Nanotechnology:
The Technology for the 21st Century

Volume 1 – Summary Report of a Foresight Project

Asia-Pacific Economic Cooperation
APEC Industrial Science and Technology
Working Group

The APEC Center for Technology Foresight
National Science and Technology Development Agency
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The APEC Center for Technology Foresight

The APEC Center for Technology Foresight (APEC CTF) was established in Bangkok in February 1998 by the Royal Thai Government with the objective of serving and involving all APEC member economies in diffusing foresight expertise across the APEC region. However, the aim is not just to assist member economies with their own foresight efforts, but also to conduct research at a multi-economy level. Foresight should be able to contribute to strategy and policy development on issues which cross national boundaries. Examples of studies carried out that fit this criterion include "Water Supply and Management", "Technology for Learning and Culture", "Healthy Megacities" and, now, "Nanotechnolgy"–. APEC CTF has been a pioneer in the field of multilateral foresight Other organizations that are also supporting multilateral foresight studies include the Institute for Prospective Technological Studies in Seville, Spain, and the United Nations Development Organisation based in Vienna, Austria.

The APEC Center for Technology Foresight has adopted a broad definition of foresight, as follows:

> *"Foresight involves systematic attempts to look into the future of science, technology, society and the economy, and their interactions, in order to promote social, economic and environmental benefits."*

Foresight is concerned with the development of a range of possible futures which emerge from alternative sets of assumptions about emerging trends and opportunities.The knowledge developed through foresight allows organizations to make strategic choices and enables them to adapt quickly to changing trends based on social, technical or economic drivers.

Foreword

In this study, foresight is applied to the development of a new and exciting research field - nanoscience and nanotechnology.

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, mathematics, physics biology and engineering, to form the new field of nanotechnology. We can define nanotechnology as "materials and systems whose structures and components exhibit novel and significantly improved physical, chemical and biological properties, phenomenoa and processes due to their nanoscale size. The goal of nanotechnology is to exploit these properties by gaining control of structures and devices at atomic, molecular and supramolecular levels and to learn to efficiently manufacture and use these devices.

The field of Nanotechnology covers a wide range of activities including fabrication of functional nanostructures with engineered properties, synthesis and processing of nanoparticles and materials, 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 thin films. Given such a wide range of technology options, which will potentially have broad impacts on the world economy and on society, APEC CTF decided to carry out a foresight study of nanotechnology in the APEC region.

The APEC CTF is grateful for the substantial contribution of Position Papers by four economies on nanobiosystems (Australia), nanoelectronics (Japan), nanophotonics (Canada) and nanostructured materials (Chinese Taipei), and to the Philippines for a paper on issues for developing economies. We are particularly grateful to the authors and the institutions that allowed them to devote time to this project.

The CTF would also like to thank the National Research Council of Canada for hosting an Experts Meeting of 26 nanotechnology researchers from 9 APEC members economies and for providing opportunities for informal interaction that contributed substantially to the success of the project. We are particularly grateful to the Experts for giving their time and experience to create a successful meeting and to their economies which supported their attendance. The short papers presented by these Experts on the state of nanotechnology in their respective economies, together with the

Position Papers and the Issues Papers, are published in Volume 2 as a contribution to increasing the awareness of nanotechnology among researchers and industrialists in the APEC economies.

This report (Volume 1) is aimed at policymakers and their advisors and sets out the essential steps of the process, the key issues for the development of nanotechnology and the views of the Experts on future directions. APEC CTF trusts that the study will contribute to the strategic management of nanoscience and nanotechnology in APEC economies.

APEC CTF is pleased to acknowledge the continued financial support of the Royal Thai Government through the National Science and Technology Development Agency. This project was run as a self-funded project by APEC CTF under the APEC Industrial Science and Technology Working Group.

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Executive Summary

This report describes a foresight study of 'Nanotechnology: The Technology for the 21st Century', conducted by the APEC CTF (Asia-Pacific Economic Cooperation Center for Technology Foresight) located within the National Science and Technology Development Agency of Thailand. The driver for the study was the recognition by the International Advisory Board of APEC CTF that nanotechnology is a rapidly developing field of science and technology with the capability of making even greater change to society than information and communications technologies or biotechnology.

The conduct of the study involved: the preparation by APEC member economies of four position papers on nanobiosystems, nanoelectronics, nanophotonics and nanostructured materials and a paper on the implications of nanotechnology for developing economies; the development of an issues paper by APEC CTF and the identification of opportunities and policies for nanotechnology through scenario development and analysis by Experts at a workshop in Ottawa in November 2001. The Workshop involved 26 Experts from 9 economies who represented a wide range of disciplines.

Ten key issues were identified for the development of nanotechnology in APEC economies namely:

1. Definition of nanotechnology

Nanotechnology has resulted from the convergence of chemistry, physics, mathematics, biology and engineering to form a new field of science and technology. This often causes confusion and there is a need for APEC economies to develop effective public awareness programs to alert their societies to the new technology and its implications.

2. Opportunities for nanotechnology

The three main categories of opportunities are: molecular engineering inspired by biotechnology, electronic and photonic technology based on conventional and novel semiconductor materials, and other devices and processes based on new materials. Each area has enormous growth potential and APEC economies need to identify the opportunities in their respective economic, industrial and social contexts.

3. Scientific and technological inputs and implications for facilities

A wide range of physical and chemical techniques is used in the development of materials and devices at the nanometer level. These all require sophisticated and expensive facilities. Thus APEC economies need to focus resources to create national competence in nanotechnology.

4. Education and training

The development of nanotechnology challenges the traditional separation of academic disciplines into chemistry, physics, mathematics, biology and engineering. There is a need for APEC economies to increase multidisciplinarity which implies significant changes in their academic institutions.

5. Funding of nanotechnology R&D

Some large APEC economies have funded major national programs to develop nanotechnology. Smaller economies need to assess their strategic position and make adequate provision to create and maintain a critical mass of expertise.

6. Regional collaboration and networks

The magnitude of investment needed for equipment and facilities for nanotechnology disadvantages smaller economies and APEC can assist by encouraging regional collaboration to allow wider access to specialised facilities in larger economies.

7. Commercialisation of nanotechnology

Nanotechnology is creating a new paradigm in manufacturing and much of industry in many APEC economies will have to change management approaches and company strategies. Economies need to ensure that their business leaders are made aware of opportunities arising from nanotechnology and that close interaction is developed between researchers and industrialists.

8. Nanomeasurement and standards

The establishment of standards and a metrology system at the nanotechnology level is the key to the further growth of an industry sector. APEC economies must ensure that their national standards bodies are aware of the challenges posed by nanotechnology while APEC needs to press for establishment of a universally recognised system for nanometrology.

9. Implications for small and less developed economies

These economies face a series of critical decisions in defining the role of nanotechnology in their futures. These cover provision of equipment and facilities, education and training of nanotechnologists, identification of industry opportunities etc. Decision-makers in such economies need to set up advisory groups of specialists to assist them.

10. Societal implications of nanotechnology

The enormous potential for nanotechnology to radically change the current situations in manufacturing, health care, energy supplies, communications and defence has significant social implications for the future of all APEC economies. It is vital for leaders to encourage widespread debate at this early stage of the development of nanotechnology in order to define issues unique to their economies in applications such as agriculture, environment, employment and health care.

For APEC economies to participate in the benefits flowing from the development of nanotechnology, it is essential for national governments to make strategic decisions on allocation of resources, education and training, international linkages, support to local industry, adoption of nanostandards and safeguards. APEC has a role to play by ensuring that experience in nanotechnology issues is shared among economies by promoting multi-economy R & D programs, by encouraging sharing of specialised equipment and facilities, and by recognising that nanotechnology has benefits and possibly poses some threats.

The choices that economies make in the near future will influence profoundly their future economic growth and the development of nanotechnology in the APEC region.

1. Introduction

1.1 The Rationale for Selection of Nanotechnology

Recent years have seen an explosive growth of interest in nanotechnology. There is potential for enormous industrial developments flowing from nanotechnology research, as well as very significant social consequences if nanotechnology is widely adopted. This has been recognised by many scientists, and by some (but by no means all) national governments. Such growing interest in the topic is confirmed by the strong and unanimous support given to this project by APEC members[1] at the APEC Industrial Science and Technology Working Group at its meeting in Hanoi on 24-26 April 2001.

The APEC CTF recognised the importance of Nanotechnology to the future of APEC member economies and agreed that it fitted the Center's chosen criteria for a foresight study. Nanotechnology may have a profound impact on most if not all member economies and many of the concerns about its development and impacts transcend national boundaries, so that an international foresight study can go beyond what might be achieved by a national or bi-lateral study. It has been argued that APEC economies stand on the brink of a "Nanotechnology Revolution" whose effects on societies and economies will be as pervasive and dramatic as the "ICT(information and communications technology) Revolution" of the late twentieth century. Thus it is imperative to start the debate immediately about how to develop nanotechnology effectively and for the public good, and to engage a very wide range of stakeholders including non-scientists in this debate.

1.2 Nanotechnology – a new paradigm

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, mathematics ,biology and engineering to form the new field of nanotechnology. Nanotechnology is concerned with the fabrication and use of materials, devices and systems so small that the convenient unit of measurement is the nanometer (a billionth of a meter). At this very small scale the characteristics of molecules and atoms in the material exhibit important new properties different from the material's bulk properties .These novel properties are being harnessed to develop devices and materials , which significantly improve performance. The theme of the field is "novel performance through nanotechnology".

We can define nanotechnology as "materials and systems whose structures and components exhibit novel and significantly improved physical, chemical and biological properties, phenomenoa and processes due to their nanoscale size. The goal of nanotechnology is to exploit these properties by gaining control of structures and devices at atomic, molecular and supramolecular levels and to learn to efficiently manufacture and use these devices". The field of Nanotechnology covers a wide range of activities including fabrication of functional nanostructures with engineered properties, synthesis and processing of nanoparticles and materials, 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. Given such a wide range of technology options, which will potentially have broad impacts on the world economy and on society, APEC CTF decided to carry out a foresight study of nanotechnology in the APEC region.

Researchers and technologists are approaching the field of nanotechnology from three directions:

[1] APEC's 21 members are referred to as 'economies' rather than countries or nations, and include: Australia; Brunei; Canada; Chile; China; Hong Kong, China; Indonesia; Japan; South Korea; Malaysia; Mexico; New Zealand; Papua New Guinea; Peru; the Philippines; Russia; Singapore; Chinese Taipei; Thailand; the USA and Vietnam.

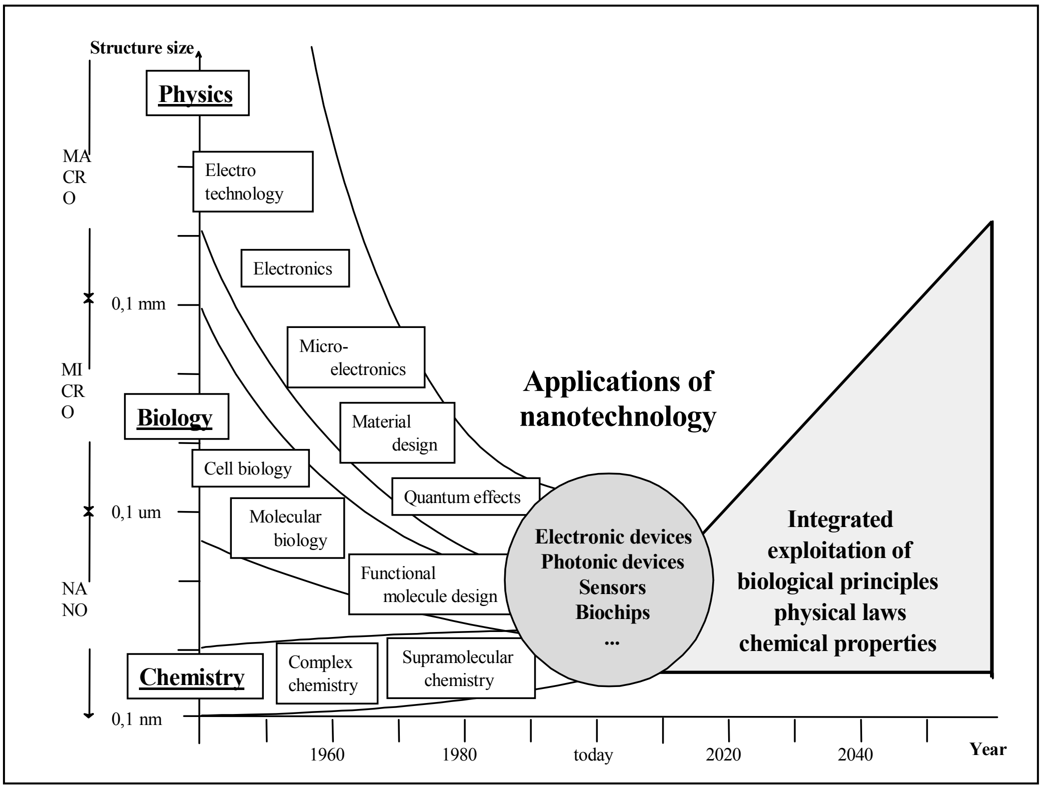
- In physics, the field of nanoelectronics is moving towards smaller feature sizes and is already at 100 nanometer line widths. Processors in computing systems will need nanometer line widths in the future as miniaturisation proceeds.

- In chemistry, improved knowledge of complex systems has 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 and sensors.

The convergence of disciplines is well illustrated in Figure 1 which also shows the scales of the areas of interaction. There is considerable debate in the scientific community about the boundaries of the new disciplines emerging from this convergence e.g. 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.

2. The Conduct of the Study

Given the breadth of the study and the diversity of professionals involved, APEC CTF[2] decided to set the scene by having position papers prepared by expert teams from four

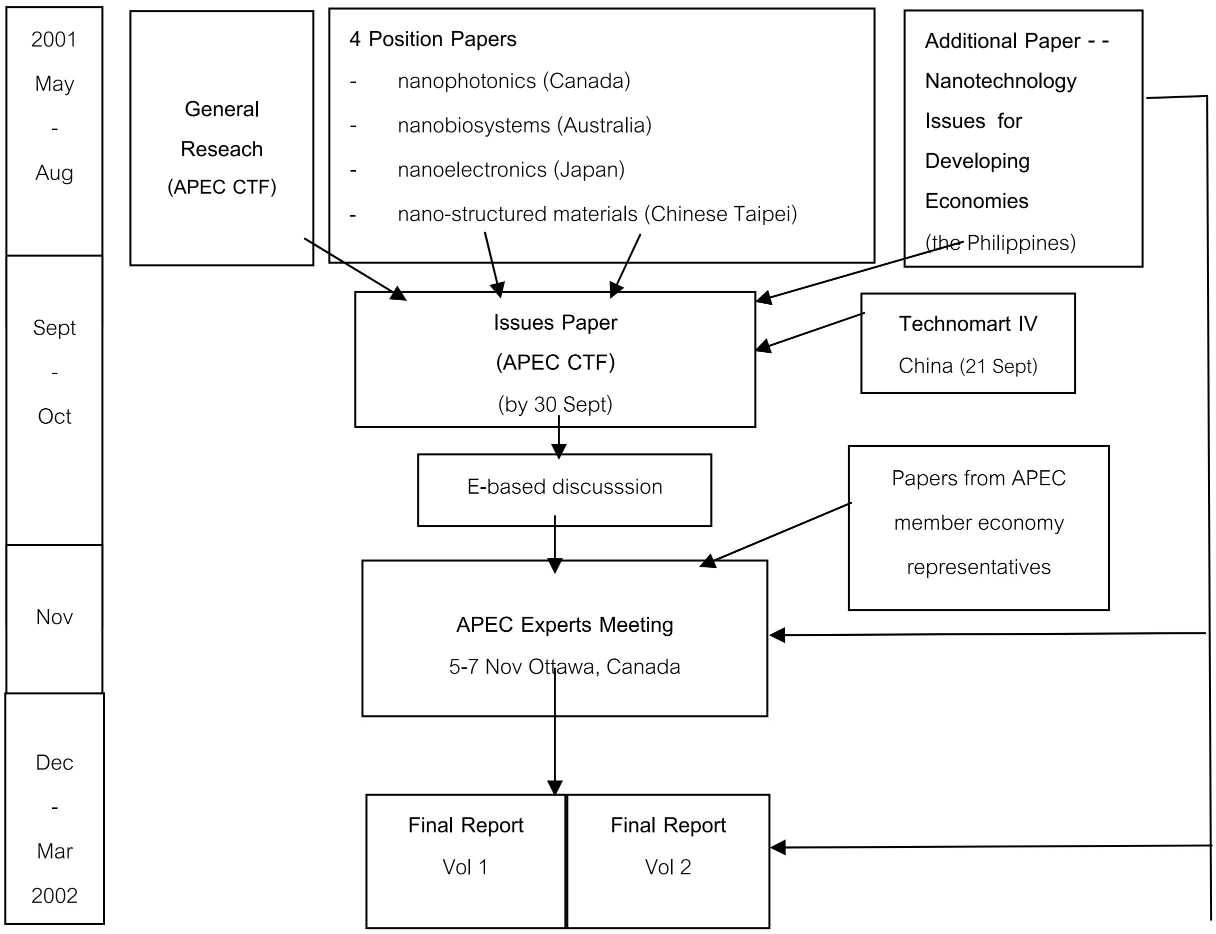
[2] The project was led by Prof Greg Tegart, Executive Advisor of the APEC CTF, with strong support from the Center's International Advisory Board and its staff. For more details, see <http://www.apectf.nstda.or.th/html/our_org.html>

economies. These were: *nanophotonics* (Canada), *nanobiosystems* (Australia), *nanoelectronics* (Japan) *and nanostructured materials* (Chinese Taipei). In addition, a paper was prepared on *nanotechnology issues for developing economies* by the Philippines.

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. These issues are discussed in Section 3. All of this material was placed on the APEC CTF web site with a view to creating awareness of nanotechnology in the APEC region and to stimulating debate with experts around the region. These aims were also pursued at a special session on nanotechnology organised at APEC Technomart IV in Suzhou, China.

An Experts' Meeting was held in Ottawa from 5-7 November 2001, generously hosted and supported by the National Research Council of Canada. 26 Experts from 9 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. All of this background material is gathered together in Volume 2 to present a picture of activity in nanotechnology in the APEC region. 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 the policy implications. This is discussed in Section 4.

Project Process



3. Key issues in the Development of Nanotechnology

These issues were identified through examination of the extensive literature and the material provided by the commissioned position papers, and were discussed by the APEC experts at the meeting in Ottawa. More details can be found in Volume 2.

3.1 Definition of Nanotechnology

In Section 1.2, we have seen that a new paradigm 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, mathematics biology and engineering to form the new field of nanotechnology as shown in Figure 1. A general definition, which captures the present thrust in the field, is:

. "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. The goal of nanotechnology is to exploit these properties by gaining control of structures and devices at atomic, molecular and supramolecular levels and to learn to efficiently manufacture and use these devices.

Because of the diversity of interests involved in nanotechnology, there is often confusion in the rest of society about the nature of nanotechnology. Many consider an effective public awareness program is necessary to clarify misunderstandings about nanotechnology. A threat to shaping a new understanding required by nanotechnology is posed by the temptation to re-badge old technology which has some similar characteristics as nanotechnology.

3.2 Opportunities for Nanotechnology

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

- *Molecular engineering inspired by biotechnology*

The scale of living systems (at the cellular or sub-cellular levels) is in the range from micrometers down to nanometers. One biological application of nanotechnology is the possibility of combining biological units such as enzymes into manmade nanostructures, which has stimulated the study of the interface of biological molecules with inorganic materials. For example, by combining enzymes and silicon chips we can produce biosensors. These could be implanted in humans or animals to monitor health or 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. Other applications of biosensors will be in environmental control of food production and of water supplies. Development of human biomedical replacements such as artificial skin, smart bandages, pacemakers, etc will also benefit from developments in nanotechnology.

- *Electronic technology based in semiconductors*

There is potential to increase the capacity of electronic chips to contain up to 1 billion components per chip with the application of conventional technoloogies. 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 of electronic components and increasing the complexity of chips using conventional technologies. Research is focussing on the fabrication of electronic structures on the nanometer scale based on entirely new processes. Devices under development include: molecular electronics and photonics, lasers for optoelectronics, ultrafast switches, memory storage devices for computers and, ultimately, devices controlled by single electron events. These have the potential to revolutionise communications and information technology with flow-on through all aspects of modern life.

- *Devices and processes based on new materials*

Materials chemistry and surface science are 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. Modification of surfaces to a depth of 1-100 nm can lead to significant changes in properties such as friction, corrosion and reactivity.

Products based on nanotechnology are already widely used, e.g. 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, communications, 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 in Volume 2 of this report.

These opportunities were reinforced in the discussions at the Experts' Meeting in Ottawa. However, there is surprisingly little agreement even among nanotechology experts about the likely timing of developments. Nevertheless, the Experts were asked to attempt to identify promising opportunities in 3 years and in 10 years for the three main categories as summarised in Table 1.

Although the timing may be uncertain, it is nevertheless absolutely clear that there are a multitude of opportunities for the development of devices and materials based on nanotechnology. Some of these will create new industry sectors and replace existing ones. It is clear that nanotechnology has the potential to change significantly a large cross-section of life in all APEC economies in the next decades.

Some examples are:

Electronics: Nanotechnology is projected to yield annual production about US$300 billion for the semiconductor industry and even more for global integrated circuit sales within 10 to 15 years.

Improved Healthcare: Nanotechnology will help extend the life span, improve its quality, and extend human physical capabilities.

Pharmaceuticals: About half of all production will be dependent on nanotechnology – affecting over US$180 billion per year in 10 to 15 years.

Chemical Plants: Nanostructured catalysts have applications in the petroleum and chemical processing industries, with an estimated annual impact of US$100 billion in 10 to 15 years.

Environment: In 10 to 15 years, projections indicate that nanotechnology-based lighting advances have the potential to reduce worldwide consumption of energy by more than 10% reflecting a savings of $100 billion dollars per year and a corresponding reduction of 200 million tonnes of carbon emissions.

The scale and breadth of such impacts of nanotechnology mean that Governments must start now to develop strategies to cope with significant social and economic changes similar to those already flowing from the information technology revolution and the moves to a knowledge society.

Table 1. ***Estimated timing of the realisation of some Technological Opportunities in Nanotechnology, Identified at Experts' Meeting in Ottawa***
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

3.3 Scientific and Technological Inputs and Implications for Facilities

Since nanotechnology is based on inputs from different disciplines, a wide range of facilities and techniques is used in the development of materials and devices at the nanometer level. Examples of these are: ultra precision machinery; lithography using electrons, UV radiation or X-rays; microelectromechanical systems using micromachinery and substrate bonding; scanning probe microscopes; computer modelling; cluster science or mesoscience based on aggregation of atoms or molecules; nanostructured materials in one dimension (thin film), two dimensions (fibres) and three dimensions (powders).

All of these require sophisticated and expensive facilities which are dispersed in different laboratories in academia, government research establishments and industry. This has significant implications for APEC economies in terms of organisation of their R & D resources to create national competence in nanotechnology and in funding and provision of trained personnel to operate specialised equipment.

3.4 Education and Training

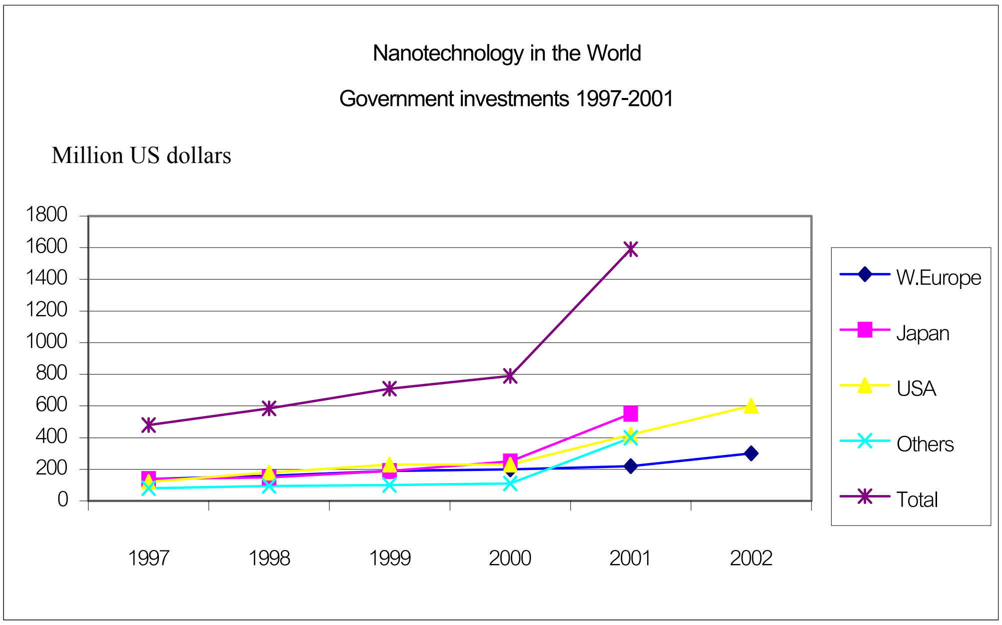
The range of inputs and equipment needed for development of nanotechnology challenges the traditional separation of academic disciplines into physics, chemistry, biology and engineering. There is a need to increase multi-disciplinarity which implies significant changes in academic institutions. The challenge is then to achieve the breadth and depth of training of people to enable them to create new concepts in nanotechnology. Courses on surface science, molecular dynamics, quantum effects and manufacturing at a molecular level could help integration of research and education into a new paradigm of a cross-disciplinary approach rather than one based on individual disciplines .

One approach is for universities to set up interdisciplinary centres of expertise in nanotechnology and then link these to industry to provide an environment to educate young scientists and technologists and to train the current workforce in the techniques of nanotechnology. This 'bottom-up' approach has worked well in other areas, e.g., ICT and biotechnology, particularly in institutions with generous discretionary funding.

3.5 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. Several APEC economies have strong national programs, e.g. USA, Japan, China, Korea, Chinese Taipei and Canada. 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.

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 used, 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 APEC economies will be assisted by national recognition of the importance of nanotechnology and provision of special funding to support research, development and demonstration.



Source: MC Roco *International Strategy for Nanotechnology Research and Development.* Journal of Nanoparticle Research 3: 353-360, 2001

3.6 Regional Collaboration and Networks

The magnitude of investments in equipment and facilities will mean that all but the very largest economies will only be able to afford a limited number of major centres in nanotechnology. Thus it is necessary to consider how national facilities in such economies can be made available to researchers in less well-endowed economies. Opportunities for visiting researchers to participate in collaborative projects is one mechanism to assist in developing expertise in nanotechnology throughout the APEC region.

The setting-up of an APEC network in nanotechnology would also serve to link the research community in the region. Similar networks exist in Europe and the USA and these could provide linking points to wider international access for APEC researches.

3.7 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. As noted above, in some developed economies, companies have recognised the potential of nanotechnology and nanostructured materials; however, they are looking carefully for the right opportunity to become involved in this field. 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-business 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 competent networks with academia and government labs, 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.

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

The situation is particularly difficult in small or less developed economies where such attitudes of industry leaders are generally more marked. The need for a public awareness program to promote nanotechnology and its potential for society and industry is clear and Governments must be made aware of such a need.

3.8. Nanomeasurement and Standards

The position papers on Nanophotonics and Nanostructured Materials have both highlighted the importance of metrology in the commercialisation of nanotechnology. They emphasise 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. The Department of Energy in the USA recently organised a workshop to deal with this problem, and a number of specific goals were set for the next 5-10 years. These included: 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.

General areas for R&D in this area are:-

- **New atomic scale measurements** for length, mass, chemical composition, and other properties;
- **New nanoscale manufacturing technologies** to be used by industry in assembling new devices at the atom or molecule level;
- **New standard methods, data, and materials** to transfer nanotechnology to industry and to assure the quality of the new nano-based commercial products.

3.9 Implications for Small and Less Developed Economies

Implications of development of expertise in nanotechnology have been noted in previous issues, e.g. need for expensive facilities, major changes in teaching and research approaches, awareness programs for industry, identification of opportunities in nanotechnology, funding allocations, networking. For small and less developed economies, these issues pose major policy decisions.

The magnitude of the investments will mean that all but the very largest economies will not be able to afford to have more than a handful of sites for nanotechnology R&D. Therefore sharing of national facilities will be a major need. Such common laboratory settings can provide an excellent means for a for the mixture of ideas from one discipline to another, and from one economy to another. Indeed, it can be imagined that this may be an excellent platform for smaller and less developed APEC economies to share in the development of nanotechnology.

The position paper produced by the Philippines highlighted the need for less developed economies to use funding for nanotechnology to build on their existing resources and capabilities, but also to identify niche areas where opportunities exist. Thus in the Philippines, the following areas have been identified: biosensors, optoelectronic devices, pharmaceuticals and polymers and composites. These have been selected on the basis of strategic importance and competitive advantage.

3.10 Societal 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 probably defence, then it will transform labour and the workplace, the medical system, the transportation and power infrastructures and the military. None of the 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 genetically modified biotechnology products, it would be prudent to consider now the societal implications, both positive and negative, of nanotechnology.

It seems likely that the first wave of useful technologies will be in the area of detection and sensing. The capacity to detect precisely and identify viruses and even single molecules has broad applications in medical diagnosis, forensics, national defence and environmental monitoring and control. The potential benefits are obvious but what are the threats?

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 congenital defects in fetuses for which the only ‘cure’ is abortion. Better detection through nanotechnology will increase the number of these. Another example is detection of pollutants at extremely low concentrations which raises complex questions about risk thresholds and appropriate remediation standards. Thus the presence of tiny amounts of toxic material in groundwater may justifiably raise alarm in society even if the health risks cannot be assessed and the technological capability of remediation does not exist. This may have unintended consequences of closing industry in an area, with social ramifications. 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.

It is possible to identify several general societal implications of nanotechnology as:

- Social equity: distribution of the benefits of nanotechnology
- Social purpose: the actual goals of societal development that we want to advance

- Economic and social enterprises: the structure of the institutions at the interface between nanotechnology and society.

Following discussion at the Experts Meeting, these ten issues were accepted as a sound basis for policy development and strategic planning. A further issue was added, namely that of the need for a flagship project (national or regional) for the development of a product or process that could only be achieved through the application of nanotechnology. One suggestion was the development of technology to cope with bioterrorism, but there are clearly others that could be identified.

4. Scenario-Based Futures

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 the Experts identified a large number of drivers using the STEEP approach. Their findings can be summarised as in Table 2.

Table 2. Key Drivers for the Development of Nanotechnology Identified by Experts in Ottawa

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

Economies
- 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

The Experts then speculated on possible, even improbable, events which could occur to change the pattern of development of nanotechnology. Again they identified a large number of uncertainties which have been summarised as in Table 3.

Table 3. Critical Uncertainties for the Development of Nanotechnology Identified by Experts in Ottawa

Technical Uncertainties
- Nanotechnology fails to deliver
- Inability to solve standards issues
- Breakthroughs in current technical paradigms – devices and materials

Environmental / Economic Uncertainties
- Major financial crisis
- Kyoto Protocol ratified by all economies
- Major disruption of energy supplies

Political / Societal Uncertainties
- Lack of public acceptance of nanotechnology
- Nanotechnology facilitates major advances in bio-health
- Terrorism and national security

Global Uncertainties
- World War III
- Widespread epidemic

Using these inputs and bearing in mind the technological opportunities identified in Section 1 and the issues identified in Section 3, the Experts constructed three scenarios for 2015. (The full scenarios are presented in Volume 2).

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 technical position papers and 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. Policy Implications for Future of Nanotechnology in the APEC Region

This study has identified a set of issues critical to the future of nanotechnology and policymakers in APEC economies must take account of these in considering the strategic management of their S&T resources, both people and facilities. Based on these issues, the following policy responses are recommended:

- ***Broader recognition of nanotechnology in APEC economies as a new technology arising from a fusion of physics, chemistry, mathematics, biology and engineering.***

A good example of a response is the educational outreach program being supported by the US National Science Foundation. This is designed to reach the general public through exhibits in museums and to reach middle and high school students through special designed learning modules. Opportunities are provided to interact with research scientists in nanotechnology.

A critical area is the introduction of nanotechnology into courses for technicians and for managers in industry to alert them to the changing paradigm of manufacturing.

- ***Identification and Assembly of Resources for R&D in Nanotechnology as a National Program***

Such programs already exist in the larger developed APEC economies but other economies need to move rapidly to ensure that they are not left behind in the exploitation of nanotechnology. Given the very large capital investments needed in facilities for research in physical and chemical aspects of nanotechnology, it is possible that small, and less developed, economies may see the biological route to nanotechnology development as more applicable to their economies.

- ***Increased Multidisciplinarity in Universities to Ensure Development of a Nanotechnology Workforce***

Academic disciplines such as physics, chemistry, biology and engineering have been separated by culture, management and terminology. New approaches to course design and to the setting-up of interdisciplinary research centres are needed. These must interact with industry to exploit research results.

- ***Adequate Funding to Ensure that Economies can Develop and Foster Expertise in Nanotechnology***

Large developed APEC economies have earmarked large sums for R&D in nanotechnology. Small, and less developed, economies must make adequate provision for funding to create and maintain a critical mass of expertise in the nanotechnology area.

- ***Developing a Network of APEC Resources in Nanotechnology***

This is particularly important for the smaller, and less developed, economies to ensure that their researchers gain rapid access to development in nanotechnology throughout the APEC region. A network also offers the opportunity for researchers from different economies to collaborate on projects of mutual interest and to identify possibilities for future development.

- ***Identification of Opportunity Areas in Technology***

Foresight techniques offer a tool to assist in tackling this challenge and APEC economies need to start prospective dialogues among officials, academics, researchers, industrialists and the community on the possibilities of nanotechnology in their different contexts.

- ***Changing of Mindsets of Industry Leaders and Investors in APEC Economies***

To take advantage of opportunities offered by nanotechnology there needs to be radical changes in management approaches and company strategies. Most industry leaders and investors are unaware of the potential for change and economies must develop awareness programs aimed at industry leaders and investors. Management courses must include discussion of emerging technologies including nanotechnology. Researchers can assist by offering their services to help industries solve their problems by application of nanotechnology.

- ***Establishment of Standards and a Nanometrology System***

National and international standards bodies must recognise the importance of establishment of a universally – recognised system for nanotechnology. Measurements and calibration at nanometer levels will require completely new approaches to those currently employed. However, without a nanometrology system, commercialisation will be inhibited.

- ***Implications for Small and Less Developed Economies***

As noted above, small and less developed, economies face a series of critical decisions in defining the role of nanotechnology in their futures. The formation of an advisory group of researchers with multidisciplinary skills is perhaps the most immediate way to assist decision-makers by provision of advice on nanotechnology.

- ***Ethical and Moral Concerns Arising from Nanotechnology***

The ethical and moral problems that have arisen in the development and commercialisation of biotechnology can be envisaged to arise with nanotechnology. It is important for APEC economies to encourage debates between researchers, social scientists and community representatives at an early stage to define issues unique to their economies eg in agriculture, environment and health care.

While individual economies must tackle these key policy areas within their own systems, there is a role for APEC, through Ministerial and Working Group meetings, to:

- Give leadership in ensuring that experience with these different issues is shared;
- Facilitate the development of nanometrology databases;
- Support multi-economy and multidisciplinary programs on nanotechnology;
- Stimulate the move to a new paradigm in manufacturing based on nanotechnology;
- Encourage economies to address the institutional barriers to the equal participation of women in APEC's S&T workforce, since it is clear that woman are under-represented within the field of nanotechnology research as in so many other branches of science and technology.

- Support the concept of sharing facilities and specialised equipment to enable less-developed economies to gain expertise in nanotechnology.

The choices that APEC economies make in the next few years will influence profoundly their future economic growth and the development of nanotechnology in the APEC region.

6. Conclusion

Nanotechnology represents the beginning of a revolution in our ability to manipulate materials for the good of humanity. As with all new technologies there are benefits and threats. The challenge for policymakers is to recognise these at an early stage through techniques such as the foresight approach and to put in place appropriate policy measures. The choices that APEC economies make in the next few years will influence profoundly their economic growth and the well-being of their citizens.