relations between nations and thinking about war and international security. Superweapons made possible by nanotechnology are stock items by now in science fiction, and to some extent that literature has already begun to explore the technical logic to see where NT may lead us.[2] Military writers have also taken note of these emerging ideas,[3] while in the USA the military enthusiastically spends one quarter to one third of all Federal nanotechnology research and development funds, and its visionary powerpoint artists portray a future of nano-enabled supersoldiers fighting on nanotech battlefields.

Here we try to consider the impact of evolving and possibly disruptive military NT applications within the context of history, conflict, international security and world order. The international community seeks to avoid war through a variety of mechanisms, including military deterrence, international organizations and treaties, arms control and disarmament. These mechanisms are created and evolve in a changing technological environment. Arms control in the past has included restrictions on new or emerging military technologies. Today, emerging military NT applications and their consequences need to be analyzed. We advocate preventive arms control where one can identify specific negative impacts which may be subject to feasible controls.

1. General Aspects of War and Peace

Throughout history, improved technology has provided advantages in battle. In the 20th century, science and technology became tightly integrated with the system for waging and preparing war. Following the Second World War, military research and development (R&D) continued to expand, in particular in the USA and USSR. The 1950s to 1970s, roughly, marked the era of "big science" – big in budget and in physical scale, while often in pursuit of control over the very small. Nuclear bombs, nuclear-driven submarines, long-range ballistic missiles, and orbiting satellites mark some of the important milestones in the qualitative and quantitative arms race of the Cold War – achieved at extremely high cost and effort.

Even though the Cold War is over, military threats are still at work as instruments of geopolitical will as well as the basic mechanisms of national and international security. Nuclear deterrence is a doctrine still in effect, and thus nuclear war could still start at any time, although this may be improbable. Despite massive reductions (from a high of 65,000 in 1986), there remain about 20,000 nuclear warheads on Earth.

The experience of the World Wars has led to a fundamental change in international law. Through the centuries, states assumed a natural right to go to war – for whatever reason or purpose. With the founding of the UN and the acceptance of its Charter in 1945, maintaining international peace and security became the central imperative (Art. 1). The use of force and threat to use force in international relations were forbidden (Art. 2), with few exceptions: one is force legitimized by the UN Security Council to restore peace and security (Chapter VII, Art. 39-51), and the other is in self-defense until the Security Council has taken its measures (Art. 51).[4]

The security mechanisms foreseen in the UN Charter were hardly implemented, and nuclear war after 1945 was not prevented by adherence to its articles, but rather by the threat of mutual annihilation. Yet the norm established in the UN Charter has had strong effects on the international community. Wars waged since 1945 have usually been claimed to be defensive, and when such claims have been rejected the offending power has often come under collective pressure to cease or restrain its aggression.

Of course, the principle of refraining from the use of force except in self-defense is severely endangered if preventive wars are being waged based on perceptions of threats, not on actual aggression. Thus, we believe the 2003 US war against Iraq has weakened the UN and the international mechanisms of maintaining and restoring peace and security.

When armed conflict occurs, regardless of whether it constitutes legitimate or illegitimate use of force according to the UN Charter, the warring parties are limited in their choice of means and methods of warfare by international humanitarian law, which consists of basic as well as specific rules, often written down in international agreements, which evolve over time. Many rules have become customary international law and are binding for all parties to a conflict; this holds, *e.g.*, for the principle of attacking only military targets or of humane treatment of combatants *hors de combat*. Some rules are only obligatory for the respective signatory parties, *e.g.*, the Additional Protocol 2 to the Geneva Conventions of 1949 on non-international armed conflict. Before introducing a new weapon, means or method of warfare, the states are obliged to check whether its employment would be prohibited by international law.[5]

2. New Military Technologies

The purpose of armed forces is to break the will of an organized opponent by violent force. Who will prevail depends to some extent on comparative recklessness. Thus, war and the preparations for it do not only go beyond civilized behavior, but carry an inherent tendency to transcend all other rules, including the ones applying to armed conflict.

Innovation in military technology can become an extension of warfare itself. Being ahead in technology provides an important advantage in armed conflict, and if the lead position is not attainable, then one should at least stay as close as possible behind. Thus, all potential opponents have constant strong motives for military research and development and for incorporating their results into the armed forces. Secrecy and worst-case assumptions – both to some extent necessary elements of military preparation – increase these motives.[6]

Military applications of new technologies take place in a framework that is quite different from civilian ones: the bad and ugly uses are not results of accidents or criminal actions – they are prepared in an organized way on a large scale by and with the resources of the state. A special problem arises here: states have to reckon with an opponent using any means at hand. If technology allows new, more effective weapons, they might be used – even if they violate the law of warfare. In order to protect oneself, one needs to know the characteristics of the new weapon; this creates a motive to research and develop the new weapon oneself – which, in turn, creates mistrust and fear between potential opponents.[7] An example of this mechanism can be seen in the debate regarding biological-weapons – what constitutes legitimate defensive research, and where does forbidden development of biological-warfare agents begin?[8]

Of course, the economic capacity of the state limits its pursuit of weapons, and limitation is also possible by political decision. Self-restraint may be exercised in respect of national or international public opinion. Limits are also implied by the international law of warfare. Finally, potential opponents may agree on mutual limitations (arms control). In general, for these to be effective, there need to be reliable ways of verifying compliance.

3. Arms Control and Disarmament

Despite the nuclear threat that loomed throughout the 1950s, limitation talks between the Cold War antagonists were unsuccessful until the experience of the Cuban missile crisis (1962) when nuclear war seemed imminent. Real progress in arms control started with the Partial Test Ban Treaty in 1963. Important multilateral treaties that followed included the Outer Space Treaty (1967) and the Nuclear Non-Proliferation Treaty (1968). Political relations between the USA and the USSR improved enough to permit the bilateral Anti-Ballistic Missile (ABM) Treaty and SALT I (1972), later SALT II (1979). Another tense period of confrontation and impasse in bilateral arms control followed, until the Soviet approach changed under Gorbachev, leading to the INF and START I Treaties (1987/1991).[9] Full disarmament, that is reduction to zero, was agreed for biological weapons (1972, multilateral), and chemical weapons (1993, multilateral).[10] Nuclear test explosions (1996), and anti-personnel land mines (1997) have also been banned. These agreements have been mostly successful, despite the lack of full participation by all relevant powers, and despite some serious violations which have been detected and exposed – most notably with respect to the Biological Weapons Convention which was implemented without provisions for verification, inviting contempt.[11] General and complete disarmament (all countries, all armaments and armed forces) has been the declared goal of the UN and was mentioned in several arms-control treaties,[12] but this goal has not been seriously pursued in actual policy.

Arms control must be considered an unfinished project, and important gaps remain: there is no ban on nuclear weapons, there is no prohibition on space weapons (except for weapons of mass destruction deployed in space), and limitations on conventional arms and forces exist only in Europe. Recently, arms control and humanitarian law have become endangered by actions of the USA. Even before Sept. 11, 2001 the US refused to ratify the

Comprehensive Test Ban Treaty and blocked the negotiations on a Verification Protocol to the Biological Weapons Convention. Recently there have been moves towards easier resumption of nuclear tests. In 2002, the USA abrogated the ABM Treaty. The US has also systematically sought to undermine the International Criminal Court that was instituted by the international community.

4. Preventive Arms Control

Preventive arms control is qualitative arms control applied to the future; it is about stopping or at least limiting dangerous military developments before they become actual, in particular weapons exploiting or based on new technologies. Limitations can be designed to intervene at the stages of development or testing, or sometimes research. Precedents include: i) the ABM Treaty, which prohibited not only deployment, but also development of anti-ballistic missile systems that are sea-based, air-based, space-based or mobile land-based; ii) the nuclear testing treaties, which preclude certain experiments with actual nuclear explosions; and iii), the Protocol on Blinding Laser Weapons (1995), which explicitly bans only the use of blinding lasers but led to halting their development.

Preventive arms control assesses a potential new military technology using several criteria. One group of criteria concerns dangers to arms control and the international law of warfare: will the new technology undermine existing controls, law and norms? Another set of criteria concerns stability: will the new technology destabilize the military situation, *e.g.*, by reducing reaction times? Will it lead to a technological arms race? How about proliferation, in particular to regions with high probability of conflict? Finally, one needs to consider unintended hazards to humans, society or the environment.

If there are good arguments for restricting a particular technology, then one needs to take into account any positive uses – in particular in the civilian realm – and if possible devise rules that exclude the negative applications without overly restricting the positive ones. Methods for verifying compliance also have to be thought out – they must provide assurance that illegal activity would be detected, but must not be too intrusive or too burdensome.

5. Military Nanotechnology

Nanotechnology will change many aspects of our lives. Powerful computers will be ubiquitous. With the advance of artificial intelligence, the replacement of human labor by artificial systems will accelerate. New materials will lead to higher energy efficiency. Therapeutic drugs will be designed for the individual. Along with opportunities, there are also potential risks, be it to health, the environment, social justice or privacy. Convergence of nanoscale, biomedical, information, and cognitive science and technology (NBIC) can lead to applications with profound impacts on the human condition. The 2001/2 U.S. workshop on NBIC convergence mentioned, *e.g.*, nano-implant devices, slowing down or reversing aging, direct brain-machine interfaces, human-like artificial intelligence.[13] These and other far-reaching concepts of manipulating the human body and mind imply risks and dangers, as well as ethical challenges, on an unprecedented scale. Containing abuse and unintended consequences will be difficult even in the civilian realm.

Military NT applications pose special risks – first, because of the preparations for destructive uses and second because of secrecy. Tackling this problem calls for special efforts. In order to provide reliable information, one can look at actual military NT research and development in the USA, which is both the leader in military NT and also much more transparent about its military research and development than any other country. In addition, one can extrapolate scientific-technical advances and assess what military applications will become possible in principle.

5.1 Military NT R&D in the USA

In the USA, military research and development in nanotechnology (NT) has surged. Of the funds for the National Nanotechnology Initiative, one quarter to one third goes to the Department of Defense – in 2003, $ 243 million of $ 774 million.[14] This is far more than any other country – the UK expenditures, for example, were stated as about $ 2.6 million in 2001.[15] Assuming total West European funding five times as high, with similar levels respectively for Russia, China and the remaining countries that are active in military NT R&D, the US expenditure would be five times the sum of all the rest of the world. (In military R&D at large, the USA accounts for two thirds of the global total.)[16]

U.S. work spans a wide range in the spectrum from basic research to advanced technology development – development of actual systems for deployment is still several to many years off. University research grants fund nanoscale machines, carbon nanotubes, quantum computing and magnetic nanoparticles. The Defense Advanced Projects Agency funds projects in magnetic memory, bio-computing, bio-molecular motors, sensors for chemical and biological warfare agents, and micro robots, among many others. The research laboratories of the armed services work on self-assembly of nanostructures, organic light-emitting diodes, carbon nanotubes and composites, nanomaterials for explosives and propellants as well as for armor and projectiles, and many similar topics.

In 2002, the Army selected the Massachusetts Institute of Technology to house an Institute for Soldier Nanotechnologies, with up to 150 staff to work in seven multidisciplinary research teams. Their goals include a battle suit that protects against bullets, chemical and biological agents, and stiffens on demand to act as compress or splint. Sensors are to monitor the body status. For carrying heavy loads, an exoskeleton with "muscles" from artificial molecules is envisaged.

5.2 Potential Military Applications of NT

In general, NT can lead to improvements in traditional military systems and to qualitatively new ones. Very small but highly capable computers will be used in weapons, uniforms, logistics, and communication systems. Increasingly sophisticated and discriminating sensors may become very small, and cheap enough that they can be scattered in high numbers to saturate an area, ostensibly yielding "total awareness". Guns will shoot farther, projectiles and missiles with cheap guidance systems will become smaller and more accurate. Vehicles will become lighter and more agile, with more powerful engines and greater range. Energy storage is a key problem for many military systems, and NT is often considered a key to solving it. Autonomous vehicles (robots) for reconnaissance and communication, but also for fighting, will arrive; some of them may be very small. NT ultimately raises the prospect of even microscopic mobile robots, although macroscopic vehicles are needed for high speed or long distance travel. Sophisticated fighting robots, the successor to today's killer drones and prototype robot combat planes (UCAVs), will be enabled by advanced computers, smart materials, advanced energy and propulsion systems, and other NT-based refinements. Similarly, NT will contribute to lowering the cost and increasing the capability of space systems, including possibly very small antisatellite weapons. Robotics will be used in logistics, production and automation of complex weapons systems. A key enabler of robotics applications will be advanced computers capable of situation assessment and action planning, for example the motion planning needed to coordinate dextrous manipulators, or to maneuver through "battlespace".

New chemical or biological warfare (CBW) agents may become possible that act selectively only against the intended targets. Nanobiotechnology is ambitious enough to propose robotized artificial microbes, which could become tools of assassination or mass murder. At the same time, nanomaterials for filtration and neutralization, and NT-based sensors and nanomedicine in general may provide new approaches to CBW defense. Advances in biocompatible materials and portable biomedical systems may allow the creation of body implants to monitor health status, release drugs or interface to the nerves and brains of fighters. Their portable computers may evolve into wearable information appliances producing an "augmented reality" which simultaneously gives the fighter access to information from the net and also gives command access to the soldier, placing her under some degree of "remote control". The tendency toward cyborgization follows directly from such military goals and culminates in the vision of direct brain-technology interfaces, but the possibility of improving in this way on the performance of well-trained human senses and bodies, whether for fighting or for piloting or for thinking interactively, seems remote.

NT can be used in enhanced versions of existing nuclear weapons incorporating improvements to safety, reliability, etc., or possibly new types of conventional explosive in the fission primary. More speculative concepts include qualitatively new weapon types such as pure-fusion explosives of arbitrarily small yield. It is hard to predict how NT advances may impact nuclear weapons production and barriers to proliferation, but we have seen substantial advances in these technologies since 1945 and further improvement seems possible.

Scenarios along these lines, of more or less visionary character, are being discussed within the military and national security establishments of the world, particularly the USA, but many of these concepts will not prove militarily effective, as has been the case throughout history. Countermeasures to NT weapons will exploit NT as well, giving rise to complicated correlations of forces and complex arsenals within which unexpected interactions can arise.

6. Preliminary Assessment

When considering the various potential military NT applications under criteria of preventive arms control, one finds several that will be close to civil uses, such as small, fast, distributed computers or strong, light-weight structural materials. A few uses could help to protect against terrorism or would act mostly defensively. Examples are sensors and decontamination agents for biological weapons or improved injury care. Preventive limitation would be unrealistic or counterproductive in such areas.

However, there are several potential military applications of NT and/or NBIC at large that raise serious concerns under criteria of preventive arms control. In the medium term, the most dangerous ones involve:

- New selective chemical or biological warfare agents: These would violate the existing conventions, while posing new challenges to verification; they could be used either as weapons of mass destruction or for targeted assassinations, not only by armed forces but also by terrorists.
- Autonomous fighting systems – robots and robotic vehicles on land, in water or air: They would violate the international law of warfare if they would produce superfluous injury or could not recognize non-combatants or combatants *hors de combat*. Autonomous tanks or combat aircraft considered outside of the definitions of the Treaty on Conventional Armed Forces in Europe could undermine and endanger that treaty. Small satellites capable or attacking other satellites by direct hit or by manipulation after docking would destabilize the situation in outer space – not without consequences on Earth.

- Mini-/micro-sensors and -robots, including biological/artificial hybrids: They could be pre-deployed covertly in an opponent's territory to strike at an appointed time or on command, or to guide other weapons. If such devices are produced at low cost in large numbers, diffusion to other countries and to criminals is probable, creating the possibility of their use in asymmetric warfare or terrorist attacks.
- Body manipulation including implants: Under the imperative of combat efficiency, armed forces may more readily explore new possibilities for body manipulation than civilian society. Soldiers might voluntarily, or maybe under some pressure, accept risky or ethically questionable technologies that modify body chemistry, rewire brain, nerve and muscle, or otherwise radically alter the human organism. This could create "facts" and circumvent barriers in civilian society, preempting a thorough debate on benefits, risks, ethical aspects and needs for regulation.

7. Recommendation for Preventive Arms Control

These dangers can be contained by preventive arms control. Regulation need not focus on NT as such, but should take a wide view and address military mission areas. In many cases, the dangerous NT uses come under the headings of general agreements that exist already or that the international community has long asked for. In concrete terms, we recommend:

- The existing arms control and disarmament treaties that are in force as well as humanitarian international law should be respected and preserved. The Biological Weapons Convention should be augmented by a Verification Protocol.
- A general ban on space weapons should be adopted, with special rules for small satellites.
- There should be limits on military autonomous vehicles and robots, in particular with a combat function. Particularly important is a ban on autonomous killing.
- Small mobile systems should be mostly prohibited in the military as well as in civilian society, with very few exceptions (*e.g.* for search of collapsed buildings).
- Implants and other body manipulations that are not motivated by a direct medical condition should be subject to a renewable moratorium of ten years' duration.

For consistency and completeness, all rules for the military need to be coordinated with the regulation that is to be developed for the civilian realm.

8. Aspects of Molecular Nanotechnology

Particularly dramatic issues are posed by the vision of "molecular" or "machine phase" nanotechnology (MNT) as conceived by Drexler, Merkle and others.[17] In this vision, complex systems would be structured, like living systems, from the nanoscale up. Using tough materials and machinelike principles not found in naturally evolved organisms, they could manufacture products from molecular components in lifelike processes similar to growth and self-replication. The products of such a technology would have performance characteristics far beyond what is achievable today. For example, these might utilize carbon materials with fully-integrated nanostructure and nanosystems. Artificial intelligence supported by MNT hardware should easily surpass human capabilities and could be used to direct the production and use of MNT systems without requiring human supervision.

Realization of this vision would create extreme dangers under all the criteria of preventive arms control, with the greatest problems arising from the potential for an arms race using autonomous production, and destabilization by pressures to attack first.[18] The first task in addressing this area is to provide reliable assessments of the feasibility and time frame to develop the technology. MNT proponents have suggested that their vision could be realized in as little as a few decades. If this turns out to be a realistic possibility, the regulation, including international preventive arms control, needs to be developed well in advance.[19]

9. Topics for Further Research

Concrete interdisciplinary investigations in the coming years should examine military NT programs in several countries, including the USA, potential opponents (NT-capable as well as threshold countries), U.S. partners and friends. This should be done with a view to building cooperation and avoiding exaggerated perceptions as motives for NT arms races. Other important topics for research include the potential for terrorist uses, and the use of NT to improve verification of compliance with agreements.

10. Concluding Remark

Containing NT dangers in civil society will require rules, checks, and penal measures comparable to those in effect for dangerous chemicals, nuclear technologies, genetic modification of pathogens, etc. Reliably preventing dangerous military uses by international agreement will need similar degrees of monitoring and juridical prosecution. This is difficult to conceive in an international system where national security is built on the threat of using armed forces. Unfortunately, the logic of today's international system points to confrontations, at the level of deterrence at least, between states armed with nanotechnology-based weapons. As advanced capabilities mature, this could become a new arms race tending toward instability. We better decide early which road we are to take, and it better be the one that leads to regulation.

Will powerful new technologies act as a lever to qualitatively strengthen the rule of law and other elements of civil society in the international system? Or will they provide ways to circumvent existing rules and render them ever less meaningful, ushering in an unregulated future in which technology itself dictates the fate of humanity?

Notes

1 Altmann, J. & Gubrud M. A.: 2002, 'Risks from Military Uses of Nanotechnology – the Need for Technology Assessment and Preventive Control', in: M. Roco & R. Tomellini (eds.), *Nanotechnology – Revolutionary Opportunities and Societal Implications*, Luxembourg: European Communities, 2002, pp. 144-148 (available at http://www.ep3.ruhr-uni-bochum.de/bvp/riskmilnt_lecce.html); Altmann, J.: 2004, 'Military Uses of Nanotechnology: Perspectives and Concerns', *Security Dialogue* **35**(1): 61-79.

2 This had begun as early as 1983 – see Lem, Stanislav: 1986, 'The Upside-Down Evolution', available in the collection *One Human Minute*, San Diego etc.: Harcourt

3 See, for example, Metz S.: 2000, 'The Next Twist of the RMA', *Parameters* **30**(3): 40-53; available at carlisle-www.army.mil/usawc/parameters/00autumn/metz.htm (4 June 2004); Petersen J.L. & Egan D.M.: 2002, 'Small Security: Nanotechnology and Future Defense', *Defense Horizons* 8, available at www.ndu.edu.inss/DefHor/DH8/DH08.pdf (13 Dec. 2002); see also the section on National Security in Roco, M.C. & Bainbridge, W.S. (eds.): 2002, *Converging Technologies for Improving Human Performance – Nanotechnology, Biotechnology, Information Technology and Cognitive Science* (NSF/DOC-sponsored report) (Arlington VA) (www.wtec.org/ConvergingTechnologies/Report/NBIC_report.pdf (23 Sept. 2003)).

4 Use of force (armed struggle) for liberation from the colonialist powers or racist minority regimes was legitimized implicitly and explicitly by UN General Assembly resolutions, see, *e.g.*: Declaration on the Granting of Independence to Colonial Countries and Peoples, General Assembly resolution 1514 (XV) of 14 Dec. 1960, available at www.unhchr.ch/html/menu3/b/c_coloni.htm (1 June 2004); Importance of the universal realization of the right of peoples to self-determination and the speedy granting of independence to colonial countries and peoples for the effective guarantee and observance of human rights,

A/RES/32/14 of 7 Nov. 1977; Policies of apartheid of the Government of South Africa, A/RES/39/72 of 13 Dec. 1984 (latter two available at www.un.org/documents/ga/res (1 June 2004).

5 Art. 36, Protocol Additional to the Geneva Conventions of 12 Aug. 1949, and relating to the Protection of Victims of International Armed Conflicts (Protocol I), of 8 June 1977 (available via www.icrc.org/ihl.nsf, 1 June 2004).

6 Forces who cannot compete in technology have the option of guerilla warfare or of asymmetric warfare.

7 This is an example of the so-called security dilemma in an international system without higher authority where military preparations for improving the security of one state deteriorate the security of the others.

8 Article 1 of the Biological Weapons Convention bans possession of biological agents “of types and in quantities that have no justification for prophylactic, protective or other peaceful purposes”, without further clarification of acceptable types, quantities or justifications (www.state.gov/t/ac/trt/4718.htm). In the wake of the 2001 attacks, it was revealed that the US has developed new weaponized forms of anthrax in recent years, ostensibly for defensive testing purposes (Washington Post, December 13, 2001, Page A16, http://www.washingtonpost.com/ac2/wp-dyn/A34707-2001Dec12). Some would argue that this reveals the existence of an offensive US BW program, in that testing of protective equipment does not require the use of virulent agents, much less the development of new ones. However, development of vaccines and treatments would clearly benefit from testing against a maximally virulent agent. See also note 11.

9 SALT: Strategic Arms Limitation Talks; INF: Intermediate-range Nuclear Forces; START: Strategic Arms Reductions Talks.

10 The INF Treaty brought reduction to zero in a specific category of nuclear-weapons carriers, namely ballistic missiles and land-based cruise missiles with ranges between 500 and 5,500 km.

11 BWC parties Iraq (UNSCOM document S/1998/308, www.un.org/Depts/unscom/s98-308.pdf (4 June 2004)) and the USSR (Alibek K.: 1999, *Biohazard*, New York: Random House) each developed extensive biological weapons research and production facilities and produced hundreds of tons of biological agents, while publicly maintaining their adherence to the BWC. A number of countries are suspected today of biological weapons possession or activities, some of them parties to the BWC (cns.miis.edu/research/cbw/possess.htm (4 June 2004)).

12 *E.g.*, Art. VI of the Non-Proliferation Treaty reads: “Each of the Parties to the Treaty undertakes to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament, and on a Treaty on general and complete disarmament under strict and effective international control.”

13 Roco & Bainbridge 2002 (note 3).

14 National Nanotechnology Initiative – Research and Development Supporting the Next Industrial Revolution – Supplement to the President’s FY 2004 Budget, Washington DC, National Science and Technology Council, Committee on Technology, Subcommittee on Nanoscale Science, Engineering, and Technology, August 2003; available at nano.gov/nni04_budget_supplement.pdf (17 Nov. 2003).

15 *Nanotechnology: Its Impact on Defence and the MoD*, www.mod.uk/linked_files/nanotech.pdf (see also www.mod.uk/issues/nanotech/contents.htm) (18 Nov. 2003).

16 Annual expenditures for military R&D in recent years were about $ 40 billion in the USA, followed by $ 4, 3, and 2 billion in the UK, France, and Russia, respectively, Bonn International Center for Conversion: 2001, *conversion survey 2001 – Global Disarmament, Demilitarization and Demobilization*, Baden-Baden: Nomos; China’s spending was estimated in 1994 at about $ 1 billion, E. Arnett: 1999, ‘Military research and development’, in: *SIPRI-Yearbook 1999 – World Armaments and Disarmament*, Stockholm/Oxford: SIPRI/Oxford University Press, pp. 351-370.

17 Drexler K.E.: 1986/1990, *Engines of Creation – The Coming Era of Nanotechnology*, New York: Anchor/Doubleday; Merkle R.C.: 1994, ‘Self replicating systems and low cost manufacturing’, in: M.E. Welland, J.K. Gimzewski (eds.), *The ultimate limits of fabrication and measurement*, Dordrecht: Kluwer, pp. 25-32.

18 Gubrud M.A.: 1997, ‘Nanotechnology and International Security’, Fifth Foresight Conference on Molecular Nanotechnology, www.foresight.org/Conferences/MNT05/Papers/Gubrud/index. html (4 June 2004).

19 The Foresight Institute has published proposed safety guidelines for an MNT industry which give valuable ideas for the civilian context, but dismiss arms control on the grounds that 100% verification may be impossible, apparently assuming that arms control can only mean shunning all knowledge and that everything is lost if anyone cheats. This accords with the idea of an "assembler breakthrough" that may shake the world. A more conventional view would suggest that rogue actors are unlikely to make great technological breakthroughs that cannot be detected in a timely fashion and countered by the world’s major powers. *Foresight Guidelines on Molecular Nanotechnology*, Revised Draft Version 3.7: June 4, 2000, www.foresight.org/guidelines/current.html (13 May 2004).