Nanotechnology: The Technology for the 21st Century

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1. INTRODUCTION

We are now at a threshold of a revolution in the ways in which materials and products are created. This has resulted from the convergence of the traditional fields of chemistry, physics and biology to form the new field of nanotechnology. Nanotechnology is concerned with the fabrication and use of devices so small that the convenient unit of measurement is the nanometer (a billionth of a meter). At this very small scale the characteristics of individual molecules and atoms in the material become more important than the material's bulk properties and thus new concepts need to be used. The theme of the field is "novel performance through nanotechnology".

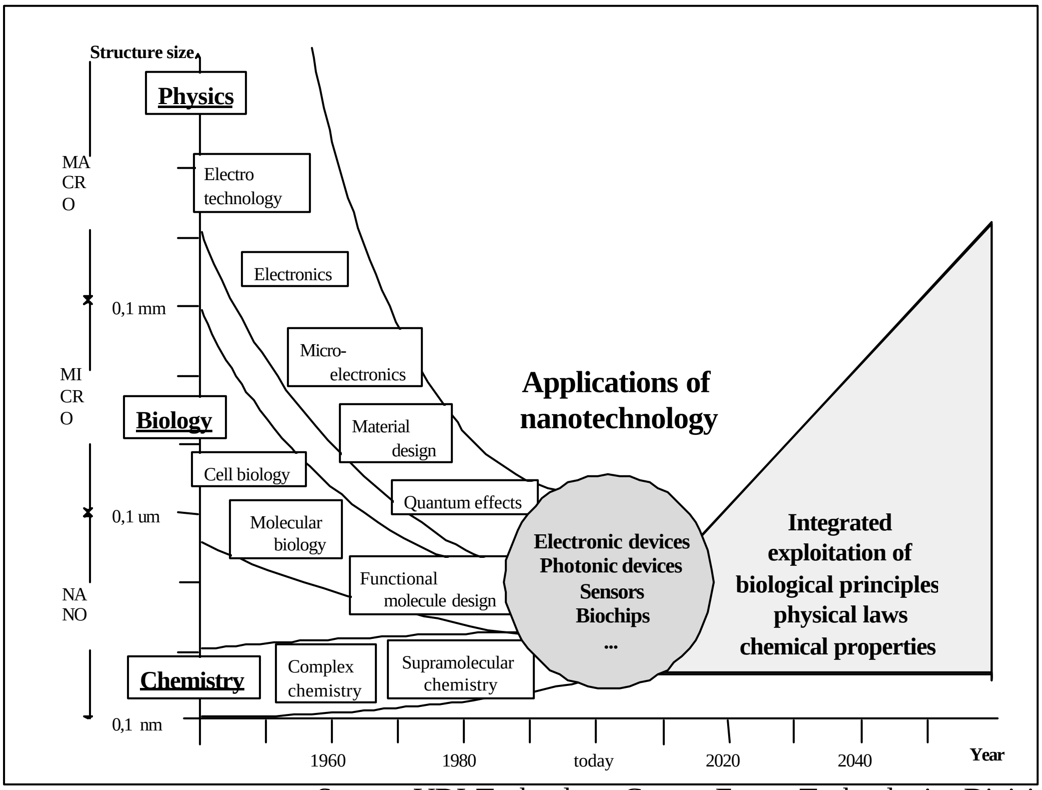
Nanotechnology covers a wide range including fabrication of functional nanostructures with engineered properties, synthesis and processing of nanoparticles, supramolecular chemistry, self-assembly and replication techniques, sintering of nanostructured metallic alloys, use of quantum effects, creation of chemical and biological templates and sensors, surface modification and films.

Researchers and technologists are approaching the field of nanotechnology from three directions (see Figure 1, Bachmann 2002)

- In physics, the field of microelectronics is moving towards smaller feature sizes and is already at submicron line widths. Processors in computing systems will need nanometer line widths in the future as miniaturisation proceeds.
- In chemistry, improved knowledge of complex systems had led to new catalyst, membrane, sensor and coating technologies which rely on the ability to tailor structures at atomic and molecular levels.
- In biology, living systems have sub-units with sizes between micron and nanometer scales and these can be combined with non-living nanostructured materials to create new devices.

There is considerable debate in the scientific community about the boundaries of the new disciplines emerging from this convergence eg between microtechnology and nanotechnology, but it is becoming clear that, in practice, no clear division can be made. Thus for example sensors and biochips at the nanotechnology scale need to be packaged for commercial applications using microtechnology.

Figure 1. Physics, biology and chemistry meet in nanotechnology



Source: VDI-Technology Center, Future Technologies Division

The interdisciplinary nature of nanotechnology also poses problems for researchers and institutions used to traditional disciplines with defined boundaries. Changing traditional mindsets is a major challenge and a particular need is to develop nanotechnology experts with interdisciplinary skills.

Given the potential significant implications for research, industry and society, the APEC Center for Technology Foresight (APEC CTF) with the strong support of the APEC Industrial Science and Technology Working Group recently carried out a Foresight study of nanotechnology in the APEC region (APEC 2002, Tegart and Sripaipan 2002)). The Appendix describes the conduct of the study.

2. SOME KEY ISSUES IN THE DEVELOPMENT OF NANOTECHNOLOGY

2.1. Definition of Nanotechnology

A new paradigm in science and technology is emerging with the manipulation of atoms and molecules at the nanometer level (1 nm = 10^{-9}m). This has resulted from the convergence of the traditional fields of chemistry, physics, biology and engineering to form the new field of nanotechnology. A crude division of areas contributing to nanotechnology is given in Figure 2. Because of this diversity of interests involved in nanotechnology, there is often confusion in the rest of society the about the nature of nanotechnology since there are now topics being researched such as nanobiotechnology, nanoelectronics, nanomaterials and nanophotonics

We can define **nanotechnology** as: "**materials and systems whose structures and components exhibit novel and significantly improved physical, chemical and biological properties, phenomena and processes due to their nanoscale size**".

An effective public awareness program is necessary to clarify misunderstandings about nanotechnology.

Figure 2. A crude division of areas contributing to nanotechnology

	Inorganic	**Organic**
Physics	Mesoscopic physics Lasers Scanning electron microscopy Electronics	Molecular electronics
Chemistry	Inorganic chemistry Aerosol science Computer modelling	Supramolecular chemistry Physical chemistry
Biology	—	Biotechnology Medicine
Engineering	Precision engineering Materials science and engineering	

2.2. Opportunities for Nanotechnology

The opportunities for nanotechnology can be divided into three main categories:

Molecular engineering inspired by biotechnology

The scale of living systems is in the range from micrometers down to nanometers and it is possible to combine biological units such as enzymes with manmade nanostructures. One of the most significant impacts of nanotechnology is at the bioinorganic materials interface. By combining enzymes and silicon chips we can produce biosensors. These can be implanted in humans or animals to monitor health and to deliver corrective doses of drugs. They have the potential to produce improved health care for humans at lower cost and to improve animal productivity. Development of human biomedical replacements such as artificial skin, smart bandages, pacemakers, etc will also be dependent on nanotechnology.

In the longer term is the possibility of making robotic machines, called assemblers, on a molecular scale, that are capable of constructing materials an atom or a molecule at a time by precisely placing reactive groups. This could lead to creation of new substances not found in nature- so-called molecular manufacturing (Drexler 1992). In addition there is the potential for understanding how Nature produces self-replicating structures with exceptional properties- biomimetic engineering.

Electronic technology based on semiconductors

There is potential to increase the capacity of microchips up to 1 billion bits of information per chip. However the costs of production are increasing dramatically and there is intense study around the world to determine the point in physical scaling where it either becomes physically unfeasible or financially unattractive to continue the trend towards reducing the size and increasing the complexity of microchips. Nanoscale structures such as quantum dots offer a path to a new type of computer-the quantum computer. There is extensive research on the fabrication of electronic structures on the nanometer scale based on entirely new physics. Devices under development include lasers for optoelectronics, ultrafast switches, memory storage devices for computers and, ultimately, devices controlled by single electron events.

Devices and processes based on new materials

Creative materials and surface science is critical to further advancement of nanotechnology. One of the interesting properties of materials such as metals or ceramics at the nanometer size level is their very high surface area per unit volume which has potential for speeding-up catalytic reactions and biochemical and pharmaceutical separations, and thus improving the efficiency of many processes. Such materials can be produced by either the 'bottom-up' approach, i.e. building-up from individual atoms or molecules, or the 'top-down' approach i.e. breaking-up bulk materials into nanoparticles by mechanical milling or nanocutting. The former can produce films or clusters for nanoscale devices while the latter enables fabrication of micro-components by consolidation of nanoparticles.

One of the most interesting groups of nanomaterials is nanotubes. Carbon nanotubes have remarkable strength (up to 100 times that of steel), can be electrical conductors or semiconductors and are excellent conductors of heat. They have many potential applications eg strong composites, field emission devices for displays, sensors and storage of hydrogen.

Products based on nanotechnology are already widely used eg paints, pharmaceuticals, microelectronic devices, and the industry has been estimated already to be worth US $40 billion. Growth prospects are enormous. The seven largest areas of demand are: IT peripherals, medical and biomedical applications, automotive and industrial equipment, telecommunications, process control, environmental monitoring and household products.

The current situation of research in these categories and the opportunities are discussed in detail in the four position papers on nanophotonics, nanobiosystems, nanoelectronics and nanostructured materials prepared as part of the APEC CTF study (APEC 2000). Other recent reviews are available (Anton et al 2001,Harper and Hollister 2001, Compano 2002). In the workshop discussions of the APEC CTF study promising opportunities in 3 years and in 10 years time were identified as noted in Table 1.

Table 1. Estimated timing of the realisation of some Technological Opportunities in Nanotechology, Identified in the APEC CTF Study
In 3 years   **Category 1**   Selective bio nano-sensors   Specific drug delivery systems
Category 2   Nano-electronics based on miniaturised silicon devices   Novel devices based on magnetic spin electronics
Category 3   Nanostructured materials as industrial catalysts   Self-cleaning surfaces based on nanomaterials
In 10 years   **Category 1**   Advanced medical diagnostics   Targeted human cells for organ repair
Category 2   Single electron devices   Optical computing
Category 3   Portable fuel cell and advanced battery   Artificial photosynthesis

2.3. Education and Training

A looming problem is the education and training of a new generation of researchers and skilled workers with the interdisciplinary perspectives needed for nanotechnology development. A recent estimate of the people needed for nanotechnology in 2010-2015 is 0.8-0.9 million in the USA, 0.5-0.6 million in Japan, 0.3-0.4 million in Europe and 0.1-0.2 million in Asia- Pacific region without Japan, and about 0.1 million in other regions (Roco 2001).
The range of inputs and equipment needed for education and training of nanotechnologists challenges the traditional separation of academic disciplines into physics, chemistry, biology and engineering (Tegart 2002). There is a need to increase multi-disciplinarity which implies significant changes in academic institutions. The challenge is then to achieve breadth and depth to produce people of creating new concepts in nanotechnology (Campano 2002, Bachmann 2002). A thorough grounding in basic physics, biology and mathematics is essential but a new paradigm of molecular models is needed rather than a microscopic approach. Thus courses on surface science, molecular dynamics, quantum effects and manufacturing at a molecular level present opportunities for new approaches.

One approach has been for universities to set up interdisciplinary centres of expertise in nanotechnology to train postgraduates and then link these to industry. This approach has worked well in other areas eg ICT and biotechnology. Further a number of universities around the world are now offering undergraduate courses in nanotechnology. In addition there is an urgent need to train technicians and also managers to alert them to the changing paradigm of manufacturing.

2.4. Funding of Nanotechnology R & D

Governments which have recognised the potential of nanotechnology have supported the development in their economies by directing special funding to the area. The scale of funding is large, up to several hundred million US $ per annum in USA and Japan, with much of the funding provided by industry, notably in Japan and Korea(Table 2).

Table 2 Government Expenditure on Nanotechnology R&D ($ US million)

	1998	1999	2000	2001	2002
W.Europe	151	179	200	225	285
Japan	135	157	245	550	753
USA	190	255	270	422	518
Others	83	96	110	380	?
	559	687	825	1577	?

(After Roco 2001)

Clearly, smaller, and also less developed, economies cannot compete at these levels of R & D investment. They must carefully assess their strategy to ensure that their limited resources are use, on one hand, to ensure maintenance of a capability to adapt imported technology and, on the other, to exploit opportunities provided by unique national resources or scientific breakthroughs. The development of nanotechnology in smaller and less-developed economies will be assisted by national recognition of the importance of nanotechnology and provision of special funding to support research, development and demonstration.

2.5. Commercialisation of Nanotechnology

In order to take advantage of the opportunities stemming from nanotechnology, much of industry in many economies will have to radically change management approaches and company strategies. Although the possibilities of nanostructured materials and other possible applications of nanotechnologies seem endless, firms are facing the dilemmas of where to invest, asking what are the winning technologies, and having problems with identifying them. The current downturn in the world economy and the collapse of the e-commerce sector has dampened enthusiasm for investment in new technology ventures.

In R&D in emerging fields such as nanotechnology, where new findings and innovations come up nearly every day, the need for flexible strategies is evident. Inventors need fast and unbureaucratic help to realise an idea with importance for the future, and companies must build strong networks with academia to get the best partners for a fast transfer of the research results into products.

A barrier to industry seeing itself as a participant in nanotechnology is the current practice in many economies of defining an enterprise as narrowly as possible, so that 'core' business often embraces a single discipline and very few functions. Such a mental picture coupled with a limited understanding of nanotechnology and how an enterprise will engage with it explains the absence of the concepts from industry vision and mission statements or ten-year strategic plans. The situation is particularly difficult in small or less developed economies.

As with other rapidly developing technologies, the issue of intellectual property rights is a significant one in considering commercialisation. Problems can arise when university or government researchers are seen to be getting too close to industry 'know-how' and when industry wishes to have exclusive rights.

2.6. Nanomeasurement and Standards

The position papers in the APEC CTF study covering Nanophotonics and Nanostructured Materials both highlighted the importance of metrology in the commercialisation of nanotechnology. They emphasised that the establishment of standards and a metrology system is a key element in the development of an industry. Nanometrology will be an enabling tool for the development of nanotechnology; however, the challenges for developing an useful and universally-recognised standards system for nanotechnology are many.

For example, maintaining or even finding positions on a surface with nanometer accuracy and precision is very challenging in a research environment, but is especially so for areal dimensions relevant to manufacturing. Reference materials (e.g. nanoparticles of known size and composition) are not available, which makes intercomparison or calibration of characterisation tools and approaches difficult if not impossible. A number of vital breakthroughs needed in the next 5-10 years are: the development of particle size calibration standards for 3 nm, 10nm and 30 nm size particles; improvements in nanomeasurements methods for nano-sized particles; and quantification of uncertainty in transmission electron microscopes. However, standards are only useful when they are accepted internationally. In the case of nanostructured materials, the standards system will play a decisive role in deciding product standards for materials, manufacturing procedures and calibration techniques.

2.7. Societal and Ethical Implications of Nanotechnology

Scientific discoveries do not generally change society directly; they can set the stage for change that comes through the confluence of old and new technologies in a context of evolving economic needs. Nanotechnology is so diverse that its effects will take decades to work through the socio-economic systems. A major problem in anticipating its effects is that subsequent developments may be in the hands of the users and not the innovators. If nanotechnology is going to revolutionise manufacturing, health care, energy supply, communications and defence, then it will transform labour and the workplace, the medical system, the transportation and power infrastructures and the military. None of these latter will be changed without significant social disruption.

Initially, the impact of nanotechnology is likely to be limited to a few products and services where consumers are willing to pay a premium for new or improved performance. As a result, nanotechnology will co-exist for a long time with older technologies rather than displacing them. This may give time to assess the potential social and ethical implications of nanotechnology. However, given the problems encountered in the introduction of biotechnology products, it is prudent to consider now the societal implications, both positive and negative, of nanotechnology.Thus the new undergraduate courses in nanotechnology must include social and ethical studies.

It seems likely that the first wave of useful technologies will be in the area of detection and sensing. When detection outpaces response capability – as it usually does – ethical and policy dilemmas inevitably arise. For example, it is already possible to identify genetic predispositions to certain diseases for which there is no known cure, or to diagnose congenial defects in foetuses for which the only 'cure' is abortion. Better detection through nonotechnology will increase the number of these..In medical areas, nanotechnology-based treatments may develop from the initial sensor technologies; they may initially be expensive and hence only available to the very rich, increasing the inequalities already present in societies.

3. SCENARIO-BASED FUTURES FOR NANOTECHNOLOGY

Scenario creation is a way of envisaging what the future might hold for a particular economy, industry sector or organisation. Rather than using projections from past trends, scenario creation attempts to develop stories about possible and plausible futures. It follows a systematic sequence of steps. First the key STEEP drivers - social, technological, economic, environmental and political – are identified. The next step is the 'scenario logic' or pattern of interactions that determines how the key drivers could contribute to future directions in each scenario. The key drivers are separated into predetermined elements e.g. demographics, and critical uncertainties e.g. public opinion or economic crises. This analysis is then used to create scenarios for a period 10-20 years in the future. These are internally consistent stories which present distinctly different possible futures – the actual outcome may be a blend of elements from more than one scenario. From these scenarios it is possible to draw out policy issues and make strategic decisions.

In the Ottawa meeting of the APEC CTF study a number of drivers were identified using the STEEP approach (Table3).

The participants then speculated on possible, even improbable, events which could occur to change the pattern of development of nanotechnology (Table 4).

Table 3. Key Drivers for the Development of Nanotechnology Identified in the APEC CTF Study

Society:	Ageing population Enhanced quality of life More effective health care
Technology:	Scientific breakthroughs Need for miniaturisation in production Demands of information and communication technology industry
Economics:	Novel / unique products to stimulate industry development Investment in high technology Rise of knowledge society
Environment:	Clean and leaner production processes Improved air and water quality New energy sources
Policies:	National security issues Changing patterns of S&T expenditure Public perception of technological change

Table 4. Critical Uncertainties for the Development of Nanotechnology Identified in the APEC CTF Study

Technical uncertainties:	Nanotechnology fails to deliver Inability to solve standards issues Breakthroughs in current technical paradigms
Environmental/Economic uncertainties:	Major financial crisis Kyoto Protocol ratified by all economies Major disruption of energy supplies
Public/Societal uncertainties:	Lack of public acceptance of nanotechnology Major nanotechnology-facilitated advances in human health Terrorism and national security
Global uncertainties:	World War III Widespread epidemic

Using these inputs, three scenarios for 2015 were created. These are available in full (APEC 2002) but can be summarised as:

Nano-Paradox – Things are more the same today than they have ever been.

Under the threat of global terrorism, coupled with problems of energy security, research in nanotechnology, particularly in the US, made major progress in the early 2000s. Small fuel cells and energy efficient vehicles were in the market by 2006. However repeated biofood and GMO scares, coupled with scandals on genetic profiling and DNA chips, led to a poor public image for nanotechnology products. Nevertheless R&D in APEC economies increased and products based on nanotechnology continued to be introduced, although increasingly little mention was made of nanotechnology. By 2015, products based on nanotechnology had achieved clear technical success in many areas but widespread adoption and acceptance of the full potential has been clouded by uncertainty and nanotechnology is scarcely visible. It had to be rebranded and integrated with other technology labels to be accepted.

Green Energy Triggers Collapse in Energy Markets

Following defeat of global terrorist movements and a return to growth in the early 2000s, demand for oil increased so that high prices were sought by producers. Under this pressure, research on alternative energy systems was accelerated, based on nanotechnology. Thus, hydrogen storage systems and portable fuel cells were installed in vehicles for demonstration. By 2012 significant breakthroughs enabled car manufacturers to abandon petrol-fuelled vehicles and switch over to mass production of new fuel-efficient hydrogen-powered vehicles. Hydrogen fuel cells challenged conventional energy producers such as oil and natural gas power stations and by 2015 the demand for fossil fuel energy systems had collapsed.

Nanotech Wins the War!

The threats of bioterrorism in the early 2000s led to intensive R&D on nanodevices to detect and neutralise lethal micro-organisms. Similarly, problems with energy supplies focussed attention on possible new energy sources such as solar cells and fuel cells. However these needed time for commercialisation. By 2010 instability in the Middle East and disruption of oil supplies led to a major war, involving both conventional and biological weapons. Redoubled efforts on nanodevices for virus detection and on energy systems enabled a coalition of Western powers to win the war. The intensive commercialisation of these technologies led to new industries and sustained global economic growth by 2015.

Despite starting from different combinations of key drivers and uncertainties, the three scenarios present similar futures where intensive R&D in nanotechnology enables significant advances in health care e.g. biodiagnostic and drug delivery systems and in energy systems e.g. solar cells and fuel cells based on hydrogen to be achieved in 5-10 years. Commercialisation is envisaged in 12-15 years. These developments are in accord with the views expressed in Table 1.

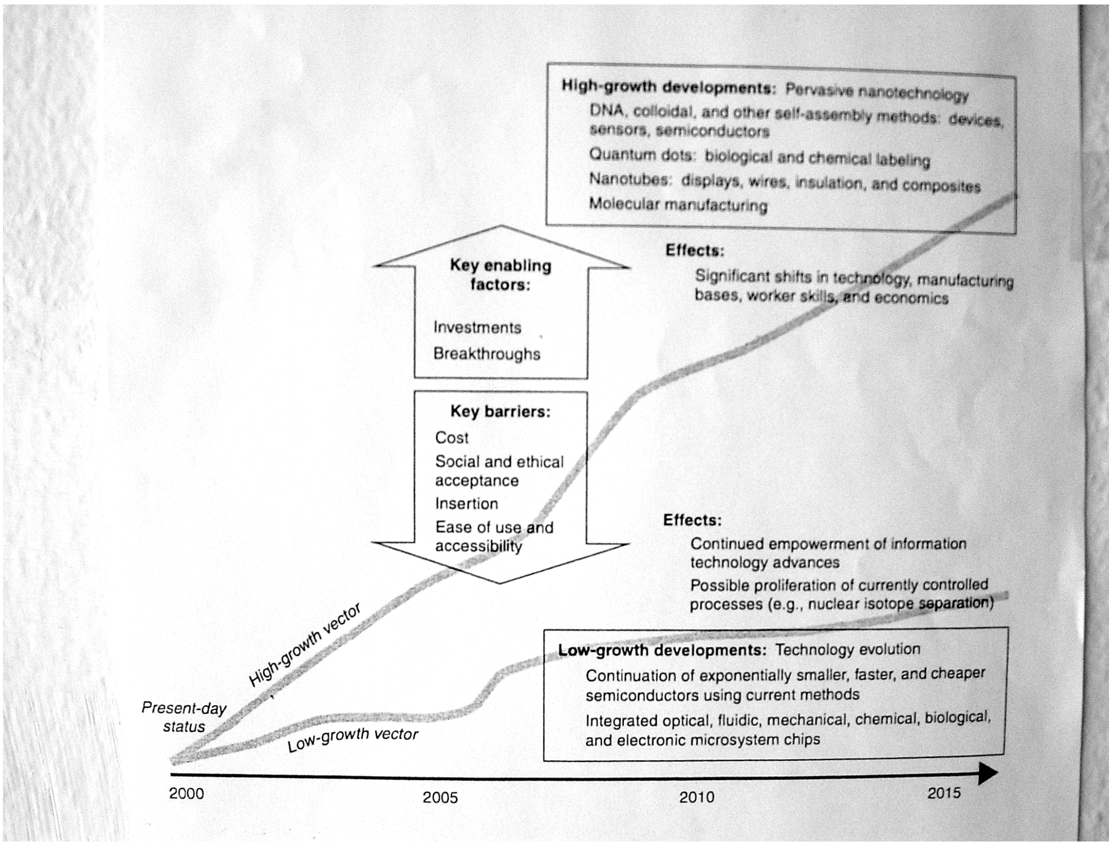
In two of the scenarios, nanotechnology is accepted strongly by society, albeit as a solution to problems posed by external forces such as bioterrorism and oil shortages. In the other, nanotechnology is rejected by society because of a more general backlash against science and technology although nanotechnology products continue to be used. These alternative views of the future support the need to address social and ethical concerns of nanotechnology at an early stage.

5. CONCLUSION

It is clear that there are a number of possible futures for nanotechnology. Figure 3 shows a range of opinions on where nanotechnology might be by 2015 (Anton et al

2001). Continued high-visibility investments and technology breakthroughs will be needed to realise its full potential, but soaring R&D costs, complexity, accessibility and social and ethical acceptance could slow its growth. The optimistic future is best exemplified by the vision of pervasive manufacturing involving molecular manufacturing of a range of nanosystems which could take place on a global scale giving developing countries the opportunity to invest in and use nanotechnology. From a more pragmatic approach, lack of technological breakthroughs and problems with standards could limit the outcome by 2015 to a path where the current trend to smaller, faster and cheaper systems continues through advances in semiconductor production.

Figure 3 – Range of Possible Future Developments and Effects of Nanotechnology



APPENDIX

The Conduct of the APEC CTF Study (APEC 2002)

Given the breadth of the study and the diversity of professionals involved, APEC CTF decided in early 2001 to set the scene by having position papers prepared by expert teams from four economies. These were: nanophotonics (Canada), nanobiosystems (Australia), nanoelectronics (Japan) and nanostructured materials (Chinese Taipei). There was also a paper from the Philippines on implications of nanotechnology for developing economies.

On the basis of these and independent research by APEC CTF, an issues paper was prepared which identified ten general issues deemed to be important for the future of nanotechnology. All of this material was placed on the APEC CTF website to create awareness of nanotechnology in the region and to stimulate debate. A presentation of the issues was made at Technomart IV in Suzhou, China in September 2001.

An Experts' Meeting was held in Ottawa in November 2001, generously hosted by the National Research Council of Canada. 29 Experts from nine APEC economies participated in the meeting. To complement short presentations of the commissioned position papers, representatives of the economies present gave short reviews of the state of nanotechnology in their respective economies. Experts at this meeting were then invited to brainstorm technological opportunities in nanotechnology in the near and long term, before discussing the issues set out in the APEC CTF paper. The scenario creation technique was then used to identify possible futures for nanotechnology in the region and to draw out more clearly time scales for technological development and also the policy implications which are set out elsewhere (APEC 2002, Tegart and Sripaipan 2002).

REFERENCES

Anton, P S, Silberglitt,R and Schneider,J 2001 "The Global Technology Revolution: Bio/Nano/Materials Trends and their Synergies with Information Technology by 2015", RAND, Santa Monica/Arlington, pp69.

APEC 2002 " Nanotechnology; the technology for the 21st century" Vol 1 Summary Report, June, pp28; Vol 2 The Full Report, August,pp194, NSTDA Bangkok.

Bachmann,G 2002 "Interdisciplinary Co-operation: a critical need in nanotechnology", Asia Pacific Tech Monitor, Vol 19, No5, pp34-40.

Comparo,R 2002 "Nanotechnology: what is at stake?", Asia Pacific Tech Monitor, Vol 19, No5, pp25-33.

Drexler,K E 1992 "Nanosystems: Molecular Machinery, Manufacturing and Computation", John Wiley and Sons, New York.

Harper, T E and Hollister, P 2002 " Nanotechnology: the emerging cutting-edge technology", Asia Pacific Tech Monitor, Vol 19, No5, pp41-46.

Roco, M C 2001 "International strategy for nanotechnology research and development", J. Nanoparticle Research, Vol3, pp353-360.

Tegart, G, and Sripaipan 2002 "The Technology for the 21st Century" , Asia Pacific Tech Monitor, Vol 19, No5, pp17-24.

Tegart, G 2002 "Nanotechnology: the challenge for educators", ATSE focus No 124 Nov/Dec, pp 22-26(this paper is also on the APEC CTF website under Nanotechnology Education and Training).