



MINISTRY OF DEFENCE

NANOTECHNOLOGY: ITS IMPACT ON DEFENCE AND THE MOD

This is the first of a series of information sheets, on emerging technologies to inform the Department about topics that are likely to be of growing importance to defence, produced by a panel comprising some of the UK's leading experts (see box below).

The Nanotechnology Panel

In addition to MOD staff led by the Chief Scientific Advisor (CSA), the Nanotechnology Panel comprised UK and world leading scientists and engineers from academia.

Professor Richard Bushby is Professor of physical organic chemistry at Leeds University and Director of the Centre for Self-Organising Molecular Systems (SOMS). His main scientific interests are in self-organised molecular systems, particularly polymer magnets, liquid crystals and biomembrane based sensors.

Professor John Chapman is a Professor of physics at Glasgow University and his research activities centre around the high spatial resolution characterisation of advanced functional materials and devices. He has a particular interest in nanomagnetism and, until recently, chaired the now completed EPSRC Advanced Magnetism Programme.

Professor John Pethica is Professor of Materials Science at Oxford University and is a Fellow of the Royal Society. His interests include probe microscopy, nanomechanics and thin films, interfaces, liquid and molecular structure as well as atom manipulation. He was formerly Director of Nano Instruments Inc. USA.

Professor Michael C Petty is a Professor in, and formerly Chairman of, the School of Engineering at the University of Durham. He is currently Co-Director of the Durham Centre for Molecular and Nanoscale Electronics, a board member of the Institute of Nanotechnology and UK editor of the journal "Materials Science and Engineering C".

Nanotechnology - Why Should Defence Take Notice?

Nanotechnology is the name given to a new field of science and technology where the component parts can be measured in some tens of atom diameters or even less; around a millionth of a millimetre. This not only means that complex and sophisticated systems can be incredibly small, but because they work at the atomic scale, new principles of physics apply and novel and revolutionary applications are possible.

For defence the implications could be enormous, both in terms of the opportunities it might offer to grow our own military capability, and the new threats it might lead to.

The list of possibilities is long but includes:-

- **Completely secure messaging**
- **Intelligent and completely autonomous short and long range highly accurate weapons**
- **Improved stealth but also means to defeat current stealth techniques**
- **Global information networks and local battlefield systems with "all-seeing" sensors**
- **Miniature high energy battery and power supplies**
- **Intelligent decision aids**
- **Self repairing military equipment**
- **New vaccines and medical treatments**
- **Highly sensitive miniature multiple biological and chemical sensors**
- **Un-ethical use leading to new biological and chemical weapons**

What Is Causing The Interest In Nanotechnology?

We are all very familiar with technology that operates on the micrometer scale (around one thousandth of a millimetre) since this is the province of microelectronics which has driven the information technology, electronics and communications revolution. The very ability to produce structures and devices at the microscopic scale has enabled the production of highly complex and sophisticated systems and tools such as mobile telephones, personal computers and a range of electronic entertainment equipment.

Whilst research and development continues to exploit this 'microtechnology', scientists and engineers around the world have recognised that it is a technology that has fundamental limits. Consequently the advances we have come to

expect on almost a monthly basis can only continue for perhaps another decade. Yet even though the limits of current microtechnology are recognised, the potential demand of the markets fed by almost continuous advances in electronic, computer and information systems is likely to remain insatiable. What is more, it is expected that more exacting legislation affecting the environment, for example in pollution monitoring and control, will require the use of a wide range of low cost, sensitive and discriminating sensors well beyond what microtechnology can provide.

Thus if further leaps in performance and new applications are to take place a new approach is needed. Enter nanotechnology.

Nanotechnology Affects Every Branch Of Science And Engineering

The scope of nanotechnology is vast but it is most easily summarised as the technology of processes, structures and devices that operate on a scale of between one ten millionth of a millimetre and one ten thousandth of a millimetre. At first sight this would seem little more than just a continuation of the shrinking scale of microtechnology, but it is fundamentally quite different and driven by the development of new tools to manufacture, manipulate and measure on this scale (Figure 5 on page 6 illustrates an example). A challenge in any new technology is how to produce new material or devices on a large scale. Consequently nanotechnology based on manipulation of molecules in structures like DNA could lead to new materials that can be produced utilising biological growth. The possibilities nanotechnology presents both for technological advances, and the impact of technology on all aspects of society will be profound.

Operating at this incredibly small scale, also moves to a regime of science where the so called classical laws of physics that adequately describe how things operate in our macroscopic, every day life, and even on the scale of microtechnology no longer apply. On nanotechnology scales, devices operate at the molecular or few atom level where so called quantum effects (see box opposite) can dominate rather than the intuitive effects that we associate with current technology.

Nanotechnology will have a profound impact on new materials, electronic devices, chemical, biological and mechanical systems. It is a truly multi and cross disciplinary technology that draws on the world's experts in physics, chemistry, biology, engineering and mathematics.

Classical And Quantum Physics

In physics, the term 'classical' is used to describe the physical principles deduced and applied by such great men as Galileo and Newton. These and other great scientists of the period pre 1900 developed an understanding of our physical world based on the observations that they made of how things about them behaved. Galileo is famous for his observations of the planets and stars, and his belief that the planets travelled around the sun.

Newton also studied 'heavenly bodies', but did much to explain how everyday things on earth move in response to the forces applied to them. Thanks to Newton we have an understanding of the forces that affect the design of buildings, cranes and even why billiard balls behave the way they do as they collide and spin. In the world described by Newton and Galileo, things happen in smooth, continuous steps, for example of increasing and decreasing energy.

But these every day things comprise uncountable numbers of atoms (more than a billion billion in a billiard ball). The forces that cause the atoms to hold together depend on many factors, and in effect, the way a billiard ball behaves is a sort of average of the individual behaviours of all its atoms. But as we know, the atom is not the smallest building block, atoms comprise so called sub-atomic particles (electrons, protons and neutrons) which themselves comprise even smaller particles.

What we find at these even smaller size scales is that the laws of physics are different to the 'classical' laws, we are in the regime where things do not happen in smooth continuous steps. At this scale, things have very discrete values (say of energy), we are in the arena of quantum physics. In quantum physics, particles are described by a series of quantum numbers that do not have an easy explanation in terms of the large-world effects with which we are so familiar. In effect, our large sized world is the result of the averaging of all of these 'quantised' particles.

As With Microelectronics, The Major Driver Will Be The Civil Markets

The promise is of systems which are smaller, lighter, cheaper and requiring less power to run and much of the current interest in nanotechnology is directed simply towards more sophisticated and vastly more powerful versions of microtechnology products. Recognising the limits of microtechnology, this is not surprising. Hence logical extensions of microtechnology into nanotechnology will lead to sensors detecting at the single molecule level, using ever more powerful computer processing and vastly greater memory. Together these technologies will enable us to build sophisticated information networks that will lead to more effective surveillance, for example for natural resource and pollution monitoring.

Other areas where nanotechnology will impact the civil sector are the automotive industry, and around the home for a whole range of domestic products. Therefore, as with microtechnology, it is anticipated that these large markets will drive down the costs of products, leading to an even wider use of advanced sensors and processing.

Nanotechnology will bring together electronic and biological technologies that could yield new materials and devices. For example, new forms of sensors, systems that can perform complex functions in places where it is not possible or safe for people (e.g. within process plants to monitor levels of harmful chemicals), new protective

coatings, and revolutionary new means for electrical energy storage and conversion.

Operating at the atomic and individual molecule level, it is possible to make gear wheels where the cogs are individual atoms on the outside of a ring of carbon atoms. Molecular motors have been envisaged that use chemical reactions to spin nanoscale nickel shafts. **Figure 1** shows a carbon nanomotor powered by laser fields and **Figure 4 on page 6** shows a molecular planetary gear system. All this leads to the possibility of nanoscale mechanical devices that could yield a whole new class of applications. It is clearly too early to be specific, but at one extreme, this could lead to nano-robots for combating disease. Nano-robots could also be incorporated within military equipment for example to aid self repair.

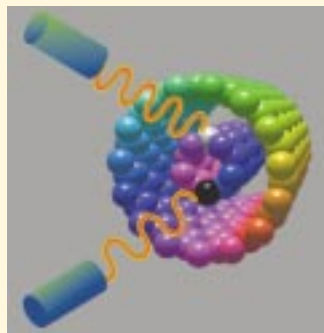
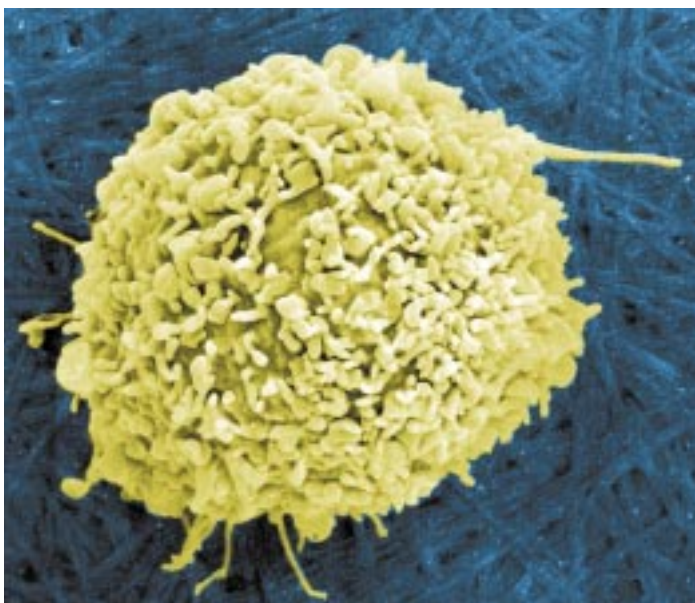


Figure 1: A Carbon Nanomotor – The electrically charged shaft is made to rotate under the action of oscillating laser fields.

Health Treatments Could Be Transformed



The combination of nanotechnology and genomics (which offers the possibility of manipulation of the DNA of humans and other species) will lead to the development of new vaccines, and treatments for genetically based illnesses. More generally in health, key applications are seen as simple and effective diagnostic sensors (**see figure 2**), means to provide new therapies and mass screening systems.

Figure 2: Immune system cell attached to a supporting base acting as a detector of toxic substances.

At The Nanoscale, New Science Means New Applications

Many of the potential applications are based on exploiting effects that are part of our current understanding of science. However, producing structures and operating at the atomic level will produce effects not exploitable before that will stimulate new science and hence lead to possibly even more new applications.

The major leap in computer and information processing could be made possible with nanotechnology by exploiting quantum effects. Current electronics relies on components which are able to store and switch between two electronic states, where the two states represent either the number "0" or "1". These states are either voltage or current levels measured at the device outputs. Quantum processing will use quantum states (see box on page 2) to represent numbers, but the states will be characteristics of atomic particles that affect how they interact with each other. This might lead to new computers, but

perhaps more significant is that it might be possible to arrange quantum interactions so that the information can only be extracted by somebody who has a precise knowledge of the particular atomic manipulations used in setting the various states. Thus there is the potential for what is called quantum cryptography. Quantum cryptography could lead to totally secure messaging.

Although there is an obvious business (and defence) benefit from this, the ability to send information over large distances that would normally be kept locked away could have major impact on our every day lives. For example, widely available, totally secure messaging linked to new sensors and information processing could transform medical diagnosis and treatment. Also, similar advances could lead finally to all financial transactions being performed completely electronically.

Current Research Investment

Research spending on nanotechnology, mainly within the USA is large and growing as part of a National Nanotechnology Initiative worth approximately £360m in FY2001. The largest US spender on nanotechnology research is the National Science Foundation (£160m pa), followed by the Department Of Defense (mainly the Defense Advanced Research Projects Agency (DARPA)) which is spending around £80m per annum in the area. The next biggest spender is the Department of Energy (£70m pa) with the National Institutes of Health spending £25m pa.

The current US administration is committed to nanotechnology. Last year, in what was a very supportive speech, President Clinton stated that nanotechnology has the potential to lead to memory devices where the whole USA Library of Congress could be stored on a device the size of a sugar cube.

Continental European research currently at £100m pa, is on the increase but does not match the level of US investment.

Japan also has a substantial research programme funded by government to a level of about £50m pa.

Within the UK the Research Councils are starting a number of initiatives in support of building expertise and knowledge in nanotechnology. The Engineering and Physical Sciences Research Council (EPSRC), and the Medical Research Council (MRC) are each already sponsoring a number of related grants together worth more than £15m pa and have both separately conducted 'theme day' conferences in the past year. Furthermore, they together with the Biotechnology and Biological Sciences Research Council (BBSRC) and MOD are considering sponsoring a small number of nanotechnology Interdisciplinary Research Collaborations worth a total of about £3 million per year.

Around the world, much of the research is being conducted in universities. Looking to the production of commercial devices, it is quite possible that initially only large multinational companies will be able to go to production. However, as with microtechnology, once the markets pick up, smaller organisations, such as Small to Medium Enterprises (SMEs) may spring up and take the lead in product development and manufacture.

When Will Nanotechnology Start To Affect Our Lives ?

It is possible that new materials exploiting some of the nanotechnology structures, for example nanotubes, will become available within the next 5 years or so. Nanotubes (see Figure 3) are based on carbon and are a few millionths of a millimetre in diameter but many thousandths of a millimetre long, and have been shown to have extraordinary strength and the ability to bind to other important chemicals. New nanotube materials could be strong, light and have useful electrical properties. Looking to wider take-up, it is unlikely that nanotechnology will lead to the full range of applications mentioned so far much earlier than the next 20 to 30 years. Yet with this technology that has such great potential, we dare not rule-out more immediate progress if the right advances and investments come early.

Whilst there is not yet an equivalent to micro-technology's Moore's Law (which states that the number of processing and storage elements on

electronic chips will double every 18 months), once established, it is likely that nanotechnology will develop at a great pace.

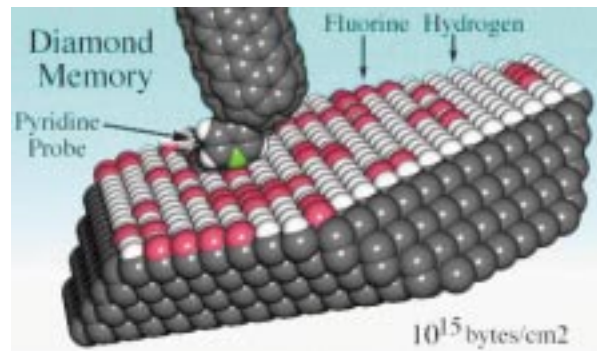


Figure 3: A nanotube probe accessing an atomic memory. The different atomic elements (fluorine (red) and hydrogen (white)) could represent memory '1's and '0's, this would lead to memory of one million gigabytes on a device the size of a thumbnail.

Impact On Defence And The MOD

Nanotechnology will offer both new opportunities for UK defence and also new threats to the UK and its allies. The main initial impact will be in the information system areas involving new sensors, information processing and communications. However, as nanotechnology develops, defence specific applications are likely to become more extensive.

New forms of sensors, information processing and communication will enable small unmanned systems to have the level of performance at relatively low cost which is currently only possible in large expensive systems. Consequently autonomous weapons will carry detailed knowledge of the terrain and environment they must travel through to reach their target, the ability to adapt to unexpected changes in weather and also the ability to detect and counter threats directed at them.

A whole range of military equipment including clothing, armour, weapons, personal communications will, thanks to low cost but powerful sensing and processing, be able to optimise their characteristics, operation and performance to meet changing conditions automatically. Although it is unlikely that the human will be taken out of the loop for key decisions like weapon release, commanders will nevertheless be supported by a wide range of decision aids that will ensure that they have available all of the information necessary in a pre-processed form, without being overwhelmed.

New nanotechnology materials might be possible that offer improved stealth spanning the electro-

magnetic spectrum from the visible, through the infrared and into the radar bands. Whilst fully self repairing bulk structures might be some way off, self repairing soft skins on a range of platforms and equipment could be possible on a significantly shorter timescale.

Specially prepared clouds of nanotechnology particles could be used to disrupt electronic systems, affect the stealth characteristics of platforms flying through them and reduce the performance of communications and sensor systems.

However it must be recognised that since much of the base technology needed to achieve all of these capabilities will be produced through the civil sector, it will also be available to our would-be enemies. Furthermore, since these potential aggressors might be able to acquire equipment through simpler acquisition systems than ours, they will be able to capitalise more easily on new advances in the technology.

There is also the threat from those who are prepared to use the technology in a way and under circumstances that we in the UK would find ethically unacceptable. Manipulation of biological and chemical species using nanotechnology techniques could result in new threats that might be hard to detect and counter. Terrorist and Non-Governmental Organisation (NGO) groups might attack elements of the national infrastructure, for example by some form of non-traceable activity affecting crops or animal livestock.

The MOD Response To Nanotechnology

Within the MOD, nanotechnology research is funded through the Corporate Research Programme (CRP) to the tune of about £1.5 million per annum. The main topics of research are on new structural materials, electronic devices and quantum interference.

Looking to the near-term future, it is not necessary for MOD to launch a major research programme in nanotechnology. As has already been explained, the worldwide investment in nanotechnology research is already large and is set to grow stimulated by potentially vast civil markets for products.

However, MOD will undertake Technology Watch of nanotechnology, both to determine its benefits for UK defence and to determine the threats that the technology might pose against the UK and its allies, recognising they may come in key areas more quickly than we think. To be an effective technology watcher and obtain key information from the international research community in particular, MOD will need to sponsor some nanotechnology research. This will be on topics of recognised defence significance. Without the MOD having something to offer in exchange, it is unlikely that researchers will be prepared to share their key knowledge. Collaborative research offers the benefit of gearing and enables MOD to be sufficiently knowledgeable to identify and explore defence specific issues, as well as interpret the opportunities and threats posed by the technology in general.

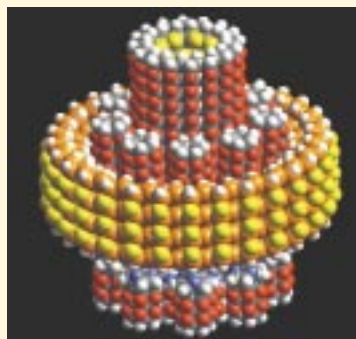


Figure 4: Model of a molecular planetary gear system.

Since the majority of UK research is currently taking place in the universities, MOD sponsored research will involve close working with them, which in turn will provide a link to the international research scene.

In addition to developing knowledge of the science and technology, CSA staff will work with other MOD agencies in the force development, concepts, doctrine, equipment, policy and intelligence areas.

The size of the MOD research sponsorship will increase slightly in the short term. However, the level of funding will be monitored regularly in the light of new advances and discoveries.

Nanotechnology will almost certainly affect our lives and have a major impact on defence. We must not miss the vital opportunities it offers nor be caught off-guard by new threats.

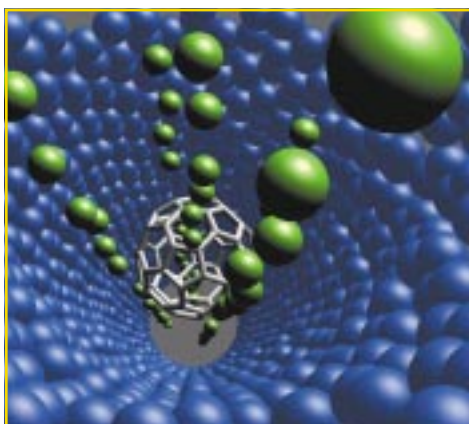


Figure 5: A molecule consisting of carbon atoms in the form of a geodesic ball (a "buckyball") is shown moving helium atoms (green) through a nanotube ("buckytube"). This process could be used to deliver a specific type of atom or a single molecule to a site at which it might be required.

Acknowledgements

Figures 1 and 5 courtesy of Dr Don Noid and Dr Bobby Sumpter, Oak Ridge National Laboratory.

Figure 2 is Crown Copyright MOD

Figure 3 courtesy of Al Globus, Charlie Bauschlicher and Ralph Merkle, NASA Ames.

Figure 4 by permission of the Institute for Molecular Manufacturing (IMM), www.imm.org

Contacts

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